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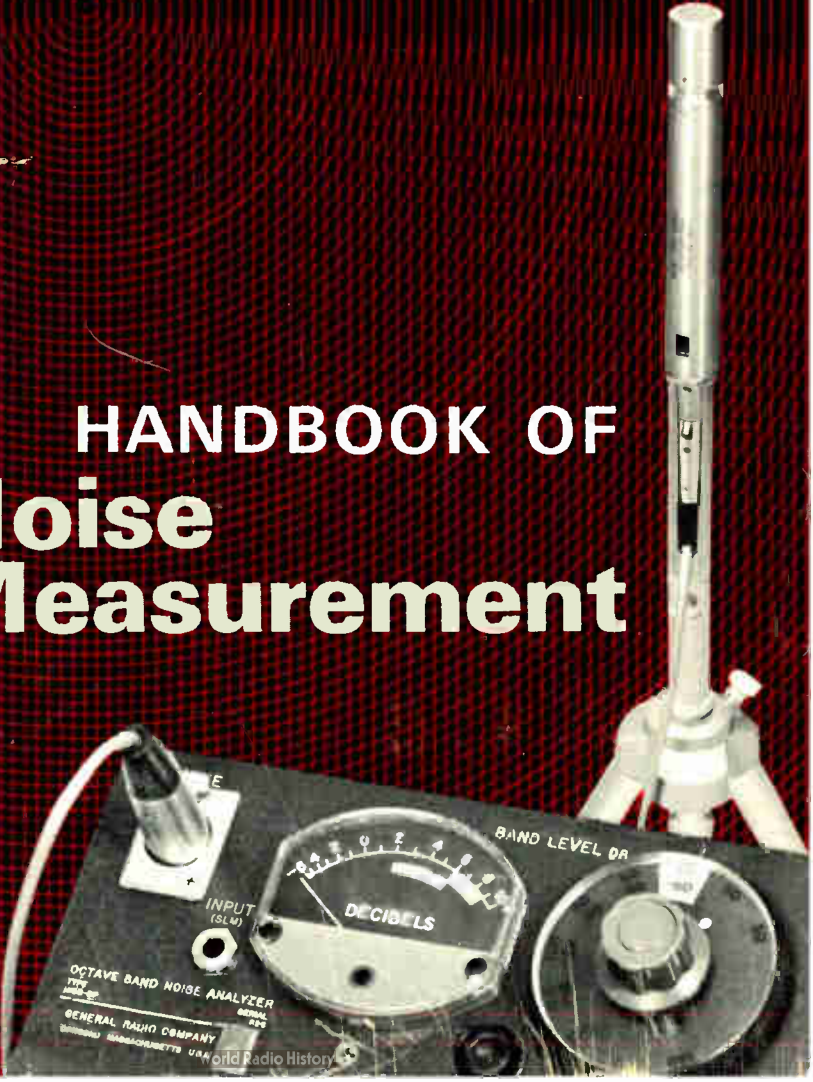
# HANDBOOK OF Noise Measurement



# HANDBOOK OF Noise Measurement

## (SIXTH EDITION)

by Arnold P. G. Peterson
and Ervin E. Gross, Jr.

Price: $2.00

GENERAL RADIO COMPANY

*West Concord, Massachusetts, U.S.A.*
PRINTED IN U.S.A. Form 811-G

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# ACKNOWLEDGEMENT

This handbook has been almost completely rewritten to bring it up-to-date and to follow the helpful suggestions made by our associates and by many users of General Radio Company instruments. We appreciate the continued interest shown by so many in this work, and we wish to thank in particular, Richard P. LaJeunesse for his extensive help in preparing this revision.

We also want to take this opportunity to thank Charles E. Worthen for the many years he has guided us in the art of technical writing. We can do this now; because of his retirement, he cannot edit out this acknowledgement.

Arnold P. G. Peterson
Ervin E. Gross

## chapter 1

# INTRODUCTION

During the past decade more and more people have become concerned with the problem of noise in everyday life. Manufacturers of home appliances, such as vacuum cleaners, mixers, and washers, have found that a noisy product meets sales resistance. Manufacturers of large industrial equipment, such as distribution transformers that must be located in or near residential areas, have found that care must be taken in the construction and installation in order that noise levels do not annoy the residents. Trucking companies receive complaints when mufflers are inadequate or defective.

There is danger of permanent hearing loss when exposure to an intense sound field is long and protective measures are not taken. This problem has become a matter of serious concern to industrial corporations, labor unions, and insurance companies.

Lack of proper sound treatment in the classroom may lead to excessive noise levels and reverberations, with resulting difficulties in communication between teacher and class. The school teacher's job may become a nightmare because a few corners were cut to decrease, by some small fraction, the initial cost of the classroom.

The General Radio Sound-Measuring System has been developed to help the many people whose job it is to determine the noise output from machines, trucks, airplanes, and appliances, or the noise environment in homes, schools, factories, and recreation centers.

In addition to the measurement of noise, this equipment has many applications in measuring the performance of systems transmitting music and speech, in evaluating the characteristics of acoustic materials, in psychoacoustical studies, and in many other fields of physical science, engineering, and the social sciences.

To the physicist, noise is a sound, whose character can be defined and whose properties can be measured with the same equipment that measures other sounds. To the psychologist, who is also interested in all types of sounds, noise is an *undesired* sound, as contrasted with music and speech, which are usually desired sounds. Whenever we study the effects of physical phenomena on human beings, we are working in a field where the interests of the psychologist and those of the physicist overlap. The result is usually a happy collaboration, and in no field has this collaboration been more fruitful than in the measurement and evaluation of the effects of noise.

The study of mechanical vibration is closely related to that of sound, because sound is produced by the transfer of mechanical vibration to air. Hence, the process of quieting a machine or device often includes a study of the vibrations involved.

Conversely, high-energy acoustical noise such as generated by powerful jet or rocket engines, can produce vibrations that may weaken structural members of a vehicle or cause electronic components to fail.

Other important effects of vibration include: human discomfort and fatigue from excessive vibration of a vehicle, fatigue and rupture of structural members, and increased maintenance of machines, appliances, vehicles, and other devices.

Vibration, then, is a source not only of noise, annoyance, and discomfort, but often of danger as well. The present refinement of high-speed planes, ships, and automobiles could never have been achieved without thorough measurement and study of mechanical vibration.

The instruments used in sound and vibration measurement are mainly electronic. Furthermore, some of the concepts and techniques developed by electronics engineers and physicists for dealing with random or interfering signals (for which they have borrowed the term "noise") are now used in sound and vibration studies.

The purpose of this book is to help those who are faced, possibly for the first time, with the necessity of making noise measurements. It attempts to clarify the terminology and definitions used in these measurements, to describe the measuring instruments and their use, to aid the prospective user in selecting the proper equipment for the measurements he must make, and to show how these measurements can be interpreted to solve typical problems.

Although some may wish to read the chapters of this book in sequence, many will find it more convenient to consult the table of contents or the index to find the sections of immediate interest. They then can refer to the other sections of the book as they need further information. For example, Chapter 5 ("What Noise and Vibration Measurements Should be Made") could be consulted first if a specific problem is at hand. The reader can then find further details on the instruments recommended (Chapter 4) and on the techniques of use (Chapter 6).

Some sections of this book are marked by an asterisk to indicate that they might well be omitted during an initial reading, since they are highly specialized or very technical.

chapter 2

# WHAT ARE NOISE AND VIBRATION?

## 2.1 INTRODUCTION.

When an object moves back and forth, it is said to vibrate. This vibration disturbs the air particles near the object and sets them vibrating, producing a variation in normal atmospheric pressure. The disturbance spreads, and when the pressure variations reach our ear drums, they too are set to vibrating. This vibration of our ear drums is translated by our complicated hearing mechanisms into the sensation we call "sound."

To put it in more general terms, sound in the physical sense is a vibration of particles either in a gas, a liquid, or a solid. The measurement and control of air-borne sound is the basic subject of this book. Because the chief sources of sounds in air are vibrations of solid objects, the measurement and control of vibration will also be discussed. Vibrations of and in solids often have important effects other than those classified as sound, and some of these will also be included.

We have mentioned that a sound disturbance spreads. The speed with which it spreads depends on the mass and on the elastic properties of the material. In air the speed is about 1100 feet/second (about 750 miles/hour) or about 340 meters/second; in sea water it is about 1490 meters/second. The speed of sound has been popularized in aerodynamic concepts of the sound barrier and the supersonic transport, and its effects are commonly observed in echoes and in the apparent delay between a flash of lightning and the accompanying thunder.

The variation in normal atmospheric pressure that is a part of a sound wave is characterized by the rate at which the variation occurs and the extent of the variation. Thus, the standard tone "A" occurs when the pressure changes through a complete cycle 440 times per second. The frequency of this tone is then said to be 440 hertz, or 440 cycles per second (abbreviated "Hz" and "c/s", respectively). "Hertz" and "cycles per second" are synonymous terms, but most standardizing agencies have adopted "hertz" as the preferred unit of frequency.

Many prefixes are used with the unit of frequency, but the one that is common in acoustics and vibrations is "kilo-," abbreviated "k," which stands for a factor of 1000. Thus, 8000 Hz or 8000 c/s becomes 8 kHz or 8 kc/s.

The extent of the variation in pressure is measured in terms of a unit called the "microbar[1]," which is approximately one-millionth of the normal atmospheric pressure (standard atmospheric pressure = 1,013,250 microbars), or in terms of newtons per square meter, which is 10 microbars. Actually, these units are not often mentioned in noise measurements. Results are stated in decibels.

## 2.2 THE DECIBEL — WHAT IS IT?

Although to many laymen the decibel (abbreviated "dB") is uniquely associated with noise measurements, it is a term borrowed from electrical communication engineering, and it represents a relative quantity. When it is used to express noise level, a reference quantity is implied. Usually, this reference value is a sound pressure of 20 micronewtons per square meter (abbreviated 20 $\mu N/m^2$). For the present, the reference level can be referred to as "0 decibels," the starting point of the scale of noise levels. This starting point is about the level of the weakest sound that can be heard by a person with very good hearing in an extremely quiet location. Other typical points on this scale of noise levels are shown in Figure 2-1. For example, the noise level in a large office usually is between 50 and 60 decibels. Among the very loud sounds are those produced by nearby airplanes, railroad trains, riveting machines, thunder, and so on, which are in the range near 100 decibels. These typical values should help the newcomer to develop a feeling for this term "decibel" as applied to sound level.

For some purposes it is not essential to know more about decibels than the above general statements. But when we need to modify or to manipulate the measured "decibels," it is desirable to know more specifically what the term means. There is then less danger of misusing the measured values. From a strictly technical standpoint, the decibel is a logarithm of a ratio of two values of power, and equal changes in decibels represent equal ratios.

Although we shall use decibels for giving the results of power level calculations, the decibel is most often used in acoustics for expressing the sound-pressure level and the sound level. These are extensions of the original use of the term, and all three expressions will be discussed in the following sections. First, however, it is worthwhile to notice that the above quantities include the word "level." Whenever "level" is included in the name of the quantity, it can be expected that the value of this level will be given in decibels or

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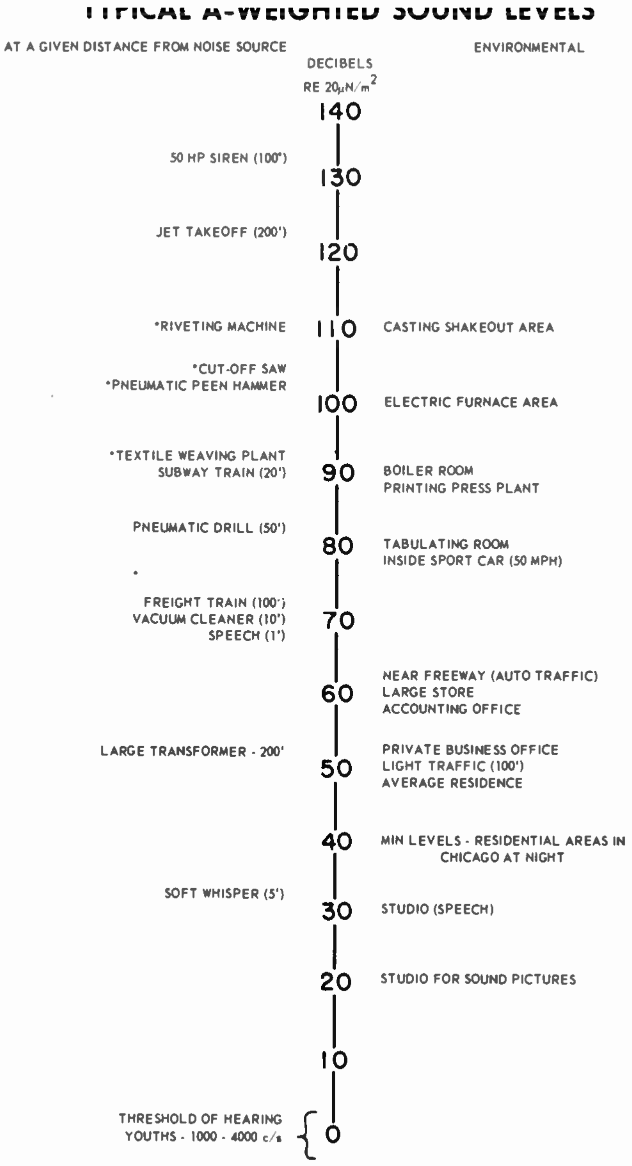
[1] Here, the prefix "micro" stands for a factor of one-millionth, and that prefix is abbreviated by the use of the Greek letter "μ" (mu). Thus "μN" stands for 0.000001 newton.



*OPERATOR'S POSITION

*Figure 2-1. Typical A-weighted sound levels measured with a sound-level meter. These values are taken from the literature. Sound-level measurements give only part of the information usually necessary to handle noise problems, and are often supplemented by analysis of the noise spectra.*

in some related term and that a reference power, pressure, or other quantity is stated or implied.

## 2.3 POWER LEVEL.

Because the range of acoustic powers that are of interest in noise measurements is about one billion billion to one ($10^{18}$:1), it is convenient to relate these powers on the decibel scale, which is logarithmic. The correspondingly smaller range of numerical values is easier to use, and, at the same time, some calculations are simplified.

The decibel scale can be used for expressing the ratio between any two powers; and tables for converting from a power ratio to decibels and vice-versa are given in Appendix I of this book. For example, if one power is four times another, the number of decibels is 6; if one power is 10,000 times another, the number is 40 decibels.

It is also convenient to express the power as a power level with respect to a reference power. Throughout this book the reference power will be $10^{-12}$ watt. Then the power level (PWL) is defined as

$$\underline{\text{PWL}} = 10 \log \frac{W}{10^{-12}} \text{ dB } \underline{\text{re}}\ 10^{-12} \text{ watt}$$

where W is the acoustic power in watts, the logarithm is to the base 10, and re means referred to. This power level is conveniently computed from

$$\underline{\text{PWL}} = 10 \log W + 120$$

since $10^{-12}$ as a power ratio corresponds to -120 dB. The quantity 10 log W, which is the number of decibels corresponding to the numerical value of W watts, can be readily obtained from the decibel tables in the Appendix. For example, 0.02 watt corresponds to a power level of

$$-17 + 120 = 103 \text{ dB}.$$

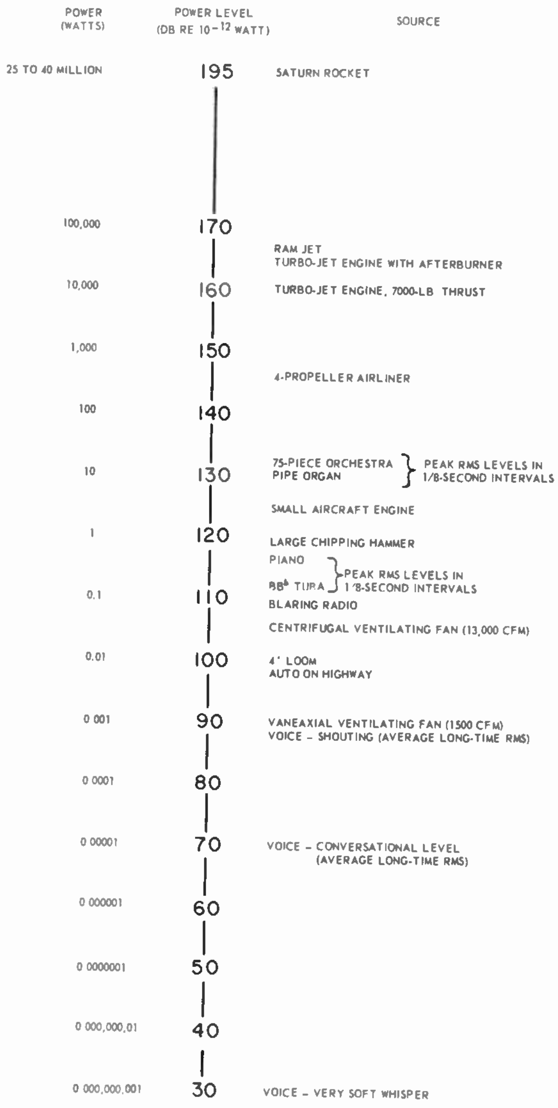
Some typical power levels for various acoustic sources are shown in Figure 2-2.

No instrument for directly measuring power level of a source is available. Power levels can be computed from the sound-pressure measurements described in Section 2.8.5.

## 2.4 SOUND-PRESSURE LEVEL.

It is also convenient to use the decibel scale to express the ratio between any two sound pressures; tables for converting from a pressure ratio to decibels and vice-versa are given in

## ACOUSTIC POWER



| POWER (WATTS) | POWER LEVEL (DB RE $10^{-12}$ WATT) | SOURCE |
|---|---|---|
| 25 TO 40 MILLION | 195 | SATURN ROCKET |
| 100,000 | 170 | |
| | | RAM JET<br>TURBO-JET ENGINE WITH AFTERBURNER |
| 10,000 | 160 | TURBO-JET ENGINE, 7000-LB THRUST |
| 1,000 | 150 | |
| | | 4-PROPELLER AIRLINER |
| 100 | 140 | |
| 10 | 130 | 75-PIECE ORCHESTRA<br>PIPE ORGAN } PEAK RMS LEVELS IN 1/8-SECOND INTERVALS |
| | | SMALL AIRCRAFT ENGINE |
| 1 | 120 | LARGE CHIPPING HAMMER |
| | | PIANO<br>BB♭ TUBA } PEAK RMS LEVELS IN 1/8-SECOND INTERVALS |
| 0.1 | 110 | BLARING RADIO |
| | | CENTRIFUGAL VENTILATING FAN (13,000 CFM) |
| 0.01 | 100 | 4' LOOM<br>AUTO ON HIGHWAY |
| 0.001 | 90 | VANEAXIAL VENTILATING FAN (1500 CFM)<br>VOICE – SHOUTING (AVERAGE LONG-TIME RMS) |
| 0.0001 | 80 | |
| 0.00001 | 70 | VOICE – CONVERSATIONAL LEVEL (AVERAGE LONG-TIME RMS) |
| 0.000001 | 60 | |
| 0.0000001 | 50 | |
| 0.000,000,01 | 40 | |
| 0.000,000,001 | 30 | VOICE – VERY SOFT WHISPER |

*Figure 2-2. Typical power levels for various acoustic sources. These levels bear no simple relation to the sound levels of Figure 2-1. See Section 2.8.5.*

the Appendix. Since sound pressure is usually proportional to the square root of the sound power, the sound-pressure ratio for a given number of decibels is the square root of the corresponding power ratio. For example, if one sound pressure is twice another, the number of decibels is 6; if one sound pressure is 100 times another, the number is 40 decibels.

The sound pressure can also be expressed as a sound-pressure level with respect to a reference sound pressure. For air-borne sounds this reference sound pressure is generally 20 $\mu N/m^2$. For some purposes a reference pressure of one microbar (0.1 $N/m^2$) has been used, but throughout this book the value of 20 $\mu N/m^2$ will always be used as the reference for sound-pressure level. Then the definition of sound-pressure level (SPL) is

$$\text{SPL} = 20 \log \frac{P}{.00002} \text{ dB } \underline{\text{re}} \text{ 20 micronewtons/meter squared}$$

where $\underline{P}$ is the root-mean-square sound pressure in newtons/meter squared for the sound in question. For example, if the sound pressure is one $N/m^2$, then the corresponding sound pressure ratio is

$$\frac{1}{.00002} \text{ or } 50000.$$

From the tables, we find that the pressure level is 94 dB re 20 $\mu N/m^2$. If decibel tables are not available, the level can, of course, be determined from a table of logarithms.

The instrument used to measure sound-pressure level consists of a microphone, attenuator, amplifier, and indicating meter. This instrument must have an over-all response that is uniform ("flat') as a function of frequency, and the instrument is calibrated in decibels according to the above equation.

The position of the selector switch of the instrument for this measurement is often called "FLAT" or "20-KC" to indicate the wide frequency range that is covered. The result of a measurement of this type is also called "overall sound-pressure level."

## 2.5 SOUND LEVEL.

The apparent loudness that we attribute to a sound varies not only with the sound pressure but also with the frequency (or pitch) of the sound. In addition, the way it varies with frequency depends on the sound pressure. This effect is taken into account to some extent for pure tones by "weighting" networks included in an instrument designed to measure sound-pressure level, and then the instrument is called a sound-level meter. In order to assist in obtaining reasonable uniformity among different instruments of this type, the USA

Standards Institute (formerly, American Standards Association), in collaboration with scientific and engineering societies, has established a standard to which sound-level meters should conform.

The current USA Standard for Sound-Level Meters (S1.4, 1961) requires that three alternate frequency-response characteristics be provided in the instrument (see Figure 2-3). These three responses are obtained by weighting networks designated as A, B, and C. Responses A, B, and C selectively discriminate against low and high frequencies in accordance with certain equal-loudness contours, which will be described in a later section.

Whenever one of these networks is used, the reading obtained should be described as in the following examples: the "A-weighted sound level is 45 dB" or "sound level (A) = 45 dB."[2] Note that when a weighting characteristic is used,

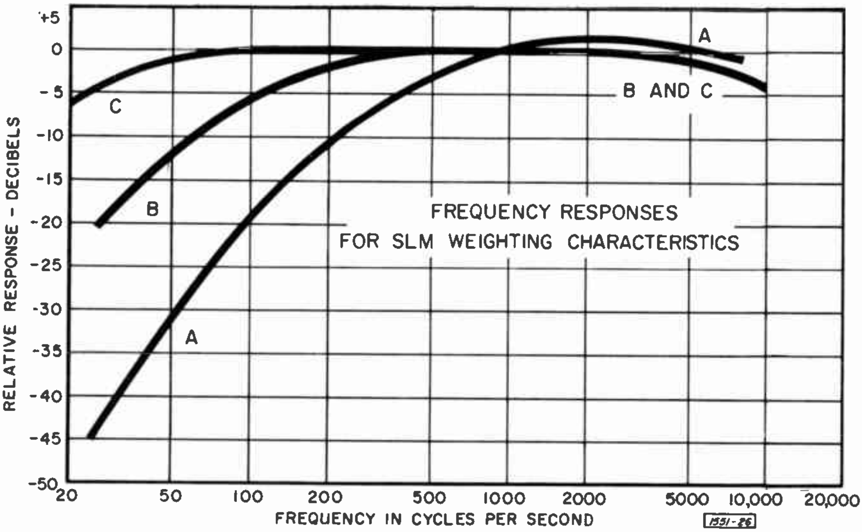


*Figure 2-3. Frequency-response characteristics in the USA Standard for Sound-Level Meters, S1.4, 1961.*

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[2] In a table, the abbreviated form "$L_A$" with the unit "dB" is suggested, or where exceptional compactness is necessary, "dB (A)." The form "dBA" has also been used, but this notation implies that a new unit has been introduced and is therefore not recommended.

the reading obtained is said to be the "sound level."[3] Only when the over-all frequency response of the instrument is "flat" are sound-pressure levels measured. Since the reading obtained depends on the weighting characteristic used, the characteristic that was used must be specified or the recorded level may be useless.

In general, it is recommended that readings on all noises be taken with all three weighting positions. The three readings provide some indication of the frequency distribution of the noise. If the level is essentially the same on all three networks, the sound probably predominates in frequencies above 600 Hz. If the level is greater on the C network than on the A and B networks by several decibels, much of the noise is probably below 600 Hz.

In the measurement of the noise produced by distribution and power transformers, the difference in readings of level with the C-weighting and A-weighting networks ($L_C$-$L_A$) is frequently noted. This difference in decibels is called the "harmonic index." It serves, as indicated above, to give some idea of the frequency distribution of the noise.

## 2.6 COMBINING DECIBELS.

A number of possible situations require the combining of several noise levels stated in decibels. For example, we may want to predict the effect of adding a noisy machine in an office where there is already a significant noise level, to correct a noise measurement for some existing background noise, to predict the combined noise level of several different noise sources, or to obtain a combined level of several levels in different frequency bands.

In none of these situations should the numbers of decibels be added directly. The method that is usually correct is to combine on an energy basis. The procedure for doing this is to convert the numbers of decibels to relative powers, to add or subtract them, as the situation may require, and then to convert back to the corresponding decibels. By this procedure it is easy to see that a noise level of 80 decibels combined with a noise level of 80 decibels yields 83 decibels and not 160 dB. A table showing the relation between power ratio and decibels appears in Appendix I. A chart for combining or subtracting different decibel levels is shown in Appendix II.

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[3] It was customary, if a single sound-level reading was desired, to select the weighting position according to level, as follows: for levels below 55 dB, A weighting; for levels from 55 dB to 85 dB, B weighting; and for levels above 85 dB, C weighting. Now, however, the A-weighted sound level is the one most widely used regardless of level. See Page 57.

## 2.7 ANALYSIS IN FREQUENCY BANDS.

The noises that we measure are rarely pure tones. They are usually a jumble of sounds that may range from a low-frequency roar to a high-frequency squeal. We react to these sounds in different ways that depend not only on the over-all levels, but also on the composition of the noise as a function of frequency. In order to measure this composition, we make a frequency analysis, which indicates how the sound energy is distributed over the audible range of frequencies.

In this analysis, the acoustic energy is electronically separated into various frequency bands, for example, octave bands, each of which covers a 2-to-1 range of frequencies. The analysis yields a series of levels, one for each band, called "band levels," or, for octave bands, "octave-band levels." Here it is apparent that the band in which a reading of level was obtained must be specified if the information is to be of value.

2.7.1 OCTAVE BANDS. The preferred series of octave bands for acoustic measurements cover the audible range in ten bands. The center frequencies of these bands are 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. The actual nominal frequency range of any one of these bands is 2-to-1; for example, the effective band for the 1000 Hz octave band extends from 707 to 1414 Hz.

Another series of octave bands has been widely used in the past. The older bands were a 75-Hz low-pass unit, and the octave bands of 75 to 150, 150 to 300, 300 to 600, 600 to 1200, 1200 to 2400, 2400 to 4800, and 4800 to 9600 Hz, but these are no longer preferred, according to USASI standards. This older series is still specified in a number of test codes, however, and the published data obtained with this series is extensive.[4]

When a graph is made of the results of octave-band pressure level measurements, the frequency scale is commonly divided into equal intervals between the position designated for each band and the position for the band adjacent to it in frequency. The pressure level in each band is plotted as a point on each of these positions along the other axis. Adjacent points are then connected by straight lines. An example of a plot of this type is given in Figure 2.4.

2.7.2 ONE-THIRD-OCTAVE BANDS. For more detailed analysis of the distribution of sound energy as a function of

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[4] A method for converting octave-band levels measured with this older series to levels for the new series is given in Appendix A of USASI S1.11-1966, USA Standard Specification for Octave, Half-Octave, and Third-Octave Band Filter Sets.

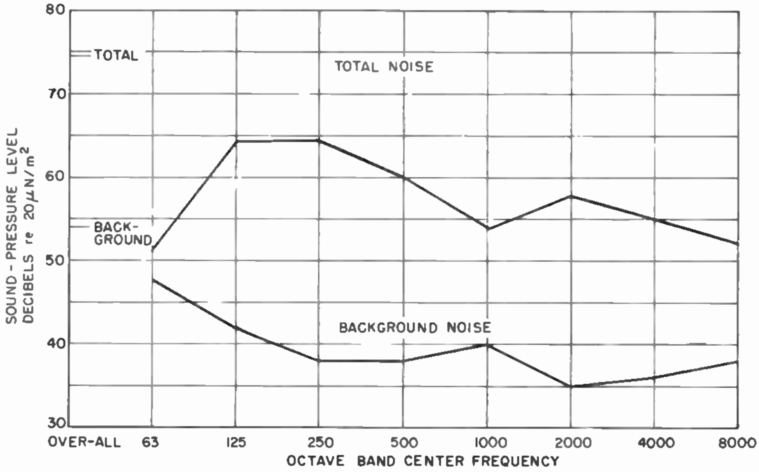

*Figure 2-4. A plot of the octave-band analysis of noise from a calculating machine. Graph paper for plotting octave band levels is available from Codex Book Co., Inc., Norwood, Mass., as Forms 31464 and 31460 for the preferred octaves and the older series, respectively.*

frequency, still narrower bands are used. The next popular division is a split of the octave into three parts. This choice is based partly on the fact that ten such filters can be arranged effectively to cover a 10-to-1 frequency range. The preferred center frequencies for such a series would be, for example, 100, 125, 160, 200, 250, 315, 400, 500, 630, and 800 Hz. The next 10-to-1 set would start with 1000 Hz as the center frequency and continue by multiplying each number by 10 and so on (1000, 1250, 1600, 2000 . . .). Similarly, lower preferred frequencies are obtained by a division of 10, 100, etc. For practical reasons the usual span of third octaves for acoustic noise analysis runs from 25 to 10,000 Hz.

The actual effective band for a one-third-octave filter at 1000 Hz extends from about 891 to 1122 Hz. That is, the bandwidth is about 23% of the center frequency.

2.7.3 NARROWER BANDS. Still narrower bands are essential for some purposes, and this will be apparent later. Frequency analyzers with one-tenth-octave bands, about 7% in width, and another with 1% bands are also available. Another type of analyzer divides the frequency range into bands that are a constant number of hertz (e.g. 10 Hz or 50 Hz) wide. None of these narrower band systems is standardized, but they are often essential for use in noise and vibration control.

These highly selective systems are usually built so that the center frequency of the band can be set to any frequency

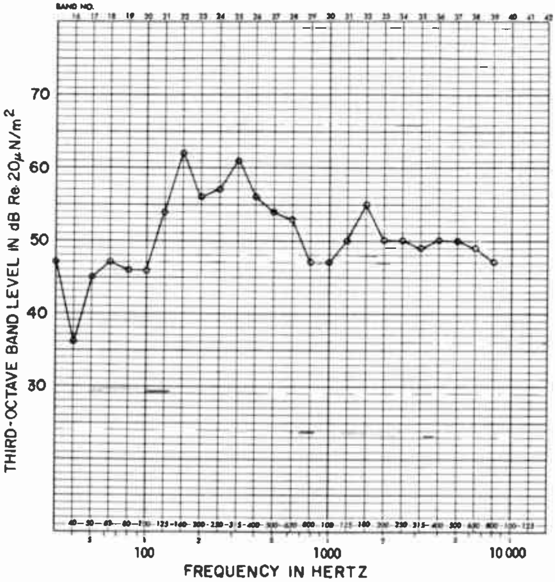

*Figure 2-5. Plot of one-third-octave analysis of noise from calculating machine. Codex Book Co., Form 31462.*

within the audio range and not just in discrete steps. This feature is often helpful for tracking down sources of noise and vibration.

2.7.4 SPECTRUM LEVEL. The spectrum level of a noise is the level that would be measured if an analyzer had an ideal response characteristic with a bandwidth of 1 Hz. The main uses of this concept are comparing data taken with analyzers of different band widths and checking compliance with specifications given in terms of spectrum level. Charts for converting to this spectrum level from the band levels obtained with the octave- and third-octave-band analyzers are given in the accompanying table and in Figure 2-6.

The corrections for spectrum level for a constant-bandwidth analyzer are independent of the center frequency to which it is tuned but do depend on the bandwidth used. For a 3-Hz band subtract 3.7 dB; 10-Hz, subtract 9 dB; 50-Hz, subtract 15.9 dB to obtain the spectrum level. (These correction numbers take into account average-type metering characteristics as well as the bandwidth.)

This conversion has meaning only if the spectrum of the noise is continuous within the measured band and if the noise does not contain prominent pure-tone components. For this reason the results of this conversion should be interpreted with great care to avoid drawing false conclusions.

The sloping characteristic given for the third-octave analyzer in Figure 2-6 results from the fact that the analyzer is a constant-percentage-bandwidth analyzer; that is, its bandwidth increases in direct proportion to the increase in the frequency to which the analyzer is tuned. For that reason a noise that is uniform in spectrum level over the frequency range will give higher-level readings for high frequencies than for lower frequencies, with this analyzer.

| Band Center | Decibels* |
|---|---|
| 31.5 | 13.5 |
| 63 | 16.5 |
| 125 | 19.5 |
| 250 | 22.5 |
| 500 | 25.5 |
| 1000 | 28.5 |
| 2000 | 31.5 |
| 4000 | 34.5 |
| 8000 | 37.5 |
| 16,000 | 40.5 |

| Band | Decibels* | Geometric Mean Frequency |
|---|---|---|
| 18.75 - 37.5 | 12.7 | 26.5 |
| 37.5 - 75 | 15.7 | 53 |
| 75 - 150 | 18.8 | 106 |
| 150 - 300 | 21.8 | 212 |
| 300 - 600 | 24.8 | 424 |
| 600 - 1200 | 27.8 | 849 |
| 1200 - 2400 | 30.8 | 1700 |
| 2400 - 4800 | 33.8 | 3390 |
| 4800 - 9600 | 36.8 | 6790 |
| 9600 - 19,200 | 39.8 | 13,580 |

*To be subtracted from octave-band level readings to obtain spectrum level.

2.7.5 BASIC USES FOR NOISE ANALYSIS. Octave-band analyzers are widely used for noise ratings. One-third-octave analyzers are also used for noise ratings, but they are also helpful in deciding how best to reduce noise and vibration. Analyses with still narrower bands are mainly useful in noise and vibration control where the results of the analysis can be related to specific operation characteristics of the device. These points will be more readily apparent after the discussions in subsequent chapters.

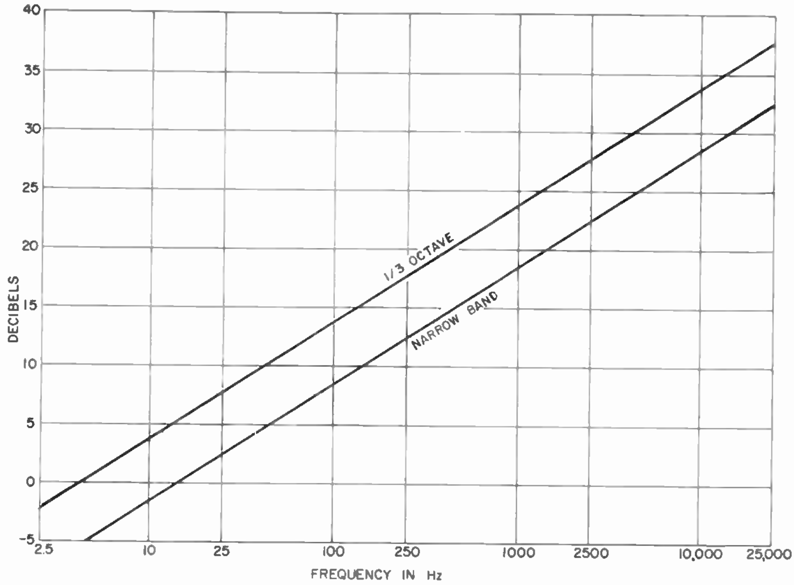

*Figure 2-6. Plot showing number of decibels to be subtracted from Type 1564-A readings to obtain spectrum level. The "Narrow Band" is about 7% wide, the "1/3 octave" is about 23% wide.*

## 2.8 SOUND FIELDS.

In order to describe some of the important characteristics of the sound fields that noise sources produce, we shall begin with a discussion of a simple source under idealized conditions. Then we shall point out various factors that alter the idealized conditions and discuss in general what the important effects are.

### 2.8.1 SIMPLE SOURCE IN FREE FIELD.

2.8.1.1 Point Source. Any vibrating object will radiate sound into the air. The amount of sound radiated depends on (1) the amplitude of vibration of each vibrating part, (2) the area of each part, and (3) the time pattern of the vibrations, including the relative time pattern compared with that of the other parts.

The simplest form of source is a sphere that vibrates uniformly over its entire surface. We can think of this source as a round balloon with air in it. We periodically pump some more air into it and then let the same amount of air out. If the surface of the balloon then expanded and contracted uniformly, the balloon would be a simple, spherical source. This source radiates sound equally in all directions from an apparent center, which is the center of the balloon. It then is a "point" source, insofar as sound radiation is concerned.

2.8.1.2 Free Field. If such a point (or spherical) source is in the air far from any other objects, including the ground, the sound pressure produced by the source is the same in every direction at equal distances from the point source. Furthermore, the sound pressure is halved for each doubling of distance from the point. This change is usually expressed as a decrease in sound-pressure level of 6 dB. The sound field produced under these idealized conditions is called a free sound field or, simply a free field because it is uniform, it is free from all bounding surfaces, and it is undisturbed by other sources of sound.

2.8.1.3 Power Level in Free Field. Under free-field conditions, a single measurement[1] of the sound-pressure level at a known distance from a point source is enough to tell us all about the sound field radiated by the source. For example, we can then predict the level at any other point, since the sound pressure varies inversely as the distance from the source. We can also compute the total sound power radiated by the point source. This calculation is usually made in terms of the power level re $10^{-12}$ watt (PWL) of the source (Section 2.3). Then the required relation to the sound-pressure level (SPL) is:

$$\text{PWL} = \text{SPL} + 20 \log r + 0.5 \text{ dB} \qquad (r \text{ in feet})$$

where r is the distance in feet from the point source to the point where the sound-pressure level is measured. This relation is correct for a point source in a free field at normal room temperature and barometric pressure, that is, 20°C and 1013 millibars. At other temperatures and pressures, the correction shown in the graph of Figure 2-7 applies. This correction is usually unimportant.

As an example, suppose that we measure a sound-pressure level of 73.5 dB re 20 $\mu N/m^2$ at a distance of 20 feet from a point source. Then

$$\text{PWL} = 73.5 + 20 \log 20 + 0.5 = 100 \text{ dB re } 10^{-12} \text{ watt.}$$

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[1] The concept of a point source is an idealized one. It is not reasonable to assume that an actual source is a true point source, so that one should never be content with a single measurement (refer to Section 2.8.2).

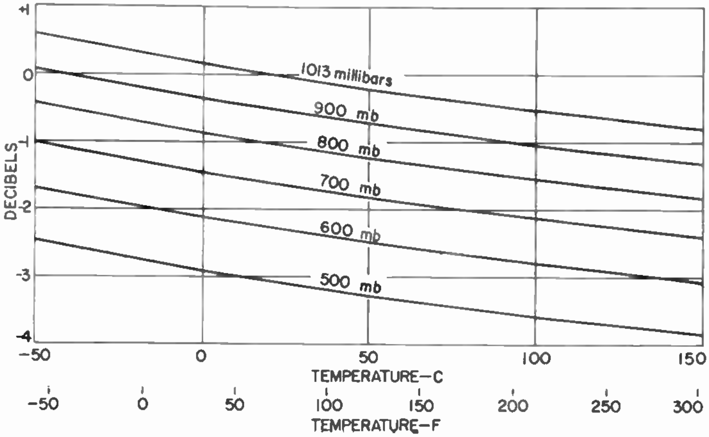

*Figure 2-7. Corrections for temperature and barometric pressure to be applied when the equations relating power level (PWL) and sound-pressure level (SPL) are used. The correction is to be added to, if positive, or subtracted from, if negative, the sound-pressure level computed by the equation from the power level. If the power level is to be computed from a given sound-pressure level, the correction should be subtracted from, if positive, or added to, if negative, the given sound-pressure level before the numerical value is substituted in the equation.*

The value for 20 log r can be found from a table of logarithms or from the decibel tables in the Appendix, where the columns labeled as pressure ratios should be used for this distance.

The power level can be converted to actual acoustic power in watts as explained in Section 2.3. For the example above, the 100 dB corresponds to an acoustic power of 0.01 watt.

We can also use the equation to predict sound-pressure levels at any distance in the free field if we know the acoustic power radiated. Thus, this point source radiating 0.01 watt, corresponding to a power level of 100 dB re $10^{-12}$ watt, produces a sound-pressure level of $100 - 20.5 = 79.5$ dB re 20 $\mu N/m^2$ at 10 feet from the source.

### 2.8.2 DIRECTIONAL SOURCE IN FREE FIELD

2.8.2.1 Directional Source. In actual practice, noise sources are not as simple as point sources. The sound is not radiated uniformly in all directions, either because the shape of the sound source is not spherical or because the amplitude and time phase of the vibrations of the different parts are not uniform or both. The net result is that more sound is radiated in some directions than in others.

2.8.2.2 Sound-Pressure Contours. In other words, the sound-pressure level for a given distance is different in different directions. As an example, let us observe the sound field surrounding a large 60-cycle power-distribution transformer, as shown in Figure 2-8. The contours around the transformer correspond to the indicated values of sound-pressure level. This source is obviously directional, since the contours are not circular.

When such a directional sound source is far from any other objects, however, it behaves in some ways like a point source. For example, the sound-pressure level decreases 6 dB for each doubling of distance, provided we start our measurements at a distance away from the source that is several times the largest dimension of the source, and provided we move directly away from the source. For the example of the transformer in Figure 2-8 we see that, at distances greater than several times the length of the transformer, the contours are similar in shape and the levels decrease approximately 6 dB for each doubling of distance. In actual practice this

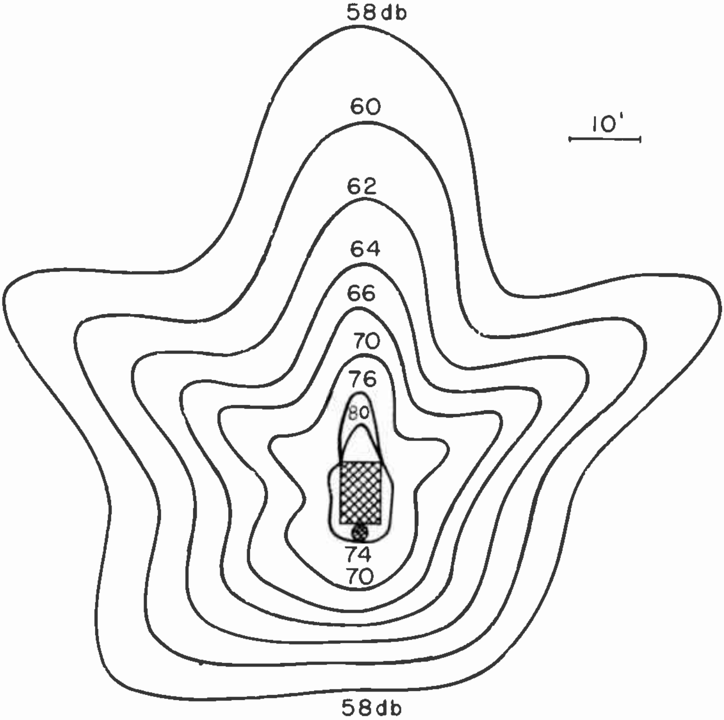

*Figure 2-8. Simplified contours of equal sound-pressure level around a large power-distribution transformer.*

idealized behavior is upset by the effects of variation in terrain, atmospheric conditions, and the interference of nearby objects.

*2.8.2.3 Near Field and Far Field. We can also see that at locations close to the transformer the sound-level contours are different in shape from those at a distance. Furthermore, there is no apparent center from which one finds the 6-dB drop for each doubling of distance. Consequently, this "near field" behavior cannot readily be used to predict the behavior at a distance. The differences between the "near field" and "far field" can be described in part as follows: Assume we have a source in which one part moves outwardly while another moves inwardly and vice versa. The air pushed away by one part will then tend to move over to compensate for the decrease in air pressure at the inward moving part. If the air can move over quickly enough, there will be considerable motion of air between the two parts, without contributing much to radiation of sound away from the source. The time factor in this motion of air can be expressed as a relation between the distance to be covered and the wavelength of the sound in air. The wavelength, λ, at normal temperature is as follows:

$$\lambda = \frac{1130}{f} \text{ feet} \simeq \frac{344}{f} \text{ meters}$$

where f is the frequency in hertz and 1130 feet per second is the speed of sound. Then, in order that the "near field" effect should not be very important, one should be at least one wavelength away from the source. This dimension should be determined on the basis of the lowest frequency of interest. For the example of the 60-Hz transformer, the lowest frequency of sound is 120 Hz, which corresponds to a wavelength of about 10 feet.

Another factor that enters into the differences between the "near field" and "far field" behavior is the way the sound waves spread out from a source. The sound waves from a large source vary with distance differently from waves produced by a small source. But at a distance of several (3 to 4) times the largest dimension of the radiating source, "spherical spreading" is said to exist, and the behavior is then essentially independent of the size of the source.

*2.8.2.4 Directivity Factor. When we are interested in sound-pressure levels beyond the immediate vicinity of the source, any sound can be treated as a point source provided we introduce a directivity factor. This factor takes into account the variation in sound-pressure level with direction to the source. This directivity factor, which is a function of direction and frequency, is usually labeled Q. It can be expressed as the ratio of two acoustic powers. One of these powers is that which would be radiated by a point source in order to produce the observed sound-pressure level in the specified direction. The other power is the total acoustic power radiated by the actual source.

*2.8.2.5 Sound-Pressure Level for a Directional Source. When we know this directivity factor for the direction of interest, we can use it, in the earlier equation for a point source, as a multiplying factor on the power. Expressed in terms of level the new equation is as follows:

$$SPL = PWL + 10 \log Q - 20 \log r - 0.5 \text{ dB} \qquad (r \text{ in feet})$$

This equation relates the power level of the source, the sound-pressure level in a given direction at a distance r feet from the source, and the directivity factor for that direction. (This equation is also subject to the minor corrections for temperature and pressure shown in Figure 2-7.)

For example, let us assume that an auto horn whose measured power level is 104 dB is sounded. We are interested in the sound-pressure level at a distance of 20 feet in the horizontal plane of the horn, but at an angle of 20° from the principal axis of the horn. Along this direction of 20° from the axis the directivity factor is 5, say. Then we have

$$SPL = 104 + 10 \log 5 - 20 \log 20 - 0.5 = 84.5 \text{ dB}$$

at 20 feet in the required direction.

2.8.3 SIMULATED FREE FIELD. The free-field condition does not occur in practice, because of the effects of sound reflected from the ground or floor, from nearby objects, and from walls and ceiling. The result of these reflections is that the sound-pressure level measured at a distance from the source is different from that predicted by the free-field equations. The reflections can be reduced by acoustic absorbing materials applied to the reflecting surfaces. By the proper design and application of this treatment, one can produce in a room a limited space having the essential characteristics of a free field over a wide frequency range. Many such rooms, called "anechoic" or "free-field" rooms, have been built and are described in the literature. When accurate measurements of the radiated sound power and directivity are required, the measurements should be made in such an environment.

2.8.4 EFFECT OF REFLECTIONS IN ROOM. The sound that a noise source radiates in a room is reflected by the walls, floor, and ceiling. The reflected sound will again be reflected when it strikes another boundary, with some absorption of energy at each reflection. The net result is that the intensity of the sound is different from what it would be if these reflecting surfaces were not there.

Close to the source of sound there is little effect from these reflections, since the direct sound dominates. But far from the source, unless the boundaries are very absorbing, the reflected sound dominates, and this region is called the reverberant field. The sound-pressure level in this region depends on the acoustic power radiated, the size of the room, and the acoustic absorption characteristics of the materials in the room. These factors and the directivity characteristics of the source also determine the region over which the transition between reverberant and direct sound occurs.

A second effect of reflected sound is that measured sound does not necessarily decrease steadily as the measuring position is moved away from the source. At certain frequencies in a room with hard walls, marked patterns of variations of sound pressure with position may be observed. Variations of up to 10 dB are common and, in particular situations, much more may be found. These variations are usually of the following form: As the measuring microphone is moved away from the source, the measured sound pressure decreases to a minimum, rises again to a maximum, decreases to a minimum again, etc. These patterns are called standing waves. They are noticeable mainly when the sound source has strong frequency components in the vicinity of one of the very many possible resonances of the room. They also are more likely to be observed when a frequency analysis is made; and the narrower the bandwidth of the analyzer, the more marked these variations will be.

In a room, the spacing from one minimum in sound pressure to another is on the average greater than one-half wavelength.

2.8.4.1 Reverberation Room. If a room has very little sound absorption, the room is said to be "live" or reverberant. Sound from a source in such a room will be reflected many times as it bounces back and forth on the surfaces of the room. At any one point in this room the sound will have arrived there from many directions because of the many reflections. If the room dimensions are properly proportioned and certain other design features are included, the flow of sound energy in all directions can be made nearly equally probable, and the field is then said to be diffuse. This type of room is called a reverberation room, and it is widely used for the measurement of the sound absorption of materials, as well as for sound power measurements when the directivity characteristics are not required.

2.8.4.2 Additional Room Characteristics. As described earlier, at a distance from a source in a free field the sound-pressure level tends to decrease 6 dB for each doubling of the distance. In contrast, in a well designed reverberation room, the sound-pressure level on the average does not vary much about the room except right near the source. Most other rooms have characteristics that fall between these extremes.[2] In flat rooms (i.e., rooms whose ceilings are low relative to room length and width), the sound pressure level, at a distance from the source, tends to decrease a fixed amount, but less than 6 dB, for each doubling of distance. The decrease depends on the sound absorption in the room. In very long rooms or halls the sound-pressure level tends to decrease a fixed number of decibels for a constant increment in the distance from the source.

2.8.5 MEASUREMENT OF ACOUSTIC POWER. A noise rating is often intended to make possible the prediction of the noise level that the apparatus will produce when installed. In order for the rating to be adequate for this purpose, the total acoustic power radiated by the source and the acoustic directivity pattern of the source should be included as part of the rating. We shall explain in this section how the power and directivity can be determined, but first we shall discuss the limitations of the usual method of noise rating.

For example, an air compressor may be rated by the manufacturer as producing a noise level of 85 dB at a distance of five feet. This level may have been calculated by an averaging of a few sound level readings five feet from the compressor. When it is installed and the level is measured, the new level may be, say, 90 dB at five feet. Naturally, the purchaser feels that he should complain because the machine was incorrectly rated; perhaps he returns the compressor, or he decides that he can no longer trust the manufacturer. Actually, the manufacturer may have been entirely correct in his noise measurements, but the rating was inadequate. The difference of 5 dB may have been caused by incorrect installation, but usually such a difference is a result of the acoustical characteristics of the factory space. By the use of an adequate rating system and a knowledge of acoustical room characteristics, it would have been possible to predict this effect.

Another part of this problem is the prediction of levels at places in the factory other than at the measurement distance. For example, the nearest worker may be 20 feet away, and the level at a distance of 20 feet is then more important than at 5 feet. Again, a knowledge of the acoustic power radiated and the acoustical characteristics of the factory space will be needed to predict the probable level at this distance.

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[2] Y. Ogawa, "The Applicable Limit of Beranek's Formula and Ishii's Formula of Sound Pressure Level Distribution in a Room," Journal of the Acoustical Society of Japan, Vol. 21, No. 3, May 1965, pp. 137-140. H. J. Gober & E. Lübcke, "Sound Field in Very Wide and Long Rooms, "Journal of the Acoustical Society of America, Vol. 39, No. 6, June 1966, p. 1266.

The procedure suggested here for determining the power and directivity is based on measurements of the sound-pressure level at a number of points around the noise source. The measurement of sound-pressure level has already been discussed. We shall discuss here the selection of the points at which to measure the sound-pressure levels, the method of calculating acoustic power, and the requirements on the characteristics of the space in which the measurement is to be made.

*2.8.5.1 Measurement Procedures. The source characteristics are obtained by use of the principles discussed earlier in this chapter.[3] Generally, the following characteristics must be determined:

(1) The total sound power radiated by the source, as expressed by the power level, as a function of frequency.
(2) The directional characteristics of the source, as expressed by the directivity factor, as a function of direction and frequency.

### *2.8.5.2 Measurement Positions.

*2.8.5.2.1 Measurements Around the Source. If free-field conditions can be closely approximated, the power level and directivity can be calculated from the sound-pressure levels measured at a number of points. These measurements are made at points at equal distances from the source and all around the source. The points can be considered as being on the surface of a hypothetical sphere surrounding the source. The radius of this sphere should be at least three times the largest dimension of the source, and should exceed the wavelength corresponding to the lowest noise frequency of interest (refer to paragraph 2.8.2.3).

Theoretically, the sound-pressure levels over the entire surface of the sphere should be measured. The practical procedure for approximating this exploration is to select a number of points at which measurements will be made. Areas on the sphere are then associated with these points. These areas have the measurement points as their centers, and the extent of each area is determined by the nearness of the other measuring points. In the process of making the basic measurements the microphone should be moved around to determine the variation in sound-pressure level within each area. If the variations in sound-pressure level within any one area are greater than 2 dB, it is advisable to select additional measuring points in that area. However, if no attempt is being

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[3] The procedures outlined here and in subsequent sections are similar to those given in USASI S1.2-1962, USA Standard Method for the Physical Measurement of Sound, and that should be consulted for specific details on the standard method.

made to obtain an accurate picture of the directivity pattern, the extent of the variation can be noted. Then, provided the variation is less than 6 dB, the average level can be used as a representative value for the area.

*2.8.5.2.2 Uniformly Distributed Measuring Points. The calculations for the radiated power are simplified if the measuring points are uniformly distributed on the surface of the sphere. Because of the nature of the geometric pattern, only six such sets of points are possible. These six sets have 2, 4, 6, 8, 12, and 20 uniformly distributed points. The locations for the sets of 8, 12, and 20 points are shown in Figures 2-9, 2-10, and 2-11. The particular orientation of the points shown was first published in the 1953 edition of this handbook; these are now generally used, although a different orientation with respect to the ground plane may be found desirable for some particular applications. The areas associated with the sets of 8, 12, and 20 points are regular spherical triangles, regular spherical pentagons, and regular spherical triangles, respectively.

Other sets of points that may be useful are those that correspond to the vertices of an Archimedean semiregular polyhedron. The most interesting of these have 24 (see R. M. Robinson, "Arrangement of 24 Points on a Sphere," Math. Annalen, 144, 17-48 (1961)), 48, and 60 points. Although these points are not uniformly distibuted, they are all of equal importance, because the distribution of points around any one point is the same for all points.

*2.8.5.2.3 Hemispherical Measurements. When the device to be tested is normally mounted on a concrete foundation or on the ground, it is often desirable to test it while it is so mounted. Then the sound-pressure level measurements should be made at points on a hypothetical hemisphere surrounding the source. The sets of points that lead to simple calculations of power level are now modified. A set of four points (half the set of eight) can be properly used, and a set of six points (half the set of 12) can be used even though the distribution is not exactly uniform. A set of 12 can also be used, but then four of the set must be weighted by a factor of one-half (or, 3 dB is subtracted from the levels at these four points). (See Figure 2-11.)

By a rotation of the set of 20 points shown in Figure 2-11, a set of 10 points can be selected from this set with all the points above the plane. This procedure avoids the problems associated with the points in a plane. This new set is shown in Figure 2-12.

When the hemisphere is used, the procedure for calculating power is the same as that described for the sphere (paragraph

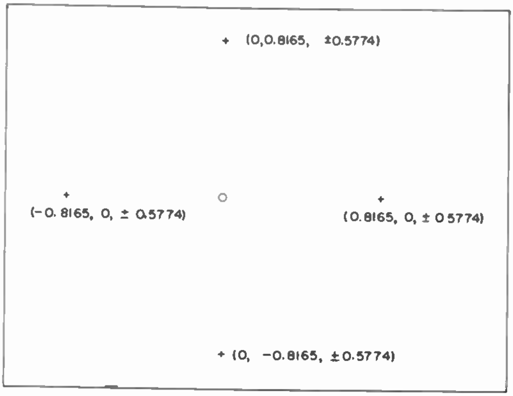

*Figure 2-9. Plan view of eight points uniformly distributed on a sphere of unit radius. Coordinates are given in terms of distances from center along three mutually perpendicular axes (x, y, z). The "±" refers to the existence of two points, one above the x-y reference plane and one below. When measurements are to be made on a hemisphere, only the four points above the plane are used.*

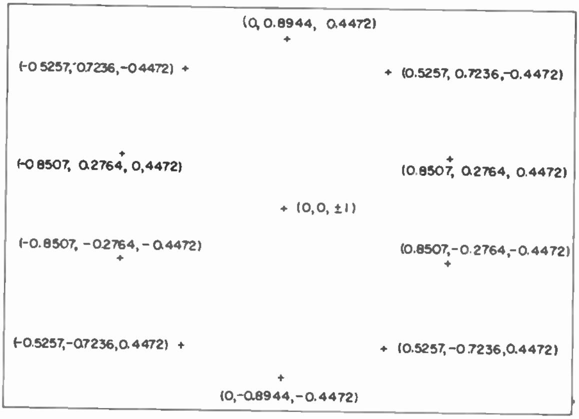

*Figure 2-10. Plan view of 12 points uniformly distributed on a sphere of unit radius. Coordinates are given as in the previous figure. When measurements are to be made on a hemisphere, only the six points above the x-y reference plane (positive values of Z) are used.*

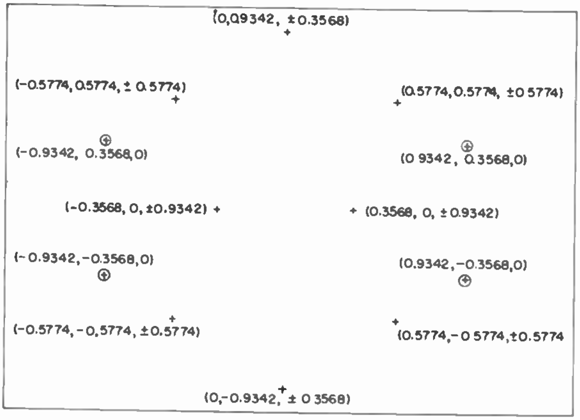

*Figure 2-11. Plan view of 20 points uniformly distributed on a sphere of unit radius. Coordinates are given as in Figure 2-9. When measurements are to be made on a hemisphere, 12 points are used, eight above the reference plane and four in plane (Z = 0, shown encircled). The four in the plane are weighted by a factor of 1/2 in power (see text).*

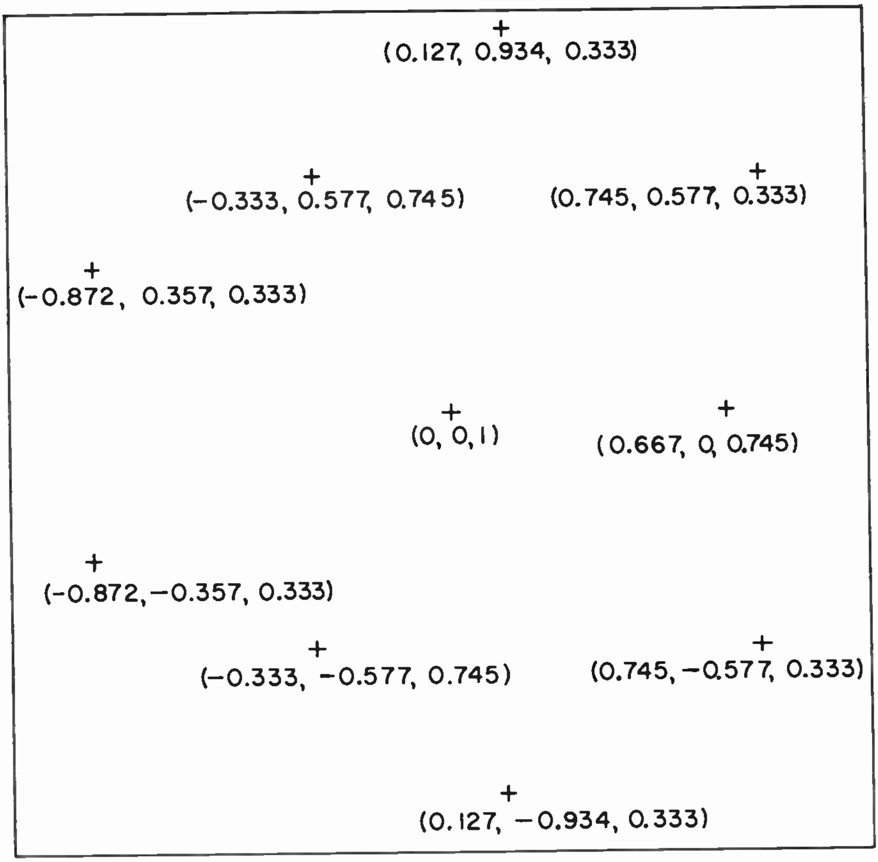

*Figure 2-12. Plan view of 10 points distributed on a hemisphere of unit radius.*

2.8.5.3). But 3 dB should be subtracted from the power level finally obtained, because the area of the hemisphere is just one-half that of the sphere.

*2.8.5.2.4 Rotation of Source. Another way of simplifying the calculations is to rotate the source, with the microphones placed on the surface of a hypothetical sphere surrounding the source, so that the projections of their positions on the axis of rotation are uniformly distributed. A variation of this method, practiced by the Bell Telephone Laboratories, calls for the rotation of a set of microphones about a stationary source.

*2.8.5.3 Calculation of Power Level. If exploration shows that the basic set of points yields representative data, the calculations of the power level and directivity factor can be made. For a uniformly distributed set of points, first calculate the average level on a power basis. If the total range of sound-pressure levels is less than 6 dB, a simple arithmetical average is usually adequate. The accurate method for any situation is as follows: Convert the decibel readings at each of the points of measurement to power ratios by using the tables in the Appendix, add these power ratios, and convert back to a decibel level. Then subtract the decibel value corresponding to a power ratio numerically equal to the number of levels used (for 8, 12, and 20 readings subtract 9, 10.8, and 13 dB respectively). The result is then the average level, which we shall call $\overline{\text{SPL}}$. Provided free-field conditions exist, the power level is then calculated from the equation:

$$\text{PWL} = \overline{\text{SPL}} + 20 \log r + 0.5 \text{ dB}$$

where r is the radius, in feet, of the measuring sphere. When the rotating source or rotating microphones are used as described in paragraph 2.8.5.2.4, the average energy during a complete rotation as well as for all the microphone positions should be taken, and the corresponding average sound-pressure level used in the above formula.

*2.8.5.4 Calculation of Directivity Factor. After the average sound-pressure level, $\overline{\text{SPL}}$, has been determined, the directivity factor can also be calculated. If it is desired for a particular direction, the sound-pressure level on the measuring sphere corresponding to that direction, $\text{SPL}_1$, is measured. The difference between this level and the average level is called the directional gain, $\text{DG}_1$. Thus,

$$\text{DG}_1 = \text{SPL}_1 - \overline{\text{SPL}} \text{ dB}$$

To determine the directivity factor, Q, convert the $\text{DG}_1$ value in decibels into a power ratio by using the decibel tables in the Appendix. Thus, a directional gain of -2 dB corresponds to a directivity factor of 0.63.

*2.8.5.5 Effect of Room on Measurements. The space in which power level and directivity are to be determined must be carefully considered. As explained previously and in paragraph 2.8.5.5.1, the measurement should ordinarily be made in an anechoic chamber. Sometimes the measurement can be made outdoors, far from other objects. If the device under test is normally mounted on the ground, this outdoor measurement may be ideal, provided that the location is free from interfering objects and the background noise level is low enough.

*2.8.5.5.1 Requirements on Room Characteristics. If the measurement is to be made in a room, it should be a large room, with extensive acoustic treatment. The measurement points should not be closer to the acoustic treatment than one-fourth wavelength at the center frequency for the lowest required band (approximately 5 feet for the lowest standard octave). Large acoustic absorption is particularly important if the directivity characteristics must be accurately determined. In order to obtain satisfactory results in moderate-sized rooms, extra-ordinarily good acoustic treatment must be used. Many of these special anechoic chambers have been built,[4] and some of them have been described in the Journal of the Acoustical Society of America.

*2.8.5.6 Sound Source in a Reverberant Room[5]. All sources that radiate sound as discrete tones or as very narrow-band components and all sources whose directivity must be determined can be measured only by the above "free-field" procedure. The total power radiated by a source whose sound energy is distributed over a wide band of frequencies can, however, be determined in a reverberant room — that is, a room with hard walls, floor, and ceiling.

*2.8.5.6.1 Measurements in a Reverberant Room. In a reverberant room, sound power can be determined from measurements of average sound pressure in the room and of the total absorption. The absorption is determined from a measurement of the rate at which a transient sound in the room decays. The procedure is as follows: The sound source in the room is turned on and the sound is allowed to reach a steady value. The sound is picked up by the microphone of a sound-level meter whose output is recorded on a graphic level recorder. The sound source is abruptly turned off, the sound in the room decays, and this decay is plotted by the graphic level recorder. The initial slope of the decay curve in dB per second is the rate of decay, D.

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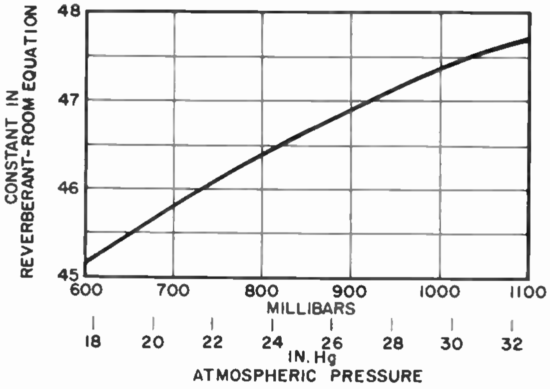
[4] Anechoic chambers of various sizes are manufactured by, for example, The Eckel Corporation, 155 Fawcett Street, Cambridge, Mass.

[5] The procedures given in Sections 2.8.5.6 and 2.8.5.7 are based to a great extent on R. W. Young, "Sabine Reverberation Equation and Sound Power Calculations", Journal Acoust Soc Am, Vol 31, No. 7, July, 1959, pp 912-921; H. C. Hardy, "Standard Mechanical Noise Sources," Noise Control, Vol 5, No. 3, May, 1959, pp 22-25; R. J. Wells and F. M. Wiener, "On the Determination of the Acoustic Power of a Source of Sound in Semi-Reverberant Spaces", Noise Control, Vol 7, No. 1, Jan-Feb, 1961, pp 21-29, and on the work of Am Stds Assoc Committee S1-W-25, F. M. Wiener, Chairman

*Figure 2-13. Variation of numerical constant in equation relating power level and sound-pressure level for a reverberant room.*



For a highly reverberant room, that is, where D is small (say 50 dB/sec or less), the sound power level of the source is then given by the following expression.

$$\text{PWL} = \overline{\text{SPL}} + 10 \log V + 10 \log D - 47.3$$

where V is the volume of the room in cubic feet and $\overline{\text{SPL}}$ is the average sound-pressure level in the reverberant field. The numerical value of 47.3 in the above formula varies with atmospheric pressure, as shown in Figure 2-13. For most measurements at sea level the value of 47.3 can be used.

*2.8.5.6.2 Room Requirements. In order for the measurement to be accurate, the room must satisfy the following conditions:

1. If the source has a broad spectrum and the measurements are made in octave bands, the smallest dimension of the room should be at least equal to a wavelength at the center frequency of the lowest octave band of interest.

2. No two dimensions of the room should be alike. A ratio of $1:\sqrt[3]{2}:\sqrt[3]{4}$ for the height, width, and length is often recommended.

3. The walls of the room should be hard and smooth. Large, hard objects should be near the boundaries of the room to help diffuse the sound.

4. The absorption should be small so that the decay rate is less than about 50 dB/sec for a room of 1000 cubic feet, and less than about 30 dB/sec for a room of 10,000 cubic feet. For the lowest frequency band, these decay rates may be doubled.

5. The source should be mounted on the floor or other surface if normally used that way. Otherwise, it may be suspended in the room, but not in the center, at least one-fourth wavelength from the walls. No large surface of the source should be parallel to any nearby wall.

*2.8.5.6.3 Sampling and Averaging Procedure. The desired sound-pressure level is an average taken at several positions about the source but at a distance from the source at least equal to the largest dimension of the source and yet not closer to any wall than one-fourth wavelength. The measurement positions should also be at least one-half wavelength apart. The average sound-pressure level should be determined on an energy basis, as described in paragraph 2.8.5.3.

The initial decay rates at the same set of measurement positions should be averaged for each measured band. If the ultimate measurements are to be in octave bands, an octave-band noise source should be used; for instance, a random noise generator, filtered by an octave-band analyzer, may be used as the source. The decay rate for a given set of room conditions will remain constant over a considerable time, except at the high audio frequencies where air absorption is critically dependent on relative humidity.

In a well designed reverberation room fewer measurement points are needed than for the free-field measurement. If the source is not highly directional, and if large rotating vanes are used to alter the standing-wave pattern during the measurement, one microphone position may be adequate for the measurement. This procedure in effect averages the sound-pressure level over a large area. The single-microphone method is not recommended, however, unless extensive experience has shown that the results are the same as those obtained with several microphone positions.

Another method of exploring the sound field to obtain an average is to swing the microphone around a wide area. Still another is to rotate the source.

*2.8.5.7 Comparison Method. The procedures given above require special rooms for the measurement of radiated power. When such measurements must be made in an ordinary room, a different technique has been proposed by Hardy, Wiener, Wells, and others. This is a comparison method, in which a standard source similar to that to be measured is used as a reference. The radiated power of this standard source must have been determined by one of the preceding techniques.

*2.8.5.7.1 Measurement Procedure. The measurement procedure is as follows:

1. The standard source is turned on in the room. Sound-pressure level is measured at several places around the source at a distance from the source equal to at least the maximum dimension of the source. The measurements are usually made in octave bands. The measured levels are averaged on an energy basis for each band.

2. The unknown source is operated in place of the standard source. The sound-pressure levels are measured at the same points as before and averaged for each octave band.

3. For each octave band the difference in average level between the standard and the unknown is applied to the known power level of the standard source.

*2.8.5.7.2 Requirements for Standard Source. The standard source should produce a stable and reproducible sound. Such sources have been developed for the Compressed Air and Gas Institute and for the fan and blower industry. The spectrum and directional properties of the standard source should be nearly the same as those of the unknown source.

*2.8.5.7.3 Requirements for Room. The measurement room should be large, and its characteristics should approach those of a reverberant room. No obstructing object should be in the immediate vicinity of the source or the microphone positions.

*2.8.6 PREDICTING NOISE LEVELS. When the acoustic power output and the directivity pattern of a device are known, the noise levels that it will produce under a variety of conditions can be predicted on the average with fair accuracy. These predictions are based on the principles discussed earlier in this chapter.

If a noisy device is placed in a room that is not anechoic, it is desirable to measure the decay rate of sound, D, in the room; and then the following formula, adapted from one by Young, can be used to predict the average level of sound in that part of the room where the reverberant field dominates:

$$\overline{SPL} = PWL - 10 \log V - 10 \log D + 47.8$$

where V is the volume of the room in cubic feet. PWL is the source power level, and the constant 47.8 varies with atmospheric pressure (to determine the variation add 0.5 dB to the values shown in Figure 2-13).

Close to the source the level is almost as if free-field conditions existed. The level decreases with increasing distance from the source and the average approaches the reverberant field level. Here standing waves will exist, and it is only the average level that can ordinarily be predicted. At points less than one-fourth wavelength from a hard wall, the level will be higher than the average in the reverberant field. Very near a hard wall the increase may be as much as 3 dB; very close to an edge, 6 dB; and right at the vertex of a corner, 9 dB.

When the decay rate in the room cannot be measured, it can be estimated from a detailed knowledge of the room and its surface conditions. The procedures are given in books on architectural acoustics. There the calculation procedure is normally given for reverberation time, T. The decay rate, D, is then easily obtained as follows:

$$D = \frac{60}{T}$$

The sound-pressure level produced by the source is also affected by its position in the room—that is, if it is suspended in the middle of the room, or mounted on the floor, wall, or ceiling, or in a corner. It is often very difficult to predict the exact effect, however.[6] Ordinarily the level is higher where the source is very near a hard surface than when it is in the middle of the room, and, as explained earlier, if the source is generally mounted on a hard surface it should be measured that way so that the effect on the source is taken into account. Then the levels in another room can be predicted with better accuracy.

## 2.9 VIBRATION.

Vibration is the term used to describe continuing or steady-state periodic motion. The motion may be simple harmonic motion like that of a pendulum, or it may be complex like a ride in the "whip" at an amusement park. The motion may involve tiny air particles that produce sound when the rate of vibration is in the audible frequency range (20 to 20,000 Hz), or it may involve, wholly or in part, structures found in vacuum tubes, bridges, or battleships. Usually the word vibration is used to describe motions of the latter types, and is classed as solid-borne, or mechanical, vibration.

Many important mechanical vibrations lie in the frequency range of 1 or 2 to 2,000 Hz (corresponding to rotational speeds of 60 to 120,000 rpm). In some specialized fields, however, both lower and higher frequencies are important. For example, in seismological work, vibration studies may extend down to a small fraction of a Hz, while in loudspeaker cone design, vibrations up to 20,000 Hz must be studied.

2.9.1 NATURE OF VIBRATORY MOTION. Vibration problems occur in so many devices and operations that a listing of these would be impractical. Rather, we shall give a classification on the basis of the vibratory motion together with numerous examples of where that motion occurs to show the practical application. The classes of vibratory motion that have been

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[6] R. V. Waterhouse and R. K. Cook, "Interference Patterns in Reverberant Sound Fields II," Journal of the Acoustical Society of America, Vol. 37, No. 3, March, 1965, pp. 424-428.

selected are given in Table 2-1. They are not mutually exclusive, and, furthermore, most devices and operations involve more than one class of vibratory motion.

2.9.2 VIBRATION TERMS: DISPLACEMENT, VELOCITY, ACCELERATION, AND JERK. Vibration can be measured in terms of displacement, velocity, acceleration and jerk. The easiest measurement to understand is that of displacement, or the magnitude of motion of the body being studied. When the rate of motion (frequency of vibration) is low enough, the displacement can be measured directly with the dial gauge micrometer. When the motion of the body is great enough, its displacement can be measured with the common scale.

In its simplest case, displacement may be considered as simple harmonic motion, like that of the bob of a pendulum, that is, a sinusoidal function having the form

$$x = A \sin \omega t \qquad (1)$$

where A is a constant, $\omega$ is $2\pi$ times the frequency, and t is the time, as shown in Figure 2-14. The maximum peak-to-peak displacement, also called double amplitude, (a quantity indicated by a dial gauge) is 2A, and the rms[7] displacement is $A/\sqrt{2}$ (=0.707A). The average (full-wave rectified average) value of the displacement is $2A/\pi$ (=0.636A), while the "average double amplitude" (a term occasionally encountered) would be $4A/\pi$ (=1.272A). Displacement measurements are significant in the study of deformation and bending of structures.

In many practical problems, however, displacement is not the important property of the vibration. A vibrating mechanical part will radiate sound in much the same way as does a loudspeaker. In general, velocities of the radiating part (which corresponds to the cone of the loudspeaker) and the air next to it will be the same, and if the distance from the front of the part to the back is large compared with one-half of the wavelength of the sound in air, the actual sound pressure in air will be proportional to the velocity of the vibration. The sound energy radiated by the vibrating surface is the product of the velocity squared and the resistive component of the air load. Under these conditions it is the velocity of the vibrating part and not its displacement that is of greatest importance.

Velocity has also been shown by practical experience to be the best single criterion for use in preventive maintenance of rotating machinery. Peak-to-peak displacement has been widely used for this purpose, but then the amplitude selected as a desirable upper limit varies markedly with rotational speed.

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[7] root-mean-square

## Table 2-1 - Nature of Vibratory Motion

1. Torsional or twisting vibration

   Examples:
   - Reciprocating devices
     - Gasoline and diesel engines
     - Valves
     - Compressors
     - Pumps
   - Rotating devices
     - Electric motors
     - Fans
     - Turbines
     - Gears
     - Turntables
     - Pulleys
     - Propellers

2. Bending vibration

   Examples:
   - Shafts in motors, engines
   - String instruments
   - Springs
   - Belts
   - Chains
   - Tape in recorders
   - Pipes
   - Bridges
   - Propellers
   - Transmission lines
   - Aircraft wings
   - Reeds on reed instruments
   - Rails
   - Washing machines

3. Flexural and plate-mode vibration

   Examples:
   - Aircraft
   - Circular saws
   - Loudspeaker cones
   - Sounding boards
   - Ship hulls and decks
   - Turbine blades
   - Gears
   - Bridges
   - Floors
   - Walls

4. Translational, axial, or rigid-body vibration

   Examples:
   - Reciprocating devices
     - Gasoline and diesel engines
     - Compressors
     - Air hammers
     - Tamping machines
     - Shakers
     - Punch presses
   - Autos
   - Motors
   - Devices on vibration mounts

5. Extensional and shear vibration

   Examples:
   - Transformer hum
   - Hum in electric motors and generators
   - Moving tapes
   - Belts
   - Punch presses
   - Tamping machines

6. Intermittent vibration including impacting, explosive and seismic motion (mechanical shock)

   Examples:
   - Blasting
   - Gun shots
   - Earthquakes
   - Drop forges
   - Heels impacting floors
   - Typewriters
   - Ratchets
   - Geneva mechanisms
   - Stepping motors
   - Autos
   - Catapults
   - Planers
   - Shapers
   - Chipping hammers
   - Riveters
   - Impact wrenches

7. Random and miscellaneous motions

   Examples:
   - Combustion
   - Ocean waves
   - Tides
   - Tumblers
   - Turbulence
   - Earthquakes
   - Gas and fluid motion and their interaction with mechanisms

Velocity is the time rate of change of displacement, so that for the sinusoidal vibration of equation (1) the velocity is:

$$v = \omega A \cos \omega t \tag{2}$$

Thus velocity is proportional to displacement and to frequency of vibration.

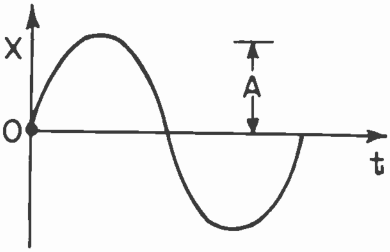

*Figure 2-14. A simple sinusoidal function.*

The analogy cited above covers the case where a loudspeaker cone or baffle is large compared with the wavelength of the sound involved. In most machines this relation does not hold, since relatively small parts are vibrating at relatively low frequencies. This situation may be compared to a small loudspeaker without a baffle. At low frequencies the air may be pumped back and forth from one side of the cone to the other with a very high velocity, but without building up much of a pressure or radiating much sound energy because of the very low air load, which has a reactive mechanical impedance. Under these conditions an acceleration measurement provides a better measure of the amount of noise radiated than does a velocity measurement.

In many cases of mechanical vibration, and especially where mechanical failure is a consideration, the actual forces set up in the vibrating parts are important factors. The acceleration of a given mass is proportional to the applied force, and a reacting force equal but opposite in direction results. Members of a vibrating structure, therefore, exert forces on the total structure that are a function of the masses and the accelerations of the vibrating parts. For this reason, acceleration measurements are important when vibrations are severe enough to cause actual mechanical failure.

Acceleration is the time rate of change of velocity, so that for a sinusoidal vibration.

$$a = -\omega^2 A \sin \omega t \tag{3}$$

It is proportional to the displacement and to the square of the frequency or to the velocity and the frequency.

Jerk is the time rate of change of acceleration. At low frequencies this change is related to riding comfort of autos and elevators. It is also important for determining load tiedown in planes, trains, and trucks.

2.9.3 ACCELERATION AND VELOCITY LEVEL. Some use is now being made of "acceleration level" and "velocity level," which, as the names imply, express the acceleration and velocity in decibels with respect to a reference acceleration and velocity. The reference value of $10^{-8}$m/s ($10^{-6}$cm/s) for velocity and $10^{-5}$m/s$^2$ ($10^{-3}$cm/s$^2$) for acceleration are now being used, although other references have been proposed. The selection of suitable standard reference values for acceleration, velocity, and displacement is now being studied.

2.9.4 NONSINUSOIDAL VIBRATIONS. Equations (1), (2), and (3) represent only sinusoidal vibrations, but as with other complex waves, complex periodic vibrations can also be represented as a Fourier series of sinusoidal vibrations. These simple equations may therefore be expanded to include as many terms as desirable in order to express any particular type of vibration. For a given sinusoidal displacement, velocity is proportional to frequency and acceleration is proportional to the square of the frequency, so that the higher-frequency components in a vibration are progressively more important in velocity and acceleration measurements than in displacement readings.

## 2.10 SUMMARY.

2.10.1 SOUND. Reference levels and relations presented in this chapter included the following:

Reference sound pressure: 20 micronewtons/square meter (20 $\mu$N/m$^2$)*

Reference power: $10^{-12}$ watt.**

Power level (PWL):

$$\underline{\text{PWL}} = 10 \log \frac{W}{10^{-12}} \text{ dB } \underline{\text{re}}\ 10^{-12} \text{ watt.}$$

where W is the acoustic power in watts.

Sound-pressure level (SPL):

$$\underline{SPL} = 20 \log \frac{P}{.00002} \text{ dB } \underline{re} \text{ } 20\ \mu N/m^2$$

where $\underline{P}$ is the root-mean-square sound pressure in newtons/square meter.

(Logarithms are taken to the base 10 in both PWL and SPL calculations.)

Important concepts that aid in interpreting noise measurement results can be summarized as follows:

To measure sound level, use a sound-level meter with one or more of its frequency response weightings (A, B, and C).

To measure sound-pressure level, use a sound-level meter with the controls set for as uniform a frequency response as possible.

Decibels are usually combined on an energy basis, not added directly.

Speed of sound in air:

at 0° C is 1087 ft/s or 331.4 m/s
at 20° C is 1127 ft/s or 343.4 m/s

| Pressure | Pressure Level re 20 $\mu N/m^2$ |
|---|---|
| 1 Newton/$m^2$ | 94 dB |
| 1 microbar | 74 dB |
| 1 pound/ft.$^2$ | 127.6 dB |
| 1 pound/in.$^2$ | 170.8 dB |
| 1 atmosphere | 194.1 dB |

*At one time the reference for a sound-level meter was taken as $10^{-16}$ watt/square centimeter or $10^{-12}$ watt/square meter. For most practical purposes, this reference is equivalent to the presently used pressure. This earlier reference value is not a reference for power, since it is power divided by an area. The pressure 20 $\mu N/m^2$ is also expressed as $2 \times 10^{-5}$ newton/square meter, 0.0002 microbar, or 0.0002 dyne/cm$^2$.

**A reference power of $10^{-13}$ watt is also used in the USA, and has been used in very early editions of this handbook, but the reference power of $10^{-12}$ watt is used here because of its increasing acceptance internationally.

Note: The reference pressure and the reference power have been selected independently because they are not uniquely related.

The preferred octave-band series* is the following:

| Center Frequency hertz | Effective Band hertz | Band No. |
|---|---|---|
| 31.5 | 22.1 to 44.2 | 15 |
| 63 | 44.2 to 88.4 | 18 |
| 125 | 88.4 to 177 | 21 |
| 250 | 177 to 354 | 24 |
| 500 | 354 to 707 | 27 |
| 1000 | 707 to 1414 | 30 |
| 2000 | 1414 to 2828 | 33 |
| 4000 | 2828 to 5657 | 36 |
| 8000 | 5657 to 11314 | 39 |

*USASI, S1.6 - 1960

The preferred center frequencies* in one-third-octave steps are:

| No. | hertz | No. | hertz | No. | hertz | |
|---|---|---|---|---|---|---|
| 10 | 10 | 20 | 100 | 30 | 1000 | etc. |
| 11 | 12.5 | 21 | 125 | 31 | 1250 | |
| 12 | 16 | 22 | 160 | 32 | 1600 | |
| 13 | 20 | 23 | 200 | 33 | 2000 | |
| 14 | 25 | 24 | 250 | 34 | 2500 | |
| 15 | 31.5 | 25 | 315 | 35 | 3150 | |
| 16 | 40 | 26 | 400 | 36 | 4000 | |
| 17 | 50 | 27 | 500 | 37 | 5000 | |
| 18 | 63 | 28 | 630 | 38 | 6300 | |
| 19 | 80 | 29 | 800 | 39 | 8000 | |

*These values are rounded off for simplicity of reference. The actual values used for filter design differ slightly from these except for 10, 100, 1000, etc., which are exact. The actual values are derived from the series $10^{n/10}$, where n takes on all integer values, and n is the number assigned to the band.

## 2.10.2 VIBRATION.

Displacement is magnitude of the motion.

Velocity is the time rate of change of displacement.

Acceleration is the time rate of change of velocity.

Jerk is the time rate of change of acceleration.

Reference quantities:

Velocity: $10^{-8}$ meters/second ($10^{-6}$ cm/s)
Acceleration: $10^{-5}$ meters/second/second ($10^{-3}$ cm/s$^2$)

chapter 3

# WHAT NOISE AND VIBRATION DO AND HOW MUCH IS ACCEPTABLE

## 3.1 WHY WE MEASURE NOISE.

That we are annoyed by a noisy device and a noisy environment, that noise may interfere with our sleep, our work, and our recreation, or that very intense noise may cause hearing loss is frequently the basic fact that leads to noise measurements and attempts at quieting. In order to make the most significant measurements and to do the job of quieting most efficiently, it is clearly necessary to learn about these effects of noise. We seek to estimate from these effects what levels of noise are acceptable, and thus establish suitable noise criteria. Then if we measure the existing noise level, the difference between this level and the acceptable level is the noise reduction necessary.

Unfortunately, not all the factors involved in annoyance, interference, and hearing loss are known at present. Nor are we yet sure how the known factors can best be used. But a brief discussion of our reactions to sounds will serve to show some of the factors and their relative significance. This information will be useful as a guide for selecting electronic equipment to make the most significant measurements for the problem at hand.

## 3.2 PSYCHOACOUSTICAL EXPERIMENTS.

Scientists and engineers have investigated many aspects of man's reactions to sounds. For example, they have measured the levels of the weakest sounds that various observers could just hear in a very quiet room (threshold of hearing), they have measured the levels of the sounds that are sufficiently high in level to cause pain (threshold of pain), and they have measured the least change in level and in frequency that various observers could detect (differential threshold). These experimenters have also asked various observers to set the levels of some sounds so that they are judged equal in loudness to reference sounds (equal loudness), and they have asked the observers to rate sounds for loudness on a numerical scale.

In order to get reliable measures of these reactions, the experimenters have to simplify the conditions under which people react to sounds. This simplification is mainly one of maintaining unchanged as many conditions as possible while a relatively few characteristics of the sound are varied. Some of the conditions that have to be controlled and specified are the following: the physical environment of the observer, particularly the background or ambient level; the method of presenting the changing signals, including the order of presentation, duration, frequency, and intensity; the selection of the observers; the instructions to the observers; the experience of the observers in the specific test procedure; the normal hearing characteristics of the observers; the method of getting the responses; and the method of handling the data.

Variations in the conditions of the measurement will affect the result. Such interaction is the reason for requiring controlled and specified conditions. It is desirable to know, however, how much the various conditions do affect the result. For example, small changes in room temperature are usually of little significance. But if the observer is exposed to a noise of even moderate level just before a threshold measurement, the measured threshold level will, temporarily, be significantly higher than normal.

The basic method used by the observer to present his reaction to the signals is also important in the end result. Numerous methods have been developed for this presentation. Three of these psychophysical methods are as follows: 1. In the method of adjustment the observer sets an adjustable control to the level he judges suitable for the test. 2. In the method of the just noticeable difference the observer states when two signals differ sufficiently so that he can tell they are different. 3. In the method of constant stimuli the observer states whether two signals are the same, or which is the greater, if they seem to differ.

When psychoacoustical experiments are performed, the resultant data show variability in the judgments of a given observer as well as variability in the judgments of a group of observers. The data must then be handled by statistical methods to obtain an average result as well as a measure of the deviations from the average. In general it is the average result that is of most interest, but the extent of the deviations is also of value, and in some experiments these deviations are of major interest.

The deviations are not usually shown on graphs of averaged psychoacoustical data, but they should be kept in mind. To picture these deviations one might think of the curves as if they were drawn with a wide brush instead of a fine pen.

The measured psychoacoustical responses also have a certain degree of stability, although it is not the degree of stability that we find in physical measurements. In the normal course of events, if one's threshold of hearing is measured today, a similar measurement tomorrow should give the same threshold level within a few decibels.

In the process of standardizing the measurement conditions for the sake of reliability and stability, the experiments have been controlled to the point where they do not duplicate the conditions encountered in actual practice. They are then useful mainly as a guide in interpreting objective measurements in subjective terms, provided one allows for those conditions that seriously affect the result. As a general rule, the trend of human reactions to changes in the sound is all that can be estimated with validity. A conservative approach in using psychoacoustical data with some margin as an engineering safety factor is usually essential in actual practice.

## 3.3 THRESHOLDS OF HEARING AND TOLERANCE.

Many experimenters have made measurements of the threshold of hearing of various observers. When young persons with good hearing are tested, a characteristic similar to that labeled MAF (minimum audible field) in Figure 3-1 is usually obtained. This shows the level of the simple tone that can just be heard in an exceptionally quiet location under free-field conditions (see Section 2.8.1 for an explanation of "free-field") as a function of the frequency of the tone. For example, if a simple tone having a frequency of 250 Hz (about the same as the fundamental frequency of middle C) is sounded in a very quiet location, and if its sound-pressure level is greater than 12 dB $\overline{\text{re}}$ 20 $\mu$N/m$^2$ at the ear of the listener, it will usually be heard by a young person. In addition to the restrictions mentioned above there are a number of other factors that need careful attention. For example, what is meant by "can just be heard" needs definition. References on these experiments can be found in the bibliography at the end of this handbook. (See also Figure 3-3.)

Some variation in the threshold of a person can be expected even if the experiments are carefully controlled. Threshold determinations made in rapid succession may possibly differ by as much as 5 dB, and with longer intervals more variation between particular values is possible. But the average of a number of threshold measurements will generally be consistent with the average of another set to within less than 5 dB.

The variability among individuals is, of course, much greater than the day-to-day variability of a single individual. For example, the sensitivity of some young people is slightly better than that shown in Fig. 3-1 as the minimum audible field, and, at the other extreme, some people have no usable hearing. Most noise-quieting problems, however, involve people whose hearing characteristics, on the average, are only somewhat poorer than shown in Fig. 3-1.

The threshold curve (Figure 3-1) shows that at low frequencies the sound-pressure level must be comparatively high before the tone can be heard. In contrast we can hear tones in the frequency range from 200 to 10,000 Hz even though the levels are very low. This variation in acuity of hearing with

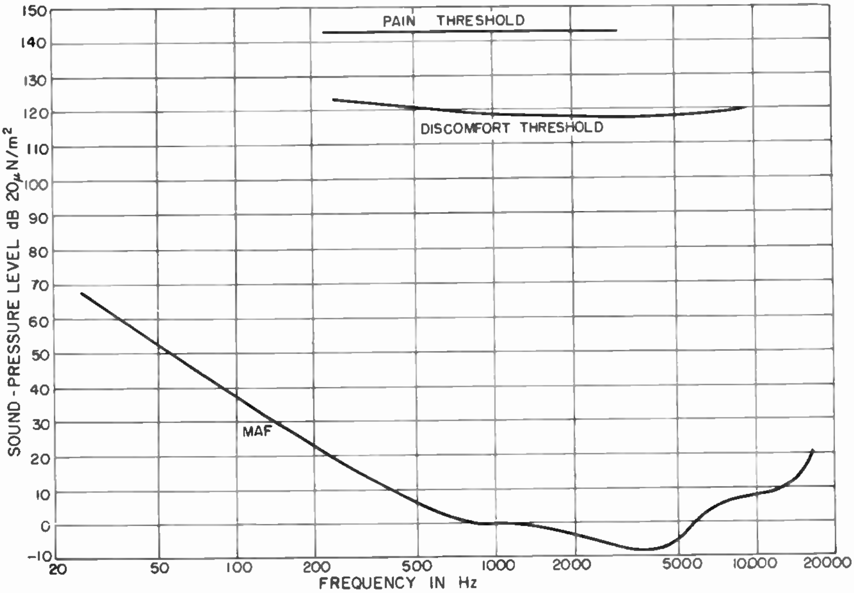

*Figure 3-1. Thresholds of hearing and tolerance.*

frequency is one of the reasons that in most noise problems it is essential to know the frequency composition of the noise. For example, is it made up of a number of components all below 100 Hz? Or are they all between 1000 and 5000 Hz? The importance of a given sound-pressure level is significantly different in those two examples.

The upper limit of frequency at which we can hear airborne sounds depends primarily on the condition of our hearing and on the intensity of the sound. This upper limit is usually quoted as being somewhere between 16,000 and 20,000 Hz. For most practical purposes the actual figure is not important. It is important, however, to realize that it is in this upper frequency region where we can expect to lose sensitivity as we grow older.

The aging effect (called "presbycusis") has been determined by statistical analysis of hearing threshold measurements on many people. A recent analysis of such data* has given the results shown in Figure 3-2. This set of curves shows, for a number of simple tones of differing frequencies,

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*American Standards Association Subcommittee Z24-X-2, The Relations of Hearing Loss to Noise Exposure, January, 1954, New York.

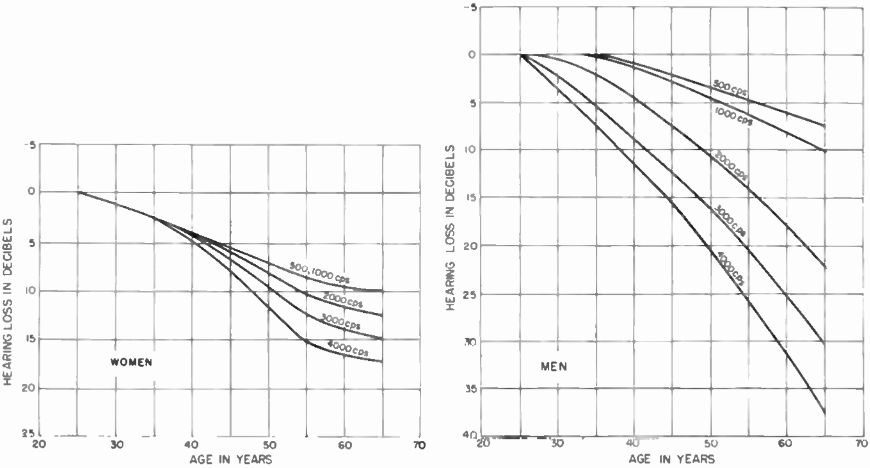

*Figure 3-2. Presbycusis curves for women and men. These sets of curves show the average shifts with age of the threshold of hearing for pure tones (ASA Subcommittee Z24-X-2, "The Relations of Hearing Loss to Noise Exposure," New York, 1954, pp 16-17).*

the extent of the shift in threshold that we can expect, on the average, as we grow older.

Many threshold measurements are made by otologists and other hearing specialists in the process of analyzing the condition of a person's hearing. An instrument known as an audiometer is used for this purpose. Its calibration is made with respect to a "normal" threshold. This "normal" level is somewhat different from the curve labeled MAF in Figure 3-1. The difference between the audiometer threshold and the minimum audible field can be ascribed to the differences in technique used in the tests, to the selection of a different sample of observers, and to generally prevailing ambient noise conditions during audiometer tests.

When a sound is very high in level, one can feel very uncomfortable listening to it. The "Discomfort Threshold" (Silverman) shown in Figure 3-1 is drawn in to show the general level at which such a reaction is to be expected. At still higher levels the sound may become painful, and the order of magnitude of these levels (Silverman) is also shown in Figure 3-1.

## 3.4 "WHAT NOISE ANNOYS AN OYSTER?"

No adequate measures of the annoyance levels of noises have yet been devised. Various aspects of the problem have been investigated, but the psychological difficulties in making these investigations are very great. For example, the extent of our annoyance depends greatly on what we are trying to do at the moment, it depends on our previous conditioning, and it depends on the character of the noise.

The annoyance level of a noise is sometimes assumed to be related directly to the loudness level of the noise. Although not completely justifiable, this assumption is sometimes helpful because a loud sound is usually more annoying than one of similar character that is not so loud.

Psychologists have found that high-frequency sounds (above about 2000 Hz) are usually more annoying than are lower-frequency sounds of the same sound-pressure level. Therefore, when it is determined, by methods to be explained later, that a significant portion of the noise is in the higher frequency bands, considerable effort at reducing these levels from the viewpoint of annoyance may be justified.

A further effect concerns localization of sound. When a large office has acoustically hard walls, floor, and ceiling, the room is "live," reverberant. The noise from any office machinery then is reflected back and forth, and the workers are immersed in the noise with the feeling that it comes from everywhere. If the office is heavily treated with absorbing material, the reflected sound is reduced, and the workers then feel that the noise is coming directly from the machine. This localized noise seems to be less annoying. While no adequate measures of this effect have been developed, the general principle discussed here seems to be accepted by many who are experienced in noise problems.

## 3.5 RATING THE LOUDNESS OF A SOUND.

Many psychoacoustical experiments have been made in which listeners have been asked to rate the loudness of a sound. As a result of these experiments involving all sorts of sounds in various arrangements much has been learned about the concept of loudness in laboratory situations. The way in which the judgment of loudness has been obtained seems to affect the results sufficiently, however, so that it seems unwise at the present time to try to scale the sounds of everyday life on an absolute basis. In particular, it does not seem possible to give a numerical value to the loudness ratio of two sounds and have this ratio be reasonably independent of the conditions of comparison. It does seem possible, however, to rank a sound with satisfactory reliability according to its loudness. For example, if sound A is judged louder than sound B and if sound B is judged louder than sound C, then, in general, sound A will also be judged louder than sound C.

3.5.1 EQUAL-LOUDNESS CONTOURS AND LOUDNESS LEVEL. One step in the direction of rating the loudness of a sound has been to determine the sound-pressure levels of simple tones of various frequencies that sound just as loud to an observer as a 1000-Hz tone of a given sound-pressure level. The results of this determination by Robinson and Dadson are given as equal-loudness contours in Figure 3-3. The number on each curve is the sound-pressure level of the 1000-Hz tone used for comparison for that curve. To use the contours for determining the equally loud levels at other frequencies, we find the point on the curve corresponding to the desired frequency and read off the corresponding sound-pressure level as the ordinate. For example, the 60-dB contour line shows that a 67-dB level at 100 Hz is just as loud as a 60-dB 1000-Hz tone. We can also interpolate to find that a 60-dB 100-Hz

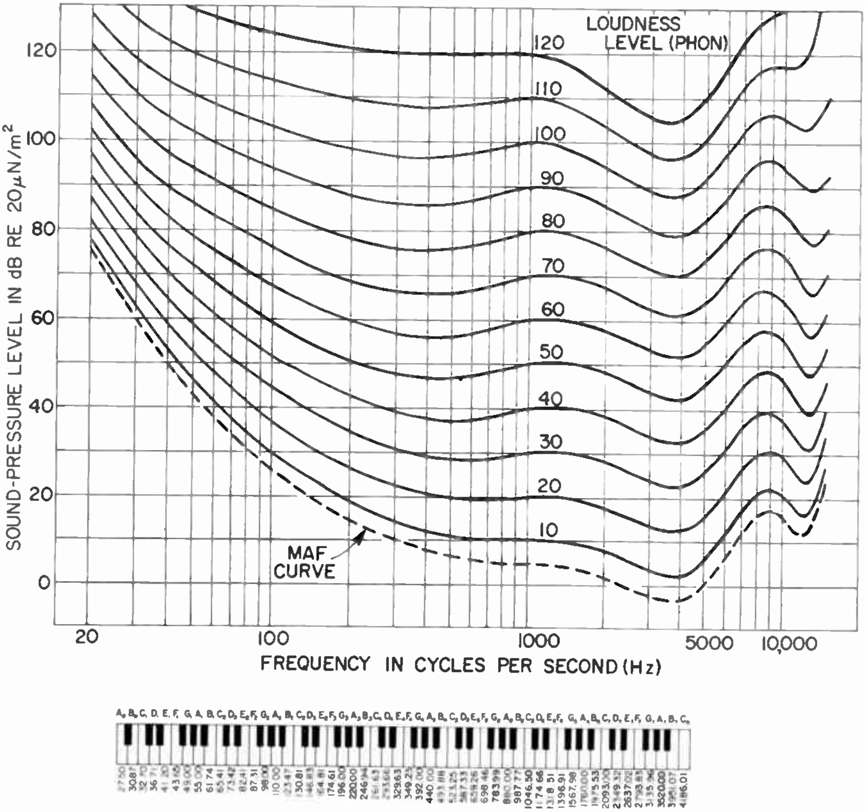

*Figure 3-3. Free-field equal-loudness contours for pure tones (observer facing source), determined by Robinson and Dadson at the National Physical Laboratory, Teddington, England. (ISO/R226-1961) Piano keyboard helps identify the frequency scale. Only the fundamental frequency of each piano key is indicated.*

tone is equal in loudness to a 51-dB 1000-Hz tone. The corresponding sound-pressure level in dB for the 1000-Hz tone has been defined as the loudness level in phons. Therefore, a 100-Hz tone at a sound-pressure level of 60 dB has a loudness level of 51 phons.

The weighting networks for the standard sound-level meter are based on similar contours, developed much earlier by Fletcher and Munson. The "A" and "B" weighting characteristics are in accordance with the 40- and 70-phon Fletcher-Munson contours, but with modifications to take into account the usually random nature of the sound field in a room.

A set of equal-loudness contours (Pollack) for bands of random noise is shown in Figure 3-4. Random noise is a common type of noise that occurs in ventilating systems, jets, blowers, combustion chambers, etc. It does not have a well defined pitch, such as characterizes a tone with the energy concentrated in components of definite frequencies. Rather, random noise has energy distributed over a band of frequen-

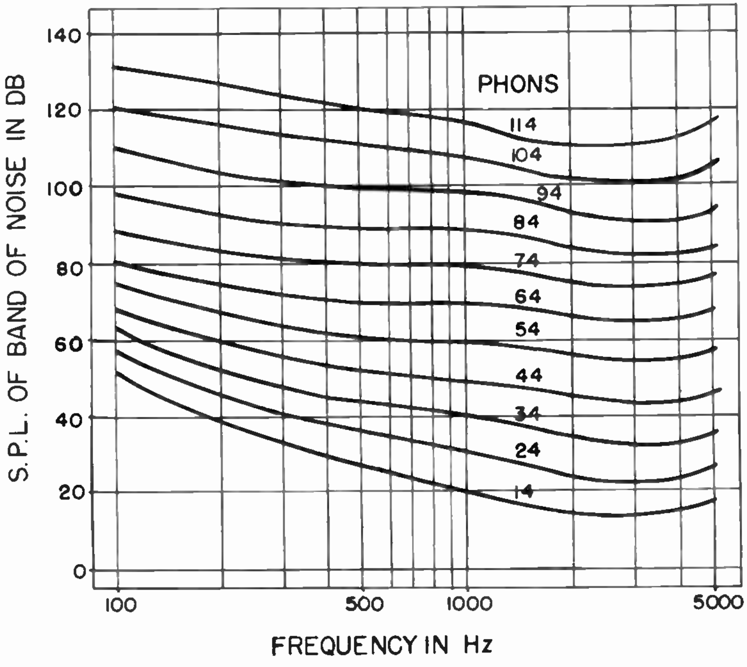

*Figure 3-4. Equal-loudness contours for relatively narrow bands of random noise. The center frequency of the band is shown as the abscissa, and the numbers on the curves are phons (Irwin Pollack, "The Loudness of Bands of Noise," Journal of the Acoustical Society of America, Vol 24, Sept. 1952, pp 533-538).*

cies. If the noise energy is uniform over a wide range, it is called "white noise," being analogous in spectrum characteristics to white light. When the energy is distributed over a very wide band, it is a sort of hishing sound. When the broadband noise has little energy at low frequencies, it is more of a hissing sound. When it is concentrated in narrower bands, the sound takes on some aspects of pitch. For example, low-frequency random noise may be a sort of roar.

The contours shown in Figure 3-4 are for relatively narrow bands of noise, such that 11 bands cover the range from 60 to 5800 Hz. They are distributed uniformly on a scale of pitch for simple tones (see Section 3.9.2). The numbers on the curves are phons, that is, the sound-pressure levels of equally loud 1000-Hz tones, and the levels are plotted according to the centers of the bands. For example, one band covers the range from 350 to 700-Hz. From the curves we can see that when the sound-pressure level of the noise in that band is 43 dB re 20 $\mu N/m^2$, the indicated loudness level is about 34 phons.

3.5.4 LOUDNESS AND LOUDNESS LEVEL. Although we may remark that some sounds are louder than others, we do not ordinarily rate sounds for loudness on a numerical basis. Experimenters have asked observers to make judgments of the loudness ratio of sounds, that is, to state when one sound is twice, four times, one-half, etc., as loud as another. The resultant judgments depend to a considerable extent on how the problem is presented to the observer. But on the basis of such judgments several scales of loudness have been devised, which rate sounds from "soft" to "loud" in units of sones. As a reference, the loudness of a 1000-Hz tone with a sound-pressure level of 40 dB re 20 $\mu N/m^2$ (a loudness level of 40 phons) is taken to be 1 sone. A tone that sounds twice as loud has a loudness of 2 sones. This scale is shown on the vertical axis of Figure 3-5, and the horizontal scale is the sound-pressure level of the sound in decibels. The curve shown in this figure relates the loudness in sones to the sound-pressure level for a 1000-Hz simple tone. This relation was developed as a useful engineering approximation by Stevens as a result of his analysis of the data reported by many experimenters, who used a wide variety of techniques. He also performed a series of experiments in which the loudness estimates were made on an unusually direct basis, and these experiments confirmed the relation shown. Robinson has also suggested this relation, which is published as a Recommendation of the International Standards Organization. See Appendix III.

Incidentally, the relation shown in Fig. 3-5 tends to refute the point of view that the decibel is used in acoustics because we respond to sound pressure in a logarithmic manner. Actually, the loudness is approximately proportional to the sound pressure raised to the 0.6 power.

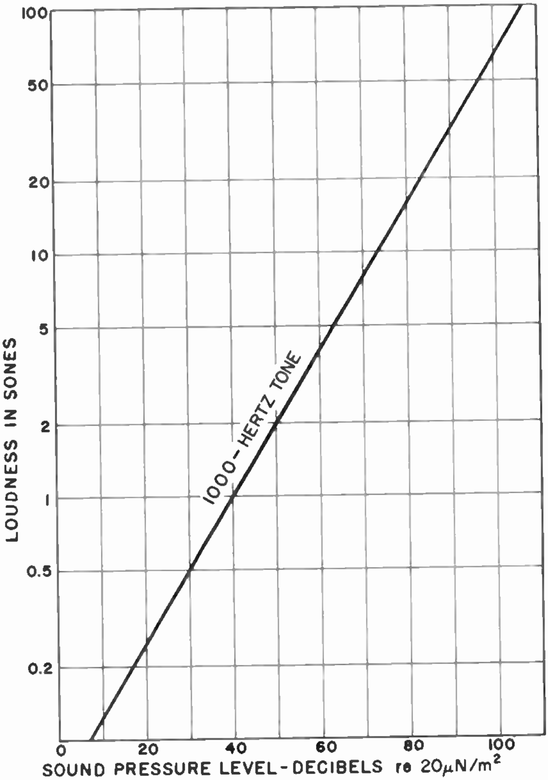

*Figure 3-5. Loudness vs sound-pressure level for a pure tone of 1000 Hz.*

3.5.3 LOUDNESS LEVEL CALCULATIONS FROM MEASUREMENTS. If the sound to be measured is known to be a simple tone, the procedure for determination of loudness level is relatively easy. The sound-pressure level and the frequency of the tone are determined, and the equal-loudness contours of Figure 3-3 then indicate the loudness level. Since the weighting networks on a sound-level meter approximate two of the equal-loudness contours, a determination of the weighted level (sound level) can be used to give an estimate of the loudness level of a simple tone.

For any other type of sound, however, the measured sound level will be lower than the loudness level. The error in estimating loudness level will depend on the type of sound and for many noises will be more than 10 phons. For example, if we have a uniform wide-band noise from 20 to 6000 Hz of 80 dB sound-pressure level, the B-weighted sound level would be about 79 dB and the A-weighted sound level would be about 80 dB, whereas the actual loudness level of such a noise is about 100 phons. Here we see that the sound level is not only misleading, but is no nearer the loudness level than is the sound-pressure level. This result, for most noises, illustrates the fact that we need to know more about a sound than just its sound-pressure level or its sound level. If we know how the energy in a sound is distributed as a function of frequency we can make a more useful estimate of its probable subjective effect than we can by knowing just its sound-pressure level. One of the ways such knowledge is used is in the calculation of loudness level.

A number of workers in noise measurements have found it useful to translate their noise measurements into such loudness terms. Then they can say the measured sound is for example, about equal in loudness to another, more familiar, sound. To some groups, such as excecutive and lay clients, this type of statement is seemingly more meaningful than levels quoted in decibels.

For steady, wide-band noises, a technique developed by Stevens has been found to give good results. The sound is divided by an analyzer into frequency bands covering the audio spectrum. The loudness level is then calculated according to the procedure given in the next section.

*3.5.4 PROCEDURE FOR CALCULATING LOUDNESS. Table 3-1 is used to calculate the loudness from octave-band levels of the preferred series. The procedure is as follows:

1. From the table find the proper loudness index for each band level.
2. Add all the loudness indexes ($\Sigma S$).
3. Multiply this sum by 0.3
4. Add this product to 0.7 of the index for that band that has the largest index. ($0.3\ \Sigma S + 0.7\ S_{max}$) This value is the total loudness in sones.
5. This total loudness is then converted to loudness level in phons by the relation shown in the two columns at the right of the table.

The calculated loudness is labeled sones (OD) and the loudness level is labeled phons (OD) to designate that they have been calculated from octave-band levels (O) and for a diffuse field (D).

A similar calculation can be made for third-octave bands, and they are labeled (TD).

For steady noises having a broad frequency spectrum, the loudness calculated by means of the tables, which are based on Stevens's[1] method agrees reasonably well with direct assessments made by loudness balances against a 1000-Hz tone.

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[1] The method used here is that given in S. S. Stevens, "Procedure for Calculating Loudness: Mark VI," Journal of the Acoustical Society of America, Vol. 33, No. 11, November, 1961, pp. 1577-1585. Chart paper No. 31460-A (Codex Book Company, Norwood, Massachusetts 02062) is available for this calculation when the older series of octave bands is used.

Table 3-1

| Band Level | Band Loudness Index | | | | | | | | | Loudness | Loudness Level |
|---|---|---|---|---|---|---|---|---|---|---|---|
| dB | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 | Sones | Phons |
| 20 | | | | | | .18 | .30 | .45 | .61 | .25 | 20 |
| 21 | | | | | | .22 | .35 | .50 | .67 | .27 | 21 |
| 22 | | | | | .07 | .26 | .40 | .55 | .73 | .29 | 22 |
| 23 | | | | | .12 | .30 | .45 | .61 | .80 | .31 | 23 |
| 24 | | | | | .16 | .35 | .50 | .67 | .87 | .33 | 24 |
| 25 | | | | | .21 | .40 | .55 | .73 | .94 | .35 | 25 |
| 26 | | | | | .26 | .45 | .61 | .80 | 1.02 | .38 | 26 |
| 27 | | | | | .31 | .50 | .67 | .87 | 1.10 | .41 | 27 |
| 28 | | | | .07 | .37 | .55 | .73 | .94 | 1.18 | .44 | 28 |
| 29 | | | | .12 | .43 | .61 | .80 | 1.02 | 1.27 | .47 | 29 |
| 30 | | | | .16 | .49 | .67 | .87 | 1.10 | 1.35 | .50 | 30 |
| 31 | | | | .21 | .55 | .73 | .94 | 1.18 | 1.44 | .54 | 31 |
| 32 | | | | .26 | .61 | .80 | 1.02 | 1.27 | 1.54 | .57 | 32 |
| 33 | | | | .31 | .67 | .87 | 1.10 | 1.35 | 1.64 | .62 | 33 |
| 34 | | | .07 | .37 | .73 | .94 | 1.18 | 1.44 | 1.75 | .66 | 34 |
| 35 | | | .12 | .43 | .80 | 1.02 | 1.27 | 1.54 | 1.87 | .71 | 35 |
| 36 | | | .16 | .49 | .87 | 1.10 | 1.35 | 1.64 | 1.99 | .76 | 36 |
| 37 | | | .21 | .55 | .94 | 1.18 | 1.44 | 1.75 | 2.11 | .81 | 37 |
| 38 | | | .26 | .62 | 1.02 | 1.27 | 1.54 | 1.87 | 2.24 | .87 | 38 |
| 39 | | | .31 | .69 | 1.10 | 1.35 | 1.64 | 1.99 | 2.38 | .93 | 39 |
| 40 | | .07 | .37 | .77 | 1.18 | 1.44 | 1.75 | 2.11 | 2.53 | 1.00 | 40 |
| 41 | | .12 | .43 | .85 | 1.27 | 1.54 | 1.87 | 2.24 | 2.68 | 1.07 | 41 |
| 42 | | .16 | .49 | .94 | 1.35 | 1.64 | 1.99 | 2.38 | 2.84 | 1.15 | 42 |
| 43 | | .21 | .55 | 1.04 | 1.44 | 1.75 | 2.11 | 2.53 | 3.0 | 1.23 | 43 |
| 44 | | .26 | .62 | 1.13 | 1.54 | 1.87 | 2.24 | 2.68 | 3.2 | 1.32 | 44 |
| 45 | | .31 | .69 | 1.23 | 1.64 | 1.99 | 2.38 | 2.84 | 3.4 | 1.41 | 45 |
| 46 | .07 | .37 | .77 | 1.33 | 1.75 | 2.11 | 2.53 | 3.0 | 3.6 | 1.52 | 46 |
| 47 | .12 | .43 | .85 | 1.44 | 1.87 | 2.24 | 2.68 | 3.2 | 3.8 | 1.62 | 47 |
| 48 | .16 | .49 | .94 | 1.56 | 1.99 | 2.38 | 2.84 | 3.4 | 4.1 | 1.74 | 48 |
| 49 | .21 | .55 | 1.04 | 1.69 | 2.11 | 2.53 | 3.0 | 3.6 | 4.3 | 1.87 | 49 |
| 50 | .26 | .62 | 1.13 | 1.82 | 2.24 | 2.68 | 3.2 | 3.8 | 4.6 | 2.00 | 50 |
| 51 | .31 | .69 | 1.23 | 1.96 | 2.38 | 2.84 | 3.4 | 4.1 | 4.9 | 2.14 | 51 |
| 52 | .37 | .77 | 1.33 | 2.11 | 2.53 | 3.0 | 3.6 | 4.3 | 5.2 | 2.30 | 52 |
| 53 | .43 | .85 | 1.44 | 2.24 | 2.68 | 3.2 | 3.8 | 4.6 | 5.5 | 2.46 | 53 |
| 54 | .49 | .94 | 1.56 | 2.38 | 2.84 | 3.4 | 4.1 | 4.9 | 5.8 | 2.64 | 54 |
| 55 | .55 | 1.04 | 1.69 | 2.53 | 3.0 | 3.6 | 4.3 | 5.2 | 6.2 | 2.83 | 55 |
| 56 | .62 | 1.13 | 1.82 | 2.68 | 3.2 | 3.8 | 4.6 | 5.5 | 6.6 | 3.03 | 56 |
| 57 | .69 | 1.23 | 1.96 | 2.84 | 3.4 | 4.1 | 4.9 | 5.8 | 7.0 | 3.25 | 57 |
| 58 | .77 | 1.33 | 2.11 | 3.0 | 3.6 | 4.3 | 5.2 | 6.2 | 7.4 | 3.48 | 58 |
| 59 | .85 | 1.44 | 2.27 | 3.2 | 3.8 | 4.6 | 5.5 | 6.6 | 7.8 | 3.73 | 59 |
| 60 | .94 | 1.56 | 2.44 | 3.4 | 4.1 | 4.9 | 5.8 | 7.0 | 8.3 | 4.00 | 60 |
| 61 | 1.04 | 1.69 | 2.62 | 3.6 | 4.3 | 5.2 | 6.2 | 7.4 | 8.8 | 4.29 | 61 |
| 62 | 1.13 | 1.82 | 2.81 | 3.8 | 4.6 | 5.5 | 6.6 | 7.8 | 9.3 | 4.59 | 62 |
| 63 | 1.23 | 1.96 | 3.0 | 4.1 | 4.9 | 5.8 | 7.0 | 8.3 | 9.9 | 4.92 | 63 |
| 64 | 1.33 | 2.11 | 3.2 | 4.3 | 5.2 | 6.2 | 7.4 | 8.8 | 10.5 | 5.28 | 64 |
| 65 | 1.44 | 2.27 | 3.5 | 4.6 | 5.5 | 6.6 | 7.8 | 9.3 | 11.1 | 5.66 | 65 |
| 66 | 1.56 | 2.44 | 3.7 | 4.9 | 5.8 | 7.0 | 8.3 | 9.9 | 11.8 | 6.06 | 66 |
| 67 | 1.69 | 2.62 | 4.0 | 5.2 | 6.2 | 7.4 | 8.8 | 10.5 | 12.6 | 6.50 | 67 |
| 68 | 1.82 | 2.81 | 4.3 | 5.5 | 6.6 | 7.8 | 9.3 | 11.1 | 13.5 | 6.96 | 68 |
| 69 | 1.96 | 3.0 | 4.7 | 5.8 | 7.0 | 8.3 | 9.9 | 11.8 | 14.4 | 7.46 | 69 |
| 70 | 2.11 | 3.2 | 5.0 | 6.2 | 7.4 | 8.8 | 10.5 | 12.6 | 15.3 | 8.00 | 70 |
| 71 | 2.27 | 3.5 | 5.4 | 6.6 | 7.8 | 9.3 | 11.1 | 13.5 | 16.4 | 8.6 | 71 |
| 72 | 2.44 | 3.7 | 5.8 | 7.0 | 8.3 | 9.9 | 11.8 | 14.4 | 17.5 | 9.2 | 72 |
| 73 | 2.62 | 4.0 | 6.2 | 7.4 | 8.8 | 10.5 | 12.6 | 15.3 | 18.7 | 9.8 | 73 |
| 74 | 2.81 | 4.3 | 6.6 | 7.8 | 9.3 | 11.1 | 13.5 | 16.4 | 20.0 | 10.6 | 74 |
| 75 | 3.0 | 4.7 | 7.0 | 8.3 | 9.9 | 11.8 | 14.4 | 17.5 | 21.4 | 11.3 | 75 |
| 76 | 3.2 | 5.0 | 7.4 | 8.8 | 10.5 | 12.6 | 15.3 | 18.7 | 23.0 | 12.1 | 76 |
| 77 | 3.5 | 5.4 | 7.8 | 9.3 | 11.1 | 13.5 | 16.4 | 20.0 | 24.7 | 13.0 | 77 |
| 78 | 3.7 | 5.8 | 8.3 | 9.9 | 11.8 | 14.4 | 17.5 | 21.4 | 26.5 | 13.9 | 78 |
| 79 | 4.0 | 6.2 | 8.8 | 10.5 | 12.6 | 15.3 | 18.7 | 23.0 | 28.5 | 14.9 | 79 |
| 80 | 4.3 | 6.7 | 9.3 | 11.1 | 13.5 | 16.4 | 20.0 | 24.7 | 30.5 | 16.0 | 80 |
| 81 | 4.7 | 7.2 | 9.9 | 11.8 | 14.4 | 17.5 | 21.4 | 26.5 | 32.9 | 17.1 | 81 |
| 82 | 5.0 | 7.7 | 10.5 | 12.6 | 15.3 | 18.7 | 23.0 | 28.5 | 35.3 | 18.4 | 82 |
| 83 | 5.4 | 8.2 | 11.1 | 13.5 | 16.4 | 20.0 | 24.7 | 30.5 | 38 | 19.7 | 83 |
| 84 | 5.8 | 8.8 | 11.8 | 14.4 | 17.5 | 21.4 | 26.5 | 32.9 | 41 | 21.1 | 84 |
| 85 | 6.2 | 9.4 | 12.6 | 15.3 | 18.7 | 23.0 | 28.5 | 35.3 | 44 | 22.6 | 85 |

Table 3-1 (Continued)

| Band Level | Band Loudness Index | | | | | | | | | Loudness | Loudness Level |
|---|---|---|---|---|---|---|---|---|---|---|---|
| dB | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 | Sones | Phons |
| 86 | 6.7 | 10.1 | 13.5 | 16.4 | 20.0 | 24.7 | 30.5 | 38 | 48 | 24.3 | 86 |
| 87 | 7.2 | 10.9 | 14.4 | 17.5 | 21.4 | 26.5 | 32.9 | 41 | 52 | 26.0 | 87 |
| 88 | 7.7 | 11.7 | 15.3 | 18.7 | 23.0 | 28.5 | 35.3 | 44 | 56 | 27.9 | 88 |
| 89 | 8.2 | 12.6 | 16.4 | 20.0 | 24.7 | 30.5 | 38 | 48 | 61 | 29.9 | 89 |
| 90 | 8.8 | 13.6 | 17.5 | 21.4 | 26.5 | 32.9 | 41 | 52 | 66 | 32.0 | 90 |
| 91 | 9.4 | 14.8 | 18.7 | 23.0 | 28.5 | 35.3 | 44 | 56 | 71 | 34.3 | 91 |
| 92 | 10.1 | 16.0 | 20.0 | 24.7 | 30.5 | 38 | 48 | 61 | 77 | 36.8 | 92 |
| 93 | 10.9 | 17.3 | 21.4 | 26.5 | 32.9 | 41 | 52 | 66 | 83 | 39.4 | 93 |
| 94 | 11.7 | 18.7 | 23.0 | 28.5 | 35.3 | 44 | 56 | 71 | 90 | 42.2 | 94 |
| 95 | 12.6 | 20.0 | 24.7 | 30.5 | 38 | 48 | 61 | 77 | 97 | 45.3 | 95 |
| 96 | 13.6 | 21.4 | 26.5 | 32.9 | 41 | 52 | 66 | 83 | 105 | 48.5 | 96 |
| 97 | 14.8 | 23.0 | 28.5 | 35.3 | 44 | 56 | 71 | 90 | 113 | 52.0 | 97 |
| 98 | 16.0 | 24.7 | 30.5 | 38 | 48 | 61 | 77 | 97 | 121 | 55.7 | 98 |
| 99 | 17.3 | 26.5 | 32.9 | 41 | 52 | 66 | 83 | 105 | 130 | 59.7 | 99 |
| 100 | 18.7 | 28.5 | 35.3 | 44 | 56 | 71 | 90 | 113 | 139 | 64.0 | 100 |
| 101 | 20.3 | 30.5 | 38 | 48 | 61 | 77 | 97 | 121 | 149 | 68.6 | 101 |
| 102 | 22.1 | 32.9 | 41 | 52 | 66 | 83 | 105 | 130 | 160 | 73.5 | 102 |
| 103 | 24.0 | 35.3 | 44 | 56 | 71 | 90 | 113 | 139 | 171 | 78.8 | 103 |
| 104 | 26.1 | 38 | 48 | 61 | 77 | 97 | 121 | 149 | 184 | 84.4 | 104 |
| 105 | 28.5 | 41 | 52 | 66 | 83 | 105 | 130 | 160 | 197 | 90.5 | 105 |
| 106 | 31.0 | 44 | 56 | 71 | 90 | 113 | 139 | 171 | 211 | 97 | 106 |
| 107 | 33.9 | 48 | 61 | 77 | 97 | 121 | 149 | 184 | 226 | 104 | 107 |
| 108 | 36.9 | 52 | 66 | 83 | 105 | 130 | 160 | 197 | 242 | 111 | 108 |
| 109 | 40.3 | 56 | 71 | 90 | 113 | 139 | 171 | 211 | 260 | 119 | 109 |
| 110 | 44 | 61 | 77 | 97 | 121 | 149 | 184 | 226 | 278 | 128 | 110 |
| 111 | 49 | 66 | 83 | 105 | 130 | 160 | 197 | 242 | 298 | 137 | 111 |
| 112 | 54 | 71 | 90 | 113 | 139 | 171 | 211 | 260 | 320 | 147 | 112 |
| 113 | 59 | 77 | 97 | 121 | 149 | 184 | 226 | 278 | 343 | 158 | 113 |
| 114 | 65 | 83 | 105 | 130 | 160 | 197 | 242 | 298 | 367 | 169 | 114 |
| 115 | 71 | 90 | 113 | 139 | 171 | 211 | 260 | 320 | | 181 | 115 |
| 116 | 77 | 97 | 121 | 149 | 184 | 226 | 278 | 343 | | 194 | 116 |
| 117 | 83 | 105 | 130 | 160 | 197 | 242 | 298 | 367 | | 208 | 117 |
| 118 | 90 | 113 | 139 | 171 | 211 | 260 | 320 | | | 223 | 118 |
| 119 | 97 | 121 | 149 | 184 | 226 | 278 | 343 | | | 239 | 119 |
| 120 | 105 | 130 | 160 | 197 | 242 | 298 | 367 | | | 256 | 120 |
| 121 | 113 | 139 | 171 | 211 | 260 | 320 | | | | 274 | 121 |
| 122 | 121 | 149 | 184 | 226 | 278 | 343 | | | | 294 | 122 |
| 123 | 130 | 160 | 197 | 242 | 298 | 367 | | | | 315 | 123 |
| 124 | 139 | 171 | 211 | 260 | 320 | | | | | 338 | 124 |
| 125 | 149 | 184 | 226 | 278 | 343 | | | | | 362 | 125 |

To illustrate this procedure, consider the following calculations based on octave-band measurements of the noise in a factory:

| Octave Band No. | Octave Band Hz | Band Level dB | Band Loudness Index |
|---|---|---|---|
| 15 | 31.5 | 78 | 4 |
| 18 | 63 | 76 | 5 |
| 21 | 125 | 78 | 8 |
| 24 | 250 | 82 | 13 |
| 27 | 500 | 81 | 14 |
| 30 | 1000 | 80 | 16 |
| 33 | 2000 | 80 | 20 |
| 36 | 4000 | 73 | 15 |
| 39 | 8000 | 65 | 11 |

$\Sigma S$ = Sum of Band Loudness Indexes = 106

$S_m$ = Maximum Band Loudness Index = 20

$0.3\ \Sigma S = 31.8$

$0.7\ S_m = \underline{14}$

$0.3\ \Sigma S + 0.7\ S_m = 46$ sones (OD)*

or computed loudness level = 95 phons (OD)*

*OD = Octave Diffuse (an octave-band analysis for a diffuse field).

For a quick check to find which band contributes most to the loudness, add 3 dB to the band level in the second octave, 6 dB to the third, 9 dB to the fourth, and so on. Then the highest shifted level is usually the dominant band. This check will often be all that is needed to tell where to start in a noise reduction program, if one doesn't have the loudness calculation charts at hand. This check is not reliable if the levels are low and the low frequency bands dominate.

Another and more elaborate loudness calculation procedure has been developed by Zwicker[2] for third-octave analysis. It is not at all clear, however, that this more difficult calculation results in a calculated loudness that is in better agreement with subjective data.

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[2] E. Zwicker, "Ein Verfahrer zur Berechning der Lautstärke," Acustica, Vol. 10, No. 1, 1960, pp. 304-308.

## 3.6 PERCEIVED NOISE LEVEL.

Kryter[3] and his co-workers have followed a procedure similar to that used for loudness, but they asked the observer to compare noises on the basis of their acceptability or their "noisiness." The resulting judgments were found to be similar to those for loudness, but enough difference was noticed to give a somewhat different rating for various sounds. On the basis of these results, Kryter has set up a calculation procedure for "perceived noise level," PNL in dB, also called "PNdB." The procedure is basically the same as that recommended by Stevens for loudness. The corresponding "noisiness" is given in units called "Noys."

Ratings in terms of perceived noise level are now widely used for aircraft noise, particularly for aircraft flying overhead.

Table 3-2 is used to calculate the perceived noise level from octave-band levels of the preferred series.[4] Proceed as follows:

1. From the table find the proper NOYS value for each band level.
2. Add all the NOYS values ($\Sigma N$).
3. Multiply this sum by 0.3.
4. Add this product to 0.7 of the NOYS value for that band that has the largest NOYS value ($0.3\ \Sigma N + 0.7\ N_{max}$).
5. Convert this summed NOYS value to PNL in dB, using the 1000-Hz NOYS-to-dB column.

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[3] K. D. Kryter and K. S. Pearsons, "Some Effects of Spectral Content and Duration on Perceived Noise Level," Journal of the Acoustical Society of America, Vol. 35, No. 6, June, 1963, pp. 866-883.

[4] For calculations from the older series of octave-band levels, use the table provided by K. D. Kryter and K. S. Pearsons, Journal of the Acoustical Society of America, Vol. 36, No. 2, February, 1964, p. 397. The table given here has been extrapolated from the data of Kryter and Pearsons, loc. cit., to obtain the values for the 31.5-Hz band by the use of equal-loudness contours, and a number of values have been smoothed.

Table 3-2

| Band Level dB | Perceived Noise (NOYS) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Octave Band | | | | | | | | |
| | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| 20 | | | | | | | .3 | .4 | |
| 21 | | | | | | | .4 | .5 | |
| 22 | | | | | | | .4 | .6 | |
| 23 | | | | | | | .5 | .6 | |
| 24 | | | | | | | .5 | .7 | |
| 25 | | | | | .1 | .1 | .6 | .7 | .1 |
| 26 | | | | | .2 | .2 | .7 | .8 | .2 |
| 27 | | | | | .2 | .2 | .7 | .9 | .2 |
| 28 | | | | | .3 | .3 | .8 | .9 | .3 |
| 29 | | | | .1 | .3 | .3 | .8 | 1.0 | .3 |
| 30 | | | | .2 | .4 | .4 | .9 | 1.1 | .4 |
| 31 | | | | .2 | .4 | .4 | .9 | 1.2 | .4 |
| 32 | | | | .3 | .5 | .5 | 1.0 | 1.2 | .5 |
| 33 | | | | .3 | .6 | .6 | 1.1 | 1.3 | .6 |
| 34 | | | | .4 | .6 | .6 | 1.2 | 1.4 | .7 |
| 35 | | | .1 | .4 | .7 | .7 | 1.3 | 1.5 | .8 |
| 36 | | | .1 | .5 | .7 | .7 | 1.3 | 1.6 | .9 |
| 37 | | | .2 | .5 | .8 | .8 | 1.4 | 1.8 | 1.0 |
| 38 | | | .2 | .6 | .9 | .9 | 1.5 | 1.9 | 1.2 |
| 39 | | | .3 | .7 | .9 | .9 | 1.6 | 2.0 | 1.3 |
| 40 | | | .3 | .8 | 1.0 | 1.0 | 1.8 | 2.2 | 1.4 |
| 41 | | | .4 | .8 | 1.1 | 1.1 | 1.9 | 2.3 | 1.6 |
| 42 | | | .4 | .9 | 1.1 | 1.1 | 2.0 | 2.5 | 1.7 |
| 43 | | | .5 | 1.0 | 1.2 | 1.2 | 2.2 | 2.7 | 1.8 |
| 44 | | | .6 | 1.0 | 1.3 | 1.3 | 2.3 | 2.9 | 2 |
| 45 | | | .6 | 1.1 | 1.4 | 1.4 | 2.5 | 3.1 | 2.2 |
| 46 | | | .7 | 1.2 | 1.5 | 1.5 | 2.7 | 3.3 | 2.3 |
| 47 | | | .7 | 1.3 | 1.6 | 1.6 | 2.9 | 3.5 | 2.5 |
| 48 | | .1 | .8 | 1.4 | 1.7 | 1.7 | 3.1 | 3.8 | 2.7 |
| 49 | | .2 | .9 | 1.5 | 1.9 | 1.9 | 3.3 | 4.1 | 2.9 |
| 50 | | .2 | 1.0 | 1.6 | 2.0 | 2.0 | 3.5 | 4.3 | 3.1 |
| 51 | | .3 | 1.0 | 1.7 | 2.1 | 2.1 | 3.8 | 4.7 | 3.3 |
| 52 | | .4 | 1.1 | 1.8 | 2.3 | 2.3 | 4.1 | 5.0 | 3.5 |
| 53 | | .4 | 1.2 | 2.0 | 2.5 | 2.5 | 4.3 | 5.3 | 3.8 |
| 54 | | .5 | 1.3 | 2.1 | 2.6 | 2.6 | 4.7 | 5.7 | 4.1 |
| 55 | | .6 | 1.5 | 2.3 | 2.8 | 2.8 | 5.0 | 6.1 | 4.3 |
| 56 | | .6 | 1.6 | 2.4 | 3.0 | 3.0 | 5.3 | 6.6 | 4.7 |
| 57 | | .7 | 1.7 | 2.6 | 3.2 | 3.2 | 5.7 | 7.0 | 5.0 |
| 58 | | .8 | 1.8 | 2.8 | 3.5 | 3.5 | 6.1 | 7.5 | 5.3 |
| 59 | | .9 | 2.0 | 3.0 | 3.7 | 3.7 | 6.6 | 8.1 | 5.7 |
| 60 | | 1.0 | 2.2 | 3.2 | 4.0 | 4.0 | 7.0 | 8.7 | 6.1 |
| 61 | | 1.1 | 2.3 | 3.5 | 4.3 | 4.3 | 7.5 | 9.3 | 6.6 |
| 62 | | 1.2 | 2.5 | 3.7 | 4.6 | 4.6 | 8.1 | 10.0 | 7.0 |
| 63 | | 1.3 | 2.7 | 4.0 | 4.9 | 4.9 | 8.7 | 10.7 | 7.5 |
| 64 | | 1.5 | 2.9 | 4.3 | 5.3 | 5.3 | 9.3 | 11.4 | 8.1 |
| 65 | | 1.6 | 3.2 | 4.7 | 5.7 | 5.7 | 10.0 | 12.2 | 8.7 |
| 68 | | 1.8 | 3.4 | 5.0 | 6.1 | 6.1 | 10.7 | 13.1 | 9.3 |
| 67 | | 2.0 | 3.7 | 5.4 | 6.5 | 6.5 | 11.4 | 14.1 | 10.0 |
| 68 | .1 | 2.2 | 4.0 | 5.9 | 7.0 | 7.0 | 12.2 | 15.1 | 10.7 |
| 69 | .2 | 2.4 | 4.3 | 6.4 | 7.5 | 7.5 | 13.1 | 16.1 | 11.4 |
| 70 | .3 | 2.6 | 4.6 | 6.9 | 8.0 | 8.0 | 14.1 | 17.3 | 12.2 |
| 71 | .4 | 2.8 | 5.0 | 7.4 | 8.6 | 8.6 | 15.1 | 18.5 | 13.1 |
| 72 | .5 | 3.1 | 5.4 | 8.0 | 9.2 | 9.2 | 16.1 | 19.8 | 14.1 |
| 73 | .6 | 3.4 | 5.9 | 8.6 | 9.8 | 9.8 | 17.3 | 21.2 | 15.1 |
| 74 | .7 | 3.7 | 6.4 | 9.2 | 10.6 | 10.6 | 18.5 | 22.7 | 16.1 |
| 75 | .8 | 4.1 | 7.0 | 9.8 | 11.3 | 11.3 | 19.8 | 24.3 | 17.3 |
| 76 | 1.0 | 4.5 | 7.6 | 10.6 | 12.1 | 12.1 | 21.2 | 26.1 | 18.5 |
| 77 | 1.1 | 4.9 | 8.2 | 11.3 | 13.0 | 13.0 | 22.7 | 27.9 | 19.8 |
| 78 | 1.3 | 5.4 | 9.0 | 12.1 | 13.9 | 13.9 | 24.3 | 29.8 | 21.2 |
| 79 | 1.5 | 5.9 | 9.7 | 13.0 | 14.9 | 14.9 | 26.1 | 31.9 | 22.7 |
| 80 | 1.7 | 6.4 | 10.5 | 13.9 | 16.0 | 16.0 | 27.9 | 34.2 | 24.3 |
| 81 | 1.9 | 7.0 | 11.3 | 14.9 | 17.1 | 17.1 | 29.9 | 36.6 | 26.1 |
| 82 | 2.2 | 7.7 | 12.1 | 16.0 | 18.4 | 18.4 | 32.0 | 39.1 | 27.9 |
| 83 | 2.5 | 8.4 | 13.0 | 17.1 | 19.7 | 19.7 | 34.2 | 42 | 29.8 |
| 84 | 2.8 | 9.1 | 13.9 | 18.4 | 21.1 | 21.1 | 36.6 | 45 | 31.9 |

Table 3-2 (Continued)

| Band Level dB | Perceived Noise (NOYS) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Octave Band | | | | | | | | |
| | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| 85 | 3.1 | 9.9 | 14.9 | 19.7 | 22.6 | 22.6 | 39.1 | 48 | 34.2 |
| 86 | 3.5 | 10.8 | 16.0 | 21.1 | 24.3 | 24.3 | 42 | 51 | 36.6 |
| 87 | 3.9 | 11.7 | 17.2 | 22.6 | 26.0 | 26.0 | 45 | 55 | 39.1 |
| 88 | 4.4 | 12.7 | 18.4 | 24.3 | 27.9 | 27.9 | 48 | 58 | 42 |
| 89 | 4.9 | 13.7 | 19.7 | 26.0 | 29.9 | 29.9 | 51 | 62 | 45 |
| 90 | 5.5 | 14.7 | 21.1 | 27.9 | 32.0 | 32.0 | 55 | 67 | 48 |
| 91 | 6.2 | 15.9 | 22.6 | 29.9 | 34.3 | 34.3 | 58 | 71 | 51 |
| 92 | 6.9 | 17.1 | 24.3 | 32.0 | 36.8 | 36.8 | 62 | 76 | 55 |
| 93 | 7.7 | 18.3 | 26.0 | 34.3 | 39.4 | 39.4 | 67 | 82 | 58 |
| 94 | 8.6 | 19.7 | 27.9 | 36.8 | 42.2 | 42.2 | 71 | 88 | 62 |
| 95 | 9.5 | 21.1 | 29.9 | 39.4 | 45.3 | 45.3 | 76 | 94 | 67 |
| 96 | 10.6 | 22.6 | 32.0 | 42 | 48.5 | 48.5 | 82 | 100 | 71 |
| 97 | 11.7 | 24.3 | 34.3 | 45 | 52 | 52 | 88 | 107 | 76 |
| 98 | 12.9 | 26.0 | 36.8 | 48 | 56 | 56 | 94 | 115 | 82 |
| 99 | 14.1 | 27.9 | 39.4 | 52 | 60 | 60 | 100 | 123 | 88 |
| 100 | 15.5 | 29.9 | 42 | 56 | 64 | 64 | 107 | 132 | 94 |
| 101 | 16.9 | 32.0 | 45 | 60 | 69 | 69 | 115 | 142 | 100 |
| 102 | 18.4 | 34.3 | 48 | 64 | 74 | 74 | 123 | 152 | 107 |
| 103 | 19.9 | 36.8 | 52 | 69 | 79 | 79 | 132 | 163 | 115 |
| 104 | 21.5 | 39.4 | 56 | 74 | 84 | 84 | 142 | 174 | 123 |
| 105 | 23.2 | 42 | 60 | 79 | 91 | 91 | 152 | 187 | 132 |
| 106 | 25.1 | 45 | 64 | 84 | 97 | 97 | 163 | 200 | 142 |
| 107 | 27.0 | 48 | 69 | 91 | 104 | 104 | 174 | 215 | 152 |
| 108 | 29.0 | 52 | 74 | 97 | 111 | 111 | 187 | 230 | 163 |
| 109 | 31.2 | 56 | 79 | 104 | 119 | 119 | 200 | 247 | 174 |
| 110 | 33.6 | 60 | 84 | 111 | 128 | 128 | 215 | 264 | 187 |
| 111 | 36.1 | 64 | 91 | 119 | 137 | 137 | 230 | 283 | 200 |
| 112 | 39 | 69 | 97 | 128 | 147 | 147 | 247 | 304 | 215 |
| 113 | 42 | 74 | 104 | 137 | 158 | 158 | 264 | 325 | 230 |
| 114 | 45 | 79 | 111 | 147 | 169 | 169 | 283 | 349 | 247 |
| 115 | 49 | 84 | 119 | 158 | 181 | 181 | 304 | 374 | 264 |
| 116 | 52 | 91 | 128 | 169 | 194 | 194 | 325 | 401 | 283 |
| 117 | 57 | 97 | 137 | 181 | 208 | 208 | 349 | 429 | 304 |
| 118 | 61 | 104 | 147 | 194 | 223 | 223 | 374 | 460 | 325 |
| 119 | 66 | 111 | 158 | 208 | 239 | 239 | 401 | 493 | 349 |
| 120 | 71 | 119 | 169 | 223 | 256 | 256 | 429 | 529 | 374 |
| 121 | 76 | 128 | 181 | 239 | 274 | 274 | 460 | 567 | 401 |
| 122 | 82 | 137 | 194 | 256 | 294 | 294 | 493 | 607 | 429 |
| 123 | 88 | 147 | 208 | 274 | 315 | 315 | 529 | 651 | 460 |
| 124 | 94 | 158 | 223 | 294 | 338 | 338 | 567 | 698 | 493 |
| 125 | 101 | 169 | 239 | 315 | 362 | 362 | 607 | 748 | 529 |
| 126 | 108 | 181 | 256 | 338 | 388 | 388 | 651 | 801 | 567 |
| 127 | 117 | 194 | 274 | 362 | 416 | 416 | 698 | 859 | 607 |
| 128 | 125 | 208 | 294 | 388 | 446 | 446 | 748 | 921 | 651 |
| 129 | 135 | 223 | 315 | 416 | 478 | 478 | 801 | 987 | 698 |
| 130 | 145 | 239 | 338 | 446 | 512 | 512 | 859 | 1057 | 748 |
| 131 | 156 | 256 | 362 | 478 | 549 | 549 | 921 | 1133 | 801 |
| 132 | 168 | 274 | 388 | 512 | 588 | 588 | 987 | 1215 | 859 |
| 133 | 180 | 294 | 416 | 549 | 630 | 630 | 1057 | 1302 | 921 |
| 134 | 193 | 315 | 446 | 588 | 676 | 676 | 1133 | 1395 | 987 |
| 135 | 207 | 338 | 478 | 630 | 724 | 724 | 1215 | 1495 | 1057 |
| 136 | 223 | 362 | 512 | 676 | 776 | 776 | 1302 | 1603 | 1133 |
| 137 | 239 | 388 | 549 | 724 | 832 | 832 | 1395 | 1720 | 1215 |
| 138 | 256 | 416 | 588 | 776 | 891 | 891 | 1495 | 1840 | 1302 |
| 139 | 274 | 446 | 630 | 832 | 955 | 955 | 1603 | 1970 | 1395 |
| 140 | 294 | 478 | 676 | 891 | 1024 | 1024 | 1720 | 2110 | 1495 |
| 141 | 315 | 512 | 724 | 955 | 1098 | 1098 | 1840 | | 1600 |
| 142 | 338 | 549 | 776 | 1024 | 1176 | 1176 | 1970 | | 1720 |
| 143 | 362 | 588 | 832 | 1098 | 1261 | 1261 | 2110 | | 1840 |
| 144 | 388 | 630 | 891 | 1176 | 1351 | 1351 | | | 1970 |
| 145 | 416 | 676 | 955 | 1261 | 1448 | 1448 | | | 2110 |
| 146 | 446 | 724 | 1024 | 1351 | 1552 | 1552 | | | |
| 147 | 478 | 776 | 1098 | 1448 | 1663 | 1663 | | | |
| 148 | 512 | 832 | 1176 | 1552 | 1783 | 1783 | | | |
| 149 | 549 | 891 | 1261 | 1663 | 1911 | 1911 | | | |
| 150 | 588 | 955 | 1351 | 1783 | 2048 | 2048 | | | |

Here is a sample calculation for the factory noise used previously for a loudness calculation:

| Octave Band Center Hz | Band Level dB | Band Noisiness NOYS |
|---|---|---|
| 31.5 | 78 | 1.3 |
| 63 | 76 | 4.5 |
| 125 | 78 | 9 |
| 250 | 82 | 16 |
| 500 | 81 | 17.1 |
| 1000 | 80 | 16 |
| 2000 | 80 | 27.9 |
| 4000 | 73 | 21.2 |
| 8000 | 65 | 8.7 |

$$\Sigma N = 121.7$$

$$0.3 \times 121.7 = 36.5$$

$$0.7 \times 28 = 19.6$$

$$56.1$$

56 NOYS corresponds to 98 dB perceived noise level.

The calculations outlined for PNL are valid only for broadband noises that do not have strong pure-tone components. The effects of such components have been studied, but a procedure for calculating these effects is not yet adequately proven.

## 3.7 NOISE AND NUMBER INDEX.

Another rating for aircraft noise, called NNI, noise and number index, is based on perceived noise levels. It was developed in Great Britain[5] and takes into account the effect of the number of aircraft per day on the annoyance. It is defined by the following relation:

$$\text{NNI} = (\text{Average Peak Perceived Noise Level}) + 15(\log_{10} N) - 80$$

where N is the number of aircraft per day or night. The value "80" is subtracted to bring the index to about 0 for conditions of no annoyance.

The "Average Peak Perceived Noise Level" is obtained in the following way. The peak perceived noise level that occurs during the passage of each airplane is noted. These peak levels are then converted into equivalent power and averaged

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[5] "Noise-Final Report of the Committee on the Problem of Noise," CMND. 2056, Her Majesty's Stationery Office, London, 1963.

(Section 2.6). This average value is then converted back into a level and used in the equation.

If the perceived noise level is approximated by the use of A-weighted sound levels, the average A-level is obtained in a similar fashion, the 80 is reduced to about 67, and we have NNI $\approx$ (Average Peak A-Level) + $15(\log_{10} N)-67$.

## 3.8 A-WEIGHTED SOUND LEVEL AS A SINGLE-NUMBER RATING FOR NOISE.

For simple ratings or screenings of similar devices, the A-weighted sound level at a specified distance is now widely used. This measurement is mainly useful for relatively nondirectional sources that are outdoors and where the effect of the noise also occurs outdoors and nearby. It is also useful in preliminary ratings of similar ambient noises for the human reactions that may occur.

A number of analyses of the usefulness of A-weighted sound levels for single-number ratings have been made. Some of these have shown excellent agreement between the A-level and subjective effects, while others show relatively wide discrepancies. Those that show the wide discrepancies usually include comparisons of high-level narrow-band noise or pure tones with broad-band noises. The most consistent results are found when the noises that are being compared are similar in character, as, for example, in ratings of the objectionableness of noises from a large number of automobiles. Expressed differently, the fact that similar devices produce noises with similar energy-vs-frequency distributions makes a simple A-weighted sound level useful in ranking sounds for subjective effects.[6]

A number of investigators have determined the approximate relation between the A-weighted sound level of a noise and the calculated loudness level or perceived noise level of that noise. For example,[7] values for perceived noise level (PNL) minus dB (A) have been quoted as about 12 dB for jet aircraft and 14 dB for propeller aircraft, except during approaches for which an average figure of 16 dB is given.

For office noise the difference has been found to be about 13 dB[8]. Similarly, the difference between loudness level and the A-weighted sound level for office noise is about 13.3 dB;[8]

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[6] R. W. Young, "Single-Number Criteria for Room Noise," Journal of the Acoustical Society of America, Vol. 36, No. 2, February, 1964, pp. 289-295.

[7] D. W. Robinson, J. J. Bowsher, and W. C. Copeland, "On Judging the Noise From Aircraft in Flight," Acustica, Vol. 13, No. 5, 1963, pp. 324-336.

[8] R. W. Young, loc. cit.

that is, LL in phons minus dB (A) = 13.3.

The restricted range of usefulness of an A-weighted sound level is a result of the frequency dependence of many acoustic effects. For example, if a noisy machine is to be used in a room, we need to know the acoustic characteristics of the room as a function of frequency and the radiated sound power level in octave bands in order to estimate the noise level at some distance from the machine. The A-weighted sound level would not be adequate.

A similar condition occurs if we are trying to estimate the effect of sound isolation or acoustic treatment on a noise level, because these effects depend on frequency. Or, more generally, when we measure noise in order to aid us in reducing noise output or to control noise in any of a number of ways, frequency analysis is essential.

Because A-weighted sound levels are so widely used for noise ratings, some may wish to convert measured octave-band levels to the equivalent A-level when that sound level did not happen to be measured. This conversion is readily accomplished by means of Table 3-3, which is used as follows:

1. Add the correction numbers given in the table to each of the corresponding measured octave-band levels.
2. By means of the table in Appendix I convert these corrected numbers to relative power.
3. Add the relative powers of all the bands.
4. Convert back from power to level in dB.

Note that instead of steps 2, 3, and 4 the summing of the corrected levels can be done in pairs by the chart of Appendix II.

Table 3-3

Correction numbers in dB to be applied to octave-band levels to obtain equivalent levels for A-weighted octave-band analysis.

Preferred Series of Octave Bands

| Band Center Frequency Hz | Weighting Used for Original Analysis | |
|---|---|---|
| | Flat | C |
| 31.5 | -37.0 | -34.2 |
| 63 | -24.6 | -23.9 |
| 125 | -15.1 | -14.9 |
| 250 | - 8.0 | - 8.0 |
| 500 | - 2.9 | - 2.9 |
| 1000 | 0 | 0 |
| 2000 | + 1.2 | + 1.4 |
| 4000 | + 0.9 | + 1.8 |
| 8000 | - 1.4 | + 1.9 |

Table 3-3 (Continued)

Older Series of Octave Bands

| Octave Band Hz | Weighting Used for Original Analysis Flat | C |
|---|---|---|
| 18.75 - 37.5 | -40.8 | -37.0 |
| 37.5 - 75 | -27.5 | -26.4 |
| 75 - 150 | -17.2 | -17.0 |
| 150 - 300 | - 9.6 | - 9.6 |
| 300 - 600 | - 3.9 | - 3.9 |
| 600 - 1200 | - 0.5 | - 0.5 |
| 1200 - 2400 | + 1.0 | + 1.1 |
| 2400 - 4800 | + 1.1 | + 1.7 |
| 4800 - 9600 | - 0.7 | + 1.9 |

Here is an example of these calculations for the factory noise used previously.

| Octave Band Center Hz | Band Level dB | Correction for A-wtng. | Corrected Level | Relative Power/$10^6$ |
|---|---|---|---|---|
| 31.5 | 78 | -37 | 41 | .01 |
| 63 | 76 | -25 | 51 | .13 |
| 125 | 78 | -15 | 63 | 2.0 |
| 250 | 82 | - 8 | 74 | 25.1 |
| 500 | 81 | - 3 | 78 | 63.1 |
| 1000 | 80 | 0 | 80 | 100 |
| 2000 | 80 | + 1 | 81 | 125.9 |
| 4000 | 73 | + 1 | 74 | 25.1 |
| 8000 | 65 | - 1 | 64 | 2.5 |
| | | | | 343.8 |

340 x $10^6$ corresponds to 85.4 dB (A)

## 3.9 ADDITIONAL HEARING CHARACTERISTICS.

In addition to the characteristics already described, numerous others have been investigated, and a few of these are of interest in noise-measurement problems. Therefore, we shall discuss briefly differential sensitivity for intensity and the pitch scale.

3.9.1 DIFFERENTIAL SENSITIVITY FOR INTENSITY. One question that comes up in quieting a noisy place or device is: "Just how little a change in level is worth bothering with? Is a one-decibel change significant, or does it need to be twenty decibels?" This question is partially answered in the section on loudness, but there is additional help in the following psychoacoustical evidence. Psychologists have devised various experiments to determine what change in level will usually be noticed. When two different levels are presented to the observer under laboratory conditions with little delay between them, the observer can notice as small a difference as 1/4 dB for a 1000-Hz tone at high levels. This sensitivity to change varies with level and the frequency, but over the range of most interest, this differential sensitivity is about 1/4 to 1 dB. For a wideband random noise (a hishing sound) a similar test gives a value of about 1/2 dB for sound-pressure levels of 30 to 100 dB (re 20 $\mu N/m^2$). Under everyday conditions, a 1-dB change in level is likely to be the minimum detectable by an average observer. On the basis of these tests, we can conclude that 1-dB total change in level is hardly worth much, although 6 is usually significant. It should be remembered, however, that many noise problems are solved by a number of small reductions in level. There is also the importance of a change in character of the noise. For example, the high-frequency level of a noise may be reduced markedly by acoustic treatment, but, because of strong low-frequency components, the over-all level may not change appreciably. Nevertheless, the resultant effect may be very much worth while. This example illustrates one reason for making a frequency analysis of a noise before drawing conclusions about the noise.

3.9.2 PITCH AND MELS. Just as they have done for loudness, psychologists have experimentally determined a scale for pitch. The unit for this scale is the "mel" (from "melody"), and a 1000-Hz tone at a level of 40 dB is said to have a pitch of 1000 mels. In terms of frequency, this pitch scale is found to be approximately linear below 1000-Hz and approximately logarithmic above 1000-Hz. Some people have suggested that a frequency analysis with bands of equal width in mels would be more efficient for some types of noise analysis than would one with bands of other widths. At present no commercial analyzers of this type are available, but some work has been done using such an analysis. In addition, the pitch scale has been found useful for some types of charts.

## 3.10 MASKING.

It is common experience to have one sound completely drowned out when another, louder noise occurs. For example, during the early evening when a fluorescent light is on, the ballast noise may not be heard, because of the usual background noise level in the evening. But late at night when there is much less activity and correspondingly less noise, the ballast noise may become relatively very loud and annoying. Actually, the noise level produced by the ballast may be the same in the two instances. But psychologically the noise is louder at night, because there is less of the masking noise that reduces its apparent loudness.

Experimenters have found that the masking effect of a sound is greatest upon those sounds close to it in frequency. At low levels the masking effect covers a relatively narrow region of frequencies. At higher levels, above 60 dB, say, the masking effect spreads out to cover a wide range, mainly for frequencies above the frequencies of the dominating components. In other words, the masking effect is asymmetrical with respect to frequency. Noises that include a wide range of frequencies will correspondingly be effective in masking over a wide-frequency range.

3.10.1 SPEECH-INTERFERENCE LEVEL. Most of us have been in locations where it was impossible to hear over a telephone because the noise level was too high; and, in order to hear, production machinery had to be turned off; resulting in time and money lost. Even direct discussions can be difficult and tiring because of excessive noise. Excessive noise may make it impossible to give danger warnings by shouting or to give directions to workers.

In a large classroom with heavy acoustical treatment, particularly in the ceiling, the attenuation may be so great that the teacher at one end can be but poorly heard through the background noise at the other end, even though the noise is not very great.

Incidentally, other factors also affect speech intelligibility. In a live room, speech syllables are smeared by reflected sound, and the intelligibility is consequently reduced.

Because of the annoyance of interference with speech and also because noise interferes with work where speech communication is necessary, a noise rating based on the speech-interference level is frequently useful. We should know how to improve speech communication in a noisy place. In order to effect this improvement we shall find it useful to evaluate the speech-intereference level of a noise. How this can be done will appear from a consideration of how noise interferes with speech.

Noise interference with speech is usually a masking process. The background noise increases our threshold of hearing, and, as a result, we may hear only a few or perhaps none of the sounds necessary for satisfactory intelligibility.

The consonants contain most of the information in speech, but, unfortunately, they are more readily masked than vowels, because they are weaker than vowels. Noise of a certain level may mask some speech sounds and not others, depending on the talking level, the particular sound, and the relative frequency distribution of the sound and of the noise.

The energy of the various speech sounds is distributed over the frequency range from below 100 to above 10,000 Hz. The actual instantaneous distribution depends on the particular speech sound. For example, the "s" sound has its energy broadly distributed in the range from 4000 to beyond 8000 Hz. In contrast, most of the energy in the "ee" sound of "speech" is distributed in fairly definite groups (called "formants") below 4000 Hz. All the frequency range of speech sounds is not necessary, however, for complete intelligibility. A number of experimenters have shown that nearly all the information in speech is contained in the frequency region from 200 to 6000 Hz.

In any frequency subdivision that we may make of this range, the sound-pressure levels vary over a range of about 30 dB as successive sounds occur. Tests on the intelligibility of speech show that if we can hear the full 30-dB range in each of the frequency bands into which speech is divided, the contribution to intelligibility by that band will be 100 percent. If, however, noise limits the range that can be heard to only 15 dB, the contribution will be about 50 percent, and so forth. Furthermore, if the range between 200 to 6000 Hz is divided into a large number of frequency bands of equal importance to speech intelligibility, the total contribution to speech intelligibility is equal to the average of the contributions from the individual bands. This quantity is called the articulation index, because it is a measure of the percentage of the total possible information which we might have perceived of importance to speech intelligibility.

For many noises the measurement and calculation can be simplified even further by the use of a three-band analysis. The bands chosen are the octave bands centered on 500, 1000, and 2000 Hz.[9] The arithmetic average of the sound-pressure levels in these three bands gives the quantity called the speech-interference level (SIL). One can use this level for determining when speech communication or telephone use is easy, difficult, or impossible, and one can determine what changes in level are necessary to shift from one order of difficulty to a lower order.

3.10.1.1 Face-To-Face Communication. For satisfactory intelligibility of difficult speech material, maximum permissible values of speech-interference levels for men with average voice strengths are given in Table 3-4.

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[9] The bands used before the shift to the currently preferred series were 600-1200, 1200-2400, and 2400-4800 Hz, or those three bands plus the band from 300 to 600 Hz. The results of the two measures are similar, but some shift in the reference values is necessary. (J. C. Webster, Journal of the Acoustical Society of America, Vol. 37, No. 4, April 1965, pp.692-699).

Table 3-4

Speech-interference levels (in dB re 20 $\mu N/m^2$) should be less than the values given below in order to have reliable conversation at the distances and voice levels shown.

| Distance (Feet) | Voice Level Normal | Raised | Very Loud | Shouting |
|---|---|---|---|---|
| 1 | 70 | 76 | 82 | 88 |
| 3 | 60 | 66 | 72 | 78 |
| 6 | 54 | 60 | 66 | 72 |
| 12 | 48 | 54 | 60 | 66 |

It is assumed in this table that there are no reflecting surfaces nearby, that the speaker is facing the listener, and that the spoken material is not already familiar to the listener. For example, the speech-interference level of the factory noise in paragraph 3.5.4 is 80.3 which is high, and the chart indicates that shouting is usually necessary and that the two people must be closer to each other than two feet in order to be understood satisfactorily. If the words spoken are carefully selected and limited in number, intelligible speech will be possible at greater distances.

If a number of conversations are to be held in the same reverberant room, the procedure is more complicated. This chart cannot be used on the basis of the background noise level before the conversations are in progress, because a given conversation will be subject to interference from the noise produced by all the other conversations. The general procedure for calculating a speech-interference level under those conditions has not been completely worked out.

3.10.12 TELEPHONE USABILITY IN NOISY AREAS. The speech-interference level can also be used to predict the expected usability of a telephone under given noise conditions. The following schedule has been found generally satisfactory, when the F-1 Western Electric handset is used for long-distance or suburban calls.

| Speech-Interference Level | Telephone Use |
|---|---|
| less than 65 dB | Satisfactory |
| 65 to 80 dB | Difficult |
| above 80 dB | Impossible |

For calls within a single exchange, the permissible speech-interference levels are 5 dB greater than those shown in the table.

3.10.1.3 Criteria For Indoor Noise Levels. A suggested rating system for offices, based on a number of psychological and acoustical tests, is shown in Figure 3-6. The curves on this graph relate the measured speech-interference level of the background noise and the subjective rating of the noise ranging from "very quite" to "intolerably loud." The two different rating curves illustrate that the environment influences the subjective rating. In order to be rated "noisy" the noise level must be appreciably higher in a large office than in a private office.

It can be expected that the probability of receiving complaints about noise will be high for subjective ratings above "moderately noisy" and low for subjective ratings below "moderately noisy." Furthermore, because of direct interference with transferring information, efficiency may be reduced for levels appreciably above the criterion points marked A and B.

Suggested criteria for noise control in terms of maximum permissible speech-interference level (SIL), measured when

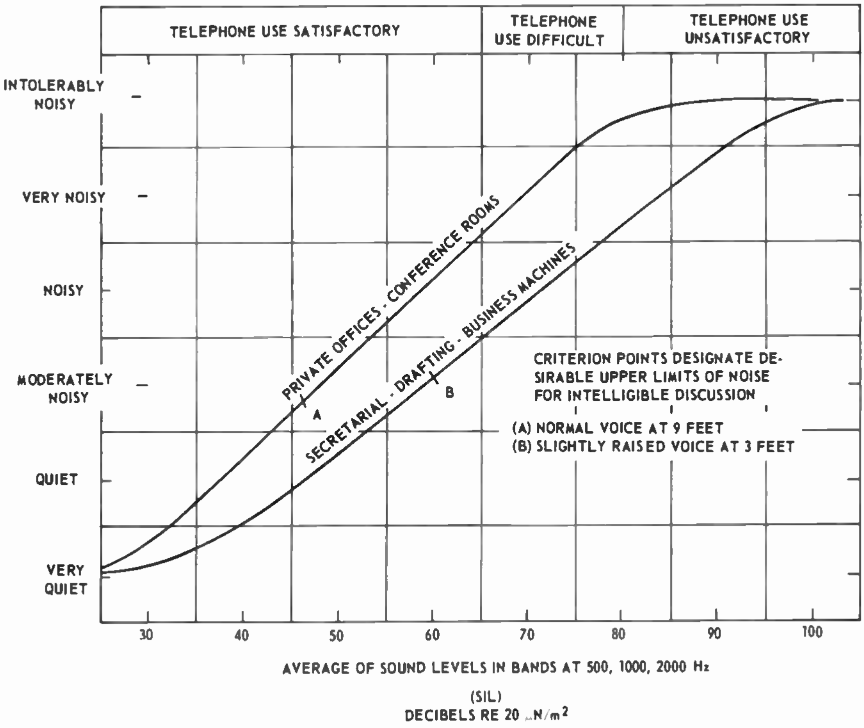

*Figure 3-6. Rating chart for office noises. Data were determined by an octave-band analysis and correlated with subjective tests. (Courtesy Beranek and Newman, but modified for preferred bands).*

the room is not in use, are given in the following table:

Table 3-5

Criteria for Noise Control

| Type of Room | Maximum Permissible SIL (measured when room is not in use) |
|---|---|
| Small Private Office | 45 |
| Conference Room for 20 | 35 |
| Conference Room for 50 | 30 |
| Movie Theatre | 35 |
| Theatres for Drama (500 seats, no amplification) | 30 |
| Coliseum for Sports Only (Amplification) | 55 |
| Concert Halls (No amplification) | 25 |
| Secretarial Offices (Typing) | 60 |
| Homes (Sleeping Areas) | 30 |
| Assembly Halls (No amplification) | 30 |
| School Rooms | 30 |

The purpose of these criteria will be shown by the following example. Assume that we are to put a small conference room in a factory space. We measure the speech-interference level at that location and find it to be 69 dB, whereas the suggested speech-interference level criterion for a small conference room is 35 dB. The room must then be designed to attenuate the noise from the factory space by about 34 dB in order to have a conference room that will be satisfactory as far as background noise level is concerned (such an attenuation is provided by a double-plastered, three- or four-inch thick stud wall, or by a hollow-tile wall plastered on one side).

A similar but more extensive set of such criteria for noise control, based on A-weighted sound levels, is given in ASHRAE Guide and Data Book - Fundamentals and Equipment, 1965-1966, Chapter 14, Table 4. (American Society of Heating, Refrigerating and Air-Conditioning Engineers.)

## 3.11 RESIDENTIAL NOISE LEVELS.

Some factories, recreation halls, electrical substations, trucks, and airplanes are so noisy that they annoy people living near them. The reactions of those that are annoyed may range from mild remarks to legal action. Those that are responsible for the noise would naturally like to avoid the expense of court action; in order to maintain the good will of the neighborhood, they are often willing to put considerable effort into controlling the noise so as to avoid anything but mild annoyance.

In order to put this noise control on a systematic basis, a number of engineering groups have analyzed the experiences obtained in many different situations.[10] They have found that reactions of annoyance cannot be successfully predicted on the basis of a single measurement, or even of computed loudness ratings, but that many factors enter into the problem. In addition to the range of reactions to be expected from different individuals, some other factors are the following: The level and spectrum of the noise; whether or not there are strong, pure-tone components; the time pattern of the noise, including the rate of repetition and the actual time of occurrence during the day; and the general background noise level in the residential area affected. So far the data that is available is limited primarily to the reactions of people in residential areas of single-family houses surrounding industrial plants. We can expect that, because of the conditioning to noises that occur in multiple-family dwellings, the reactions of the people there would be modified.

## 3.12 HEARING LOSS FROM NOISE EXPOSURE.[11]

Exposure to intense noises may lead to a loss in hearing, which will appear as a shift in the hearing threshold. Some of the loss is usually temporary with partial or complete recovery in some minutes, hours, or days. Any remaining hearing loss that persists indefinitely is called "permanent." The extent of the permanent loss will depend on many factors: the susceptibility of the individual; the duration of the exposure, including the time patterns; the intensity of the noise; the spectrum of the noise; the type of noise (impact, random, or simple-tone); and the nature of the ear protection used, if any.

Because of the many complicating factors, it is not possible to set up a single, simple relation between hearing loss and

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[10] W. A. Rosenblith and K. N. Stevens, Handbook of Acoustic Noise Control, Vol II, Noise and Man, WADC Technical Report 52-204, PB 111274, Office of Technical Services, Department of Commerce, Washington 25, D. C., June, 1953, pp 181-200. L. L. Beranek, Acoustics, McGraw-Hill: New York, 1954, Part XXXII.

K. N. Stevens, W. A. Rosenblith, and R. H. Bolt, "A Community's Reaction to Noise: Can It Be Forecast?", Noise Control, Vol 1, No. 1, January, 1955, pp 63-71.

Committee on the Problem of Noise, Noise, Final Report, Her Majesty's Stationery Office, London, 1964, Appendix XV.

[11] ASA Subcommittee Z24-X-2, The Relations of Hearing Loss to Noise Exposure, January, 1954, USA Standards Institute, 70 East 45th St., New York.

exposure to noise. Furthermore, adequate data regarding comparative audiograms and a complete history of exposure including noise levels, type of noise, time pattern, and frequency characteristics are not available. It should be remembered also that noise is not the only cause of permanent hearing loss. There is the normal loss of hearing with age (refer to Section 3.3), and some types of infection may produce permanent hearing loss.

Nevertheless, because of the importance of the problem, many tentative ratings have been proposed. These suggested ratings have been revised as more information has become available.

For those concerned with the problem of noise-induced hearing loss, we recommend that they request the latest information on this subject from the Research Center, Subcommittee on Noise of the Committee on Conservation of Hearing of the American Academy of Ophthalmology and Otolaryngology, Dr. Aram Glorig, Director, 3819 Maple Ave., Dallas, Texas 75219.

One suggested preliminary test is based on an A-weighted sound level. The reading is taken where the operator's ears would normally be, but without the operator present, if possible. An A-weighted sound level above 90 dB indicates that the noise may be unsafe for everyday exposures, at least for some people, and further measurements are then necessary to determine if noise reduction or ear protection is necessary. In most instances when the A-weighted sound level is as high as 90 dB, noise reduction is desirable for other reasons as well.

A report for CHABA[12], the Committee on Hearing, Bioacoustics, and Biomechanics of the National Academy of Science and the National Research Council, sets hearing damage risk levels for bands of noise for various exposure times per day for periods of ten years or more.

Some of the risk contour levels from that report, converted into tabular form, are given in Table 3-6. These levels apply for bands of noise and one exposure per day of the duration indicated. The table illustrates clearly the advantage to be gained from limited exposures.

These risk levels have been set so that, on the average, persons will not suffer serious hearing losses if the levels for the exposure durations are less than those indicated. Some susceptible persons may suffer significant losses, however, so that it is wise to reduce the noise level or provide ear protection if the levels approach those shown in the table.

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[12] K. D. Kryter, W. D. Ward, J. D. Miller, and D. H. Eldredge, "Hazardous Exposure to Intermittent and Steady-State Noise," Journal of the Acoustical Society of America, Vol 39, No. 3, March 1966, pp 451-464.

Table 3-6

Damage Risk Levels
dB re 20 $\mu N/m^2$

| Duration /day | 125 | 250 | 500 | 1000 | 2000 | 4000 | 7000 |
|---|---|---|---|---|---|---|---|
| | Octave Band Center - Hz | | | | | | |
| 8 hours | 96 | 92 | 88 | 86 | 85 | 85 | 86 |
| 4 hours | 103 | 96 | 91 | 88 | 86 | 85 | 87 |
| 2 hours | 110 | 101 | 94 | 91 | 88 | 87 | 90 |
| 1 hour | 118 | 107 | 99 | 95 | 91 | 90 | 95 |
| 30 min. | 126 | 114 | 105 | 100 | 95 | 93 | 99 |
| 15 min. | 135 | 122 | 112 | 106 | 99 | 98 | 104 |
| 7 min. | 135 | 135 | 122 | 114 | 105 | 104 | 111 |
| 3 min. | 135 | 135 | 134 | 124 | 113 | 111 | 120 |
| <1.5 min. | 135 | 135 | 135 | 134 | 124 | 121 | 130 |

If the level in any one octave band exceeds that in the two adjacent bands by more than 5 dB, the indicated damage-risk level for that band should be reduced by 5 dB. This rule is used to account for noises that have sharp peaks in the spectra.

The CHABA report also has risk criteria for multiple exposures per day and for pure tones. The report should be consulted for these when necessary.

The noise-level ratings given here apply only to exposure during a regular working day for a number of years and to steady noises, not to impact or impulsive sounds, such as gunfire, for which the information regarding hearing damage is not yet adequate to provide risk criteria.

Some industrial and governmental organizations have set up a program that includes periodic hearing tests[13] and records of noise exposure of their employees. The noise-exposure records give the octave-band analysis of the noise to which the particular employee is exposed, the duration of the exposure, and the protective devices — such as ear protection — used. Such a systematic approach is recommended for organizations having employees exposed to high-level noise.

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[13] A Guide for Conservation of Hearing in Industry, Subcommittee on Noise of the Committee on Conservation of Hearing, American Academy of Ophthalmology and Otolaryngology.

## 3.13 EFFECTS OF NOISE ON WORK OUTPUT.

Noise can influence work output in many ways; there is the obvious interference with communication (paragraph 3.10), the occasional condition where noise is useful as a means of masking distracting conversations, and the deterioration in quality of work output that can occur when the background noise level is above 90 dB.

Broadbent[14] and others have found that the effects of noise on work output depend greatly upon the nature of the work; a long-term job requiring constant vigilance is especially susceptible. The effect of noise is more likely to be a higher rate of errors and accidents than an actual reduction in total output. This result and other findings lead to the interpretation that attention wanders from the work at hand more often as the noise level increases.

From the standpoint of noise reduction, two findings are worth noting: first, noise is more likely to lead to increased errors in susceptible tasks if it is above 90 dB; and second, high-frequency audible noise seems more harmful in this respect than does low-frequency noise.

## 3.14 WHAT VIBRATION DOES.

Vibration related problems can be classified as follows:

1. Effect on man
    - Injury
    - Fatigue
    - Annoyance
    - Interference with performance
2. Mechanical failure
    - Excessive stress
    - Fatigue
    - Destructive impacts
3. Excessive wear
4. Excessive noise
5. Inadequate performance of device
6. Failure to satisfy vibration specifications.

These problems will be discussed in the following sections on the effects on man, maintenance, vibration specifications, and other effects. The problem of excessive noise has already been reviewed.

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[14] D. E. Broadbent, Perception and Communication, Pergamon Press: London, 1958.

3.14.1 EFFECTS OF VIBRATION ON MAN. The published work on the effects of vibration on man has recently been reviewed comprehensively by D. E. Goldman and H. E. von Gierke in the report, S3-W-39, The Effects of Shock and Vibration on Man.[15] This excellent review, which covers the injurious levels of vibration as well as subjective aspects, is recommended to those concerned with these problems. The subjective response is important to those concerned with passenger or operator comfort in automobiles, planes, boats, trains, and other vehicles. Vibration levels that are structurally safe for a vehicle are often uncomfortable, annoying, or even dangerous for the occupant. In military vehicles it may not be very important that the occupant be comfortable, but it is certainly important that excessive vibration does not cause fatigue and reduce sharply the efficiency of personnel. In order to study this problem the U. S. Naval Medical Center at Bethesda, Maryland, has built a large displacement-amplitude vibration machine, designed for a maximum load of 200 lb. at any combination of displacement (0 to 4 inches) and frequencies (2 to 50 Hz) not exceeding 15 g peak acceleration. (In the words of one reporter, "the engineering principle involved likens this project to a number of units currently being operated in New York City. In New York they call them subways.") But there are no curves that present the human responses to vibration as completely as do the Robinson-Dadson curves for human responses to simple tones of sound.

As an example of the criteria available, using only data collected by Meister[16] and Reiher and Meister[17], Janeway[18]

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[15] This report is available from USA Standards Institute, 10 East 40th Street, New York, N. Y. 10016, and is closely parallel to D. E. Goldman and H. E. von Gierke, "Effects of Shock and Vibration on Man," Chapter 44, Shock and Vibration Handbook, edited by C. M. Harris and C. E. Crede, McGraw-Hill, New York, 1961.

See also J. C. Guignard, "Effects of Vibration on Man," Journal of the Environmental Science, Vol. 9, No. 4, August, 1966, pp. 29-32.

VDI 2057, "Beurteilung der Einwirkung mechanischer Schwingungen auf der Menschen," October, 1963.

[16] Meister, F. J., "Sensitivity of Human Beings to Vibration," Forschung (V.D.I. Berlin), May-June, 1935.

[17] Reiher, H. and Meister, F. J., "Sensitivity of Human Beings to Vibration," Forschung (V.D.I. Berlin), February, 1931.

[18] Janeway, R. N., "Vertical Vibration Limits for Passenger Comfort" in Ride and Vibration Data, a set of reference charts. Society of Automotive Engineers, Inc., Special Publications Department (SP-6).

has prepared a chart giving recommended limits of vertical vibration for passenger comfort in automobiles. Janeway limited his analysis to data obtained for vertical sinusoidal vibration at a single frequency, with subjects standing or sitting on a hard seat. The recommended characteristic consists of three simple relations, each of which covers a portion of the frequency range. In the low-frequency range from 1 to 6 Hz the recommended limit is a fixed value of jerk. The corresponding maximum comfortable displacement (a) at any frequency between 1 and 6 Hz is 2 divided by the frequency cubed ($f^3$). Over the frequency range from 6 to 20 Hz the recommended limit is a constant acceleration. The corresponding displacement is $1/3f^2$. From 20 to 60 Hz the recommended limit is a constant velocity, and the corresponding displacement is 1/60f.

Litte work has been done on the effects of nonsinusoidal vibration, except for sudden acceleration and deceleration, such as occur in accidents and space travel. Apparently no technique has been evolved for predicting the effects of broadband or multicomponent vibration (such as has been developed for loudness). In short, this remains an important area of research for further investigation.

3.14.2 MAINTENANCE. It is widely recognized that excessive vibration leads to high costs for machinery maintenance. Periodic measurement of machinery vibration has become an important preventive maintenance procedure in many factories. If such a program is pursued, some acceptable limits of vibration must be set to make possible a decision as to when corrective measures must be taken. Numerous criteria have been proposed. Among those who have proposed criteria, T. C. Rathbone[19] was a pioneer in synthesizing the available experience in this area. The chart that he prepared in 1939 has been the basis for many subsequent specifications. This chart showed the maximum allowable peak-to-peak displacement as a function of rotation speed with ratings varying from "Very Smooth" to "Too Rough to Operate."

One of the important points to be gained from such charts is that a simple specification of displacement or even of acceleration is not adequate for a rating, although many have assumed from physical reasoning that one of those parameters should be specified. Actually, velocity happens to be a better parameter to use for a relatively wide range of shaft speeds. For example, Rathbone has recently recommended some simplified upper limits of vibration which can be specified in terms of velocity for vibration frequencies above 20 Hz (1200

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[19] T. C. Rathbone, Power Plant Engineering, Vol. 43, No. 11, November, 1939, pp. 721-724.

cycles per minute). The limits that he recommends[20] are: For power machinery, electric motors, large fans, turbines, pumps, dishwashers, dryers, vacuum cleaners, mixers, etc., the velocity should be less than 0.13 in/s peak (110 dB re $10^{-8}$ m/s peak[21]). For hand tools, small fans, and room air conditioning equipment, the velocity should be less than 0.1 in/s peak (108 dB re $10^{-8}$ m/s peak). For precision machinery and business machines, the velocity should be less than 0.063 in/s peak (104 dB re $10^{-8}$ m/s peak).

These values should be used only as a guide. Considerable variation in significance can be expected for several reasons. For example, the relation between the actual spindle or shaft vibration and the vibration measured on the associated bearing housings is complex and would not necessarily be the same for machines of the same type but of different design. Furthermore, the vibration at a bearing housing may vary significantly around the housing because of components of different phase being introduced external to the bearing. The nature of the vibration, that is, if it is rough or random or of an impact type rather than a simple sinusoidal motion also affects the value that is significant.

Even if no element of human reaction is involved different criteria may be set up for the same application. Thus the manufacturer of a compressor may select a velocity of 0.5 in/s peak[22], (122 dB re $10^{-8}$ m/s peak) measured on the bearing housings, as a safe upper limit, but the user may prefer to have the vibration kept to 0.1 in/s peak (108 dB re $10^{-8}$ m/s peak) or less for best performance and low maintenance costs (cf. POWER, Vol. 109, May 1965, pp. 162-164.)

The manufacturer is influenced by what can be competitively produced and still have a reasonable life, but the user should be willing to pay more for a unit with the reduced maintenance costs that usually accompany lower vibration levels.

Another valuable procedure for setting up a reference criterion is to measure the vibration on a machine when it is first installed and operating properly. If a detailed record of these measurements is kept on file, a comparison with

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[20] T. C. Rathbone, "A Proposal for Standard Vibration Limits," PRODUCT ENGINEERING, Vol. 34, March 4, 1963, pp. 68f.

[21] For the equivalent rms value (re $10^{-8}$ m/s rms) subtract 3 dB, for average values (re $10^{-8}$ m/s avg), subtract 4 dB.

[22] The ratings in terms of rms values of sinusoidal vibration as measured on some vibration meters will be about 0.7 of these peak values; for average values (actually "average absolute") use 0.6 of the peak values.

subsequent measurements will then serve as a basis for judging the condition of the machine, and it will help in tracking down worn or loose elements.[23]

These early measurements should include the vibration at the various bearing housings in all three directions, vertical and the two horizontal axes. They should be measured for the different operating conditions made possible by the various clutches and speed-changing systems on the machine. Incidentally, these early checks may occasionally reveal a faulty, new machine that should be rejected and returned to the manufacturer.

3.14. 3 VIBRATION SPECIFICATIONS. Limits on vibration on many machines have been set for a variety of reasons, generally on the basis of experience. For example, on a good lathe one may find a specification such as:

> "Vibration to 1200 rpm (20 Hz) should not exceed 0.0005" on bed and 0.0003" at spindle." These are peak-to-peak measurements and the corresponding peak velocity measurements at 1200 rpm are 0.03"/s and 0.018"/s.

Such a specification should help to insure both high quality of work and low maintenance. But it is strange to find that many manufacturers and users of precision rotating machinery neglect such an important specification.

Much machinery intended for military uses now must meet specifications that include vibration tests. For example, MIL-STD-740B (SHIPS) includes a vibration acceptance level as shown in Figure 3-7. This figure has been converted to velocity in Figure 3-8, so that the specified level can be readily compared with those cited here in other sections.

3.14.4 OTHER EFFECTS. Many of the useful effects of vibration in chemical, biological, and physical processes are

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[23] R. H. Nittinger, "Vibration Analysis Can Keep Your Plant Humming," CHEMICAL ENGINEERING, Vol. 71, August 17, 1964, pp. 152-158.

R. Y. Chapman, "Recommended Prescribed Vibration and Noise Limits for Auxiliary Machinery Aboard Submarines Using the GR 1551-A Sound Level Meter and Probe," Acoustical Research and Development Division, Engineer and Repair Department, USNSB, New London, Conn. Tech. Report #213-62, October 1, 1962.

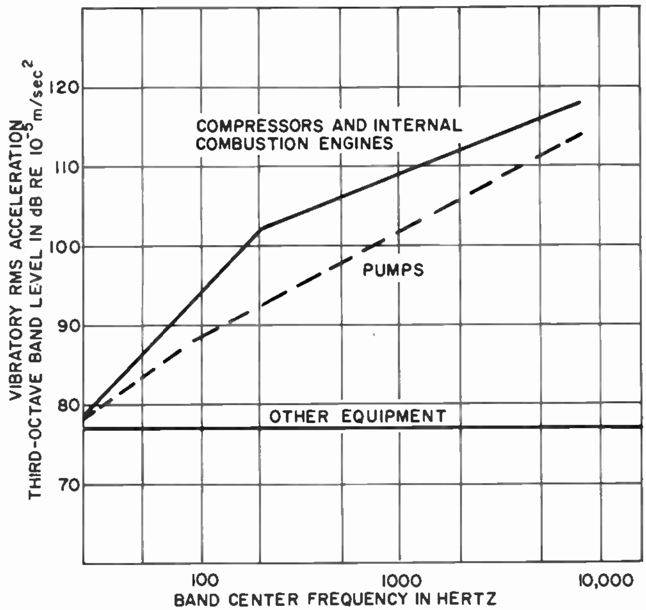

*Figure 3-7. Vibration acceptance level from MIL-STD-740B.*

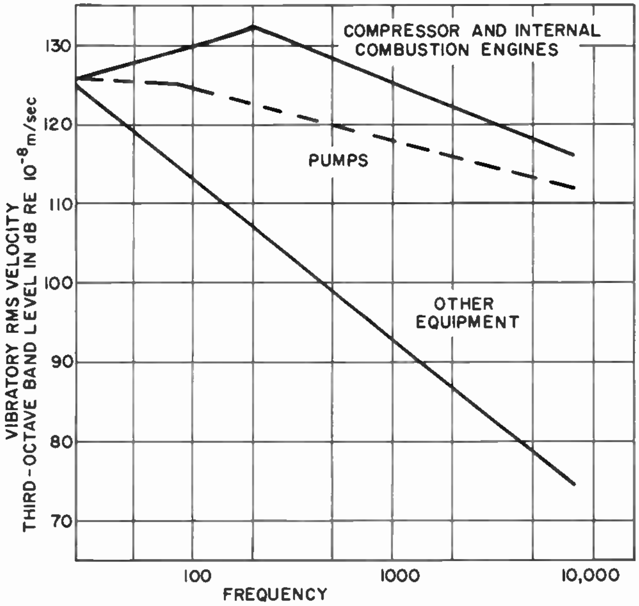

*Figure 3-8. The vibration acceptance level of Figure 3-7 plotted in terms of velocity.*

discussed by Hueter and Bolt[24], Crawford[25], and Bergman[26]. The effects of machine-tool vibration have been reviewed by S. A. Tobias[28], and metallic fatigue has been covered by Harris[27]. Many of the effects of vibration are discussed briefly in books and trade journals for the particular specialty in which the effect occurs. The handbook edited by Harris and Crede[28] is, however, remarkably comprehensive in its coverage of the many problem areas of shock and vibration.

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[24] T. F. Hueter and R. H. Bolt, Sonics, John Wiley; New York, 1955.

[25] A. E. Crawford, Ultrasonic Engineering, Academic Press, New York, 1955.

[26] L. Bergman, Der Ultraschall, S. Hirzel Verlag, Stuttgart, 1954 (Sixth Edition).

[27] W. J. Harris, Metallic Fatigue, Pergamon Press, New York, 1961.

[28] C. M. Harris and C. E. Crede, Op Cit, Chapter 40.

chapter 4

# INSTRUMENTATION FOR NOISE AND VIBRATION MEASUREMENT

## 4.1 GENERAL.

Sound measuring systems use a microphone (as a more general term, a transducer) to transform the sound-pressure variations into a corresponding electrical signal. This signal is amplified, measured and analyzed by electronic instruments.

A remarkably wide variety of systems is used to measure vibration.[1] When the vibratory motion is slow and large, the measurement can sometimes be made with a scale. If the motion is slow but small, a measuring microscope may be used. For rapid motion, a stroboscope can be used to produce an apparent slow-motion replica of the rapid motion for optical measurement. This technique is discussed in more detail later in this handbook.

The measuring system may be entirely mechanical or a mixture of mechanical, electrical, and optical elements. Many of these systems have been described in the literature.[1] Of the many possible systems, the one particularly adaptable to a broad range of applications uses a vibration pickup (also called a transducer) to transform the mechanical motion into a corresponding electrical signal. As for sound measurements, this signal is amplified, measured, and analyzed by electronic instruments.

The most commonly used vibration pickup is a piezoelectric accelerometer, in which a piezoelectric element is deflected by its own inertia when the pickup is subjected to vibration. The voltage generated is proportional to the acceleration. This type of pickup has the advantages of small size, light weight, and wide frequency range, and it does not require a fixed frame of reference for the measurement.

We shall describe the two types of transducers, microphones and vibration pickups, and then the electronic equip-

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[1] Cyril Harris and Charles Crede, Shock and Vibration Handbook, McGraw-Hill Book Co., New York, 1961, Chapters 12 through 17.

J. Ormondroyd, R. B. Allnutt, F. Mintz, and R. D. Specht, "Motion Measurements," Handbook of Experimental Stress Analysis, Edited by M. Hetenyi, John Wiley: New York, 1950, Chapter 8, pp. 301-389.

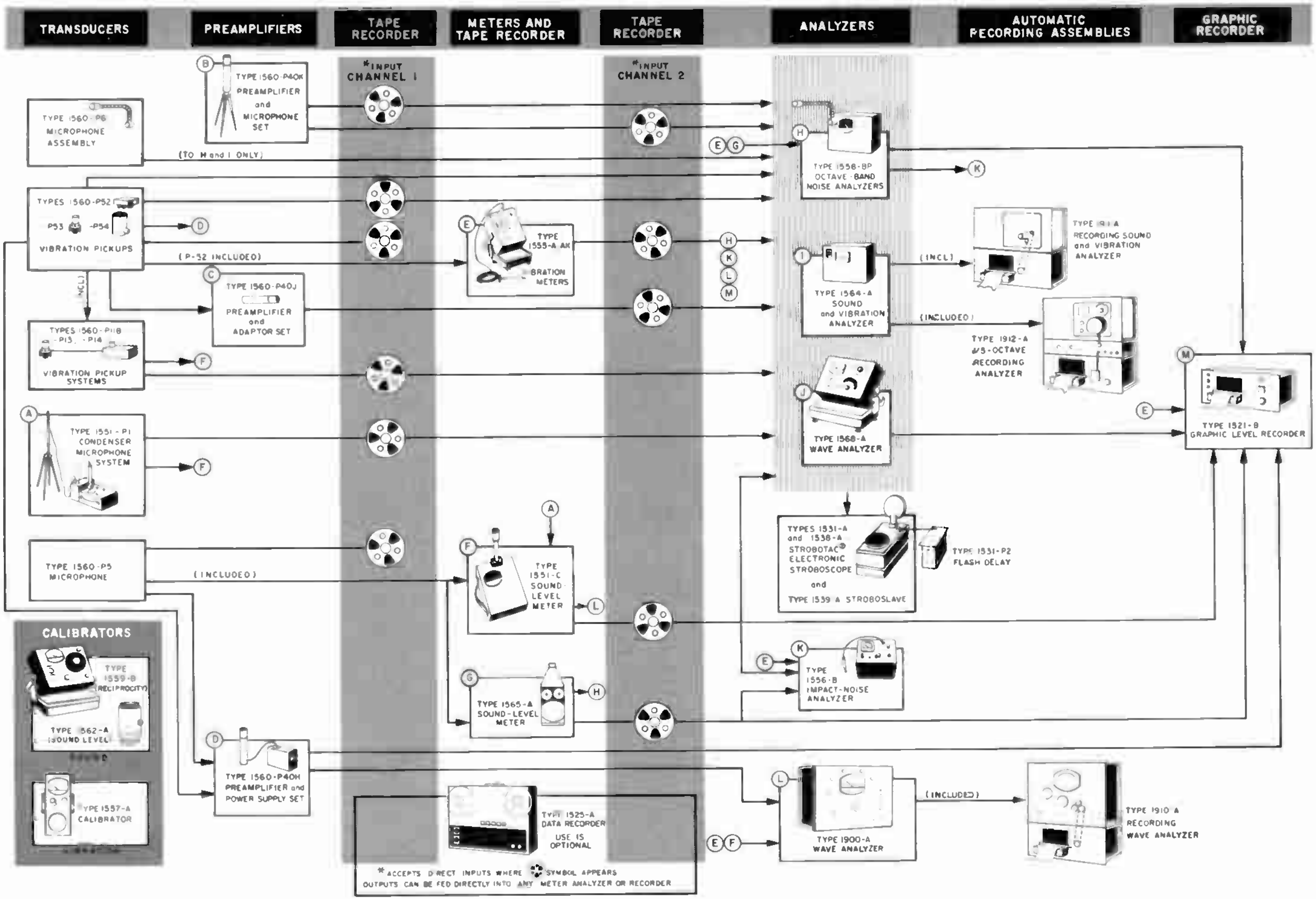


*Figure 4-1. The General Radio sound- and vibration-measuring system.*

ment. The functional relations between the transducers and the various instruments are shown in Figure 4-1.

## 4.2 TRANSDUCERS - MICROPHONES AND VIBRATION PICKUPS.

Two different types of microphones are widely used for sound measurements. They are the piezoelectric-ceramic type and the condenser type.

### 4.2.1 CERAMIC MICROPHONES.

The ceramic microphone uses a piezoelectric ceramic (lead-titanate, lead-zirconate) as the voltage-generating element. (The term "piezoelectric" indicates that the material produces a voltage when it is strained.) A diaphragm fastened to the ceramic transfers the sound-pressure variations into a corresponding varying force that bends the ceramic element.

This stable and rugged microphone has a smooth frequency response and is relatively unaffected by normal temperature and humidity changes. It is regularly supplied with the latest sound-level meters and is available for use with other measuring instruments. It can be mounted directly on the instrument or separately with connection by extension cable when it is necessary to avoid the effects of the observer and the instrument case on the acoustical measurement. Because of its good characteristics and ease of use, this type of microphone is generally preferred for most sound-measurement applications.

*Figure 4-2. General Radio Ceramic Microphones.*

4.2.2 CONDENSER MICROPHONES. Another type of microphone, known as the condenser, electrostatic or capacitor microphone, is used for measurement purposes. The variation of an electrical capacitance in this type of microphone is used to control an electrical signal. These microphones generally have excellent response characteristics. Although they require more extensive instrumentation for their use than do the ceramic microphones, they are widely used when good high-frequency characteristics are required.

Such microphones are used in the Type 1551-P1 Condenser Microphone System, which is an assembly of preamplifier, power supply, microphone, and tripod. The microphones used in this system have excellent frequency response from 20 Hz to 18 kHz. They are small in size and so create a minimum disturbance to the sound field at these higher frequencies. They are useful in testing the over-all response of high-fidelity systems or in other wide-frequency-range acoustical investigations.

4.2.3 HYDROPHONES. Microphones used for underwater sound measurements are called hydrophones. They also generally use piezoelectric ceramics as the sensitive element. Various types of hydrophones are available from such companies as Atlantic Research, Chesepeake Instrument Corporation, Clevite Ordnance, Gulton Industries, Inc., and Wilcoxon Research.

4.2.4 VIBRATION PICKUPS. The vibration pickups supplied by General Radio are all inertia-operated, lead-zirconate,

*Figure 4-3. A typical hydrophone.*

lead-titanate devices that generate a voltage proportional to the acceleration of the pickup. Integrating networks may then be used to convert this voltage into voltages proportional to velocity, displacement, and acceleration of the vibrating body.

*Figure 4-4. General Radio vibration pickups.*

## 4.3 THE SOUND-LEVEL METER.

The basic instrument of a sound-measuring system is the sound-level meter. It is an accurate, portable, low-priced meter for reading in terms of a standard reference pressure (20 $\mu N/m^2$) the sound level at its microphone. Fundamentally, the instrument consists of an omnidirectional microphone, a calibrated attenuator, an amplifier, an indicating meter, and weighting networks.

The amplifier is stabilized by means of inverse feedback. It has the three common sound-level meter responses, A, B, and C, which are specified between 25 Hz and 8000 Hz.

Two instruments of this type are available from General Radio, the Types 1565-A and 1551-C Sound-Level Meters. Both instruments conform to the requirements set forth in the USASI USA Standard Specification for General-Purpose Sound Level Meters (S1.4-1961) and IEC Recommendation R123. The Type 1565-A is small, light in weight, easy to use, and inexpensive. It can be mounted on a tripod, held in the hand, or placed on table or bench with equal facility. Readings and settings are easily made with the microphone in a vertical or horizontal position.

The Type 1551-C includes some added features, such as lower internal noise level and higher gain for measurements

*Figure 4-5.*
*The Type 1565-A*
*Sound-Level Meter.*

of lower sound levels, wider dynamic range, a fourth response characteristic that is flat from 20 to 20,000 Hz for sound-pressure-level measurements, and other wide-frequency-range applications, and a low-distortion output for driving analyzers or tape recorders.

## 4.4 THE VIBRATION METER.

The corresponding instrument for vibration measurements is the vibration meter, shown in Figure 4-7. It takes advantage of the wide frequency range of the piezoelectric type of pickup with a response for the measurement of acceleration extending smoothly from 2 to 20,000 Hz as shown in Figure 4-8. The meter is calibrated directly in terms of peak, peak-to-peak, and average displacement, velocity, acceleration, and jerk; these are indicated in mils, inches/second, inches/second$^2$, and inches/second$^3$, respectively. Another model of this instrument indicates the same quantities in metric units, i.e., mm, meters/second, meters/second$^2$, and meters/second$^3$, respectively.

Since the vibration pickup used with this meter is of the acceleration type, two stages of electrical integration and one differentiation are necessary to provide the various types of response. The integrating and differentiating circuits are built in as part of the amplifier.

The instrument is direct-reading for acceleration, velocity, and displacement from 2 to 2000 Hz, and direct-reading for jerk over the frequency range of 1 to 20 Hz, when used with

*Figure 4-6. The Type 1551-C Sound-Level Meter.*

*Figure 4-7. The Type 1553 Vibration Meter.*

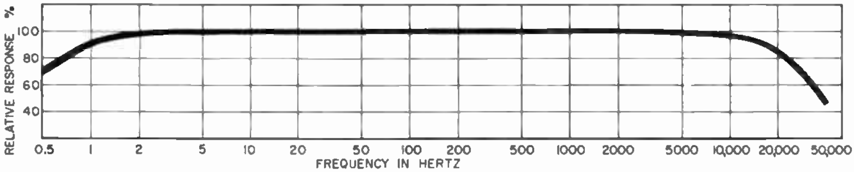


*Figure 4-8. Electrical frequency response of Type 1553-A Vibration Meter, FUNCTION switch at ACCEL, power switch at 2-20,000 Hz.*

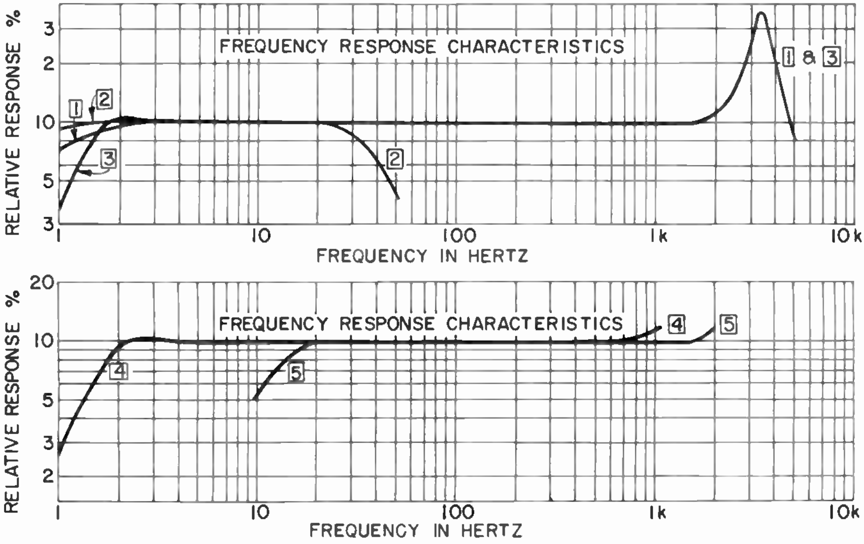


*Figure 4-9. Vibration meter response characteristics for constant applied (1) acceleration, (2) jerk, (3) velocity, (4) displacement, 2-cycle cutoff, and (5) displacement, 20-cycle cutoff when used with 1560-P52 vibration pickup. (See Figure 4-12 for responses of other pickups.)*

the Type 1560-P52 pickup normally supplied. When used with the Type 1560-P53 pickup, the direct-reading range starts at about 25 Hz and extends to 20 kHz for acceleration measurements. For velocity and displacement measurements, the high-frequency range is limited to about 2000 Hz by the internal noise level in the instrument.

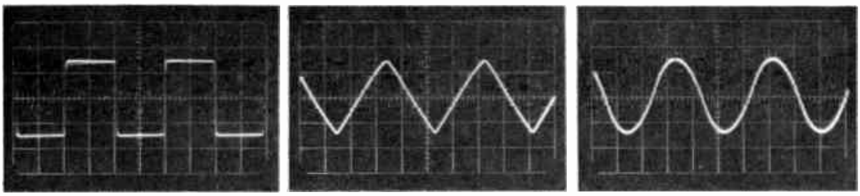


*Figure 4-10. Oscillograms showing the operation of the integrating circuits in the vibration meter. In (A) a square wave is shown as transmitted by the amplifier when set for acceleration measurements. (B) shows the wave after one stage of electrical integration for velocity measurements, and (C) shows the result of two stages of integration as used for displacement measurements.*

## 4.5 VIBRATION PICKUP SYSTEM FOR USE WITH THE SOUND-LEVEL METER.

Vibration measurements can be made with a sound-level meter when a vibration pickup is substituted for the microphone. An auxiliary control box, which is connected between the meter and the pickup, converts the response so that the meter indicates velocity and displacement as well as acceleration. The combination of pickup and control box, called a vibration pickup system, provides a convenient and inexpensive way for owners of sound-level meters to make vibration measurements within the audio-frequency range. However, the sound-level meter circuits respond down to only 20 Hz, and consequently the combination is not suitable for measuring lower-frequency vibrations. The vibration meter must be used where low frequencies are important.

The sound-level meter is calibrated in decibels, which must be converted to vibration amplitude, velocity, or acceleration. The calibration chart supplied with each vibration pickup system gives the proper conversion factors for that system when it is used with a particular sound-level meter. By means of these data, plus the decibel table in the Appendix (also supplied in the instruction book for the vibration pickup system), the readings may be readily converted to inches (displacement), inches per second (velocity), or inches per second per second (acceleration).

*Figure 4-11. The Type 1560-P11B Vibration Pickup System.*

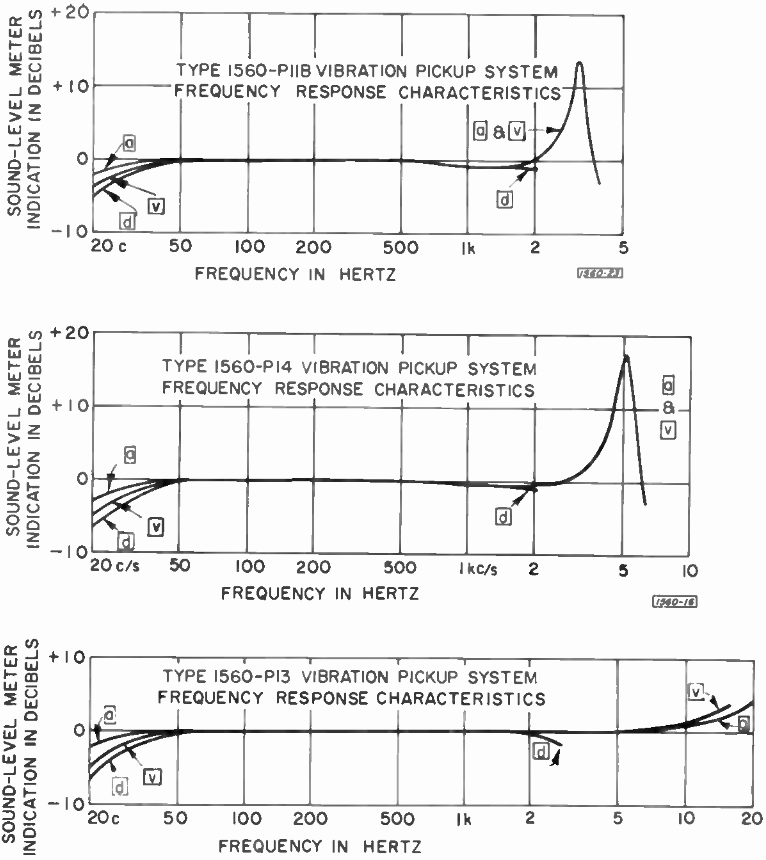


*Figure 4-12. Over-all frequency response of Type 1560-P11B, 1560-P13, and 1560-P14 Vibration Pickup Systems and sound-level meter for constant applied acceleration, displacement, and velocity.*

Three such pickup systems are available. The Type 1560-P11B Vibration Pickup System is a low-cost unit for general use, the Type 1560-P13 is for high-frequency measurements, and the Type 1560-P14 is for very low-vibration-level measurements.

## 4.6 PREAMPLIFIER.

The preamplifier shown in Figure 4-13 is a high-input-impedance, low-noise amplifier for amplifying the output of microphones and vibration pickups and for driving long connecting cables without loss in signal voltage. The gain of 20 dB (10:1) is also helpful in increasing the ultimate sensitivity of analyzers for low-level measurements.

*Figure 4-13. The General Radio Preamplifier and accessories.*

## 4.7 ANALYZERS.

Even if a sound-level meter were perfect (i.e. fit with no tolerance all the design objectives of the USASI Standards), the reading obtained by it in any given noise field is inadequate for a complete understanding of the problem. The number of decibels indicated by a sound-level meter tells nothing about the frequency distribution of the noise. It is true that by judicious use of the weighting networks in a sound-level meter one can learn something about the frequencies present, but this knowledge is only qualitative. For most important problems it is necessary to use some type of frequency analyzer to determine the noise spectrum.

The vibration meter measures the displacement, velocity, acceleration, or jerk of a vibration. Unless the waveform is substantially sinusoidal, however, the vibration meter by itself gives little information about the frequencies of the individual vibration components. An analyzer, therefore, is desirable and often is a necessity. As with noise, the analysis of vibration provides clues to the sources of the vibration components and information necessary in the suppression of the vibration.

A number of analyzers are available for use with the sound-level meter or the vibration meter or for use with microphones and vibration pickups directly or with preamplifiers. These analyzers vary in cost, complexity, and ease of operation. Choice between them is generally determined by the amount of detailed information needed to solve a particular problem. In general, the more information required, the more selective the analyzer needed. The more selective the analyzer, the more time is required to gather the information.

4.7.1 OCTAVE-BAND ANALYZERS. The octave-band noise analyzer shown in Figure 4-14 makes possible the simple and rapid analysis of noises having complex spectra. It operates directly from the output of a microphone, a vibration pickup, a sound-level meter, or a vibration meter. As described in Chapter 5, it is widely used for frequency analysis of noise, particularly if an estimate of subjective effects is desired.

This portable, battery-operated analyzer consists of a set of band-pass filters selected by means of a rotary switch, followed by an attenuator and an amplifier, which drives both an indicating meter and a monitoring output. The direct-reading range with a microphone is 44 to 150 dB. With the Type 1560-P40 Preamplifier the minimum is extended to 24 dB, even with long cables.

*Figure 4-14. The Type 1558 Octave-Band Analyzer and Type 1560-P6 Microphone Assembly.*

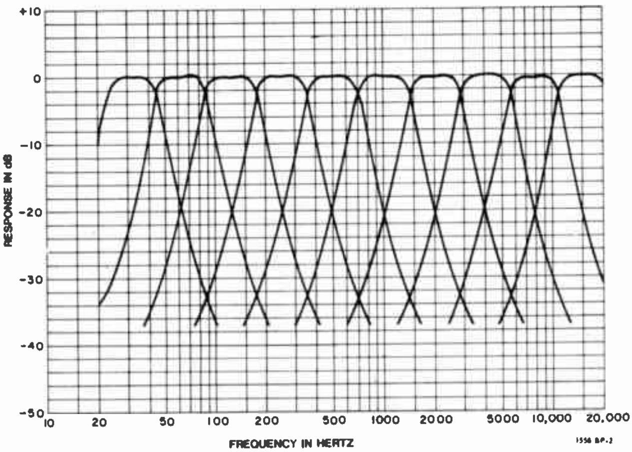


*Figure 4-15. Octave-band filter characteristics of the Type 1558-BP.*

Two models are available. The octave bands of the Type 1558-BP Octave-Band Noise Analyzer are centered on the standardized preferred frequencies, 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. It also includes an A-weighted response. The filter selectivity characteristics are shown in Figure 4-15. These filters meet the requirements of USASI S1.11-1966, Class II, Type E.

The filters included in the Type 1558-A are a 75-Hz low-pass filter and octave filters having effective bands from 18.75 to 37.5, 37.5 to 75, 75 to 150, 150 to 300, 300 to 600, 600 to 1200, 1200 to 2400, 2400 to 4800, 4800 to 9600, and 9600 to 19,200 Hz. This set includes all those specified in the older American standard, Z24.10-1953, on octave-band filter sets.

4.7.2 THIRD-OCTAVE-BANDWIDTH ANALYZER. For more detailed analysis of noise, a third-octave-band analyzer, such as that shown in Figure 4-16 is often used. In addition to the third-octave band, this instrument also has a one-tenth-octave band. A typical selectivity characteristic for these two bands is shown in Figure 4-17. This instrument can be tuned to any center frequency between 2.5 and 25,000 Hz, and the shape of the selectivity curve is constant in terms of percentage of the resonant frequency over the entire range.

The meter scale is calibrated in decibels for use in sound measurements and in linear units for vibration measurements. The direct-reading range for sound-pressure levels with a microphone attached is 44 to 150 dB and with the Type 1560-P40 Preamplifier the minimum is extended to 24 dB and long cables can be used without loss in sensitivity.

This analyzer can be operated from the power line or

*Figure 4-16. The Type 1564-A Sound and Vibration Analyzer.*

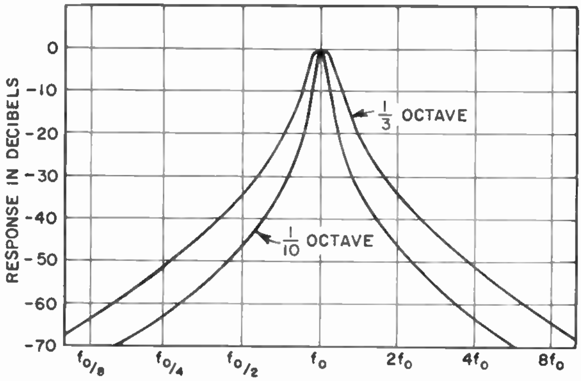


*Figure 4-17. Selectivity characteristics of the Type 1564-A Sound and Vibration Analyzer.*

from a rechargeable battery.

The filter characteristics meet the requirements of USASI, S1.11-1966, Class II, Type E.

Third-octave analysis is now widely used, particularly for checking compliance with military noise and vibration specifications. It is most often used with a graphic level recorder to give a graph of the energy distribution of the noise and vibration as a function of frequency (see paragraph 4.8).

4.7.3 ONE-PERCENT-BANDWIDTH WAVE ANALYZER. When still finer detail of analysis is desired, the Type 1568-A One-Percent-Bandwidth Wave Analyzer, shown in Figure 4-18,

*Figure 4-18. The Type 1568-A Wave Analyzer.*

may be used. It has a very selective tunable filter covering the frequency range of 20 to 20,000 Hz. The shape of the selectivity curve, shown in Figure 4-19, is constant in terms of the percentage of the resonant frequency over the entire range. The meter scale is calibrated in linear units for vibration measurements and in decibels for sound measurements.

When a Type 1560-P40K Preamplifier and Microphone Set, for which the analyzer supplies the power, is connected to the analyzer, component levels from 24 to 128 dB sound-pressure level can be measured. The output of the analyzer will drive a graphic level recorder so that an automatic recording of a noise or vibration spectrum is readily obtained.

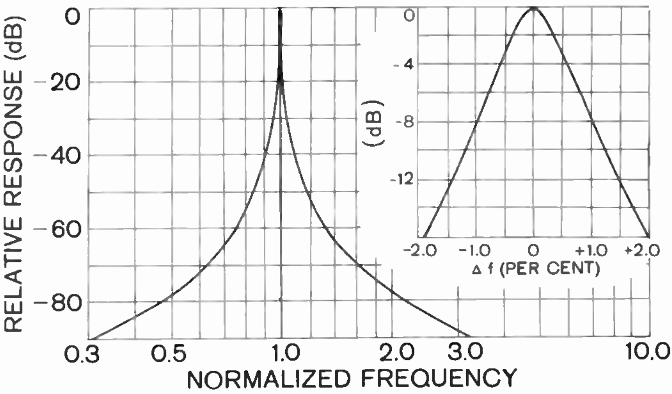


*Figure 4-19. Filter characteristics of the Type 1568-A Wave Analyzer.*

Its chief uses are in analysis for the control of noise and vibration. Another important use is in checking for compliance with certain military vibration specifications.

4.7.4 WAVE ANALYZER. The Type 1900-A Wave Analyzer, Figure 4-20, uses a fixed-frequency filter in a tunable heterodyne system similar in principle to the common superheterodyne radio receiver. It is continuously tunable from below 20 Hz throughout the audio band in a single sweep of the main tuning dial. The resulting filter characteristic is constant in response with respect to the number of hertz deviation from the center frequency over the entire tuning range.

This characteristic is convenient for analyzing random noise, because the spectrum level (refer to paragraph 2.7.4) is obtained by a constant correction of the indicated level. Most such analyzers are narrow in bandwidth (such as 4 Hz, for the older Type 736-A Wave Analyzer), however, and an analysis of noise must then proceed slowly because of the long averaging time required. A significantly wider band, such as 50 Hz, which is available on the Type 1900-A Wave Analyzer, is very much faster and relatively easy to use for noise analysis.

This analyzer has an output for recording and a linear frequency scale. When an analysis that is linear in frequency scale is made, one can readily track down harmonic relations, since successive integral harmonics are spaced uniformly. Thus the analysis of rotating or reciprocating machinery, including gear trains, electric motors, and turbines, by a wave analyzer is often to be preferred to other types of analysis.

The analyzer has an electrical output arranged so that the

*Figure 4-20. The Type 1900-A Wave Analyzer.*

system is a continuously tunable filter. Thus one can listen by means of earphones to the component or band selected by the analyzer. Furthermore, if one applies a broad-band noise signal to the input, one can obtain at the output a narrow band of noise, preferably 50 Hz wide for most acoustic measurements, whose center frequency is continuously tunable over the full range of the analyzer. This signal is desirable for some acoustic tests of rooms, walls, and hearing.

Another mode of operation of the analyzer yields a sine-wave signal at the output that is always at the frequency to which the analyzer is tuned. This is then a convenient source (to drive an amplifier and speaker) and detector for over-all electrical or acoustical response measurements.

## 4.8 GRAPHIC LEVEL RECORDER.

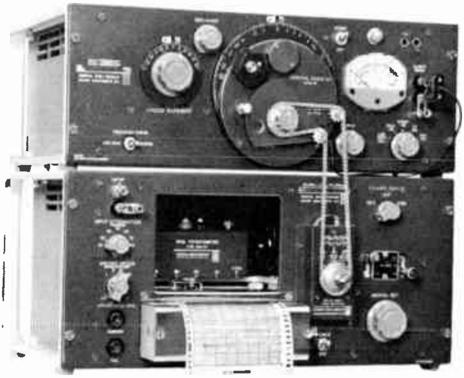
The graphic level recorder shown in Figure 4-21 produces a permanent chart record of the level of an applied signal at frequencies as low as 7 Hz. For noise and vibration measurements, this signal is usually obtained from the output of a sound-level meter, a vibration meter, or an analyzer. The recorder can be used to record over periods of time the sound levels near highways, airports, residences, or the vibration levels of building floors or walls, bridges, or airframes and to measure reverberation time. The resulting information is much more extensive than that obtainable from a few readings of a meter; and when observations over a long period are desired, the recorder can be unattended for most of the time.

The range of levels that can be recorded depends on which of three plug-in potentiometer assemblies is used. For most level recordings, the 40-dB unit, supplied with the recorder, should be used.

The combination of recorder and beat-frequency oscillator shown in Figure 4-22 produces records having a true-logarithmic frequency scale and is ideal for plotting frequency

*Figure 4-21. The Type 1521-B Graphic Level Recorder.*

*Figure 4-22. The Type 1350-A Generator-Recorder Assembly.*



characteristics of analyzers, recording systems, networks, filters, and equalizers, as well as of loudspeakers, microphones, vibration pickups, and other transducers.

Used with an analyzer, the recorder can plot the frequency spectrum of a noise source (the curve of amplitude vs frequency) or of a vibrating object (i.e., its displacement, velocity, or acceleration vs frequency). Mechanical linkages and special chart papers reproduce the frequency scale of the analyzer at the recorder.

The combination of the graphic level recorder and the sound and vibration analyzer, shown in Figure 4-23, produces permanent records of third-octave analyses, which are essential for checking compliance with certain specifications. The

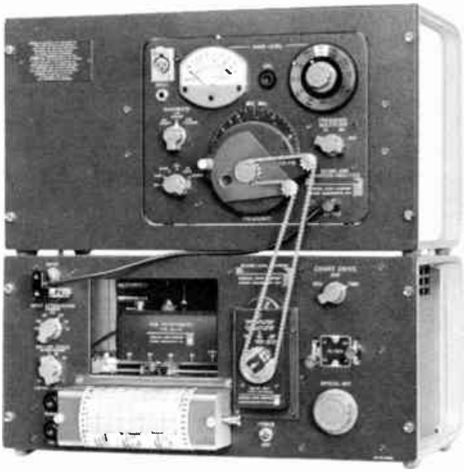


*Figure 4-23. The Type 1911-A Recording Sound and Vibration Analyzer.*

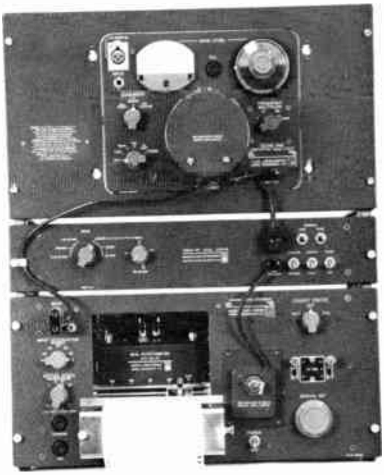


*Figure 4-24. The Types 1564 Sound and Vibration Analyzer, 1521-B Graphic Level Recorder, and 1564-P1 Dial Drive assembled for automatic 1/3-octave testing.*

recordings for analyses with the still narrower bands of one-tenth octave simplify a tedious chore when complex spectra are analyzed.

Some specifications require analyses in which the levels in only the preferred third octaves are recorded for certain periods of time. The dial drive, shown as part of the assembly in Figure 4-24, is arranged to change automatically from one-third octave to the next, allowing the analyzer to dwell at each third octave for a specified period of time as the recorder plots the level. The resulting chart is called a stepped third-octave analysis.

The recording wave analyzer shown in Figure 4-25 produces permanent records of the analysis of an input wave with a

*Figure 4-25. The Type 1910-A Recording Wave Analyzer.*

bandwidth that is constant in Hz. The spectrum level of a noise is then readily determined from the chart by subtraction of a fixed correction independent of the center frequency. The linear frequency scale also shows readily the modulation of one frequency component by another, such as occurs in gear trains.

## 4.9 MAGNETIC TAPE RECORDER.

The magnetic tape recorder, shown in Figure 4-26, has become a very useful tool for the acoustical engineer both in research and in development. It stores a signal as variations in the magnetic state of the particles on the tape. The time scale then becomes a length scale on the tape.

The signal to be stored must be supplied to the recorder as an electrical signal; and, for recording noise as a function of time, this electrical signal is usually obtained from a high-quality microphone. When measurements are to be made on the stored signal, the recorded tape is played back on the recorder and measurements are made on the electrical output signal.

The magnetic tape recorder is being used to perform the following functions in the field of noise measurements:

1. To keep reproducible records of progressive changes in a sound. These changes may be a result of the application of successive noise control procedures, for example.

2. To record a noise for analysis by a number of techniques, when the particular approach to be used is not at first obvious and it is not convenient to use the original source repeatedly.

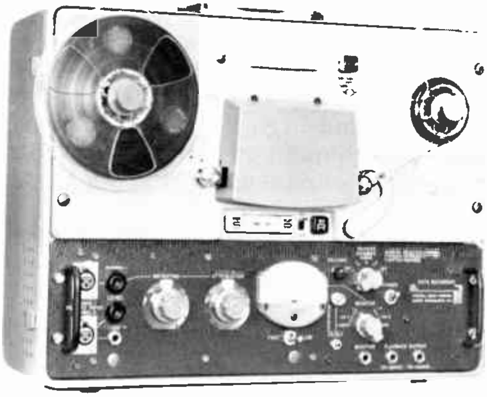


*Figure 4-26. The General Radio Type 1525-A Data Recorder.*

3. To record a noise in the field for detailed study in the laboratory, where complex instrumentation systems can be used.

4. To record a sound that varies with time. Samples can then be selected from the recording for analysis to obtain the change in spectrum as a function of time.

5. To record a short-duration sound, which can then be played back repetitively to simplify analysis.

6. To monitor over long periods to catch intermittent sounds, which can then be separated out for analysis.

7. To record noises that are erratic or intermittent, possibly by binaural techniques, to aid in tracking down sources.

8. To record a noise to permit a 2-to-1 frequency translation for convenience in analysis.

9. To record a transient noise in order to change the time scale by a factor of 2 or to invert the time scale for ease of graphic recording.

10. To permit subjective or objective comparison among sounds recorded at different times. The subjective judgment can then be made by groups listening under similar conditions.

11. To permit observation of the subjective effects of altering a signal, for example, by filtering, clipping, or adding noise.

12. As a measurement system with a recorded signal as the source and a recording channel as the detector, for example, in the measurement of reverberation characteristics.

These applications have been stated for acoustic signals, but most of them apply to vibration signals as well.

In order to perform these functions the tape recorder shown includes the characteristics of a sound-level meter, a variety of weighting networks, an accurate step attenuator, an amplifier with high gain and high input impedance, a transient overload indicator, two-channel recording, simultaneous playback on recording, good response down to 15 Hz, and tape loop guides.

The tape recorder supplies power for the Type 1560-P40 Preamplifier so that microphones and vibration pickups can be used with long cables for best signal-to-noise ratio.

*Figure 4-27. The 1525-A Data Recorder shown with Tape loop for analysis of short-duration signals.*

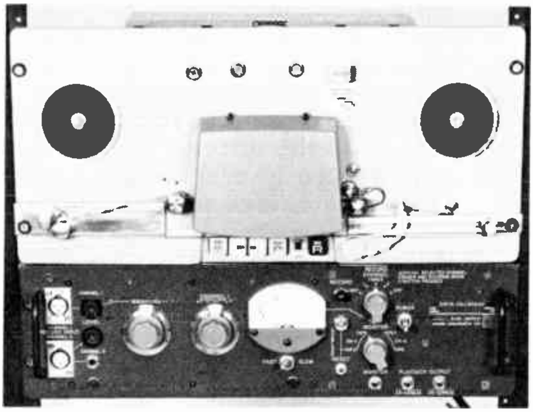


*Figure 4-28. The 1525-A Data Recorder with Preamplifiers and microphones at both input channels and headphones at its "monitor" jack.*

## 4.10 IMPACT-NOISE ANALYZER.

Impact-type waveforms, such as those produced by punch presses or drop hammers, cannot be properly evaluated by a sound-level meter, a vibration meter, or a spectrum analyzer. A cathode-ray oscilloscope can be used to study such waveforms, but measurement is complicated and often cannot be carried out at the site of the vibratory disturbance. The instrument recommended for studying impact or impulse-type waveforms is the impact-noise analyzer. This battery-operated analyzer operates directly from the output of a sound-level meter or a vibration meter to measure the peak level and approximate duration of the impact waveform. Analyzers or a magnetic tape recorder can be used as auxiliary equipment.

Through the use of electrical storage systems, three characteristics are measured by the analyzer for each impact; a peak instantaneous level, an average level, and a continuous indication of peak level. (The duration of the impact can be estimated from the difference between peak instantaneous level and average level.) Any one of the three characteristics can be switch-selected for presentation on the meter.

## 4.11 RANDOM-NOISE GENERATOR.

The random-noise generator shown in Figure 4-29 is a source of high-level, broad-band electrical noise, which can be converted to acoustic noise by means of a loudspeaker or earphone. Such acoustic noise is useful in psychoacoustic experiments, in the measurement of reverberation and noise transmission, in loudspeaker and microphone response measurements, in microphonic testing, and for calibration procedures.

The output of a random-noise generator can be filtered by one of the analyzers to provide a band of noise that is tunable over the audio range. This type of signal is sometimes preferred to the broadband noise signal for the measurements mentioned above.

The output of the random-noise generator can also be converted to a random mechanical motion by an electromechanical shaker. Random motion is used in the mechanical testing of components and structures.

## 4.12 TONE-BURST GENERATOR.

The combination of an oscillator and the tone-burst generator shown in Figure 4-30 is a source of electrical tone-

*Figure 4-29. The Type 1390-B Random-Noise Generator.*

*Figure 4-30. The Type 1396-A Tone-Burst Generator.*

burst waveforms, which can be converted to acoustical tone bursts by means of a loudspeaker or earphone. Such an acoustic signal is useful in room acoustic measurements, in psychoacoustic experiments, in studies on transducer and acoustical material properties, and in amplifier tests. It is particularly helpful in locating stray reflections in anechoic chambers and in tracing sound-transmission paths.

## 4.13 EARPHONE COUPLER.

The earphone coupler shown in Figure 4-31 is designed to couple an earphone to a measurement microphone for check-

*Figure 4-31. The Type 1560-P82 Earphone Coupler shown in use on a Type 1565-A Sound-Level Meter.*

ing the response of earphones and the characteristics of audiometers. The measurement microphone is connected to a sound-level meter or an analyzer for quantitative measurements.

## 4.14 OSCILLOSCOPE.

A cathode-ray oscilloscope is a useful means of observing the waveform of a sound or vibration signal from a sound-level meter or a vibration meter. It can be used to measure the peak amplitude of a wave, and after some experience the observer can, by adjusting the sweep frequency, tell something about frequency components by looking at the waveform. In addition, the oscilloscope makes possible the study of the instantaneous values of a vibratory motion. In contrast with the vibration analyzer and other wave analyzers that present information in terms of frequency, the oscilloscope presents information as a function of time. This time representation is often of great assistance in the solution of vibration problems. Because the oscilloscope presents information instantly and continuously and because its frequency response is not a limiting factor it is useful in the study of any vibration waveform.

For sound and vibration measurements an oscilloscope with slow sweep rates, long-persistence screen, and dc amplifier is recommended. Many oscilloscopes have provision for the addition of a camera, which makes possible the permanent record of the wave shape being studied.

## 4.15 CALIBRATORS.

Much is to be gained from the use of an accurately calibrated acoustical or vibration measurement system. When an accurate calibration is made, the consistency of comparison measurements can be improved, a closer approach to an allowed performance specification is possible, and careful attention to measurement techniques will be repaid by more accurate measurements.

4.15.1 MICROPHONE RECIPROCITY CALIBRATOR. Frequent, accurate calibrations, even in the field of acoustical systems, are now possible by the use of the microphone reciprocity calibrator shown in Figure 4-32. This instrument uses the reciprocity technique, which is widely preferred for the absolute calibration of standard microphones, to calibrate the General Radio ceramic microphones and to make an over-all calibration of the system used with them.

This microphone reciprocity calibrator uses a small acoustic cavity as an acoustic impedance reference and an accurate

*Figure 4-32. The Type 1559-B Microphone Reciprocity Calibrator.*

electrical capacitor as the electrical impedance reference. The calculations necessary to determine microphone sensitivity are automatically performed by an analog computer, so that microphone sensitivity can be read from a dial on the panel after four simple adjustments are made at any one frequency.

This calibrator can be operated from an oscillator that supplies at least 5 volts into a 600-ohm load. A sound-level meter can be used as the detector.

4.15.2 SOUND-LEVEL CALIBRATOR. When an over-all acoustical check of a system at several frequencies is desired, the sound-level calibrator can be used. It comprises a small, stabilized, and rugged loudspeaker mounted in an enclosure which fits over the microphone of the sound-level meter. The chamber is so designed that the acoustic coupling between loudspeaker and microphone is fixed and can readily be repeated. The level is high enough so that readings are unaffected by normal background noises.

The calibrator shown in Figure 4-33 includes its own battery-operated oscillator to drive the transducer which supplies a known level at 125, 250, 500, 1000, and 2000 Hz to a General Radio microphone. This device permits a quick check of the performance of an acoustic measurement system over the most important frequency range for acoustical measurements. It is also invaluable for calibrating a measurement

*Figure 4-33. The Type 1562 Sound-Level Calibrator.*

tape recorder and for supplying calibrating signals for recording.

4.15.3 VIBRATION CALIBRATOR. The vibration calibrator shown in Figure 4-34 is a small, single-frequency calibrator useful for checking the over-all operation of a vibration-measuring system. The calibrator consists of a resiliently supported cylindrical mass, driven by a small, transistorized, electromechanical oscillator mounted within the cylinder. Small accelerometers may be mounted on either of two disk-shaped platforms attached to the shaker. Large accelerometers may be mounted in place of the disk-shaped platforms. To calibrate an accelerometer, the LEVEL control is adjusted for a meter reading corresponding to the mass added to the moving system of the calibrator. The accelerometer is then being driven at an acceleration of 1 g at 100 Hz. The excursion of the calibrator can be adjusted for 1 g acceleration with any pickup weighing up to 300 grams.

## 4.16 RECORDING GALVANOMETER.

The recording galvanometer is very useful in applications where the vibration to be measured is transient in nature. Also, for steady-state vibrations, the recording galvanometer produces a permanent record of a vibration waveform for future study and analysis. Most of the many models of recording galvanometers can be used at the output of a vibration

*Figure 4-34. The Type 1557-A Vibration Calibrator.*

meter. The fidelity of recording is limited by the characteristics of the galvanometer.

Direct-writing galvanometers may write with ink on paper, with special styli on heat-sensitive or voltage-sensitive paper, or with a pointed stylus on waxed paper. The pen motors usually have relatively low resonant frequencies and require dc amplifiers when used with the vibration meter. Most manufacturers of pen motors also make the corresponding dc amplifiers. Compensation is sometimes added to extend the flat response range of the pen motor. Pen motors with compensating amplifiers are useful from dc up to about 100 Hz.

Another type of galvanometer moves a tiny mirror which reflects a light beam onto a photographic paper or film. Here sensitivity and resonant frequency can be increased because the mirror can be tiny with little mass, and the light path from the mirror to the recording surface can easily be made relatively long. Flexibility is increased because galvanometers varying widely in sensitivity and frequency range can be readily interchanged. Many of these galvanometers can be operated from the output of the vibration meter with the use of a resistive pad and no extra amplification. Units with resonant frequency as high as 3000 Hz are available. Since the record is produced on a photographic film or paper, and is not always immediately available, this type of recording galvanometer is not as convenient as the direct-writing type. To reduce the time lag between tests and viewing or interpretation of data, several companies manufacture compact photo record processors for paper oscillograms and other rolled-paper photo records. The units require no darkroom for operation and can be used at the testing site without connection to an external source of water. In addition, at least two companies have introduced light-beam-type recorders using a high-intensity light source and specially sensitized paper to produce a trace that becomes visible almost immediately.

## 4.17 VIBRATION SHAKERS.

As noted in Section 2.9, several types of vibration shakers are widely used. One of the most versatile is the electrodynamic shaker. These shakers, produced in a wide range of sizes, are used by vibration engineers in many ways to help evaluate performance of instruments, components, and structures. Typical uses are: endurance or fatigue testing of electrical and mechanical structures, testing of resilient or shock mounts, shake testing of electrical components such as switches, relays, or amplifiers, determination of damping characteristics of materials, and calibration of vibration pickups.

Some tests use sine-wave motion, with the frequency either set at a resonance of the device under test or swept over a specified band. Random motion is becoming widely accepted in vibration testing, with a random-noise generator (see Section 4.11) used as the signal source, and an adjustable band-pass filter used to shape the noise spectrum.

## 4.18 STROBOSCOPES.

The stroboscope is valuable in many vibration studies because it permits rotating or reciprocating objects to be viewed intermittently and produces the optical effect of slowing down or stopping motion. For instance, an electric fan revolving at 1800 rpm will apparently stand still if viewed under a light that flashes uniformly 1800 times per minute. At 1799 flashes per minute the fan will appear to revolve at 1 rpm, and at 1801 flashes per minute it will appear to rotate backwards at 1 rpm. Because the eye retains images for an appreciable fraction of a second, no flicker is seen except at very low speeds. The apparent slow motion is an exact replica of the higher-speed motion, so that the motion of the high speed machine can be analyzed with the stroboscope under normal operating conditions. This type of instrument can be used to measure the speeds where vibrations occur in most rotating or reciprocating machines. Displacements in vibrating parts can often be measured accurately with the aid of a microscope if a fine reference line is scribed on the part. This technique has been used to confirm the calibration of vibration calibrators, and automotive engineers have used it to measure crankshaft whip and vibration.

4.18.1 STROBOTAC® ELECTRONIC STROBOSCOPE. The Strobotac® electronic stroboscope, shown in Figure 4-35, is a small, portable stroboscope calibrated to read speed directly in revolutions per minute. The light source is a strobotron tube, mounted in a parabolic reflector. The frequency of an internal electronic pulse generator determines the flashing speed, which can be adjusted by means of a direct-reading dial. Normal flashing range is from 110 to 25,000 rpm. Another model of the Strobotac® is available for flashing rates up to 150,000 per minute, and that model can be operated from rechargeable battery. Speeds above and below this range can be measured by use of flashing rates that are simple multiples or submultiples of the speed to be measured. As the flashing rate of the Strobotac is decreased below 600 per minute, the flicker becomes pronounced due to the inability of the human eye to retain successive images long enough to give the illusion of continuous motion.

Of especial use in vibration measurements is the provision for connecting an external synchronizing signal to the Strobotac. Thus the light flashes can be triggered directly by any of several devices. These include two stroboscope accessories, the Type 1535-B Contactor, a mechanical coupling which

*Figure 4-35. Type 1531 Strobotac® electronic stroboscope (left), Type 1531-P2 Flash Delay (attached to stroboscope), and Type 1536-A Photoelectric Pickoff.*

permits synchronization of the stroboscope with a rotating shaft, and the Type 1536-A Photoelectric Pickoff, which uses a photocell to synchronize the stroboscope with repetitive mechanical motion. A major advantage of the latter is that it requires no attachment to the device being observed, and thus can be used effectively with low-torque devices. The output of the photoelectric pickoff requires amplification to trigger the stroboscope; this is provided by the Type 1531-P2 Flash Delay Unit, which also permits observation of the vibration at any point in its cycle.

The stroboscope can also be flashed by the output from one of the vibration pickup systems described earlier. For instance, a vibration pickup can be used with a sound-level meter or vibration meter to send triggering impulses to the stroboscope. Filtering is necessary between the measuring instrument and the stroboscope. An octave-band or a narrow-band analyzer can be used to provide such filtering.

4.18.2 STROBOLUME (TYPE 1532-D). The Strobolume is a source of very bright light that is triggered by an external device, such as the Type 1531 Strobotac electronic stroboscope or the Type 1535-B Contactor. It is useful where the ambient light level is high or where large areas must be illuminated. The Strobolume produces brilliant white flashes continuously at rates up to 60 per minute or for short periods at rates up to 1200 per minute. It also produces flashes of shorter duration (and of about the same intensity as those produced by the Strobotac) up to 3000 per minute.

4.18.3 MOTION ANALYSIS SET. The Type 1539-Z Motion Analysis and Photography Set is arranged for visual analysis of a repetitive motion or inspection of a process where the independent flashing rate setting of the Strobotac is not required and for high-speed photography with conventional cameras. The major application areas for the motion analysis are in machinery and metal working, including packaging, printing, textile, earthmoving machinery, metal products, shipbuilding, automotive manufacturing, ordnance, chemical processing and aerospace.

4.18.4 STROBOSCOPIC APPLICATIONS. Stroboscopic techniques are widely used for visual observation of vibration. The high-speed performance of fans, propellers, and other rotating devices can be studied by means of the slow-motion effect of the stroboscope, and sources of vibration and noise due to misadjustments, misalignment, and wear can be readily detected. The vibratory modes of turbine blades are checked as they are driven electromagnetically, and the mode shapes are observed with the aid of an optical magnifier under stroboscopic illumination. Similarly, the flapping of the blades of a model helicopter rotor has been observed in slow motion by stroboscopic illumination.

The stroboscope can also be used to observe the motion of apparatus being tested on a shaker. If the flashing rate is just slightly offset from the frequency of the shaker, a slow-motion replica of the high-speed vibration will result, so that the displacement can readily be observed. The form of the motion can be seen, and one can often tell what section needs to be strengthened and how damping material and damping devices can best be applied.

When a rotating or reciprocating machine is brought up to speed or is a variable speed device, there may be resonant vibration modes of various parts at certain speeds, known as critical speeds. If these parts are visible and can be illuminated by a stroboscope, it is often possible to use the slow-motion feature to check on the actual behavior of the part at resonance. One can see if it is a fundamental resonance or a multiple resonance with various sections going in phase and others in phase opposition. This type of observation can be of great assistance in the determination of the proper treatment to reduce the resonant vibration.

For further details on the stroboscope and its uses consult F. T. Van Veen, Handbook of Stroboscopy, General Radio Company, West Concord, Mass., 1966.

chapter 5

# WHAT NOISE AND VIBRATION MEASUREMENTS SHOULD BE MADE?

## 5.1 INTRODUCTION.

The previous chapters have reviewed many of the noise and vibration measurements that can be made. They range from a simple measurement of sound level to a detailed vibration analysis showing hundreds of components of a complex vibration. Confronted with so many possible choices, one might well ask, "What measurements should we make and what instruments do we need for our job?"

The answer to this question depends of course on what the job is. If the problem is one of checking compliance with a certain noise and vibration specification, the specification is usually set up so that the particular measurement required is reasonably clear and only some guidance as to choice of instruments and their use is needed. But if we are trying to reduce the noise produced by an appliance, the situation is more complex and extensive discussion is necessary.

In all these applications careful attention to the acoustic environment is essential. That is, if the background noise is serious or if reflected sound is significant, you may be paying a significant penalty because the measured noise is higher than it would be under ideal conditions. These problems are discussed in the next chapter.

In order to organize the many possible answers to the basic question in a manner that will make the information readily usable, this chapter is arranged on the basis of the application. The next step for you is to find the field that fits your job in the following list and then look up the referenced section.

- Devices that are Noisy or Vibrate Excessively (5.2)
    - Product Noise and Test Codes (5.2.1)
    - Production-Line Testing (5.2.2)
    - Product-Development Noise and Vibration Reduction (5.2.3)
    - Machinery Maintenance (5.2.4)
- Environmental Noise (5.3)
    - Hearing Loss from Noise Exposure (5.3.1)
    - Local Noise Ordinances (5.3.2)
    - Neighborhood Noise (5.3.3)
    - Noise Ratings (5.3.4)
    - Motor Vehicle Noise (5.3.5)

- Architectural Acoustics (5.4)
  - Sound Absorption (5.4.1)
  - Sound Transmission Loss (5.4.2)
  - Reverberation Time or Decay Rate (5.4.3)
  - Response Testing (5.4.4)
  - Tone-Burst Testing for Echoes (5.4.5)
  - Site Selection (5.4.6)

## 5.2 DEVICES THAT ARE NOISY OR VIBRATE EXCESSIVELY.

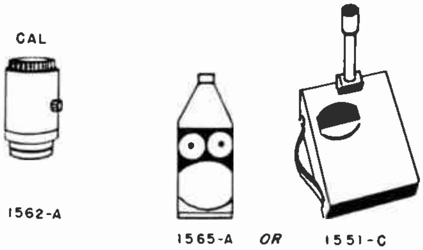
5.2.1 PRODUCT NOISE AND TEST CODES. Specifications of acceptable noise limits for products are becoming relatively common. These specifications are usually given as maximum sound levels or maximum octave-band levels or sometimes third-octave band levels at certain measuring points. Some specifications also include the measurement of radiated acoustic power.

Various engineering groups and trade associations have standardized test codes for measuring the noise from certain devices, for example, transformers, cooling towers, electric motors, fans and blowers, etc. These codes are often referenced as a part of a specification in order to standardize the measurement procedure to be used in checking for compliance to a maximum noise requirement. A representative list of test codes is given in the reference section of the Appendix.

5.2.1.1 A-Weighted Sound Levels. A simple example of noise testing is the check for compliance by a manufacturer for a customer who requires that the A-weighted sound level at 3 feet from any major surface of a motor be less than, say, 55 dB. He may also specify that the motor be mounted on a hard reflecting surface in an essentially anechoic space. Here the A-weighted sound level needs to be measured, and a sound-level meter with a microphone will do the job.

The Type 1565-A Sound-Level Meter is adequate for this test and it is generally wise to include a Type 1562-A Sound-Level Calibrator as part of the measurement system. If measurements below 44 dB may be required, the 1551-C Sound Level Meter should be substituted.

*Figure 5-1. System to measure "A"-weighted sound levels.*



5.2.1.2 Octave-Band Analysis. Some customers, for example, the military, may specify the maximum allowable octave-band levels under certain measurement conditions. The Type 1558-BP Octave-Band Noise Analyzer and a Type 1560-P6 Microphone are the logical pair to do the job. (Unless the older series of octaves is specified.) If it is expected that band levels below 44 dB may be measured, the 1560-P40K Preamplifier and Microphone Set should be substituted for the 1560-P6 Microphone.

Again, a 1562 Calibrator should be included as a check on the accuracy of the measurement.

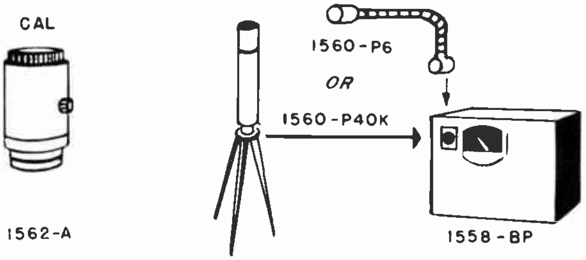


*Figure 5-2. Octave-band analysis.*

For estimates of probable customer reaction to the noise of a product, an octave-band analysis of the noise is the most widely used measurement. The band levels are used to calculate loudness level or perceived noise level. If competitors' products are measured in the same way, either procedure should permit one to rank the units in order of acceptability with good reliability.

5.2.1.3 Acoustic Power Output. The use of acoustic-power output for rating noisy devices is widely recognized as the best approach for certain measurements. Acoustic power is calculated from the results of a number of sound-pressure-level measurements, usually octave-band levels. The procedure is described in Section 2.8.5. The instrumentation required here is a calibrator, a group of microphones or some means of moving a microphone to scan a given area, a preamplifier, an octave-band or third-octave-band analyzer and a recorder.

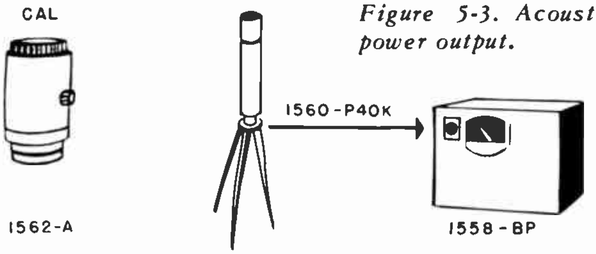


*Figure 5-3. Acoustic power output.*

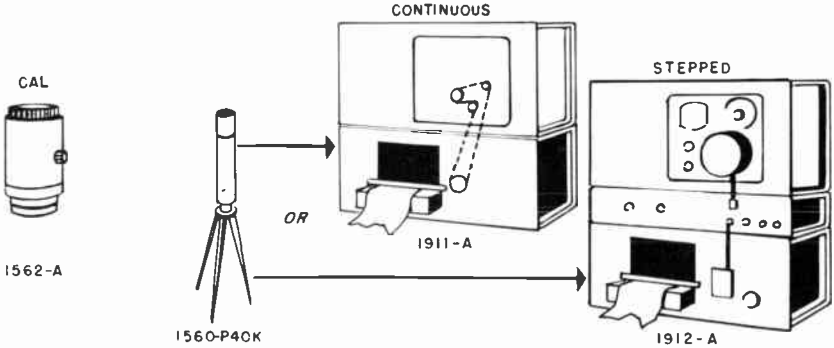


*Figure 5-4. Production-line testing instrumentation.*

5.2.2 PRODUCTION-LINE TESTING. Ideally, many devices should be tested for noise output on the production line. Noise measurements on the production line are often possible, but hardly ever in an ideal manner. That is, precision acoustical testing usually requires a large, isolated, echo-free space, which would not ordinarily be considered for inclusion as part of a production line. Nevertheless, useful noise measurements can often be made with relatively simple procedures, although the accuracy of rating may be significantly reduced compared with that possible with an ideal measurement.

In this discussion we shall consider briefly several possible solutions to this problem, ranging from the elaborate to the simple. For some expensive devices where the noise level is exceptionally important, for example, large power transformers, the required very large, isolated, echo-free chambers have been used to test each unit as it is produced. When the device is not so large and low frequencies are not important, a reasonable-size anechoic chamber with regrigerator-type doors can be used.

Although the acoustic environment is an important consideration for all the noise measurements discussed in this chapter, the requirements of production testing make the control of the environment a more difficult problem than it is in a research and development laboratory.

A massive, tight, resiliently mounted enclosure is necessary to avoid pickup of ambient stray noise that will affect the measurement. For the same reason the access door must be one that seals exceptionally well. Then, in order to get the required echo-free behavior, extensive treatment of the inside is necessary.*

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*Anechoic chambers of various sizes are manufactured by, for example, the Eckel Corporation, 155 Fawcett Street, Cambridge, Mass.

An enclosure with hard walls can also be used in some instances. Here the design should be such as to make it a reverberation room (see Sections 2.8.4.1 and 2.8.5.6).

A much simpler technique is sometimes satisfactory for production-line screening of noisy devices. This approach depends on a vibration measurement that has been correlated with the acoustic noise. For example, acoustic measurements of a number of samples may show that the noisy ones are invariably noisy in one or two octave bands, say the bands at 500 and 1000 Hz. Then a measurement of the vibration of these samples may show what vibration levels are acceptable in these bands. Some exploration of the vibration of the various surfaces of the device will be necessary to find the critical areas. Usually the major surfaces should be tried first. In production, the tests should be made with the device resting on a very thick, resilient pad or mounted in soft mounts that help isolate against ambient vibration.

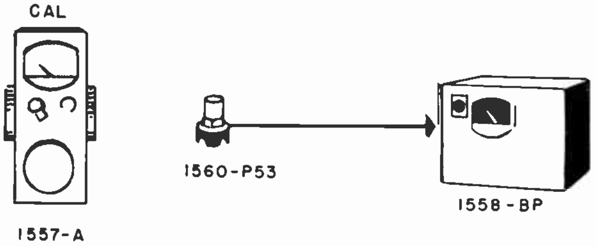

*Figure 5-5. Alternate production-line testing setup.*

5.2.3 PRODUCT DEVELOPMENT - NOISE AND VIBRATION REDUCTION. In a program for the reduction of noise and vibration, the tape recorder is a key instrument. It permits one to store in reproducible form a record of the results of successive noise and vibration control measures. Such a series of records may be particularly useful for demonstrating to a consultant's client or to the management of a plant what has been accomplished in reducing noise. From an engineering viewpoint, these recordings are also valuable when a change in plans requires a change in analysis procedure.

Some sounds vary significantly in level and character with time. Applicances that go through a cycle of different operations (dishwashers and clothes washers, for example) produce such sounds. Although an appliance can be programmed to stay in the same phase of the cycle for long periods, it is usually more convenient to make a recording of each phase. Sections can then be separated out for detailed analysis.

Some devices, for example a gas engine, drift slowly but significantly in speed. As a result, the basic noise pattern changes, and the drift is often serious enough to preclude direct, detailed analysis of the noise spectrum at a variety of speeds with the usual slow-scan techniques. One can, however, run the engine for a reasonable period at each of a number of selected nominal speeds and record short samples, say two seconds, at each of these speeds to form a series of tape loops. Each loop is played back and is analyzed by a wave analyzer. Since the inertia of the rotating system is often so large that serious fluctuations in speed do not occur in the short interval of the tape loop, the engineer obtains a series of frequency spectra that can be related to shaft speed. He may then be able to deduce much about the noise producing mechanisms from the relations between amplitude, frequency, and shaft speed.

The analysis of intermittent sounds or signals can be a helpful step in tracking down the sound sources. By means of tape recording, one can monitor the noise from a device for long periods to catch these intermittent sounds, which can then be separated out for analysis.

Background noise may make noise studies of machines impractical when acoustically isolated rooms are not available. Often, however, the background noise is much less during lunch periods or outside normal working hours, particularly early in the morning, and measurements may then be practical. Even during such periods a complete study of the noise may be awkward or inconvenient, but, if tape recordings can be made during the quiet periods, the recorded signal can be analyzed at any convenient time.

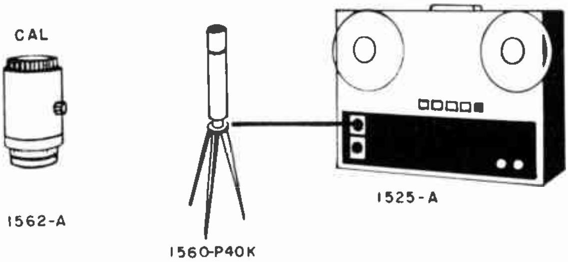

*Figure 5-6. Noise recording assembly.*

The full range of analysis equipment is helpful in the reduction of noise and vibration. The octave-band analyzer is used to check how the noise rating changes as the noise control procedures are instituted. The narrow-band analyzers such as the 1568 and 1900 Wave Analyzers are used to help track down the cause and sources of troublesome components of the noise. This process is described in Chapter 8.

Impact noises, such as those produced by punch presses, drop forges, hammers, typewriters, trippers, chain drives, and riveters, should be measured with an impact-noise analyzer at the output of a sound-level meter or an octave-band analyzer. Then the engineer can quickly determine the effect of various treatments or design modifications on the peak level of the noise.

If vibration reduction is the prime goal, vibration pickups should, of course, be used to supply the signals to the analyzers. But even if noise reduction is the desired goal, the reduction is often accomplished by reducing the vibration of various parts of the device. Here vibration pickups should be used, or the motion should be studied with stroboscopic observation of the moving parts. This procedure is also described more fully in Chapter 8.

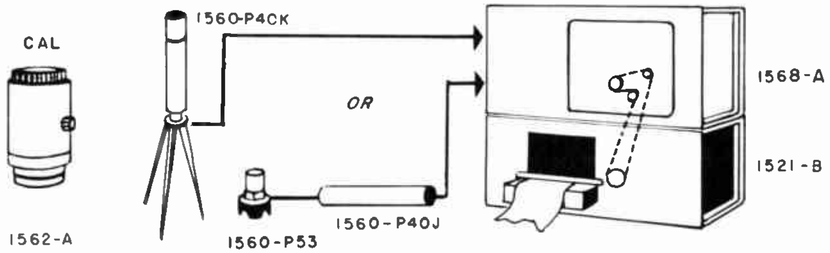

*Figure 5-7. Narrowband sound or vibration analysis*

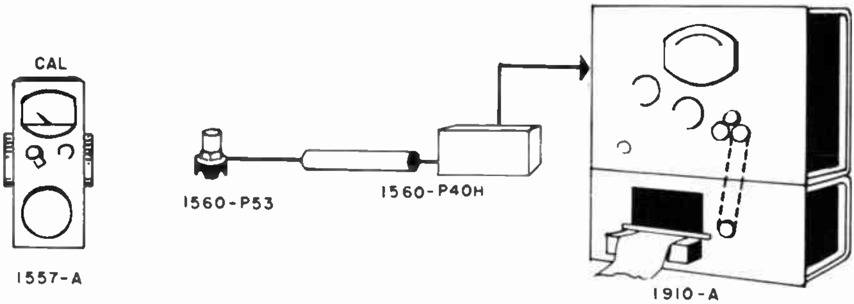

*Figure 5-8. Narrowband vibration analysis - constant bandwith.*

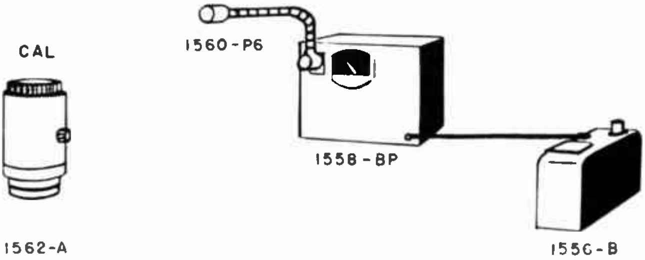

*Figure 5-9. Impact-noise analysis in octave bands.*

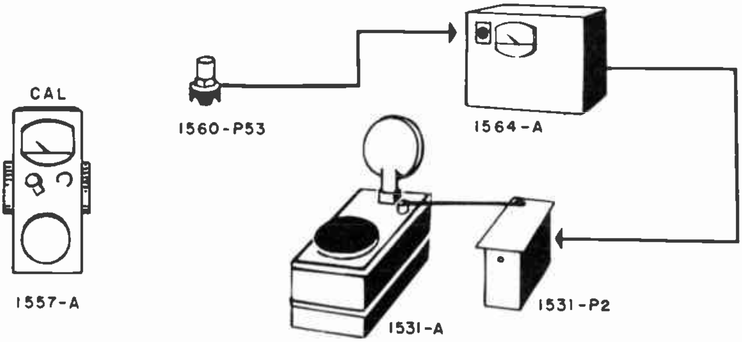

*Figure 5-10. 1/3 and 1/10 Octave-band vibration analysis with stroboscopic observation.*

5.2.4 MACHINERY MAINTENANCE. Only one aspect of machinery maintenance is considered here, namely, the relation of the vibration level of a machine to its condition. That is, vibration measurements can be the guide to predicting incipient failure of a machine, to deciding when cleaning, parts replacements, and other maintenance procedures are necessary, and to determining the relation between vibration and the performance of the machine.

The best general measurement for this purpose is velocity, and it is usually made at the bearing housings. The Type 1553 Vibration Meter is nicely adapted for this purpose, but since analysis of the vibration signal is often desirable, the 1564 Sound and Vibration Analyzer with a vibration pickup and a control box is a choice that reduces the total number of instruments required.

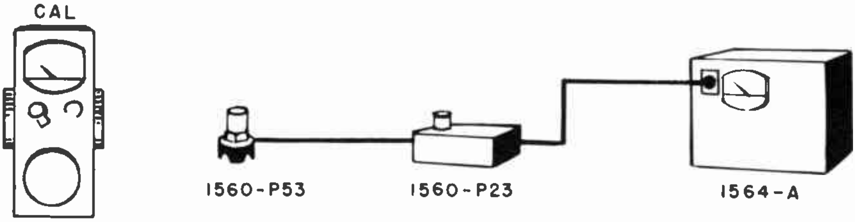

*Figure 5-11. Velocity measurement and analysis system.*

One common source of trouble in machinery is rotating unbalance. As described in Chapter 8 a measurement system to help in in-place balancing consists of a Type 1560-P54 Vibration Pickup, the Type 1564-A Sound and Vibration Analyzer, Type 1531-P2 Flash Delay, and the Type 1531 Strobotac.

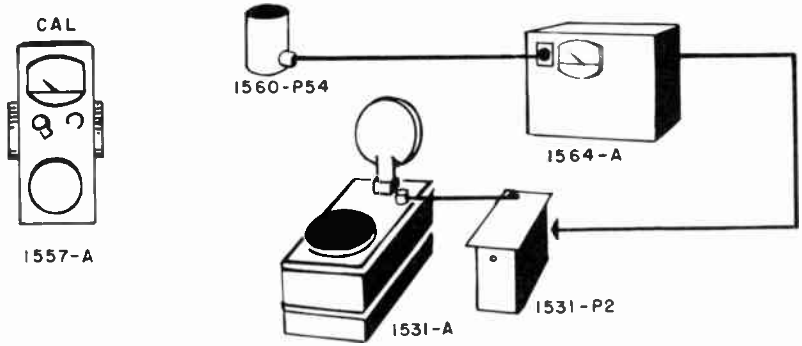

*Figure 5-12. In-place balancing assembly.*

## 5.3 ENVIRONMENTAL NOISE.

5.3.1 HEARING LOSS FROM NOISE EXPOSURE. As described in Section 3.12, the noise near some machines is intense enough to cause permanent hearing damage if the exposure to the noise continues for long periods. As explained in that section, a preliminary screening can be done on the basis of the A-weighted sound level, for which the Type 1565-A Sound-Level Meter is satisfactory. But for many sounds an analysis will be necessary, and the Type 1558-BP Octave-Band Noise Analyzer should be used. Since it includes A-weighting, it can be used for screening purposes also.

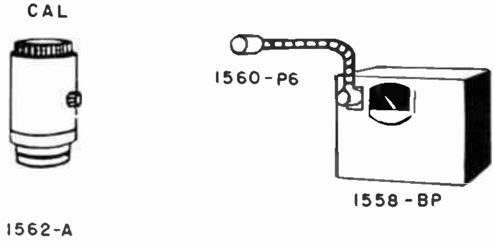

*Figure 5-13. Assembly for both "A" weighted and octave-band measurements.*

5.3.2 LOCAL NOISE ORDINANCES. Some cities and towns regulate the maximum noise permissible at the lot boundaries of a plant. These regulations are now mainly based on A-weighted sound levels, and the readings of a sound-level meter are adequate for monitoring. Since the operations in a factory can vary considerably during the day and night cycle, some plants may require monitoring with a graphic level recorder on the output of the sound-level meter.

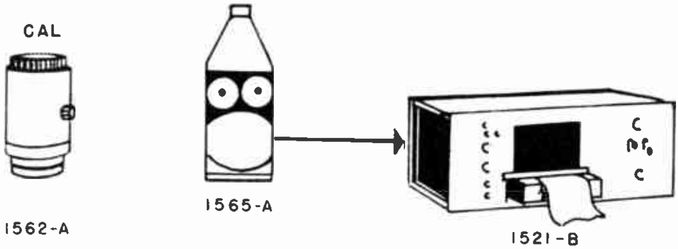

*Figure 5-14. Assembly for monitoring neighborhood noise levels.*

5.3.3 NEIGHBORHOOD NOISE. The extensive use of air-conditioning units, particularly those with outdoor heat exchangers, has led to regulations regarding noise in residential neighborhoods. These air conditioners can be particularly bothersome during night operation when some neighbors may wish to have their bedroom windows open. Here, too, the usual reference measurement is the A-weighted sound level and a Type 1551-C or Type 1565-A Sound Level Meter is the appropriate instrument to use.

5.3.4 NOISE RATINGS. A number of noise ratings have been discussed in Chapter 3. The simplest is the A-weighted sound level; the others, such as, calculated loudness level, perceived noise level, and speech interference level, require analysis in octave bands and the 1558-BP is the appropriate instrument to use.

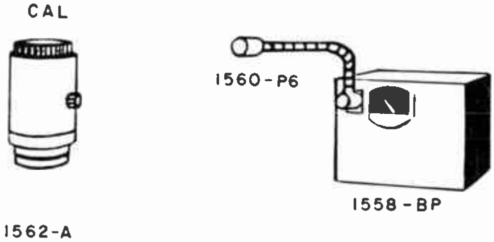

*Figure 5-15. Simple, portable noise rating assembly.*

5.3.5 MOTOR-VEHICLE NOISE. Some states and some cities and towns in the USA and many other countries have passed laws setting maximum limits on the noise a motor vehicle should make. Most of these laws are stated in terms of the A-weighted sound level and the Type 1565-A Sound Level Meter is the proper instrument to use.

## 5.4 ARCHITECTURAL ACOUSTICS.

A wide variety of measurements are made in the field of

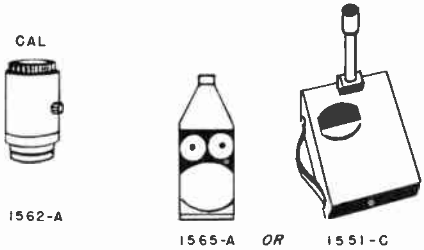

*Figure 5-16. Sound-level meters for "A" weighted traffic studies.*

architectural acoustics. Some of these are formalized by standards and others require individual judgment in deciding what needs to be measured and how it is to be measured. Many of the books listed in the references section of the Appendix, particularly those dealing with noise control and acoustical materials, have useful information on the general problem, but the book by Davis*, although devoted principally to sound reinforcement problems, is particularly helpful in its discussions of instrumentation and details of measurements. Because of the availability of Davis' book, only a brief summary of some of these measurements will be included here.

5.4.1 SOUND ABSORPTION. A method of test for the sound absorption of acoustical material in reverberation rooms is described in the American Society for Testing and Materials C423-65T. This standard specifies the requirements for the reverberant room, the test signal, and test frequencies of 125, 250, 500, 1000, 2000, and 4000 Hz, the mounting of the test specimen, and the measurement procedure. One possible arrangement of instruments is a noise generator supplying an octave-band analyzer followed by a power amplifier, which drives some loudspeakers that can be switched on and off. A microphone is connected by means of a cable to a one-third-octave analyzer which drives a graphic level recorder.

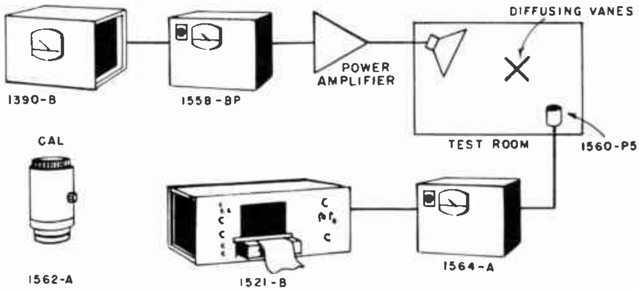

*Figure 5-17. A system for sound absorption measurements.*

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*D. Davis, "Acoustical Tests and Measurements," Indianapolis, H. W. Sams, 1965.

The basic procedure is to measure the decay rate of sound, which is a band of noise, in the room with and without the acoustical material in the room. These two measurements permit one to calculate the sound absorption of the specimen.

5.4.2 SOUND TRANSMISSION LOSS. The American Society for Testing and Materials E90-66T gives the recommended practice for the Laboratory Measurement of Airborne Sound Transmission Loss of Building Floors and Walls. Here two reverberant rooms with a common wall, the wall under test, are required. A diffuse noise field is set up and measured in one room and is also measured in the other. From these two measurements and a measurement of the sound absorption in the second room (see paragraph 5.4.1) the transmission loss can be calculated.

One possible arrangement of instruments is a noise generator supplying a third-octave filter followed by a power amplifier, which drives some loudspeakers in the first room. A microphone in each room is connected by means of cables to a third-octave analyzer so that the level in each room can be monitored. A sound-level calibrator is essential in order to compare the sensitivities of the two microphone systems.

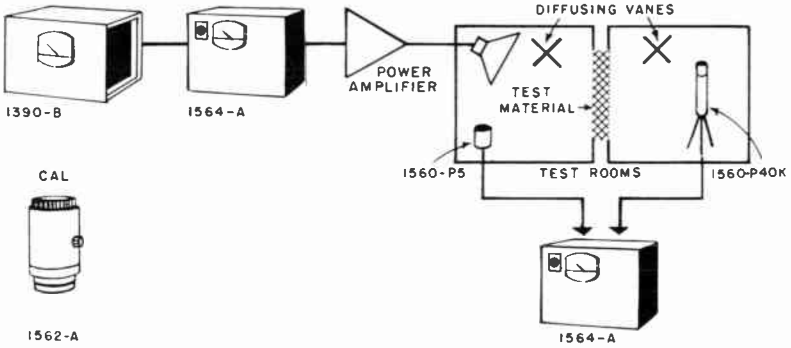

*Figure 5-18. A system for sound transmission measurements.*

5.4.3 REVERBERATION TIME OR DECAY RATE. The rate at which sound decays in an auditorium has been found to be a useful quantity in rating an auditorium. If sound decays too rapidly, the room sounds "dead," and an organ, for example, played in a dead hall loses much of its appeal. A very live room, that is, one in which the sound decays slowly, may be useless as a lecture hall, because the individual syllables of speech are obscured by the persisting sounds of previous syllables.

The more common name for the characteristic that rates sound decay is "reverberation time," which is the time taken for the sound to decay 60 dB after the source has stopped.

This time is usually measured by exciting the room with a third-octave band of noise, which requires a noise generator, a third-octave filter, and a power amplifier driving one or more loudspeakers (see Figure 5-19). In an auditorium or theater, the power amplifier and loudspeaker system for sound reinforcement can usually be used as part of this measurement system.

This sound is then picked up by a microphone feeding another third-octave filter, which drives a graphic level recorder with a 40-dB potentiometer. The pickup system is adjusted so that the level on the recorder is near full scale. The sound is then suddenly turned off, and the graphic level recorder plots the decay. A straight line is drawn on the chart to fit the average slope of the curve. From this slope one can calculate the rate of decay and the reverberation time. A number of refinements are often introduced into this process, and these are discussed in the book by Davis and in articles in the Journal of the Acoustical Society of America. These measurements are made over a wide frequency range and in a number of representative places in the hall.

A two-channel tape recorder can be of great help in this measurement.* (See Figure 5-20.) Before the measurement, a series of bursts of these bands of noise are recorded on channel 2 of the Type 1525-A Data Recorder. This channel is then used to supply the signal to the power amplifier and loudspeaker. The resultant sound in the hall is then recorded on channel 1. Afterwards the signal on channel 1 is played back to a graphic level recorder through a third-octave filter to obtain the graph of the decaying sound.

When it is necessary to simplify the testing procedure at the hall (if, for example, an audience is present), an alternative

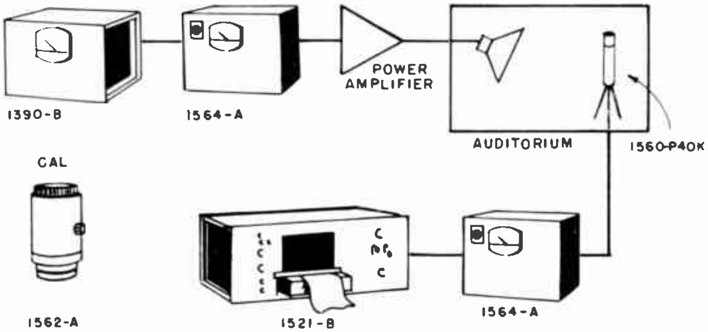

*Figure 5-19. A system for decay-rate and reverberation time measurements.*

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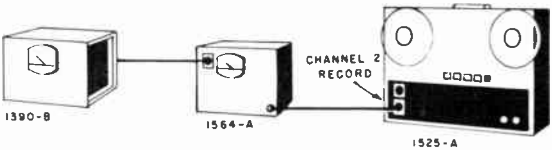
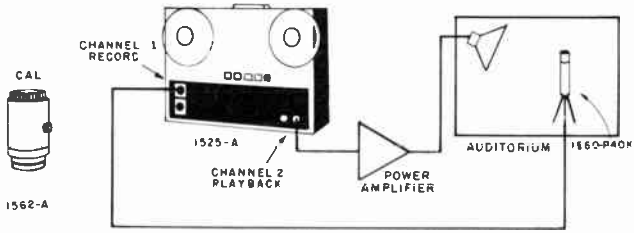
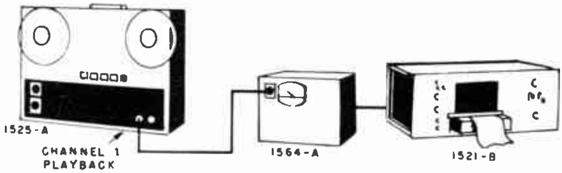
*T. J. Schultz, "Problems in the Measurement of Reverberation Time," Journal of the Audio Engineering Society, Vol. 11, No. 4, October, 1963, pp. 307-317.



*a. Record test signal.*



*b. Playback signal and record hall response.*



*c. Playback hall response for analysis.*

*Figure 5-20*

procedure may give useful information with relatively short testing time. The hall is excited by means of a broad-band of "pink" noise (noise whose spectrum level decreases with increasing frequency to yield constant energy per octave of bandwidth.) The sound in the hall is recorded on the tape recorder with the noise on and during the decay period when the noise is suddenly switched off. Later, in the laboratory, this recorded signal is played back through a third-octave analyzer and a graphic level recorder. This recording is repeated for the full range of the desired settings of frequency of the analyzer. In this way a complete picture of the decay rate as a function of frequency can be obtained with only one "exposure" at the hall. Some of the detail, particularly at lower levels, may be obscured, however, by the background noise in the hall.

5.4.4 RESPONSE TESTING. The equalization of a sound system to obtain good uniformity of response with frequency can improve the performance of the system. The suggested procedure for measuring the response is as follows: The sound system is driven by broad-band pink noise. The sound produced is then analyzed by a recording third-octave analyzer.

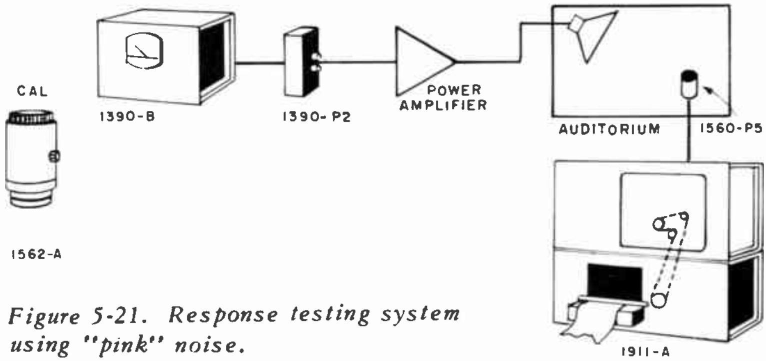


*Figure 5-21. Response testing system using "pink" noise.*

(Figure 5-21.) This analysis is carried out for a number of representative places in the area to be covered by the sound system.

The adjustments in the frequency response are then made on the basis of a study of the response curves. The fine details of the curves are ignored, and the broader trends are used to decide how best to adjust the frequency response controls. Sometimes the measurements may show up defects or errors in the system.

5.4.5 TONE-BURST TESTING FOR ECHOES. Because of the serious effects of echoes on speech intelligiblity, testing for the amplitude and time arrival of direct and reflected sounds is an important tool in evaluating a hall*. One suggested procedure is to excite the hall with a tone burst of about 16

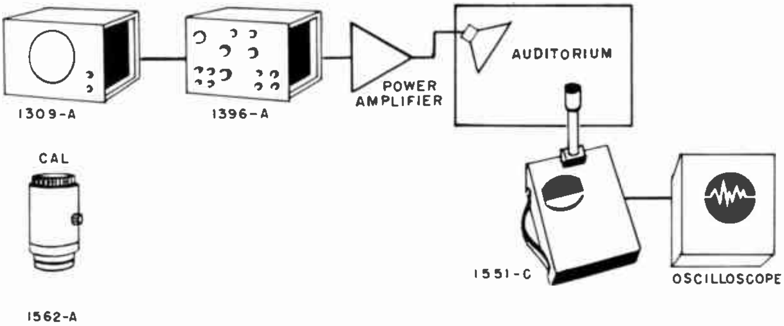


*Figure 5-22. Tone-burst testing system for echoes.*

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*T. J. Schultz & B. G. Watters, "Propagation of Sound Across Audience Seating," Journal of the Acoustical Society of America, Vol. 36, No. 5, May 1964, pp. 885-896.

milliseconds duration. The resulting sound is then picked up and displayed on an oscilloscope as a function of time. The pattern on the oscilloscope can often be interpreted in terms of the principal reflections that occur and it may point the way to significant improvements in the hall. Ideally, this study should be made over the audio-frequency range.

5.4.6 SITE SELECTION. Noise and vibration are obvious factors to consider in the selection of a building site. Buildings for certain purposes (for example, concert halls and sound studios) may be much more expensive to design and build if they must be placed in a noisy environment and at the same time have low background noise. A careful study of the sound and vibration conditions at a site is essential for a proper estimate of a suitable design for such buildings. Some useful information can be obtained with a sound-level meter and with a vibration meter. But an octave-band analysis of the sound and vibration is much more useful, because the cost of isolating against low frequency noise is much greater than that of isolating high-frequency noise, and the knowledge of the level of low-frequency sounds and vibrations may be an essential element in cost studies.

A related problem is that of locating a studio within an existing building. Here a careful survey of possible locations may lead to a significant saving in construction costs.

chapter 6

# TECHNIQUES, PRECAUTIONS, AND CALIBRATIONS FOR NOISE AND VIBRATION MEASUREMENT SYSTEMS

## 6.1 SOUND MEASUREMENTS.

Most of the applications discussed in the previous chapter require a measurement of either sound-pressure level as a function of frequency or of sound level. These quantities are measured at a single point or at a number of points that are determined by the conditions of the application. The method of measuring these quantities is discussed in this chapter. The procedure for determining from the measured data the calculated loudness level, the perceived noise level, the speech-interference level, and the possibility of hearing damage is given in Chapter 3.

The basic procedure for measuring the sound level or the sound-pressure level at a given point is to locate the sound-level-meter microphone at that point and to note the reading of the sound-level meter. Some preliminary exploration of the sound field is usually necessary to determine that the point selected is the correct one, and this exploration is discussed later in this chapter. Other practical details regarding this measurement are also given in this chapter, but the actual manipulation of the individual instrument controls is discussed in the instruction books that are furnished with the instruments.

We shall discuss the choice of microphone and auxiliary apparatus, the effects of extraneous influences, the recording of adequate data, the calibration of the instruments, and the interpretation of the data. Much of this discussion is necessary because no ideal instrument or combination of instruments and accessories is available that would be suitable for all conditions.

6.1.1 CHOICE AND USE OF MICROPHONE. The microphones supplied with modern sound-level meters are suitable for most sound measurements. For very high sound levels (above 150 dB for the ceramic microphone), for high temperature applications, and for accurate sound measurements near and above the limits of hearing (say 12,000 Hz), special microphones need to be used. The performance of these modern microphones as well as their limitations is reviewed here. In addition, some of the problems encountered with the use of microphones supplied on earlier instruments are discussed briefly.

6.1.1.1 Low Sound Levels. A microphone used to measure low sound levels must have low "self-noise," and it must produce an output voltage sufficient to override the circuit noise of the amplifier in the sound-level meter. The type of microphone supplied with the sound-level meter is very good in this respect, and sound levels down to about 24 dB can be measured with it. The Type 1551-P1L Condenser Microphone System is not suitable because even under the best conditions its self noise is equivalent to about 40-dB sound-pressure level.

When a sound is analyzed, the minimum measurable sound-pressure band level is even lower than 24 dB with the Type 1560-P5 microphone, because the equivalent internal noise in a selected band is less than the over-all noise.

When microphone cables are used, a preamplifier must be placed at the microphone if one must preserve the ability to measure low sound-pressure levels. (See Section 4.6 and 6.1.1.8.)

6.1.1.2 High Sound Levels. The sound-level meter microphone and the Type 1551-P1L Condenser Microphone System are well suited for the measurement of sound pressure levels up to 150 dB. The Type 1551-P1H System can be used up to 170 dB. Certain blast microphones (such as those made by Atlantic Research Corporation, Alexandria, Va.; Chesapeake Instrument Corporation, Shadyside, Md., and Massa Laboratories, Hingham, Mass.) can be used directly with the sound-level meter for sound-pressure levels up to about 190 dB.

6.1.1.3 Low-Frequency Noise. The ceramic and condenser-type microphones are well suited for measuring low-frequency noise. In fact, with either of these microphones, measurements may be made down to only a few Hz if special amplifiers, such as that provided by the Type 1553-A Vibration Meter, are used. The Type 1551-C Sound-Level Meter is designed to cover the frequency range down to 20 Hz and even at 10 Hz the response is down only 10 dB. This 20 Hz limit is adequate for almost all types of low-frequency noise.

6.1.1.4 High-Frequency Noise. The primary requirements on the microphone for accurate measurement of high-frequency sounds are small size and uniform frequency response at high frequencies. For measuring over-all sound levels the high-frequency characteristic is not so important because most machinery noises do not include strong high-frequency components. Even for those sounds that do include significant energy at the high-frequency end, the decrease in response required at high frequencies, for the standard weightings means that the important noise energy is generally well within the range of the regular microphone furnished on the sound-level meter.

If these noises are to be analyzed and accurate measurement of band-pressure levels at high frequencies is important, the microphone performance must be good or accurately known (see Section 6.1.3.5). If the microphone calibration is available, corrections can be applied for the frequency response as described in paragraph 6.1.3.5.5.

The typical frequency responses of the ceramic microphone made by General Radio and the Type 1551-P1 Condenser Microphone Systems are shown in Figure 6-1.

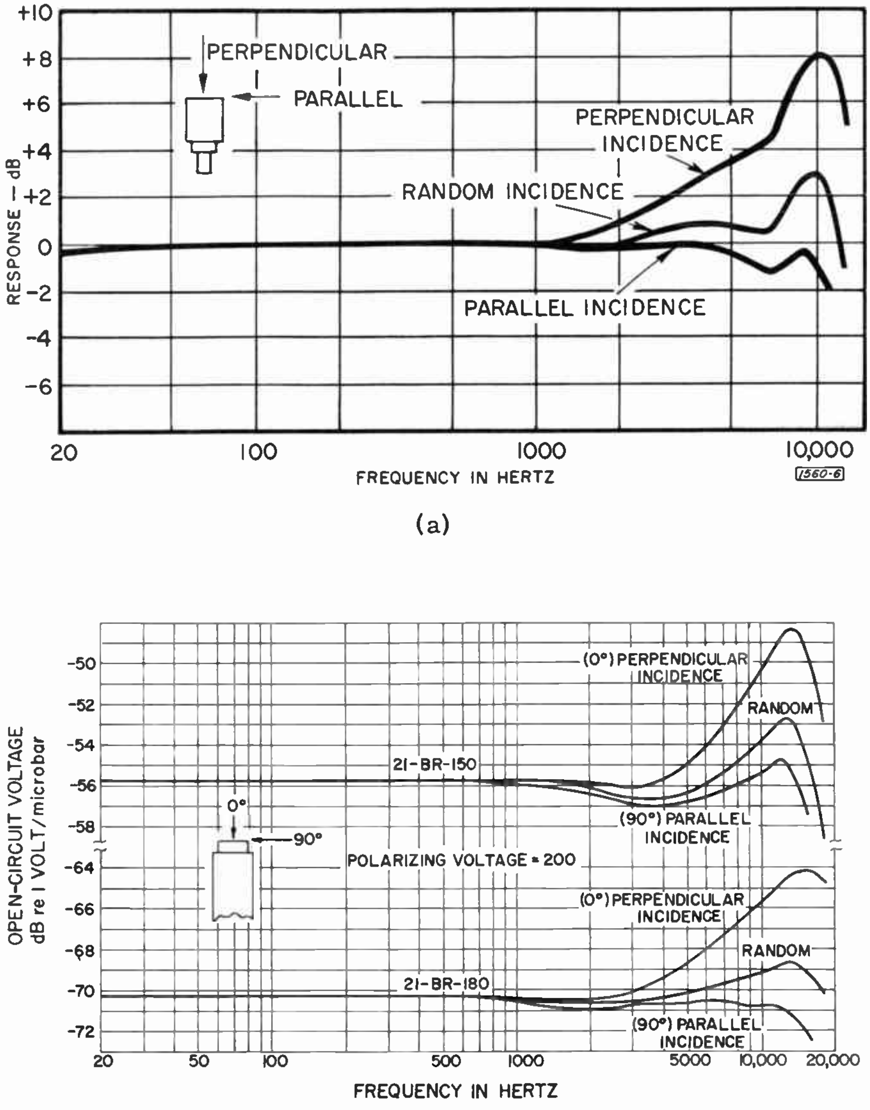
The condenser microphone system can be used for measurements up to 18,000 Hz and measurements rarely need to be made on air-borne sounds at frequencies higher than this. For some research investigations much higher frequencies have been measured by use of microphones specially designed for the purpose.

6.1.1.5 Humidity. Long exposure of any microphone to very high or very low humidity should be avoided. The ceramic microphones, however, are not damaged by extremes of humidity. The chemical Rochelle salt, which is used in microphones furnished with the earlier Types 1551-A, 1551-B, and 759-B Sound-Level Meters and in the Type 1555-A Sound-Survey Meter, however, gradually dissolves if the humidity is too high (above about 84 percent). The Rochelle-salt crystal unit in the microphone, however, is protected by a coating so that it is relatively unaffected by high humidity. Nevertheless, it is wise to avoid unnecessary exposure. A Rochelle-salt microphone should not be stored for long periods in a very dry atmosphere, since it can dry out.

Note: Rochelle-salt-crystal microphones are no longer supplied by General Radio Company.

The condenser microphone on the Type 1551-P1 Condenser Microphone System is not damaged by exposure to high humidity, but its operation may be seriously affected unless proper precautions are taken. For proper operation it is essential that very little electrical leakage occur across the microphone. The exposed insulating surface in the microphone has been specially treated to maintain this low leakage even under conditions of high humidity. In spite of this precaution, the leakage may become excessive under some conditions. Then it may be advisable to keep the microphone at a temperature higher than the ambient temperature to reduce the leakage. In climates where the humidity is normally high, it is recommended that the microphone itself be stored in a small jar containing silica gel.

6.1.1.6 High or Varying Temperature. Although most noise measurements are made indoors at average room temperatures, some measurement conditions expose the microphone to much higher or lower temperatures. When these conditions are encountered, it is essential to know the temperature



(a)

(b)

*Figure 6-1. Typical response curves for two different microphones when used with the Type 1551-C Sound-Level Meter. (a) Ceramic microphone assembly supplied with the Type 1551-C; (b) the Type 1551-P1L Condenser Microphone. Random response assumes that the microphone is placed in a diffuse sound field.*

limitations of the equipment.

The microphone supplied with the Type 1551-C Sound-Level Meter and the Type 1560-P6 Microphone Assembly will withstand temperatures of -30 to +85° C without damage. In contrast, the maximum safe operating temperature for Rochelle-salt crystal microphones formerly furnished with some sound-level meters is about 45° C (113° F). At 55.6°C (132° F) the Rochelle-salt crystal is permanently changed. It is, therefore, not safe to put a Rochelle-salt microphone in the trunk or back of a car that is to be left standing in the sun.

The maximum safe operating temperature for the microphone probe of the Type 1551-P1 Condenser Microphone System is about 100° C (212°F).

Fortunately, it is usually possible to keep the sound-level meter itself at more reasonable temperatures. Its behavior at extreme temperatures is limited by the batteries. Temperatures of even 130° F will result in much-shortened battery life. Operation below -10° F is not ordinarily possible without special low-temperature batteries.

Microphones are usually calibrated at normal room temperatures. If a microphone is operated at other temperatures, its sensitivity will be somewhat different, and a correction should be applied. The correction for sensitivity for the ceramic microphone is only about -0.01 dB per degree Celsius, so that for most purposes the correction can be neglected.

The condenser microphone used on the Type 1551-P1 Condenser Microphone System has a temperature coefficient of sensitivity of about -0.04 dB/° C.

6.1.1.7 Hum Pickup. Dynamic microphones are sometimes used for measurement purposes because they are readily used with long cables. The development of modern preamplifiers, such as the Type 1560-P40 Preamplifier, makes the use of dynamic microphones unnecessary. But if they are used, care must be taken to avoid hum pickup, which is the induction of undesired electrical signals from the external magnetic field of equipment such as transformers, motors, and generators. Ceramic and condenser microphones are relatively free from this undesirable effect.

6.1.1.8 Long Cables. For the most accurate sound measurements, only the microphone should be put into the sound field, and the measuring instruments and the observers should not be near the point where the sound-pressure is to be measured. For this reason and also for the situations when it is impossible or impractical for the observer to be near the microphone, an extension cable is ordinarily used to connect the microphone to the instruments. If the microphone is attached directly to a preamplifier, long cables can be used without any deleterious effects.

A correction for loss in sensitivity is necessary, however, when a ceramic microphone is used directly with an extension cable. This correction is readily determined by the use of a Type 1562-A Sound-Level Calibrator. (See paragraph 6.1.3.5.2.) The correction is about 7 dB when a 25-foot cable (650 pF) is used between the microphone and the instrument, so that 7 dB should be added to the indicated level to obtain the level at the microphone. For longer cables the correction is greater. For Rochelle-salt microphones the correction is a function of the temperature of the microphone; values are given in the instruction manuals for instruments using Rochelle-salt microphones.

The Type 1551-P1 Condenser Microphone System includes a 10-foot cable between the microphone base and the power supply. If more separation between the microphone and the sound-level meter is required, another cable, such as the Type 1560-P73 Extension Cable, should be used between the Type 1551-P1 Power Supply and the sound-level meter. The use of this cable will result in a slight reduction in sensitivity at high frequencies as explained in the instruction book for the condenser microphone system.

6.1.1.9 Wind Effects. The microphone should also be kept out of any appreciable wind, if possible. Wind on the microphone produces a noise, which is mainly of low frequency. This added noise may seriously upset the measurement, particularly when the microphone has a good low-frequency response. If it is not possible to avoid wind on the microphone, a wind screen should be used. This screen can be made of a single layer of silk cloth on a wire frame that encloses the microphone. The frame should be much larger than the microphone.

A fine-mesh silk cloth (80 mesh per inch), if made into a screen at least 6 inches in diameter, will not have a serious effect on the frequency response of the microphone, and it will attenuate wind noise by some 20 dB.*

6.1.1.10 Direction of Arrival of Sound at the Microphone. Some microphones are designed to be directional at all frequencies. That is, the response of the microphone depends on the direction of arrival of the sound wave. Most of the microphones used for sound measurements, however, are essentially omnidirectional at low frequencies (below about 1 kHz). At frequencies so high that the size of the microphone is comparable to the wavelength of the sound in air, even these microphones will show directional effects. This

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*J. C. Bleazey, "Experimental Determination of the Effectiveness of Microphone Wind Screens," Journal of the Audio Engineering Society, Vol. 9, November 1, January, 1961, pp. 48-54.

variation in response with direction should be considered in positioning the microphone for a measurement. The extent of these variations is shown by the frequency response characteristics of the different microphones (see Figure 6-1). The microphone is usually positioned so that the response to the incident sound is as uniform as possible.

When sound-pressure level is measured in a reverberant room at a point that is not close to a noise source, the sound arrives at the microphone from many different directions. Then the orientation of the microphone is not critical, and the response is assumed to be that labeled "RANDOM" incidence. Under these conditions, nevertheless, it is usually desirable to avoid having the microphone pointing at a nearby hard surface from which high-frequency sounds could be reflected to arrive perpendicular (0° incidence) to the plane of the diaphragm. (For all the microphones used in the General Radio Sound Measurement System this perpendicular incidence is along the axis of cylindrical symmetry of the microphone. This axis is used as the 0° reference line.) If this condition cannot be avoided, the possibility for errors from this effect can be reduced by some acoustic absorbing material placed on the reflecting surface.

When measurements are made in a reverberant room at varying distances from a noise source, the microphone should generally be oriented so that a line joining the microphone and the source is at an angle of about 70° from the axis of the microphone. When the microphone is near the source most of the sound comes directly from the source, and a 70° incidence response applies. On the other hand, near the boundaries of the room the incidence is more nearly random, and the random-incidence response applies. These two response curves are nearly the same so that there is little change in the effective response characteristic as the microphone is moved about the room. This desirable result would not be obtained if the microphone were pointed at the noise source.

6.1.1.11 Position of Microphone. In previous sections of this chapter some comments have been made on various aspects of the problem of placing the microphone in the most satisfactory position for making the noise measurement. In general, the location is determined by the type of measurement to be made. For example, the noise of a machine is usually measured with the microphone placed near the machine according to the rules of a test code, or if its characteristics as a noise source are desired, a comparatively large number of measurements are made according to the methods and the placement given in Section 2.8.5.

It is important to explore the noise field before deciding on a definite location (see Section 2.8.4) for the microphone.

Many measurement locations may be necessary for specifying the noise field, particularly if the apparatus produces a noise that is highly directional. Further discussion of directionality is given in Section 2.8.2.

If the noise level is measured for calculation of the speech-interference level or loudness level or for determination of deafness risk, it is important to explore the noise field to make sure that the measurement made is representative. The possible effects of obstacles in upsetting the distribution of sound, particularly at high frequencies, should be kept in mind during this exploration.

At first thought, it seems logical, when measurements regarding noise exposure are made, to mount the microphone at the operator's ear. Actually, because of the variables introduced by the effect of the operator's head being close to the microphone, this technique is not used, except in certain scientific tests with special probe microphones. All ratings of speech-interference, loudness, and deafness risk are based on a measurement with no person in the immediate vicinity of the microphone. The microphone should, however, be about where the operator's ear would normally be.

## 6.1.2 EFFECTS OF ROOM AND NEARBY OBJECTS.

### 6.1.2.1 Effect of Observer and Meter Case On Measured Data.

As mentioned in the previous section, the observer can affect the measured data if he is close to the microphone. When measurements are made in a live room and not close to a source, the effect is usually not important. But if measurements are made near a source, it is advisable for the observer to stand well to the side of the direct path between the source and the microphone. For precise measurements in a very dead room, such as an anechoic chamber, the instruments and the observer should be in another room with only the source, the microphone, the extension cable, and a minimum of supporting structure in the dead room.

For many measurements, however, it is most convenient to be able to carry the sound-level meter around. When held in the hand, the sound-level meter should be held in front of the observer with the sound coming in from the side. The magnitude of the error that can be caused by the way the instrument is held can be evaluated from the data shown in Figure 6-2. These data show the difference between the readings of the meter with and without the observer present, as a function of frequency. Two locations are shown: (1) the sound-level meter is between the observer and the noise source, (2) the noise source is located to one side of the observer, and the sound-level meter is held in front of the observer. It is apparent that if the instrument is held properly, little error in reading of the over-all level will occur for most noises.

(For additional information on this subject, refer to R. W. Young, "Can Accurate Measurements be Made With a Sound-Level Meter Held in Hand?," Sound, Vol 1, No. 1, pp 17-24,

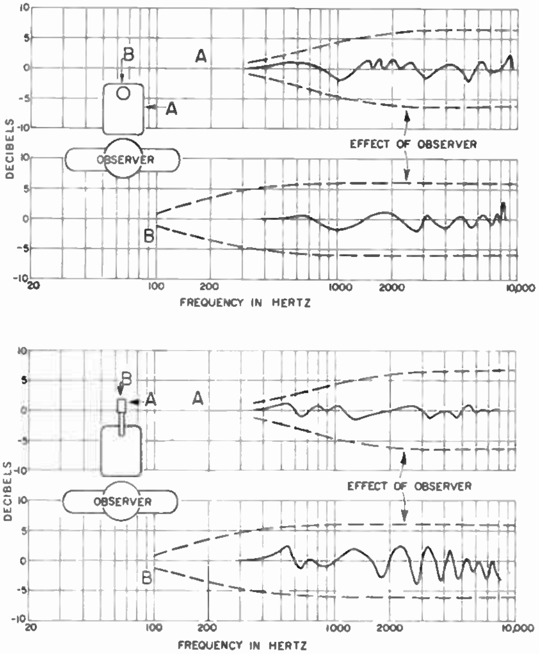

*Figure 6-2. Effect on frequency response as a result of using the microphone directly on the swivel post of the instrument (in two positions) without an observer present, and the extent of the effect with an observer present. A single-frequency, plane, acoustic wave was used in an anechoic chamber, and the decibel values are the differences between the response under the conditions noted and the response of the microphone alone.*

January-February 1962.)

The meter case itself may also disturb the sound field at the microphone as shown by the other characteristic curves in Figure 6-2. There is practically no effect below 1000 Hz, and, again, on most noises, little error in measuring overall level will result if the microphone is left on the instrument. When an analyzer is used with the sound-level meter, however, it is advisable to separate the microphone from the instruments and to use an extension cable. This refinement is not necessary, however, if the only data that are of interest are below 1000 Hz.

6.1.2.2 Room Design and Effect of Nearby Objects. When a noisy device is to be tested for its acoustic output, the space in which it is tested can have a significant effect on the results. Unless a reverberation room (Section 2.8.4.1) is used, the measurement room used for evaluating a noise source should be sufficiently well treated so that no appreciable standing wave exists. Ideally the room should be anechoic (Section 2.8.3). If any small standing-wave pattern remains, the average of the maximum and minimum decibel readings should be taken. If the differences are more than 6 dB, the level should be taken as 3 dB below the maximum readings that occur frequently. This standing-wave pattern, however, should not be confused with the normal decrease in level with distance from the source or with the directivity pattern of the source.

Objects in the room reflect the sound waves just as do the walls of the room. Consequently, all unnecessary objects should be removed from the measurement room. In general, no objects, including the observer, should be close to the microphone. If it is impractical to follow this principle, the objects should usually be treated with absorbing material.

One troublesome but not frequent effect of nearby objects results from sympathetic vibrations. A large, thin metal panel if undamped can readily be set into vibration at certain frequencies. If one of these frequency components is present in the noise, this panel can be set into motion either by air-borne sound or by vibration transmitted through the structure. This panel vibration can seriously upset the noise field in its vicinity. One way of checking that this effect is not present to any important degree is to measure the sound field as a function of the radial distance from the source. The sound should decrease, when not very close to the source, about 6 dB as the distance is doubled. This procedure also checks for reflections in general.

When the acoustical environment is being measured, no change should be made in the usual location of equipment, but the sound field should be carefully explored to make sure that the selected location for the microphone is not in an acoustic shadow cast by a nearby object or is not in a minimum of the directivity pattern of the noise source.

6.1.2.3 Effect of Background Noise. Ideally, when a noise source is measured, the measurement should determine only the direct air-borne sound from the source, without any appreciable contribution from noise produced by other sources. In order to ensure isolation from other sources, the measurement room may need to be isolated from external noise and vibration. As a test to determine that this requirement has been met, the USA Standard-Method for the Physical Measurement of Sound, S1.2, specifies the following:

> "If the increase in the sound pressure level in any given band, with the sound source operating, compared to the ambient sound pressure level alone is 10 dB or more, the sound pressure level due to both the sound source and ambient sound is essentially the sound pressure level due to the sound source. This is the preferred criterion."

If the background noise level and the apparatus noise level are steady, a correction may be applied to the measured data according to the graph of Figure 6-3. The procedure is as follows: After the test position has been selected according to the test code and after exploration of the field as outlined in paragraph 6.1.2.2, the background noise level is measured in the test position. Then the sound level is measured with

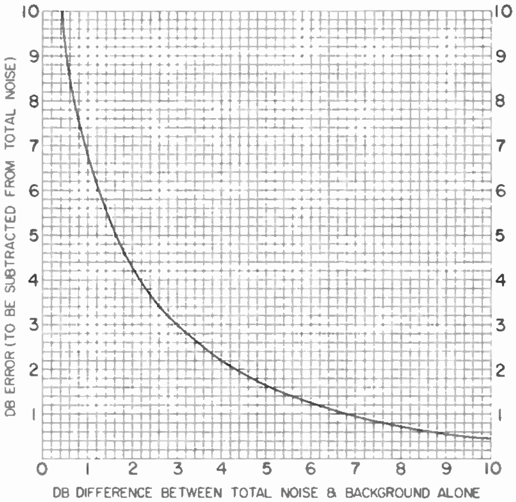

*Figure 6-3. Background noise correction for sound-level measurements.*

the apparatus operating. The difference between the sound level with the apparatus operating and the background level determines the correction to be used. If this difference is less than 3 dB, the apparatus noise is less than the background noise; and the level obtained by use of the correction should be regarded as only indicative of the true level and not as an accurate measurement. If the difference is greater than 10 dB, the background noise has virtually no effect; and the reading with the apparatus operating is the desired level. An example of a situation intermediate between these two is as follows: The background noise level is 77.5 dB, and the total noise with the machine under test operating is 83.5 dB. The correction, from the graph of Figure 6-2, for a 6.0-dB difference, is 1.2 dB, so that the corrected level is 82.3 dB.

When apparatus noise is analyzed, the background noise level in each band should also be analyzed to determine if correction for the level in each band is necessary and possible. The spectrum of the background noise is usually different from that of the noise to be measured, and the corrections in each band will be different.

If this difference between background level and total noise level is small, an attempt should be made to lower the background level. Usually the first step is to work on the source or sources of this background noise to reduce the noise directly. The second step is to work on the transmission path between the source and the point of measurement. This step may mean simply closing doors and windows if the source is external to the room or it may mean erecting barriers, applying acoustical treatment to the room, and opening doors and windows if the source is in the room. The third step is to improve the difference by the method of measurement. It may be possible to select a point closer to the apparatus, or an exploration of the background noise field may show that the measuring position can be shifted to a minimum of this noise. The latter possibility is more likely when an analysis is being made and the background level in a particular band is unusually high. It may also be possible to point the microphone at the apparatus to obtain an improvement at high frequencies (see Figure 6-1); it may be necessary to use a directional microphone; or it may be desirable to use a vibration pickup (see Section 5.2.2).

### 6.1.3 INSTRUMENT PRECAUTIONS.

6.1.3.1 Low Noise Levels - Effect of Circuit Noise. When low noise levels are to be measured, the inherent circuit noise may contribute to the measured level. This effect is usually noticeable in the range below 40 dB when the Type 1551-P1 Microphone System is used or a ceramic microphone is used on the end of a very long cable. If the microphone is directly on the sound-level meter, the level at which this effect may be important is below 30 dB if the C weighting is used or even lower if the A or B weighting is used. To measure the circuit noise the microphone may be replaced by a well-shielded capacitor of 6 picofarads for the Type 1551-P1 or of 400 picofarads for the ceramic microphone on the Type 1551-C. A correction can then be made for this noise, if necessary, by the same procedure as outlined for background noise in paragraph 6.1.2.3. If the circuit noise is comparable to the noise being measured, some improvement in the measurement can usually be obtained by use of an octave-band analyzer. The circuit noise in each band should be checked also to see if correction is necessary.

Whenever low noise levels must be measured and extension cables are used, the Type 1560-P40 Preamplifier should be used at the microphone.

6.1.3.2 Hum Pickup. When noise is measured near electrical equipment, a check should be made that there is no appreciable pickup of electromagnetic field in the sound-measuring system. The procedure depends on the directional character of the field. The orientation of the instruments should be changed to see if there is any significant change in level. If an analyzer is used, it should be tuned to the power-supply frequency, usually 60 Hz, which would be the 63 Hz band for the octave-band analyzer, when this test is made. If no analyzer is included, the C-weighting should be used in this test to make the effect of hum most noticeable, and a good quality pair of earphones with tight-fitting ear cushions should be used to listen to the output of the sound-level meter.

If a dynamic microphone is used, tests should be made with different orientations of the microphone, with the microphone disconnected, and with the sound-level meter disconnected from the analyzer. If there is pickup in the microphone, proper orientation may be adequate to make a measurement possible, or electromagnetic shielding may be necessary.

If the hum pickup is in the instruments, they can usually be moved away from the source of the electromagnetic field, or, alternatively, a proper orientation is usually sufficient to reduce the pickup to a negligible value.

When ac-operated instruments are used as part of the measuring setup, a check should be made for 120-Hz as well as 60-Hz hum. This hum may be in the instruments, or it may appear as a result of the interconnection of different instruments. These two possibilities may be distinguished by a check of the instruments individually. If each is separately essentially free from hum, different methods of grounding, balancing, or shielding should be tried. Sometimes reversal of the power-plug connection to the line helps to reduce the hum.

6.1.3.3 High Sound Levels - Microphonics. All vacuum tubes and some transistors are affected by mechanical vibration. Those used in the sound-measuring equipment have been selected to be less sensitive to vibration than the usual types. But at sufficiently high sound levels, even these can be vibrated to such an extent that they contribute an undesired signal to the output. Trouble from this effect, which is called microphonics, is not usually experienced until the sound levels are well above 100 dB, unless the instruments are placed on supports that carry vibrations directly to the instruments.

The usual test for microphonics is to disconnect the microphone and observe whether or not the residual signal is appreciably lower than the signal with the microphone connected. For the octave-band analyzer, the input cord can be disconnected to see if the indicated level comes from the input signal or if it is generated within the instrument. The instruments can also be lifted up from the support on which they have been placed to see whether or not the vibrations are transmitted through the supports or if it is the air-borne sound that is causing the vibration.

Possible remedies for microphonic troubles are as follows: 1. Place the instruments on soft rubber pads. 2. Remove the instruments from the strong field to another room and interconnect with long cables. 3. Put in deadened sound barriers between the instruments and the sound source.

Mechanical vibration also affects the microphone itself, in that the output of the microphone is dependent on the air-borne and solid-borne vibrations that are impressed upon it. The effects of the solid-borne vibrations are not usually important in the standard, sensitive microphones because of the type of construction used; but these vibrations are usually of great importance for the low-sensitivity microphones used in the measurement of high sound levels. A mechanically soft mounting should generally be used for such a microphone in order to avoid trouble from these vibrations. Often merely suspending the microphone by means of its connecting cable is adequate.

*6.1.3.4 Interpretation of the Behavior of the Meter Pointer. Two ballistic characteristics are provided for the meter on the sound-level meter: The "FAST" position is normally used. It will be noticed, however, that most sounds do not give a constant level reading. The reading fluctuates often over a range of a few decibels and sometimes over a range of many decibels, particularly in analysis at low frequencies. The maximum and minimum readings should usually be noted. These levels can be entered on the data sheet as, say, 85-91 dB or 88 ± 3 dB.

When an average sound-pressure level is desired and the fluctuations are less than 6 dB, a simple average of the maximum and minimum levels is usually taken. If the range of fluctuation is greater than 6 dB, the average sound-pressure level is usually taken to be three decibels below the maximum level. In selecting this maximum level, it is also customary to ignore any unusually high levels that occur infrequently.

The "SLOW" meter speed should be used to obtain an average reading when the fluctuations on the "FAST" position are more than 3 or 4 dB. On steady sounds the reading of the meter will be the same for either the "SLOW" or "FAST" position, while on fluctuating sounds the "SLOW" position provides a long-time average reading.

A more detailed discussion of this problem is given in succeeding paragraphs.

*6.1.3.4.1 Tones and Beats. The indicated sound level of a constant-amplitude pure tone is steady, and so is that of a mixture of tones, unless at least two components are close together in frequency. Examples of sounds that have a constant indicated sound level are transformer hum and noise from some rotating electrical machinery. When the combined noise of several machines is measured, the indicated level is also constant, unless the speed of the machines is such that some of the major noise components are only a few cycles apart in frequency. In this situation an audible beat, a periodic rise and fall in amplitude, occurs, and the indicated level also rises and falls.

*6.1.3.4.2 Varying-Speed Sources. Machinery that operates at a varying speed usually produces a noise that fluctuates in level. If the speed varies periodically, the level will also vary periodically. This variation results because the noise produced by the machine varies with speed, because the response of the room in which the measurement is made varies with frequency, and, if an analyzer is used, because the response of the measurement system varies with frequency.

If the machine speed varies erratically, the noise level will also vary erratically, and the behavior may be similar to that of random noise.

*6.1.3.4.3 Random Noise. The indicated sound level of a random noise, such as that produced by jets, blowers, combustion chambers, ventilating systems, etc., is not steady. In fact, all sounds contain some random noise energy, and most have enough so that the indicated level fluctuates noticeably. The extent of this fluctuation is a clue to the nature of the sound.

The fluctuations in level are ordinarily not a result of erratic behavior of the measuring equipment, but rather reflect the irregularities in the process of noise production. This process can often be considered as a combination of many sources that produce sound at random time intervals. The measurement of such noises can be treated on a simplified statistical basis that is satisfactory for almost all sounds.

*6.1.3.4.4 Average Energy Level of a Random Noise. When a random noise is measured, the first important result that is desired is the long-time average energy level. This concept leads to taking the average of the fluctuating pointer reading. If the fluctuations are less than about 2 dB, this average can be easily and confidently estimated to a fraction of a decibel. If the fluctuations cover a range of 10 or more decibels, the average is much less certain.

The extent of the meter fluctuation depends on the meter characteristic. The slower the movement, the smaller are the fluctuations. Thus, if the fluctuations exceed 3 or 4 dB for the "FAST" meter position, the "SLOW" meter position should be used.

*6.1.3.4.5 Effect of Bandwidth. If an analyzer is used, the extent of the fluctuations also depends on the bandwidth. The narrower the band, the greater are the fluctuations, and the longer is the meter averaging time required for a satisfactory estimate of the level.

A relatively simple principle is involved here. The narrow band is used to get fineness of detail. The finer the detail that is desired, the more time is needed to obtain the result to a certain degree of confidence. This idea can be expressed in quantitative terms by the use of statistical theory.[1,2]

*6.1.3.4.6 Example of Random-Noise Measurement. To illustrate by an actual numerical example the type of behavior that occurs, some measurements were made of an arbitrary level of a random-noise generator in the octave band from 150 to 300 Hz. With the FAST meter speed, the average of the fluctuating levels indicated on the meter was estimated to be about +5 dB, where in a period of 30 seconds the level fluctuated from a minimum of +3.3 dB to a maximum of +6.5 dB, a range of 3.2 dB. In the SLOW position the estimated level was +4.7 dB, and the level fluctuated over a three-minute period from a minimum of +3.8, to a maximum of +5.7, a range of 1.9 dB. Some sample readings were as follows: FAST position: 4.8, 4.1, 5.3, 3.7, 5.8, 4.9, 5.3, 5.2, 6.2, 4.6; SLOW position: 4.4, 5.1, 3.9, 4.9, 4.2, 5.0, 4.7, 4.1, 4.3, 4.9. (These sample readings were taken with the help of a stroboscope, to avoid observer bias in selecting readings and to make it possible to take definite readings on the rapidly moving pointer in the FAST position.) One hundred samples were taken for each position. The average value for SLOW was +4.72, with the lowest reading +3.8 and the highest +5.8. The average for FAST was +4.74, with a low reading of +3.1 and a high reading of +6.2.

Taking such a set of readings is not the usual way to obtain the indicated level; rather, one estimates a value by observing the pointer fluctuations. But these discrete samples permit one to describe statistically the behavior that can be expected.

For the FAST position one would expect only 1 in 1000 readings to differ from the average by more than about -3 dB or +2.4 dB, a range of 5.4 dB. The corresponding extremes for one chance in 100 is about -2.3 dB or +1.9 dB, a range of 4.2 dB; for 1 in 10, about -1.4 to +1.2, a range of 2.6 dB. Note that the range is not symmetrical.

These statements about variability can be expressed in another way, which is the converse of that above. If any reading is taken in the FAST position, the chances are only 1 in 100 that the long-time average value of the noise is below the observed value by more than 1.9 dB or above the observed value by more than 2.3 dB. These limits are called the 99% confidence limits.

*6.1.3.4.7 Confidence Limits for Octave Bands. A chart of the 99% confidence limits for octave bands for random noise measurement is given below:

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[1] R. B. Blackman and J. W. Tukey, The Measurement of Power Spectra, Dover, New York, 1958.

[2] T. P. Rona, "Instrumentation for Random Vibration Analysis," pp 7-27 to 7-30 in Random Vibration, edited by S. H. Crandall, Technology Press, Cambridge, Massachusetts, 1958.

| Center Freq | 99% Confidence Limits in dB<br>Meter Speed | |
|---|---|---|
| Hz | FAST | SLOW |
| 31.5 | -4.2, +7.0 | -2.5, +3.3 |
| 63 | -3.2, +4.7 | -1.8, +2.2 |
| 125 | -2.4, +3.1 | -1.3, +1.5 |
| 250 | -1.7, +2.1 | -1.0, +1.1 |
| 500 | -1.2, +1.4 | -0.7, +0.7 |
| 1000 | -0.9, +1.0 | -0.5, +0.5 |
| 2000 | -0.6, +0.7 | -0.3, +0.3 |
| 4000 | -0.5, +0.5 | -0.2, +0.2 |
| 8000 | -0.3, +0.3 | -0.2, +0.2 |
| 16000 | -0.2, +0.2 | -0.1, +0.1 |

| Octave Band | 99% Confidence Limits in dB<br>Meter Speed | |
|---|---|---|
| Hz | FAST | SLOW |
| 18.75 - 37.5 | -4.5, +8.0 | -2.6, +3.5 |
| 37.5 - 75 | -3.4, +5.0 | -1.9, +2.4 |
| 75 - 150 | -2.5, +3.4 | -1.4, +1.7 |
| 150 - 300 | -1.9, +2.3 | -1.0, +1.1 |
| 300 - 600 | -1.4, +1.6 | -0.7, +0.8 |
| 600 - 1200 | -1.0, +1.1 | -0.5, +0.5 |
| 1200 - 2400 | -0.7, +0.8 | -0.4, +0.4 |
| 2400 - 4800 | -0.5, +0.5 | -0.3, +0.3 |
| 4800 - 9600 | -0.3, +0.3 | -0.2, +0.2 |

These ranges of uncertainty can be reduced by the use of the average of a number of independent readings. The reduction in the range is approximately inversely proportional to the square root of the number of independent observations. Thus, the average of four observations would reduce the uncertainty to about one-half that shown.

The range of uncertainty is sometimes called the statistical error.

*6.1.3.4.8 Averaging By Observation. When one observes the fluctuations for a time and estimates an average, the extent of the reduction of the uncertainty is limited by the fact that all the observations are not independent, and one can remember and use only a small portion of the total observed behavior. The observations are not independent because of the finite time required for the pointer to assume a new value. In the

FAST position of the meter one should allow about a half second between observations; in the SLOW position, an interval of one to two seconds is desirable.

*6.1.3.4.9 Averaging By Circuit Time Constants. The smoothing or reduction in fluctuations achieved by the electrical circuit is often characterized by an equivalent time constant. The averaging time constant required to reduce fluctuations of a rectified noise signal to a desired amount for a given bandwidth of noise is approximately:

$$T \simeq \frac{1250}{\Delta f \sigma^2} \text{ seconds}$$

where T is the averaging time

$\Delta f$ is the bandwidth of the noise in Hz.

$\sigma$ is the standard deviation of the fluctuations at the output of a linear detector in percent.

*6.1.3.4.10 Duration of a Sample. The uncertainty that results from the limited observation time in comparison with the detail desired in the frequency domain occurs for other time limitations as well. Moreover, some of these may not be under the control of the operator. Thus, the sound source may not perform uniformly over an extended period of time; for example, a rocket may run for only a fraction of a minute. During launch, the time available for observing a rocket may be only a few seconds or less.

When a noise signal, recorded on a magnetic tape recorder, is to be studied, it is customary to take short samples for analysis. These samples are cut from the full recording and formed into loops that can be run continuously in the recorder. This procedure directly limits the fineness of detail possible in the analysis and also limits the accuracy with which one can determine the actual level in a band.

This limitation of accuracy results from the fact that the maximum time during which independent information can be obtained is the sample duration. If the noise is sufficiently uniform with time, a longer sample can be used to obtain increased accuracy, or measurements on a number of samples can be averaged.

Because of the inherent variability of random noise, analyses of distinct samples of the same noise will not yield identical results. The expected spread in values predicted by statistical theory can be used as a guide in judging whether the results of such analyses agree well enough to be useful. Unless this inherent variability is appreciated, one can be led into rejecting useful data, rejecting a useful analysis system, or placing too much reliance on a particular measurement.

*6.1.3.4.11 Fluctuations Produced in Practice. The table of values shown for the octave bands is based on the analysis of noise that is uniform in energy per hertz throughout the band. In the wider bands the values shown are misleading for acoustical signals, because the energy is not uniformly distributed. One should expect from such values that when the full range of a sound-level meter is used, the fluctuations would be a small fraction of a decibel. As a matter of fact, one can find many examples of an over-all sound level that fluctuates over many decibels.

One example is the background noise of private offices. Here, for C weighting in the SLOW meter position, one can commonly find fluctuations of three or more decibels. The fluctuation corresponds to a band that is only tens of hertz wide rather than 8000 to 10,000 hertz wide, such as that of the response of the sound-level meter. This is because the energy in the sound is concentrated in the low frequencies over a relatively narrow band. The fluctuations reflect only the relation between the equivalent frequency band of the signal applied to the metering circuit and the averaging time of the circuit. Whether the energy is concentrated in a narrow band by means of an electrical analyzer or by the source and path to the microphone is immaterial.

*6.1.3.4.12 Interpretation of the Fluctuations. One can conclude, then, that if the observed fluctuations are significantly greater than would be expected, an important part of the random-noise energy is concentrated in a band or bands that are narrower than the pass band of the measuring system. (Another possibility is that the type of noise is sufficiently different from normal that the fluctuations for a given bandwidth are inherently excessive. This behavior is possible for a tone whose frequency varies in a region where the response of the measuring system varies markedly with frequency.)

It is also clear that if the fluctuations are significantly smaller than would be expected, the noise very likely includes some discrete tones that have significant amounts of energy.

6.1.3.5 Calibration and Corrections. Satisfactory noise measurements depend on the use of measuring equipment that is kept in proper operating condition. Although the instruments are reliable and stable, in time the performance of the instruments may change. In order to insure that any important changes will be discovered and corrected, certain simple checks have been provided for the General Radio line of sound-level equipment, and these will be discussed in this section. These checks can be made as routine maintenance checks, and some of them (paragraphs 6.1.3.5.1 and 6.1.3.5.2) should usually be made before and after any set of noise measurements.

In addition to these routine checks, more complete calibration of the system may be desirable for accurate measurements, particularly above 1000 Hz. These calibrations are also discussed in this section.

6.1.3.5.1 Electrical Circuit Calibration. The Type 1551-C Sound-Level Meter and the analyzers have built-in calibration circuits for checking amplifier gain. In each case the gain of the amplifier is compared with the attenuation of a stable, resistive attenuator.

This test does not check the sensitivity of the microphone and the indicating instrument; these tests are discussed in the next section. The indicating instrument is rugged and relatively unaffected by temperature changes. Its temperature coefficient is about -0.02 dB/° F.

6.1.3.5.2 Acoustical Calibration at Preferred Frequencies. The Type 1562 Sound-Level Calibrator provides an over-all system calibration at 125, 250, 500, 1000, and 2000 Hz. If the calibration of a microphone as a function of frequency is recorded any significant change in the relative calibration is readily noticed. If such a change occurs, the microphone and the calibration should be checked as soon as possible. Here it is useful to have more than one microphone on hand so that a second microphone can be used if the first is damaged; at the same time a consistency check on its calibration can help to ensure that the calibrator has not been damaged.

In the interests of maintaining accuracy in sound measurements, another calibration service is provided for owners of General Radio instruments. If these instruments are brought in to one of the General Radio offices, the level will be checked by means of an acoustic calibrator. This calibration will usually show if the instrument is operating correctly. If there is a serious discrepancy, the situation will have to be handled as a regular service problem.

The calibrator can also be used to measure the microphone cable correction (see paragraph 6.1.1.8). The procedure is as follows: 1. After the noise measurement has been made, the calibrator is put on the microphone with the microphone at the end of the cable, and a level reading is taken on the sound-level meter. 2. The microphone is removed from the end of the cable and put directly on the sound-level meter. The calibrator is put on the microphone at the sound-level meter, and a second level reading is taken. 3. The difference between these two level readings is the cable correction.

For high accuracy, it is usually essential to have a calibration of the microphone response characteristic as a function of frequency. When this calibration is available and an analysis of a noise is made, correction can be made for the microphone frequency-response characteristic. This correction can be applied only if the noise is analyzed or if the sound is dominated by a component of known frequency, as, for example, in the measurement of loudspeaker response. Otherwise, one must check the uniformity of response of a system to be sure that the measured level of a noise is correct.

6.1.3.5.3 Acoustical Calibration From 20 to 8000 Hertz. A more accurate over-all calibration is possible by the use of the microphone reciprocity calibrator. With an auxiliary oscillator, this instrument permits, at any frequency from 20 to 8000 Hz, a rapid and accurate calibration of the General Radio ceramic microphone and the associated equipment.

For the most accurate noise measurement, the measurement system should be calibrated by means of the microphone reciprocity calibrator either before or after the measurement is made. Unless the system is already known to be operating properly, it may be desirable to make a preliminary check by using the microphone reciprocity calibrator as a sound-level calibrator. Then, after the noise measurement, the complete reciprocity calibration should be made at the frequencies of interest. These frequencies should be those at which the important energy is concentrated, as indicated by analysis of the noise. Of course, it is wise to check the calibration at a number of points over the full range of interest to make certain that any apparent lack of energy at low or high frequencies is not a result of loss in sensitivity at those frequencies.

When there is no other indication of what is necessary, a more general calibration along the following lines is suggested: (1) Set the microphone reciprocity calibrator to operate as a simple calibrator. Sweep the frequency of the source oscillator from 20 to 2000 Hz and note the variation in response of the system under calibration. Unless intentional weighting or filtering is introduced, this response should be reasonably uniform and calibration at only a few frequencies in this range is necessary. (2) If this response is nearly uniform, calibrate at the extremes of the range and a few points between to check the uniformity, for example, at 20, 100, 400, 1000, and 2000 Hz. If the response below 1 kHz is faulty, calibrate the microphone at a number of frequencies and compare the results with previous calibrations. Next, check the response of the various other elements. By proceeding in this way one can track down the reason for the faulty behavior. (3) Above 2 kHz, calibrate the system at the ASA preferred frequencies, 2000, 2500, 3150, 4000, 5000, 6300, and 8000 Hz.

Any laboratory that attempts to make accurate acoustical measurements should calibrate its microphones periodically by means of the microphone reciprocity calibrator. These calibrations should be kept on file, so that it will be readily apparent if a microphone has been damaged by rough treatment.

6.1.3.5.4 Calibration At High Frequencies. The accurate calibration of a microphone at high frequencies in terms of sensitivity vs frequency requires elaborate facilities. Only a few laboratories (e.g., The National Bureau of Standards) offer such calibration as a regular service. General Radio Company will calibrate response vs frequency only for those microphones that it supplies. Such calibration is less expensive if included in the original order for the microphone than if the microphone is returned for calibration. (The frequency-response characteristic of the Type 1551-P1 Condenser Microphone is supplied with the microphone, at no additional cost.)

At General Radio, a free-field perpendicular-incidence calibration is made by comparison with laboratory-standard condenser microphones (USA Standard Specification for Laboratory Standard Pressure Microphones, Z24.8-1949), according to the methods given in S1.10-1966, Calibration of Microphones. The working standard microphones are periodically compared with a condenser microphone that has been calibrated at the National Bureau of Standards. They are also periodically calibrated on an absolute basis by the reciprocity method.

Since the sound-level-meter standard is based on a random-incidence specification, data for converting the perpendicular-incidence calibration to random incidence and to grazing incidence are included with calibrations supplied by General Radio.

6.1.3.5.5 Correction For Frequency-Response Characteristic. It is customary to set the calibration of an acoustical measurement system to indicate the correct level at 400 or 500 Hz. At other frequencies, the differences between true and indicated levels, as determined by means of the microphone reciprocity calibrator, can be applied as corrections to the results of a noise measurement. At frequencies above 1000 Hz the directional characteristic of the microphone should be taken into account. The Type 1559-B Microphone Reciprocity Calibrator is designed to provide the random-incidence calibration of the microphone. If the microphone is used under conditions where a different response applies, for example, perpendicular-incidence response; the difference between perpendicular-incidence and random-incidence response must be included in the correction to the results of the noise measurement.

6.1.3.5.6 Comparison Tests Among Different Sound-Level Meters. When measurements are made on the same noise with two different sound-level meters, it is commonly found that the readings differ by a significant amount. The preceding material in this chapter should indicate most of the possible sources of discrepancy between the two. Differences in the microphone characteristics are usually the chief cause of this discrepancy. For example, if one sound-level meter uses a dynamic microphone and the other uses a ceramic microphone and if the noise contains strong low-frequency components, large differences can occur because of the generally poorer low-frequency response of the dynamic microphone. When these effects are understood, most of the discrepancies are readily explained.

Another factor that can contribute to this discrepancy concerns the average level. For purposes of meeting certain tolerances the average level of an instrument made by one manufacturer may be set slightly differently from that made by another.

If the instruments are not operating properly or if standing waves are not averaged out, serious discrepancies can, of course, be expected.

In order to set an upper limit to these differences among sound-level meters, the "USA Standard Specification for General-Purpose Sound Level Meters," S1.4, 1961, sets certain tolerances on the prescribed frequency characteristics. Representative values for C weighting are as follows:

| Frequency - Hz | Tolerances, dB |
|---|---|
| 25 | +2, -2.5 |
| 40 | +1, -1.5 |
| 50 to 800 | ±1 |
| 1000 | ±1.5 |
| 1600 | ±2 |
| 2000 | ±2.5 |
| 2500 | +3.5, -3 |
| 4000 | +5, -4 |
| 6300 | +6, -5 |
| 8000 | ±6 |

Incidentally, these tolerances should be considered when one is reviewing the results of an initial calibration of a microphone and sound-level meter made with a Type 1562 Sound-Level Calibrator or a reciprocity calibrator.

6.1.3.5.7 Effect of C Weighting On Band Levels. In principle, the response of the equipment supplying an analyzer should be as uniform as possible to obtain true pressure levels. It has been customary, however, to use the "C" weighting for octave-band measurements. If this is done, for instruments meeting the latest USA and International standards there will be small differences in level at the low- and high-frequency ends compared with the levels that would be obtained with a more nearly uniform response, because of the specified roll-offs in response for the C weighting. Thus, the C-weighted octave-band level is less by about 3 dB for the bands centered at 31.5 and 8000 Hz and 0.8 dB for the bands at 63 and 4000 Hz than with the uniform response weighting (FLAT). The shifts in level for the bands in between are too small to be significant.

6.1.3.5.8 Check On Over-All Level. When an octave-band analysis has been made, it is good practice to check that the sum of the individual band levels (see Appendix II) is equal within 1 or 2 dB to the over-all level. If this result is not obtained, an error exists, either in the summing or the measurement procedure, because of faulty or incorrectly used equipment, or because the noise is of an impact type. Impact-type noises sometimes give over-all levels appreciably less than the sum of the levels in the individual bands even when the "FAST" position of the meter switch is used. This result is obtained because of the inability of the meter to indicate the instantaneous levels occurring in very short intervals. The narrow-band levels at low frequencies tend to be nearer the peak value in those bands, while the over-all and high-frequency bands are significantly less than the peak value. When this type of discrepancy is noted, the Type 1556-B Impact-Noise Analyzer should be used.

6.1.3.6 Earphones and Stethoscope. A pair of high-quality earphones with tight-fitting earphone cushions is a useful accessory for noise measurements, and high-impedance dynamic or crystal-type phones are recommended. Good earphone cushions are essential to improve the low-frequency response and to help reduce the leakage of external noise under the earphone.

When a measurement system is being set up, the earphones should be plugged into the output of the sound-level meter. Then a listening test should be made to determine that the noise heard in the earphones is the same type of noise heard without the earphones. It is possible to detect trouble from microphonics (usually a ringing sound) or stray pickup in this fashion.

When the noise level is high, say, 90 dB or higher, the leakage of external noise under the earphone may be sufficient to mask the sound from the earphones. Then the earphone cushions should be checked for tightness of fit. In addition, the signal from the earphones can be increased by use of an attenuator setting on the sound-level meter 10 dB lower than that required for a satisfactory reading on the meter. This change of 10 dB is usually not enough to overload the output, but a larger change should be avoided. It may also be desirable to have a long cord available so that it is possible to listen to the output of the earphones far from the noise source.

The earphones can also be used on the output of the analyzer to detect troubles from microphonics and stray pickup. In addition, a listening test may help one to determine which frequency bands contain the noise that is most objectionable in a given situation.

When the noise level is very high, the earphones on the sound-level meter may be useful in improving speech communication between observers during a measurement run. One observer wears the earphones, then the other observer shouts into the sound-level meter microphone. A definite improvement in speech communication usually results.

A similar procedure using a nonelectrical, medical stethoscope is also possible. One observer has the ear tips in place, and the other speaks into the receiver of the stethoscope.

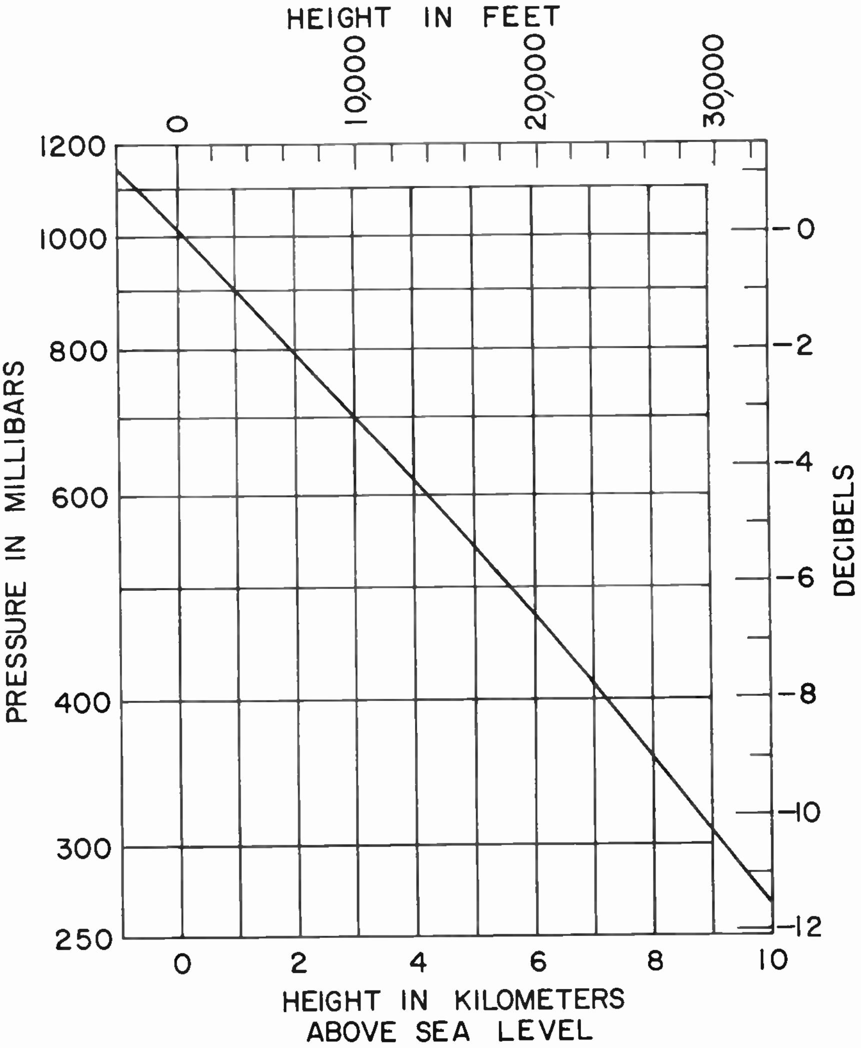
### 6.1.4 MOUNTING OF THE DEVICE UNDER TEST.

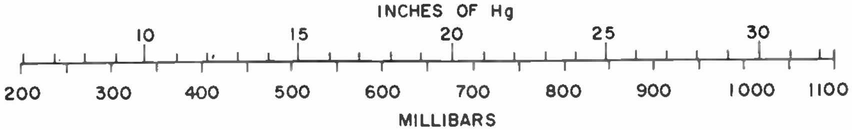
It is often noticed that the noise level produced by a machine is highly dependent on its mounting. A loose mounting may lead to loud rattles and buzzes, and contact to large resonant surfaces of wood or sheet metal may lead to a sounding-board emphasis of various noise components. For these reasons particular care should be given to the method of mounting. In general, the mounting should be as close to the method of final use as possible. If the machine is to be securely bolted to a heavy concrete floor, it should be tested that way. If the actual conditions of use cannot be duplicated, the noise measurements may not be sufficient to predict the expected behavior, because of the difference in transmission of noise energy through the supports. The usual alternative is to use a very resilient mounting so that the transmission of energy to the support is negligible.

### 6.1.5 EFFECTS OF ATMOSPHERIC PRESSURE.

Some acoustical measurements are affected by atmospheric pressure and temperature. The output of the Type 1562-A Calibrator, for instance, varies somewhat with pressure, and the rated reference level occurs at a standard atmospheric pressure of 1013 millibars. If the pressure when the calibrator is used is significantly different from 1013 millibars, a correction should be made. The altitude where the calibrator is used is usually the most significant factor in determining the average atmospheric pressure, and a chart for correcting for this effect is included in the calibrator instruction book. Since the output of most other sound sources is affected by the pressure, a chart relating height to average pressure is included here. The actual variation in output with pressure for practical sources is usually between that shown by the corresponding decibel scale on the right and one-half that value. Thus, for altitudes up to 2 kilometers (6560 feet), the change in output with altitude is generally less than 2 dB.

The variation of atmospheric pressure at a given location from day to day is usually less important, but for careful measurements where fractions of a decibel are being considered, the actual atmospheric pressure should be noted. The pressure can be obtained from the local weather bureau, and a correction for the difference in altitude between the point where the acoustical measurements are made and the weather bureau may be necessary. This correction is readily estimated from the chart.


HEIGHT IN FEET
0
10,000
20,000
30,000
1200
1000
800
600
400
300
250
PRESSURE IN MILLIBARS
-0
-2
-4
-6
-8
-10
-12
DECIBELS
0
2
4
6
8
10
HEIGHT IN KILOMETERS ABOVE SEA LEVEL

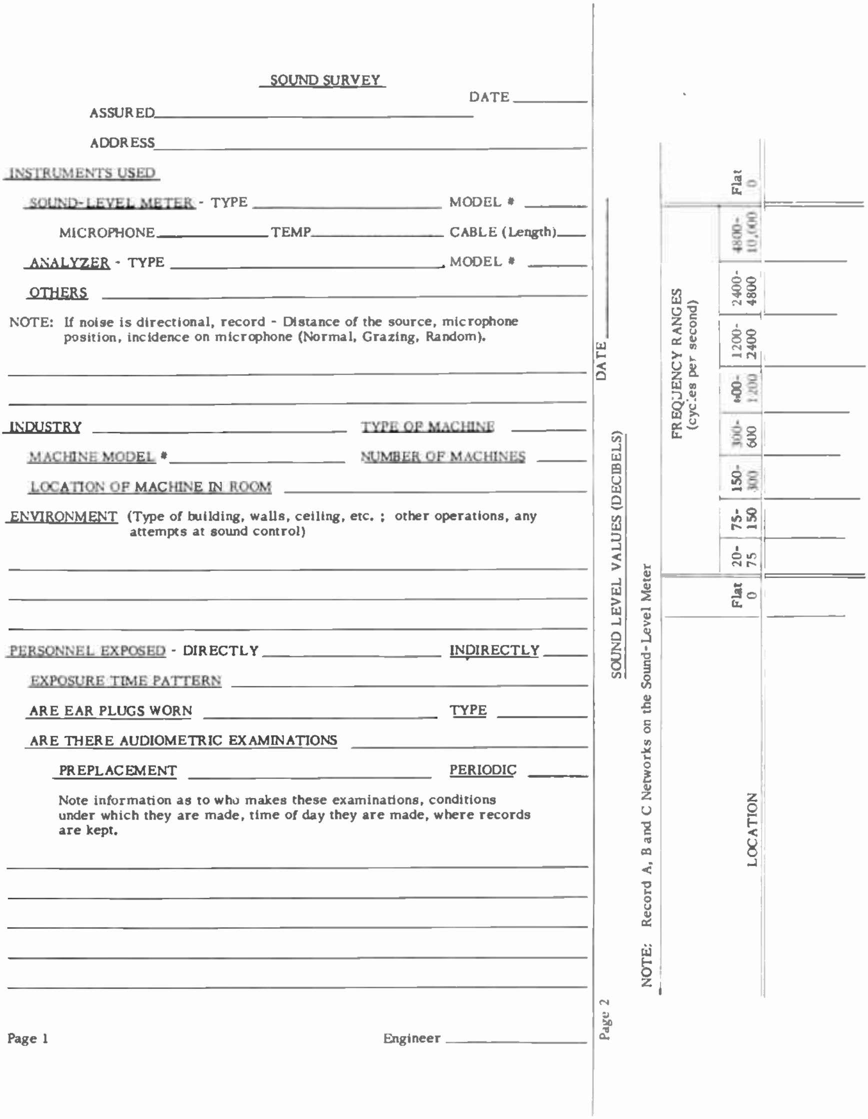

INCHES OF Hg
10
15
20
25
30
200
300
400
500
600
700
800
900
1000
1100
MILLIBARS

6.1.6 RECORD OF MEASUREMENTS. One important part of any measurement problem is obtaining sufficient data. The use of data sheets designed specifically for a noise problem helps to make sure that the desired data will be taken and recorded, and a sample data sheet is shown in Figure 6-5. The following list of important items may be found helpful in preparing data sheets of this type:

1. Description of space in which measurements were made. Nature and dimensions of floor, walls, and ceiling. Description and location of nearby objects and personnel.
2. Description of device under test (primary noise source). Dimensions, name-plate data and other pertinent facts including speed and power rating. Kinds of operations and operating conditions. Location of device and type of mounting.
3. Description of secondary noise sources. Location and types. Kinds of operations.
4. Type and serial numbers on all microphones, sound-level meters and analyzers used. Length and type of microphone cable.
5. Positions of observer.
6. Positions of microphone. Direction of arrival of sound with respect to microphone orientation. Tests of standing-wave patterns and decay of sound level with distance.
7. Temperature of microphone.
8. Results of maintenance and calibration tests.
9. Weighting network and meter speed used.
10. Measured over-all and band levels at each microphone position. Extent of meter fluctuation.
11. Background over-all and band levels at each microphone position. Device under test not operating.
12. Cable and microphone corrections.
13. Date and time.
14. Name of observer.

When the measurement is being made to determine the extent of noise exposure of personnel, the following items are also of interest:

1. Personnel exposed—directly and indirectly.
2. Time pattern of the exposure.
3. Attempts at noise control and personnel protection.
4. Audiometric examinations. Method of making examinations. Keeping of records.



SOUND SURVEY

DATE ________

ASSURED ________________________

ADDRESS ________________________

INSTRUMENTS USED

SOUND-LEVEL METER - TYPE ____________ MODEL # ______

MICROPHONE ________ TEMP ________ CABLE (Length) ______

ANALYZER - TYPE ____________ MODEL # ______

OTHERS ________________________

NOTE: If noise is directional, record - Distance of the source, microphone position, incidence on microphone (Normal, Grazing, Random).

INDUSTRY ____________ TYPE OF MACHINE ______

MACHINE MODEL # ____________ NUMBER OF MACHINES ______

LOCATION OF MACHINE IN ROOM ________________

ENVIRONMENT (Type of building, walls, ceiling, etc. ; other operations, any attempts at sound control)

PERSONNEL EXPOSED - DIRECTLY ____________ INDIRECTLY ______

EXPOSURE TIME PATTERN ________________

ARE EAR PLUGS WORN ____________ TYPE ______

ARE THERE AUDIOMETRIC EXAMINATIONS ________________

PREPLACEMENT ____________ PERIODIC ______

Note information as to who makes these examinations, conditions under which they are made, time of day they are made, where records are kept.

Page 1

Engineer ________

DATE ________

SOUND LEVEL VALUES (DECIBELS)

NOTE: Record A, B and C Networks on the Sound-Level Meter

|  |  | FREQUENCY RANGES (cycles per second) |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| LOCATION | Flat 0 | 20-75 | 75-150 | 150-300 | 300-600 | 600-1200 | 1200-2400 | 2400-4800 | 4800-10,000 | Flat 0 |

Page 2

Figure 6-5. A sound-survey data sheet, courtesy of Loss Prevention Department, Liberty Mutual Insurance Company.

## 6.2 VIBRATION MEASUREMENT TECHNIQUES.

6.2.1 INTRODUCTION. The reason for measuring vibration usually determines both the quantity to be measured and the point or points at which the vibration pickup should be placed. Sometimes, however, the correct pickup location is not obvious, and some exploration of the vibration pattern of the device being studied is necessary. Furthermore, the pickup must be correctly oriented, and this too sometimes requires exploration.

Fastening a pickup to a device is usually simple if the device is much larger than the pickup and if the important vibration frequencies are below 1000 Hz. Otherwise, difficulties may arise because of the mechanical problem of fastening the pickup at the desired point, because the pickup seriously affects the motion to be measured, or because the method of attachment affects the performance of the pickup.

### 6.2.2 CHOICE AND USE OF PICKUP

6.2.2.1 Range of Levels. A very wide range of vibration levels can be covered by the pickups available. The most sensitive pickup can be used with the vibration meter or the control box and sound-level meter to measure down to 0.01 in/s$^2$ or 0.0003 m/s$^2$. At the other extreme the Type 1560-P53 pickup can be used up to 1000 g. Special pickups are manufactured for even higher accelerations.

In order to show the limits of measurement for velocity, jerk, and displacement, charts are displayed in the Appendix for the ranges of the vibration meter.

6.2.2.2 Frequency Range. The Type 1560-P52 Pickup is particularly well suited for low-frequency vibration measurements. When connected to the Type 1553 Vibration Meter, this pickup can be used at frequencies down to 1 Hz; with the Type 1564 Sound and Vibration Analyzer it can be used down to 2.5 Hz. The other pickups can also be used down to 2.5 Hz if they are connected to a Type 1560-P40 Preamplifier.

The Type 1560-P53 Pickup has a resonance at about 28,000 Hz, which imposes a practical limit of about 20,000 Hz. The other pickups in the General Radio line are limited to about 2000 Hz.

6.2.2.3 Orientation of Pickup. The piezoelectric accelerometers used in General Radio vibration-measuring instruments are most sensitive to vibrations in the direction perpendicular to the largest flat surface on the pickup. This direction is the one for which the rated sensitivity applies. The sensitivity in other directions varies approximately as the cosine of the angle with respect to this rated direction, with a minimum of about 5 percent or less of rated sensitivity when vibrated in a direction perpendicular to the rated one.

For accurate results, the pickup must be properly oriented with respect to the direction of motion. In practice, this orientation is usually not critical, however, because sensitivity changes slowly with direction, there being a drop of only about 2 percent for a 10-degree change in orientation.

The direction of maximum vibration at a point is often obvious from the structure that is vibrating. That is, it is usually in the direction of least stiffness. But this rule is sometimes misleading, because of the many possible resonant modes of vibration, some of which are perpendicular to the obvious direction of least stiffness. Such a mode can be strongly excited if close to the frequency of a component of the driving force. Furthermore, the nature of the motion may favor one mode of vibration rather than another.

When it is important to be certain of the direction of motion, one can measure the motion along three mutually perpendicular axes. Often one can select these so that only one of these components of motion is significant, and that will determine the choice of direction. Otherwise, they must be combined vectorially to yield a resultant total; then one needs to know the relative phase of the components. To determine phase, sums and differences can be measured with two pickups, as explained later, or another set of three measurements can be made along mutually perpendicular axes that are rotated from the first step. With two sets of measurements, one can sort out the possible combinations and calculate the direction of the total motion. Often it is simple to obtain the direction of the maximum motion by experiment.

Except for simple harmonic motions, this resultant direction is of significance only as a function of frequency. Then an analyzer is essential so that one can determine the motion for the individual components.

When one attempts to measure vibration in a direction that is not the direction of the total vibration at the point of measurement, the orientation is more critical, because the vibration in the other directions will provide some signal in the output. It is often impractical to measure a directional component that is less than 5 percent of the total vibration at a point.

The above procedure does not lead to a measurement of the rotational vibration about a point. This type of measurement can be made with a torsional vibration pickup or by the technique discussed in paragraph 6.2.5.

6.2.2.4 Hand-Held Pickup. When one must explore a vibration pattern or make a quick check of the vibration amplitude, one is tempted to hold the pickup against the device being measured by hand. If the device is massive and is vibrating with a significant amplitude, this technique can be useful for frequencies below about 1000 Hz. There are enough serious limitations to this technique, however, so that it should not generally be expected to yield accurate or highly reproducible results.

When the pickup is held by hand, a test probe, a pointed metal rod, is fastened to the pickup to facilitate applying the probe to the desired point. The motion is transmitted along the rod to the pickup, and the motion in the direction of the rod actuates the pickup.

Because the test probe adds another element to the pickup, the response is different from that of the pickup alone. Typical relative frequency response characteristics are shown for two types of probe in Figures 6-6 and 6-7. More than one response run is shown to indicate the variability that can occur. Note resonance in the range from 1400 to 2000 Hz introduced by the long (6 3/8-inch) probe and the one above 2000 Hz for the probe with the short conical tip.

Unless the device being tested is massive, the force, mass, resilience, and damping introduced by the hand may seriously alter the motion, and another method of applying the pickup should be tried.

Some vibration is applied to the pickup by tremor of the hand. This vibration is made up chiefly of components below 20 Hz, and the peak-to-peak order of magnitude is 5 in./s$^2$ acceleration, 0.2 in./s velocity, and 10 mils displacement, when the pickup is held against a relatively stationary surface. These values will be appreciably attenuated by a low-frequency cutoff at 20 Hz, such as is obtained on the "DISP-20 CUTOFF" position of the vibration meter. Then the ob-

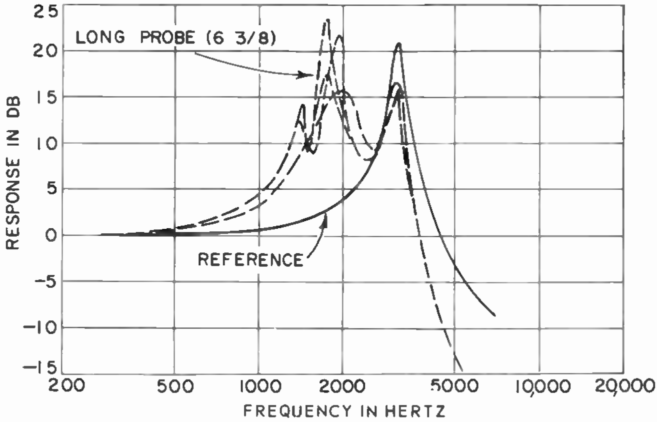


*Figure 6-6. Frequency response of vibration pickup mounted on hand-held long (6 3/8-inch) probe. Several sample responses are shown. The curve labeled REFERENCE is the frequency response of the pickup without the probe.*

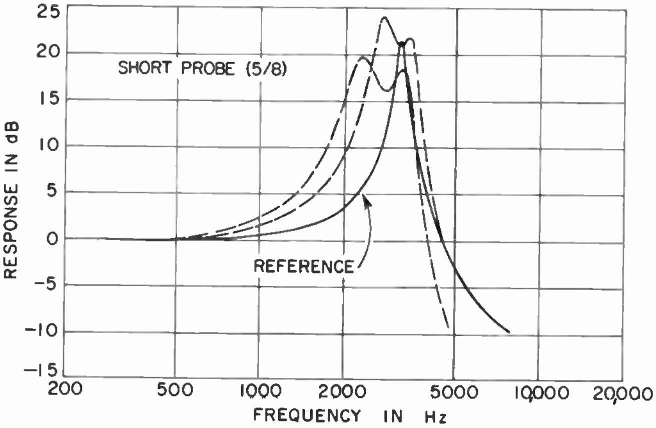


*Figure 6-7. Frequency response of vibration pickup mounted on hand-held short (5/8-inch) probe. Several sample responses are shown.*

served peak-to-peak displacement is of the order of 0.2 mil.

This tremor sets a lower limit to the vibration that can be observed when the pickup is hand-held against the vibrating device. One should not attempt to use a hand-held pickup down to the levels quoted above unless some filtering is introduced to reduce the low-frequency response.

6.2.2.5 Pickup Fastening Methods. Pickups are fastened to a vibrating surface by many different methods. For greatest accuracy the fastening should be as direct and as rigid as possible. But if the acceleration is less than gravity, if only a temporary fastening is desired, and if only low frequencies are present, simple fastenings are adequate. These may be plasticene or double-sided adhesive tape placed between the base of the pickup and a flat surface at the point desired. If the surface is horizontal, flat, and smooth, the pickup may be wrung to the surface with a thin film of petroleum jelly. Another simple technique, useful on magnetic materials, is to fasten a magnet to the pickup and then attach the magnet to the surface to be measured.

At high accelerations, these simple fastenings are not satisfactory, and a stud or bolt must be used to hold the pickup directly against the surface being measured.

The performance of some pickups is affected by any attachment to the pickup body other than to the reference surface, so that a pickup should not be attached by clamps to the body of the pickup.

When the pickup is to be permanently installed, the use of an adhesive, such as a dental cement, Eastman 910, or an epoxy cement, is often advisable. For best results, one should be careful to use only a thin layer, so that the elastic characteristics of the bonding cement will not affect the behavior of the pickup.

For maintenance tests it is often convenient to fasten a very smooth flat iron disk to bearing housings with a very hard epoxy cement. The disk should be pressed as tight as possible against the housing. Then a magnetic attachment can be used, again with a thin film of silicone grease or petroleum jelly to ensure good contact.

The fastening should be rigid, so that the pickup does not move significantly with respect to the surface to which it is fastened. Any rocking motion or looseness that might lead to chattering should be prevented. If the fastening alone is not adequate to prevent this looseness, the use of some plasticene in addition may be helpful. When fastening, even by bolts, the use of a lubricant or petroleum jelly is advisable to ensure close contact between the pickup and the fastening surface without putting undue strain on the pickup.

When the surface is not smooth or flat, the pickup is sometimes mounted on a bracket. For low vibration frequencies (below a few hundred hertz), the bracket can readily be made stiff enough so that it does not seriously affect the behavior of the pickup.

The procedure for obtaining a good connection between the pickup and the vibrating surface is illustrated by the specifications of MIL-STD-740B (SHIPS).

> "Transducers shall be attached as follows:
>
> "(a) Transducers shall be attached to blocks, which are to be brazed or welded to equipment, or subbase, as close as possible to the mounting points of the equipment to be tested.
>
> "(b) The blocks shall be made of steel and shall be as small as possible. The block surfaces on which transducers are mounted shall be plane and shall have a surface finish of 125 micro-inches rms or better and be mutually perpendicular within one degree.
>
> "(c) Three holes in the mounting blocks shall be drilled and tapped to a depth of at least 1/4 inch with 10-32 NF threads to accommodate triaxial arrays of transducers which shall be attached to the blocks with insulated steel studs. The holes shall be perpendicular to the finished surfaces within plus or minus 1 degree.
>
> "(d) Just before transducers are mounted on a block, all mating surfaces shall be cleaned of all dirt, grease, and other foreign matter in preparation for mounting. The surfaces of the attachment area and the studs shall be lightly covered with clean oil or grease.

"(e) The mounting blocks shall not be removed and shall be preserved with a rust inhibiting coating after completion of testing.

"(f) If brazing or welding cannot be accomplished, the mounting blocks shall be attached to the location with a thin layer of epoxy resin cement. Blocks attached by cement shall be removed upon completion of test. The transducers may be attached directly to the equipment being tested only where there is insufficient space to accommodate the mounting block."

The pickup is calibrated in terms of the motion of the flat contacting surface of the pickup. Because of the resilience of the fastener and the mass of the pickup, this surface of the pickup will not move exactly as the surface being measured moves. At low frequencies this difference is easily made insignificant by the relatively simple techniques discussed. But at high frequencies care must be used in fastening to keep this effect small.

The mass of the Type 1560-P52 Vibration Pickup is sufficiently small that simple temporary fastenings are adequate even to frequencies beyond the normal resonance at about 3200 Hz. This fact is illustrated by the response-vs-frequency characteristics shown in Figure 6-8 and 6-9. In each instance the pickup was driven at a constant acceleration. The reference condition is the response for the vibration pickup wrung to the smooth, flat surface of the driver with petroleum jelly lubricant. The acceleration was 0.002 g.

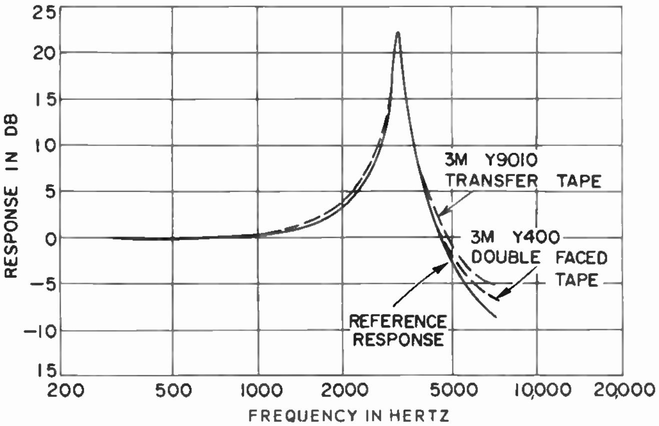


*Figure 6-8. Frequency response of vibration pickup attached by means of Minnesota Mining Types Y9010 and Y400 tapes.*

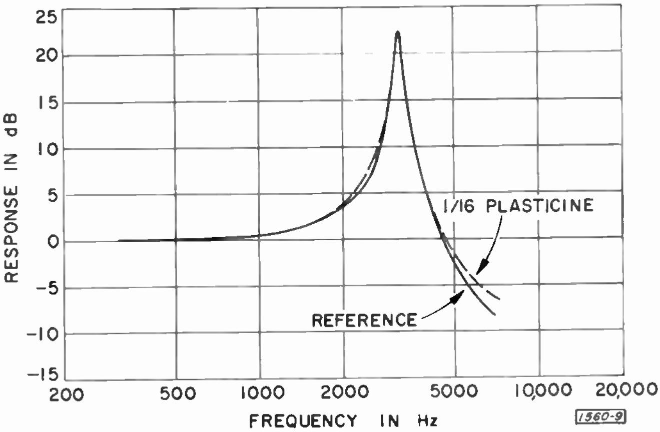


*Figure 6-9. Frequency response of vibration pickup attached by means of 1/16-inch-thick layer of plasticene.*

The effect of fastening by means of double-sided tape was generally less than 10-percent deviation from the reference condition at all frequencies up to the resonance at 3200 Hz. In some instances the deviation over the range to 3200 Hz was only about 2 percent. The variability was probably a result of changes in contact adhesion obtained with different samples of the tape.

Plasticene as a fastening means, even as thick as 1/16 inch, showed very good reproduction of the reference performance, being within 2 to 5 percent up to 4000 Hz. In one instance a marked departure from the reference performance was found even at 500 Hz, and this was quickly traced to the fact that the pickup had come loose from the plasticene. This example illustrates the importance of careful inspection of the fastening during a test, particularly when one cannot check the performance independently.

The response of the pickup when held to a smooth, flat, steel plate by means of the Type 1560-P35 Permanent Magnet Clamp is shown in Figure 6-10. Up to 5 kHz, the response is very similar to the reference response. One should fasten the pickup carefully to the magnet so that no rocking motion is possible, and the magnet itself should be placed on a smooth surface so that it, too, will not rock; otherwise serious errors may result.

### 6.2.3 STRAY EFFECTS.

6.2.3.1 Effect of the Pickup On the Vibration. The mass added by the pickup to the vibrating surface being measured changes the motion of that surface. If the added mass is much smaller

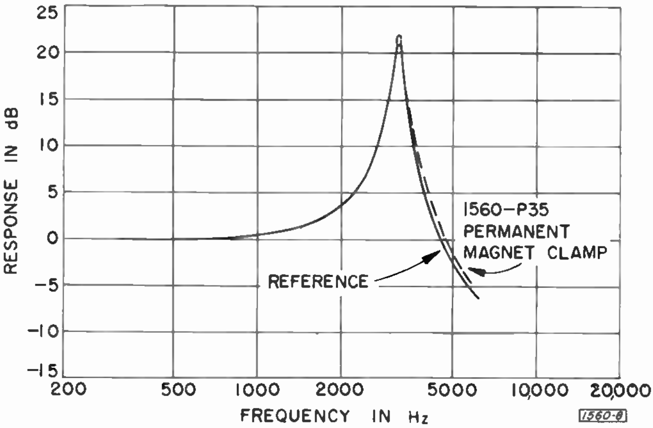


*Figure 6-10. Frequency response of vibration pickup attached by Type 1560-P35 Permanent-Magnet Clamp.*

than that of the vibrating surface or is closely coupled to it, the effect is small except near resonant modes. Thus, it is important to have a lightweight pickup.

One can often judge the effect of adding the mass of a pickup by noting the difference in behavior with the pickup fastened and with another mass equal to that of the pickup in addition to the pickup. If the difference is negligible for these two conditions, the effect of the pickup is usually unimportant. Under certain conditions near the resonant vibration frequency of the device under test, even a small mass can shift the resonance enough to affect the motion at the original resonant frequency by a large amount.

When it is possible to change the excitation rate or frequency so that resonance with the pickup in place is reestablished, the behavior at the new resonant point will often be sufficiently similar to the resonance behavior without the pickup that the resonant condition can be satisfactorily measured.

When stroboscopic observation of the motion is possible, the effect of the mass of a pickup on the motion can often be judged by direct observation of the behavior with and without the pickup present.

6.2.3.2 Mounting of the Device Under Test. The actual vibration that a device experiences will depend on the way in which it is mounted. If it is rigidly mounted to a massive concrete structure, the vibration may be much less than if it is mounted with a very resilient mount. For many tests the very resilient mounting is preferred in order to obtain the maximum motion. But often the proper procedure is to mount the device for a vibration test just as it will be mounted in actual use.

6.2.3.3 Background Vibration. Some background vibration is always present. If a motor is put on a factory floor for a vibration test, it will be possible to measure motor vibration even when it isn't running. This background vibration must be considered as a lower limit to the vibration that can be measured. But, of course, one can do something about this lower limit. Often placing the device on a thick felt or foam pad will isolate it sufficiently from the background, but then the mounting is no longer rigid. Another approach is to use a separate, massive concrete block as a table on which to mount the device in any way desired. The block is suspended by resilient mounts. The natural vibration frequency of the block on its mounts should be made significantly lower than any frequency of interest in the test. (See also 6.2.2.4.)

6.2.3.4 Peak Versus RMS or Average. Although a few applications of vibration measurements require the use of the peak or peak-to-peak amplitude, most experimenters specify these values only because they are traditional. When vibration signals are analyzed to find the individual components, however, the rms or rectified average values are more useful. This usefulness depends on two facts. First, rms component values can be summed on an energy basis to give the over-all rms value. For many wave shapes this result is also essentially true for the rectified average values. But the result of combinations of peak values of components can be misleading and confusing, particularly for coherent periodic signals, which are relatively common in vibration work. The second fact is that if the signal is random in amplitude distribution, there is an additional inconsistency among peak values. As a result, if you measure a peak value of a vibration signal, it is also wise to note the rms or average value.

### 6.2.4 CALIBRATION OF VIBRATION MEASUREMENT SYSTEMS.

In order to ensure that one can make satisfactory vibration measurements, the instruments used must be kept in proper operating condition. The vibration meter itself can be checked electrically very simply by the built-in calibration system, and the instrument should be checked at the start of a test, after the instrument has been on and allowed to stabilize for a few minutes.

The vibration calibrator should also be used regularly to check the complete measurement system. If the acceleration produced by the calibrator reads between 340 and 430 rms (or 950 to 1220, peak-to-peak) in/s$^2$ on an electrically calibrated vibration meter, there is reasonable assurance that the pickup and the meter are operating correctly. If the agreement is not satisfactory, one should first check that the correct pickup for the vibration meter is being used, and that the internal reference dial in the meter is set to the correct pickup sensitivity. If these are all checked and agreement is still unsatisfactory, another pickup should be tried (with the internal reference dial set to its nominal sensitivity). The next step would be to have the pickup and the calibrator checked at the General Radio Company.

Vibration pickups are rugged and stable, but they can be damaged. Although a damaged pickup will ordinarily be detected by the check at 100 Hz provided by the vibration calibrator, it is possible, but most unusual, for the sensitivity at other frequencies far from 100 Hz to be affected when that at 100 Hz is not. Therefore, the frequency response of pickups should be verified periodically by calibration at the National Bureau of Standards or at the General Radio Company.

### 6.2.5 A SIMPLE TWO-PICKUP METHOD FOR DETERMINING THE ROTATIONAL VIBRATION OF ROTATING MACHINERY.[1]

When analysis of rotational vibration must be made on an existing installation and a torsional pickup cannot readily be used, the following technique may be useful. Two vibration pickups and a summing network are required in addition to the vibration meter. One must assume that the engine behaves like a rigid mass and that its center of gravity is equidistant from all four mounting posts.

A simple summing circuit is shown in Figure 6-11. The voltages $e_1$ and $e_2$ represent the output signals of two vibration pickups, and the voltage $e_o$ represents the signal fed into the input of the vibration meter. If the three resistors R are equal, $e_o$ will be $1/3\ (e_1 + e_2)$. A practical arrangement of this circuit is shown in Figure 6-12. Only two resistors are shown, since the third resistor is in the input circuit of the vibration meter. One pickup is connected to input No. 1 and the other pickup is connected to input No. 2. The output of the summing circuit is connected to the input of the vibration meter. When switch S-1 is at position 1, one third of the output of pickup No. 1 is applied to the input of the vibration meter. When S-1 is set at position 2, one third of the output of pickup No. 2 is applied to the input of the vibration meter. When S-1 is at position 3, one third of the sum of the outputs from the two pickups is applied to the input of the vibration meter.

Example:

The top view of a typical engine and its mounting is outlined in Figure 6-13. A and B represent the forward engine mounts while C and D represent the rear engine mounts. With the two pickups (oriented for vertical-displacement measurement)

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[1] This method was suggested by Mr. George Kamperman of Bolt, Beranek and Newman, Inc., Cambridge, Mass. He has used this technique on numerous occasions with gratifying results.

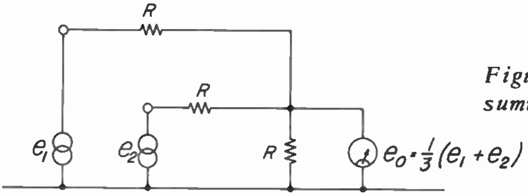
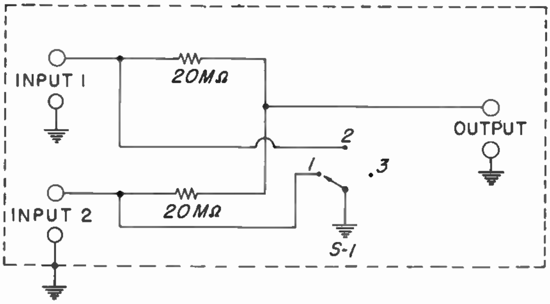


*Figure 6-11. A simple resistive summing circuit.*

*Figure 6-12. A convenient arrangement of the summing circuits of Figure 6-10.*



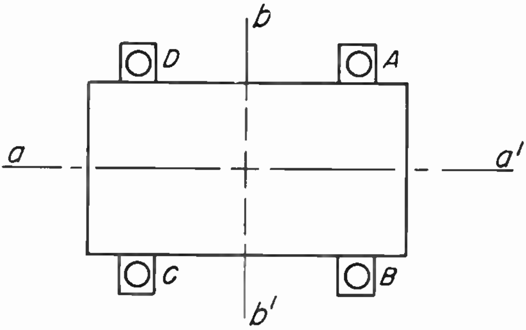


*Figure 6-13. Outline of engine and mounting (top view).*

mounted on the two forward engine mounting brackets, the translational or vertical amplitude is indicated on the vibration meter when the output signals of the two pickups are summed. The rotational mode of vibration is canceled out. When the outputs of the two pickups are summed 180° out of phase or subtracted, the rotational amplitude of vibration is indicated on the vibration meter and the translational mode of vibration is canceled out. The pickup can be mounted upside down to shift the output 180° to perform the subtraction of outputs, or, the pickup can be left in its normal mounting position and the 180° shift in the phase of its output can be achieved with an electronic phase inverter. By making the set of measurements outlined above on all pairs of mounting brackets (A,B—C,D—B,C) the amplitude of any rotational or rocking motion about the axes a-a' or b-b' can easily be sorted out from the direct vertical or translational motion of the engine.

chapter 7

# NOISE AND VIBRATION CONTROL

## 7.1 INTRODUCTION.

When we want to reduce noise or vibration, we usually begin by measuring the spectrum of the noise or vibration to obtain the quantitative information that is helpful in doing something about the problem. We compare the measured levels with the acceptable levels, which are often estimated by use of one of the criteria given in Chapter 3. The difference between these two levels is then the reduction necessary.

The next step is to find out how this reduction can be achieved most satisfactorily. A complete discussion of this problem is not possible in this handbook. But since many of those using this book are just beginning to work on noise and vibration problems, a few introductory statements on the subject will be made. Useful information on this subject will be found in books on noise control and architectural acoustics, in books on mechanical vibrations, in some books on acoustics in general, in some articles in the Journal of the Acoustical Society of America, and in articles in various trade journals. We shall discuss noise control first.

The general approach to noise reduction can be divided into two major parts as follows:

(1) Reduction of noise at its source.
(2) Reduction of noise level at the ear of the listener by changes in the path from the source.

## 7.2 NOISE CONTROL AT THE SOURCE.

It is usually wise to see first if the noise can be reduced at the source. A different type of source might be selected. For example, a process might be changed so that parts are welded instead of riveted together. A source of different basic construction but of a similar type might be used. For example, a slower fan of many blades can sometimes be substituted for a high-speed two-bladed fan. Or, the construction of the particular source at hand might be modified, and this procedure will be discussed briefly.

When modification of a source is attempted, a decrease in the radiated power is usually the most important change that can be made. This usually means a reduction of vibration amplitudes and of the radiation of sound produced by the vibration. We can separate this problem into three sections:

(1) Decrease the energy available for driving the vibrating system.
(2) Change the coupling between this energy and the acoustical radiating system.
(3) Change the structure that radiates the sound so that less is radiated.

In each of these sections it is usually helpful to track down the important sources of noise and the path of transmission by using frequency analysis of the sound and vibration. The effects of changes in the source (for example, speed, structure, and mounting) on the spectrum should also help in finding the important elements.

The reduction of the vibration that produces noise is discussed later in this chapter.

Change in the coupling system frequently means the use of vibration isolation mounts. It may also mean decreased or even increased stiffness in some members transmitting the vibration. Or it may mean better fastening of some parts to massive, rigid members. Resonant structures are often troublesome coupling members. The resonance may be in the mechanical structure or in an air chamber. In either situation it is usually possible to shift the resonance by changes in the structure or to damp the resonance by adding absorbing material. Mufflers may be needed on exhaust or intake systems.

Changing the radiating structure often means nothing more than reducing the external surface areas of the vibrating parts as much as possible. It may be possible to put holes in the radiating member to reduce the efficiency of radiation. Less stiffness of the part may help to reduce radiated sound by permitting sections to vibrate in different time patterns. Large surfaces near the vibrating parts should also be avoided, since these surfaces may increase the radiating efficiency of the vibrating parts.

Another possible way of modifying the source to improve the noise situation is to change the directivity pattern of the radiated sound. When streams of air or other gases come out of an opening, they radiate sound that may be highly directional at high frequencies. Changing the direction of flow can shift this pattern. It may be possible to direct it in such a way that noise in certain directions is considerably reduced.

## 7.3 CONTROL OF THE PATH OF SOUND.

The control of the noise by changes in the path of the sound can be analyzed into three sections:
(1) Change in relative position of source and listener.
(2) Change in acoustic environment.

(3) Introduction of attenuating structures between source and listener.

7.3.1 CHANGES IN POSITION. Increasing the distance between the noise source and the listener is often a practical method of noise control. Furthermore, merely rotating the source of noise may permit one to decrease the level if a change to a direction of low directivity factor is achieved. Both these procedures are effective only in the region where approximately free-field conditions exist.

7.3.2 CHANGE IN ENVIRONMENT. The most obvious change that can be made in a room to reduce the noise level is to add acoustical absorbing material. A wide variety of commercial acoustical materials is available. These materials are often of great value in a noise reduction program, but the limitations of this treatment should be realized. These materials are mainly useful in the room where the noise originates, and there they help mainly to reduce the noise level at some distance from the source. But at the same time not much reduction is obtained at a distance of 2 feet, say, which is a common distance between a machine and the operator's ear.

7.3.3 ATTENUATING STRUCTURES. A number of different types of attenuating structures are used for reducing the noise level for the listener. One of these is an ear defender, which may be an ear plug, waxed cotton, or earmuffs. Others are walls, barriers, and total enclosures. Almost any degree of reduction of air-borne sound can be achieved by a total enclosure or a combination of several enclosures. But as the required attenuation increases so does the complexity, weight, and cost. In addition, great care must be taken that the attenuation gained by the enclosure is not lost by sound transmission through a ventilating duct or by solid-borne vibration. Because of this possible flanking transmission in ventilating systems, total enclosures frequently require carefully designed ventilating systems with ducts lined with absorbing material. These lined ducts are essentially mufflers for the air stream.

When a door is required in a total enclosure, it should be built with air-tight seals at all joints. A refrigerator-type door is usually satisfactory when it can be used. A total enclosure should also be lined at least on part of the inside walls with absorbing material. This lining helps to keep the noise at the walls of the enclosure at the lowest practical level.

A barrier is not as effective as a total enclosure, but it does help to shield high-frequency sound. Little attenuation of low-frequency sound is obtained unless the barriers are very large, and the attenuation of high-frequency sound is usually only a few decibels unless the opening that remains is relatively small. Here, too, absorbing material should cover the barrier to avoid exaggerating the level by reflections from the barrier.

7.3.4 ILLUSTRATIVE EXAMPLE. In order to illustrate the possible noise reduction achieved by use of vibration isolation, barriers, enclosures, and acoustic treatment, an example made up for the purpose is shown in a series of figures, Figures 7-1 to 7-8. We intend to show here only the general nature of the noise reduction obtainable as given by changes in the octave-band spectrum and the speech-interference level. Actual results will vary in detail, and situations do occur where the results differ materially from those shown because of factors not considered here. But, in general, the noise reduction shown in the figures can be considered typical.

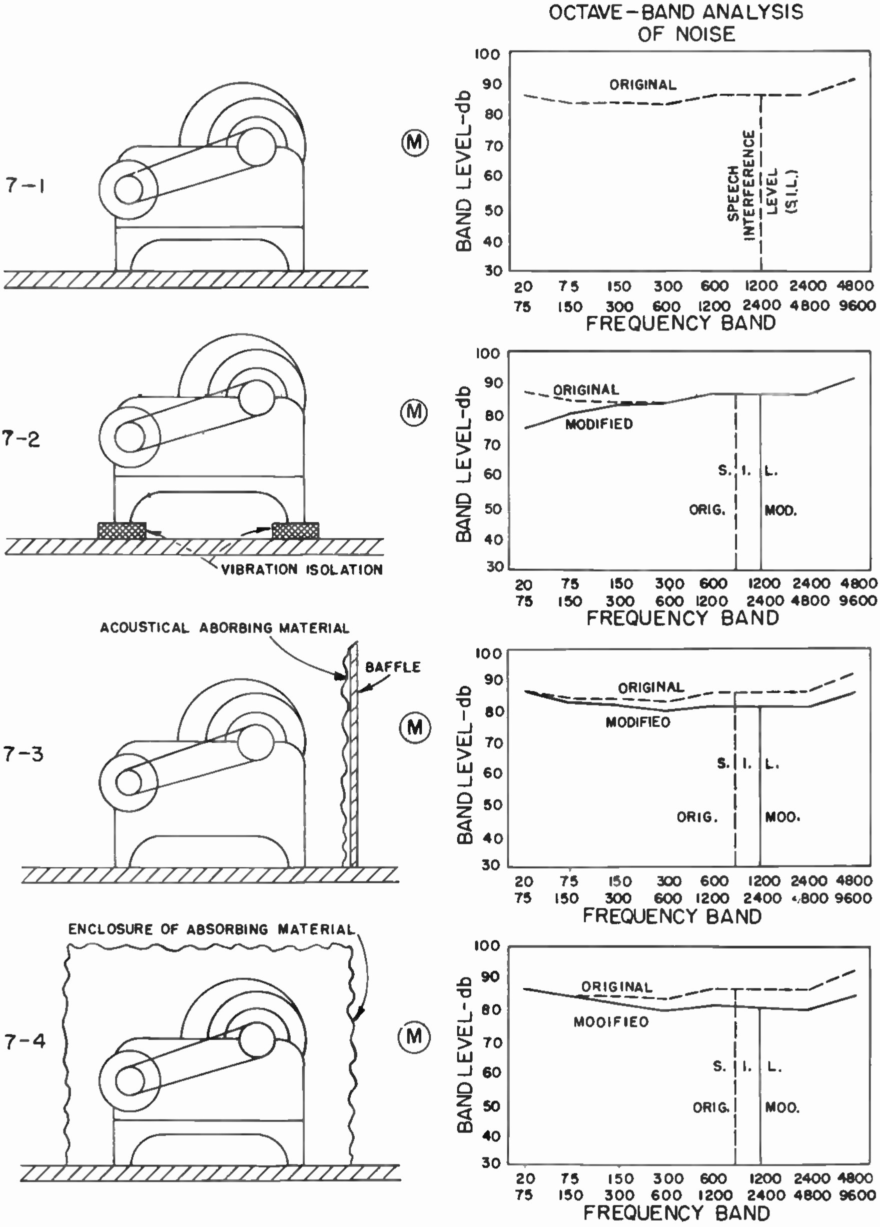
Figure 7-1 shows the octave-band analysis of the noise from the assumed machine. The speech-interference level is also shown. This machine is a noisy one with a spectrum that shows appreciable noise energy all over the audible range. All the noise measurements are assumed to be made in the relative position shown for the microphone, designated M on the figures.

The use of vibration isolation mounts may be an important step in noise control. As shown in Figure 7-2, the initial result, however, is often only a moderate reduction of the low-frequency noise. The machine itself usually radiates most of the high-frequency noise directly to the air, and the amount radiated by the floor is small. A reduction in the vibration level at the floor only is then not important at high frequencies. At low frequencies, however, the machine may be too small to be effective in radiating sound, and then the floor may act as a sounding board to contribute materially to low-frequency sound radiation.

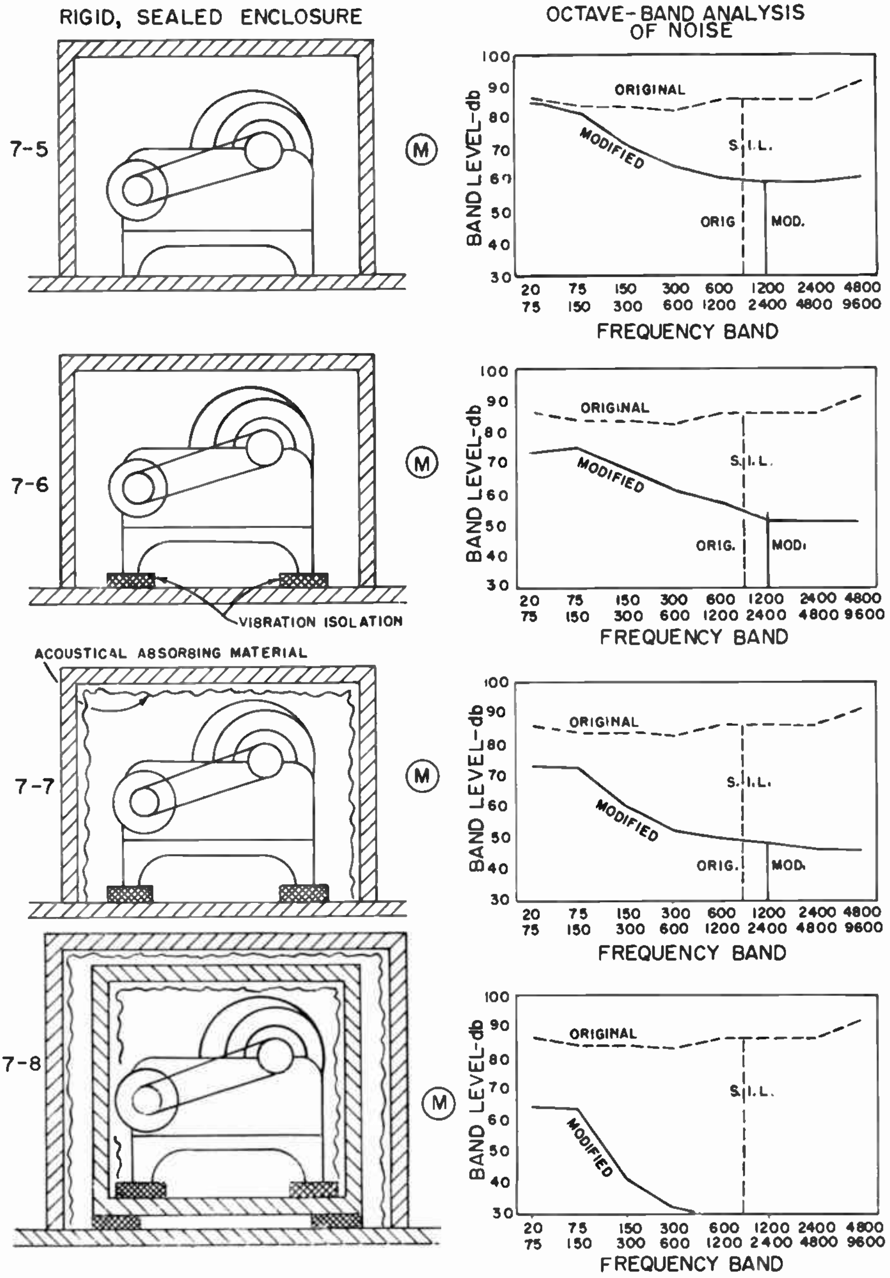
It is even possible to increase the noise as a result of the use of vibration mounts. This result is usually found when the stiffness of the mounting is of such a value that some vibration mode is exaggerated by resonance, but resonance can be avoided by proper design of the mounting. In the illustrative example it is assumed that the mounting is sufficiently soft that the basic vibration resonance of the machine on the mounting system is below 20 Hz. In this particular example no significant change in the speech-interference level is shown as a result of the use of vibration isolation mounts alone.

The results shown in Figure 7-3 illustrate that a barrier is mainly effective at high frequencies, and there it produces only a moderate reduction in noise level.

The novice in this field sometimes assumes that the materials used for sound absorption can also be used alone for sound isolation. If we build an enclosure solely of these



*Figures 7-1 through 7-4. Examples to illustrate the possible noise reduction effects of some noise control measures.*



*Figures 7-5 through 7-8. Examples to illustrate the noise reduction possible by the use of enclosures.*

materials mounted on a light framework, we would typically find the result shown in Figure 7-4. Only at high frequencies do we have a noticeable reduction in level, and even there it is a small reduction.

A more satisfactory enclosure is built of more massive and rigid constructional materials. Assume that we enclose the machine by a well-sealed, heavy, plasterboard structure. Then we might observe the result shown in Figure 7-5. Here an appreciable reduction is obtained over the middle- and high-frequency range. The enclosure is not as effective as it might be, however, because two important factors limit the reduction obtained. First, the vibration of the machine is carried by the supports to the floor and then to the whole enclosure. This vibration then may result in appreciable noise radiation. Second, the side walls of the enclosure absorb only a small percentage of the sound energy.

The addition of a suitable vibration isolation mounting will reduce the noise transmitted by solid-borne vibration. This effect is illustrated in Figure 7-6. Here we see a noticeable improvement over most of the audio spectrum.

When the sound absorption within an enclosure is small, the noise energy from the machine produces a high level within the enclosure. Then the attenuation of the enclosure operates from this initial high level. The level within the enclosure can usually be reduced by the addition of some sound-absorbing material within the enclosure, with the result that the level outside the enclosure is also reduced. This effect is shown in Figure 7-7, which should be compared with Figure 7-6.

If even more noise reduction is required than that obtained by the one enclosure, a second, lined, well-sealed enclosure can be built around the first. The first enclosure is supported within the second on soft vibration mounts. Then a noise reduction of the magnitude shown in Figure 7-8 can be obtained.

## 7.4 SUMMARY OF NOISE REDUCTION PROCEDURES.

The approach to a noise reduction problem can be summed up as follows:

(1) Consider the source.
    Can a quieter machine be substituted?
    Can the noise energy be reduced?
    Can a useful change be made in the directivity pattern?
    Are resilient mounts of any use here?
    Can a muffler be used?
(2) Consider the path from the source to the listener.
    Can the source or the listener be readily moved to reduce the level?
    Is acoustic treatment a useful solution?
    Should barriers be erected?
    Is a total enclosure required?

## 7.5 VIBRATION REDUCTION.

The basic procedure for vibration reduction will be described briefly. Many specialized techniques have been developed also, and a complete summary of these is impractical here. More extensive information on vibration reduction will be found in the references.

The approach to reducing vibration is summarized in Table 7-1.

TABLE 7-1

The general approach to vibration reduction can be divided into two major parts as follows:

1. Change source or coupling to vibrational driving force.
    a. Reduce its strength.
    b. Eliminate it by substitution, or otherwise.
    c. Isolate it.
    d. Change its character, frequency (speed).
2. Reduce response to driving force.
    a. Insert isolating members.
    b. Damp vibrating elements.
    c. Detune resonant systems.
    d. Change mass. Increase mass of stationary elements or reduce mass of moving elements.
    e. Change stiffness.
    f. Add auxiliary mass damping or resonant absorbers.

### 7.5.1 CHANGING THE DRIVING FORCE.

In order to see how the driving force can be changed, it is useful to review the many ways that a vibratory force is developed. Here there are two basic processes involved. Either mechanical energy of some type is coupled into mechanical vibratory energy by one or more methods, or energy in some other form is transformed into mechanical vibratory energy, as outlined in Table 7-2.

## TABLE 7-2

Sources of vibrational forces and coupling systems:

1. Mechanical
    - Unbalanced rotating masses.
    - Reciprocating masses.
    - Fluctuating mechanical forces or torques.
    - Fluctuating loads.
    - Fluctuating mass or stiffness.
    - Poorly formed moving components.
    - Mechanical looseness.
    - Misalignment.
2. Transformation from another form of energy.
    - Varying electrical fields.
    - Varying hydraulic forces.
    - Aerodynamic forces.
    - Acoustic excitation.
    - Varying thermal conditions.

Sometimes the source of the vibratory force is readily apparent or well known from experience. At other times use of some measuring instruments can be invaluable in tracking down sources.

Here are some examples:

Stroboscopic observation of a cam and follower showed that above a certain speed the follower did not remain in contact with the cam during certain parts of the cycle. When the cam periodically came into contact with the follower after the

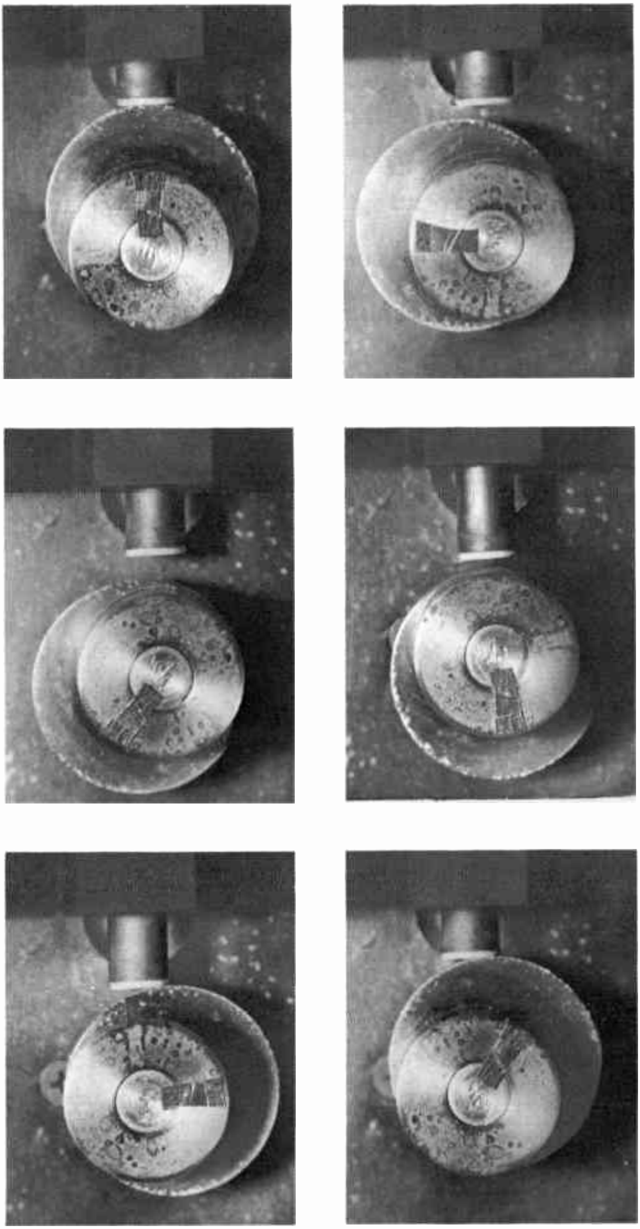


*Figure 7-9. Sequence of photographs shows misbehaving cam and follower. The cam is rotating at 2000 rpm. The photographs were taken with stroboscopic illumination at different phases of the cam cycle to show the bouncing action when the cam rotates above a critical speed.*

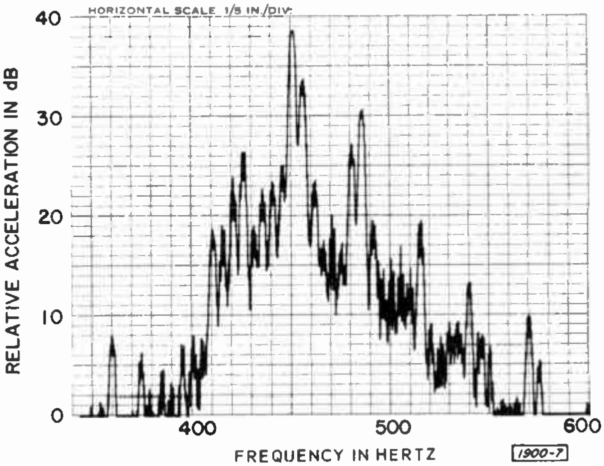


*Figure 7-10. A part of the recorded frequency analysis of the vibration of a gear-belt drive. The tooth-contact rate of 450 impacts per second determines the frequency of the dominating component, and the gear belt with its speed of 5 rps introduces a host of components spaced about the main component by multiples of 5 hertz. The torque pulsations from the 1800-rpm synchronous motor and the 120-Hz magnetically driven vibration in the motor also influence the spectrum.*

period of separation, a serious impact occurred, which resulted in excessive vibration and noise.

A frequency analysis of a vibration often shows up strong components whose frequencies can be related to certain shaft speeds or gear-tooth meshing frequencies, and in this way the source can be tracked down. Sometimes, however, the relations are not simple. As pointed out by L. S. Wirt[1] the gear-tooth meshing frequency may be modulated at rates determined by shaft speeds, because of run out, and by the rate at which the torsional loading varies.

For devices that are electrically driven, strong vibration components at frequencies that are multiples of 120 Hz are good indications that these vibration components are electromagnetically excited. Sometimes one can check this deduction by monitoring the level of such components, first when the device is operating normally, and then when the electric power is suddenly disconnected. Usually the driven devices will coast long enough so that the mechanical forces will not

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[1] L. S. Wirt, "An Amplitude Modulation Theory for Gear-Induced Vibrations," Chapter 17 in MEASUREMENT ENGINEERING by P. K. Stein, Stein Engineering Services: Tempe, Arizona, 1962.

change rapidly even though the electrical forces are changed abruptly.

When a device can be driven at varying speeds, the effect of changed speeds on the frequencies and amplitudes of the various important components can be an important clue in tracking down the sources of those components. Here the changes in shaft speeds and mesh frequencies can be related to changing or steady frequencies. This technique is particularly helpful if the relative speeds of some parts can be changed or if a clutch can be used to deactivate some sections.

When the indication on the meter of a vibration meter or of a broad-band analyzer fluctuates erratically over a range of 2 to 1 (6 dB) or more, the vibration is usually random in character, and the source is then probably to be found in some rattle, friction-induced vibration, turbulence, poor ball bearings, gases or liquids in motion, or combustion processes. The relative value of a peak and average reading also serves to differentiate this type of vibration from the simpler harmonic motion of rotating unbalanced masses. For simple harmonic motion the peak value will be about 1.5 times the average value (and the peak-to-peak, about 3 times). For random signals the ratio is usually much higher, that is 3 to 4 times (or 6 to 8 times for peak-to-peak).

Listening by means of a pair of earphones to the signal picked up by the vibration pickup can be helpful in determining the cause of a vibration, particularly if the source is defective ball or needle bearings or air leaks, which give a rough quality to the sound. The earphones should have a good pair of ear cushions or muffs to keep out extraneous sound.

Once the mechanism producing the vibratory force is recognized, a review of the possible means for reducing the force is in order. Thus, balancing techniques can be applied, better gears or bearings can be substituted, proper lubrication can be applied, the mechanical structure can be improved (for example by lightening the moving members and increasing the weight of stationary members), and gas or liquid velocities can be reduced.

7.5.2 BALANCING ROTATING MACHINERY. Unbalance in rotating devices is one of the chief causes of excessive vibration. This single cause is so important that extensive discussions of it will be found in the books cited earlier in this section. Some possible procedures for balancing are also described there. Techniques for balancing in-place with relatively simple instruments (vibration pickup, sound-level meter, narrow-band analyzer, and Strobotac® stroboscope) are described by R. Y. Chapman, "In-Place Dynamic Balancing Instrumentation," Technical Report No. 225-66, Acoustical Research and Development Division, U.S.N.S.B.N.L., Groton, Connecticut.

Criteria for balancing have been recommended by the

Association of German Engineers (VDI 2060 - October 1966), and some of their recommendations are given in Figure 7-11. Their rating is in terms of the unbalance in gram-millimeters divided by the weight of the rotor. This normalized unbalance for a given type of device is then required to be inversely proportional to the rotor speed*. Subject to this requirement different degrees of unbalance are given <u>quality numbers (Q)</u> ranging from 0.4 to 1600.

Quality
Q

630

Rotary parts of rigidly mounted 4-cycle engines.
Rotary parts of resiliently mounted ship diesel engines.

250

Rotary parts of rigidly mounted, high-speed 4-cylinder diesel engines.

100

Rotary parts of rigidly mounted, high-speed diesels with 6 or more cylinders.

40

Rotary parts of resiliently mounted, high-speed 4-cycle engines with 6 or more cylinders.
Autowheels and rims.

16

Drive shafts with special requirements.
Parts of crushing and agricultural machinery.

6.3

Centrifugal drums, blowers, flywheels, centrifugal pumps, machine and machine-tool parts, regular motor armatures, crankshafts with special requirements.

2.5

Rotors of jet engines, steam and gas turbines, blower turbines, turbogenerators; machine tool drives; medium and large motor armatures with special requirements, small motor armatures; turbine-driven pumps.

1

Tape recorder drums and hi-fi turntables; drives for grinders, small motor armatures with special requirements.

0.4

High-precision grinding spindles and pulleys, gyros.

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*This requirement is equivalent to the velocity amplitude of the periodic motion of the center of gravity being constant. Again this requirement shows the practical significance of rating in terms of velocity.

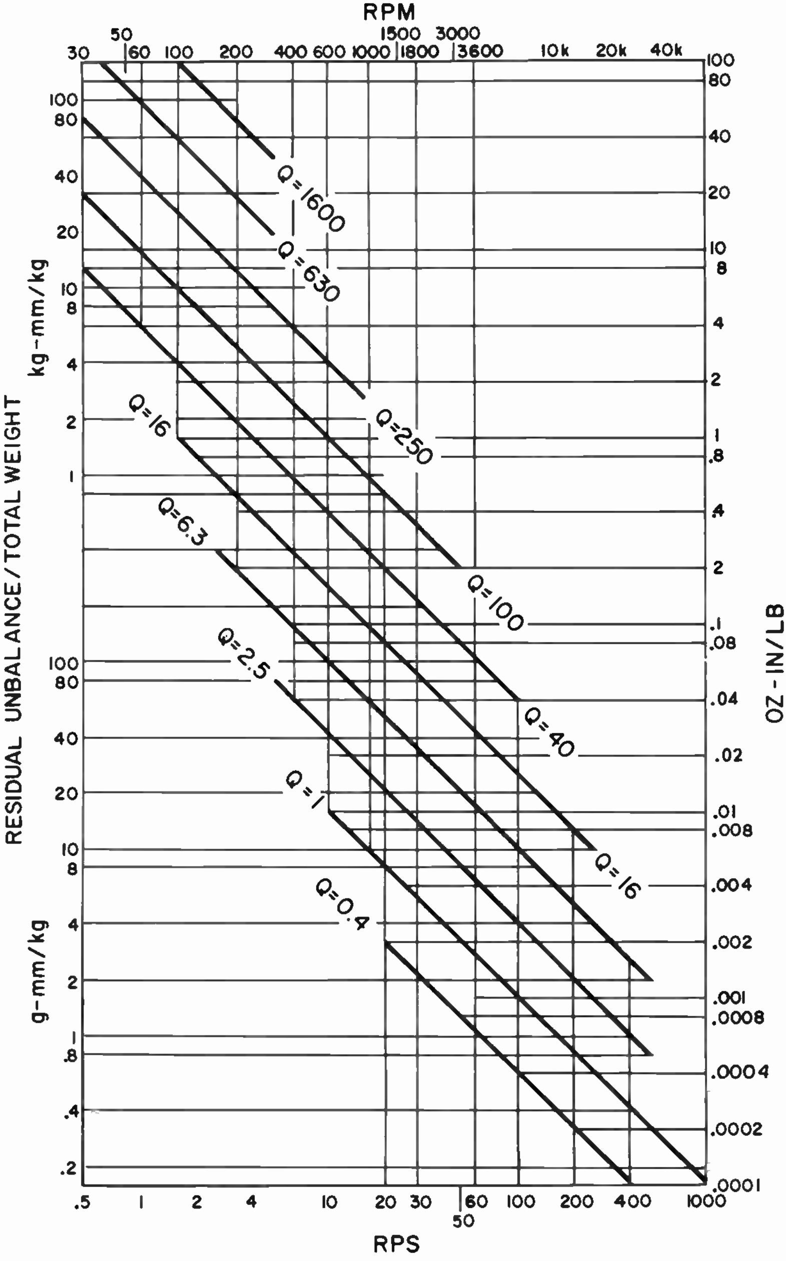

*Figure 7-11. Chart of the relation between the unbalance and the rated quality numbers (VDI 2060-176 October 1966).*

As shown by the listing of rotary devices the degree of balance required depends on the device and its applications. Thus the residual unbalance for the rotor of a small electric motor running at 3600 rpm should be less than .004 oz-in./pound of rotor weight.

7.5.3 REDUCING RESPONSE TO DRIVING FORCE. A further important step in the process of vibration reduction is to reduce the response to the driving force. Here, too, measurement techniques can be valuable in guiding the approach to reducing the response. For example, exploring for maxima in vibration level may show up resonant modes of vibrations of plates and other structural members. It can show where damping may be most effective or where resonant absorbers can be added. It may also show where detuning can be used.

7.5.3.1 Resonance Effects. The phenomenon of resonant vibration occurs frequently; for example, resonant vibration is essential to the operation of most musical instruments. The undesired resonances in some automobiles at certain speeds can be very annoying.

The effects of resonant vibration in rotating machinery can be so serious that the design of these devices includes the calculation of the critical speeds (resonant frequencies). These calculations are used to make certain that whenever possible, the critical speeds are not included in the normal operating range of the device.

The resonant or natural modes of vibration for many types of simple structures have been calculated. Some of these are beams, shafts, plates, and stretched wires. The frequencies of the resonant modes depend, for example, on the shape, dimensions, stresses, mounting, and material characteristics. The frequencies can also be affected by coupling to other structures.

The nature of resonance is readily illustrated by vibration of a table on which a mass is flexibly mounted with the table driven at a constant amplitude but at different frequencies. At a certain critical frequency the motion of the mass will be greater than for frequencies just slightly higher and slightly lower. This frequency at which a maximum in vibration occurs is a resonant frequency. If the structure being shaken is relatively complex, many such maxima can be observed. (It is often helpful to use a stroboscopic technique to make this motion visible at a slowed-down rate.) Minima of motion may also be due to resonances.

In an actual operating device, resonant conditions may be obvious because of excessive noise or observed vibration at certain speeds. Exploring by means of a vibration pickup for the points at which vibration is much larger than for other places on the device will often locate the resonant elements. The resonances may be of the simple type where a mass is

*Figure 7-12. An electronic stroboscope arranged for triggering from a photoelectric pickoff with an adjustable delay. These instruments were used to obtain the photographs of the cam and follower.*

mounted on a flexible support, or they may be of the plate-mode type where the mass and flexibility of a plate or sheet are in resonance so that different parts of the plate are moving differently. In this latter instance very complicated motions may result.

Unless there is some significant dissipation of energy (damping) as the system vibrates, the resonant amplitude of motion may become very large even with a relatively small driving force. These large amplitudes must ordinarily be avoided. The two principal ways of reducing these amplitudes are detuning and damping. If the driving force is at a relatively fixed frequency, it may be relatively easy to move the frequency of resonance out of the operating range by a change of the resonant-element mass or stiffness or both. The use of damping devices or highly damped materials is the other important possibility.

Many techniques for damping vibration have been developed. They include dashpots and other viscous absorbing systems, mastic coatings, sandwich-type dissipative materials, inherently dissipative plastics or metals, electromagnetic damping, frictional rubbing devices, and dynamic absorbers.

Measurements of the vibration levels at various parts of the device under study can help to show where damping devices can be applied most effectively. Thus if a resonant condition is to be damped, an analyzer tuned to the frequency of resonance should be used on the output of a pickup. Then when the measurements are made at different points on the vibrating device, only the vibration component at the resonant frequency will be observed so that the actual resonant maxima can be obtained without being obscured by high-amplitude low-frequency vibrations. When such measurements are made, the vibration pickup must be light in weight compared with the mass of the resonant element so that it does not appreciably detune the resonant system. Whenever possible stroboscopic observations should be made, since this can be done without affecting the vibration.

As an example of the effectiveness of damping in reducing resonant vibration, Ruzicka[2] reports on an aluminum chassis for electronic modules that was giving trouble because of fatigue failures and incorrect operation because of the collision of modules during resonant vibration of the chassis. The installation of stiffening plates made of visco-elastic-damped material reduced the vibration amplification at the main resonant modes by factors of 3 to 4, and the vibration-caused problems were eliminated.

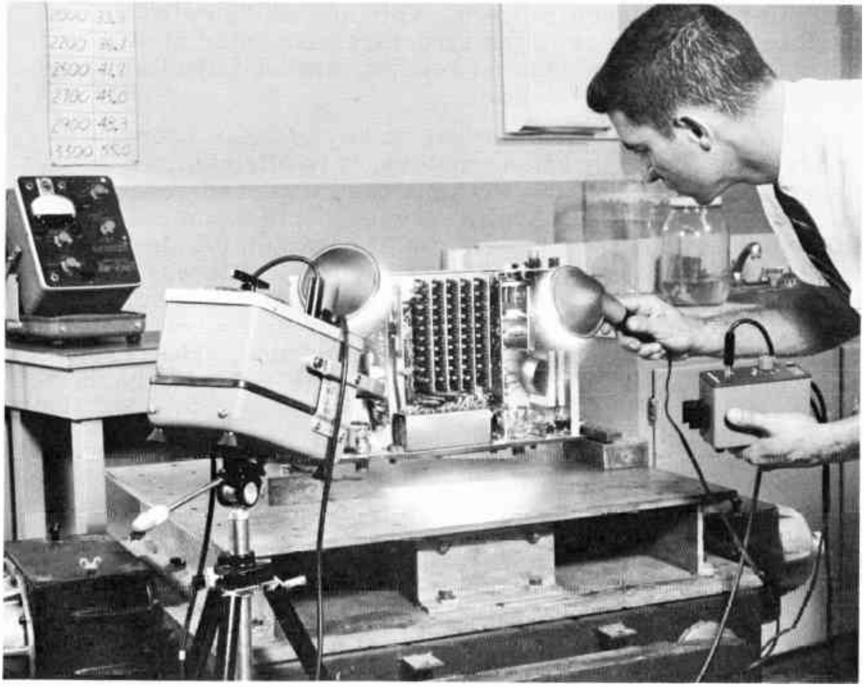

*Figure 7-13. Stroboscopic observation of the motion of parts in an electronic instrument while it is being shaken.*

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[2] J. E. Ruzicka, "Vibration Control: Applications," ELECTRO-TECHNOLOGY, Vol. 73, No. 1, January, 1964, pp. 75-82.

7.5.3.2 Oscillating Conditions. In most instances resonance is exhibited when the natural-mode frequency of a vibrating member coincides with, or is very close to, one of the component frequencies of the driving force. Certain unstable systems, however, do not require this coincidence when the conditions make the system self-oscillatory. They require what is essentially a reasonably steady driving force. Galloping transmission lines and some forms of machine-tool chatter, electrical brush squeal and automobile shimmy are examples of this type of excitation.

The galloping and torsional oscillations in some suspension bridges are aerodynamically induced forms of vibration. Such torsional oscillations destroyed the first Tacoma Narrows Bridge on November 7, 1940. The proper aerodynamic design of such a structure can essentially eliminate this vibration[3].

The Mackinac Bridge as a matter of fact is a classic example of the possible tremendous value that can accrue from careful control of vibration. In its design the vibratory driving force produced by wind was made essentially zero by the particular open structure used. This new design also made possible great savings in the structure. As an additional precaution the deck openings and roadway are arranged to damp any vibration that may occur.

7.5.3.3 Variation of Parameters. In any of these procedures for tracking down vibration troubles, it is often helpful to change some element, for example the mass, and observe how the change affects the vibration levels. This technique can be classed as the method of variation of parameters. In other words, change things and see what happens. The way of "seeing" is, of course, to use measurements that will give a good basis for judging what has changed and by how much. In general, one follows a logical guessing procedure. The results of the experiments help one to eliminate or confirm the various possible sources of vibration effects.

7.5.4 VIBRATION ISOLATION. The reduction of the effects of vibration by isolation is widely used[4]. This isolation technique

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[3] D. B. Steinman, "The Design of the Mackinac Bridge for Aerodynamic Stability," JOURNAL OF THE FRANKLIN INSTITUTE, Vol. 262, No. 6, December, 1956, pp. 453-468.

[4] C. E. Crede, VIBRATION AND SHOCK ISOLATION, John Wiley: New York, 1951.

J. P. Den Hartog, MECHANICAL VIBRATION, McGraw-Hill: New York, 1956.

I. Vigness, "Vibration Isolation," PHYSICS TODAY, Vol. 18, No. 7, July, 1965, pp. 42-48.

SAE Committee G-5: Aerospace Shock and Vibration, DESIGN OF VIBRATION ISOLATION SYSTEMS, Society of Automotive Engineers: New York, 1962.

is usually illustrated with a vibrating device mounted on a foundation by means of soft springs or other resilient devices. If the isolation system is properly designed, the vibratory force transmitted to the foundation will be less when the springs are used than when the device is clamped directly to a foundation. The device itself, however, will ordinarily vibrate with a greater amplitude when mounted on a soft mount. Thus it is essential to realize that the isolation is working in only one direction, that is, the original source of vibratory force is not reduced by this isolation. Of course, if the foundation is vibrating as a result of some other driving force, one can reduce the effects of the vibration on a device by suspending it on a suitable soft mount. Some scientific instruments must be isolated in this way from building vibrations in order to operate satisfactorily.

Many commercial vibration isolators, or shock mounts, are available, and the manufacturers of these mounts usually supply information for their proper use. It is most important in applying isolators to avoid having the natural frequency of the mass of the device and the resilient suspension be nearly the same as the frequency of the driving force. When such a condition occurs, the transmitted vibration may be greater with the use of isolators than without. A frequency analysis of the vibration, which gives the component frequencies of the driving force, and a knowledge of the mechanical constants should make it possible to avoid this simple resonance effect.

Supports should be located to avoid cross coupling from one mode of vibration to another. Such a requirement ordinarily means that the line of action of the support should pass through the center of gravity of the device being supported.

The foundation, the isolating suspension system, and the supported structure will have, individually and in combination, resonant modes at frequencies higher than the first natural resonance. Sometimes these higher modes cause trouble, because the isolation is reduced from that normally expected[5].

The usual commercial vibration isolators include sufficient damping so that effects of the higher order resonances in the isolator are not serious. But the isolation is usually significantly less at high frequencies than one would expect on the basis of the simple idea of a weight supported on a spring.

Torsional vibration is isolated by the use of flexible couplings, flexible shafts, and belts. These, too, include some damping, and they also introduce resonant modes of torsional vibration in conjunction with the rotational inertia of the coupled system.

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[5] R. Plunkett, "Interaction Between a Vibratory Machine and Its Foundation," NOISE CONTROL, Vol. 4, No. 1, January, 1958, pp. 18-22.

Multiple isolators need careful design in order to be effective. When two isolator units are used in cascade, serious effects that interfere with satisfactory isolation may occur[6].

7.5.5 MAINTENANCE. When maintenance of proper performance or acceptable noise and vibration levels is the goal, symptoms are used as a guide to discover the source of any trouble that may develop and to decide on the remedy. Before these symptoms are reviewed, it is also helpful to keep in mind the many ways that machine performance is affected by changes that occur with time. A systematic classification of the sources of these changes should serve to point up the many possibilities that exist (see Table 7-3).

TABLE 7-3

The changes in machinery that produce changes in vibration level are countless, and they include or are a result of the following:

1. Wear
2. Erosion
3. Corrosion
4. Aging
    - Curing
    - Crystalization and fatigue
    - Solidifying of grease or packing
    - Loss of adhesion or bonding
5. Inelastic behavior
    - Parts stressed out of shape
    - Bent parts
    - Increased tolerances
6. Loosening of fastenings
7. Broken or damaged parts
8. Incorrect or inadequate lubrication
9. Foreign matter
    - Dirt, chips, dust, grit
    - Contaminants
    - Humidity
    - Ice accumulation
    - Paint and other finishes
10. Environmental changes
    - Temperature
    - Humidity
    - Pressure
11. Chemical changes in materials

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[6] E. Skudrzyk, "Theory of Noise and Vibration Insulation of a System with Many Resonances," JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, Vol. 31, No. 1, January, 1959, pp. 68-74.

The existence of a vibration problem may be first noticed in a routine survey of the vibration levels on the machines in a plant, or it may become evident the performance of a machine may be obviously not so good as it should be. In either situation the usual first step in tracking down the trouble is to locate the point or area where the vibration level is the highest. Inspection at this point may show the real source of the trouble. It is important to remember, however, that vibration is transmitted very readily by metal, and occasionally the point at which the trouble is best corrected is some distance from the point of maximum vibration.

The next step in the search is often a study of the character of the vibration signal, that is, the dominant frequency (low or high), whether it is a tone, random in nature (a rough, rushing or roaring noise in the earphones at the output of a vibration meter), or an impact-type vibration.

The measurement of displacement tends to emphasize low-frequency vibration, and acceleration emphasizes high-frequency vibration. Thus a vibration meter that can measure both these quantities in addition to velocity is helpful in diagnosis. When high-frequency vibration or impact vibration is significant, listening to the character of the vibration signal can often provide an additional clue. For example, poor ball bearings have a characteristic rough tone that may wax and wane.

The nature of the vibration can be classified into three broad classes with a host of possible faults. By the use of the position information and the possible pertinent faults listed in the following classification, one may be able to track down the specific fault in a given case. Or at most only a few possibilities need to be considered and a process of elimination used. For a specific machine, the following list, if not pertinent, at least, may suggest the possibilities that must be considered.

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TABLE 7-4

Vibration Characteristics and Their Causes

Low-frequency vibration (frequency of order of shaft or belt speeds)

- Unbalanced rotor (worn, eroded, broken, or corroded parts)
- Misalignment (induces significant axial vibration)
- Eccentric shafts
- Slipping clutches
- Mechanical looseness
- Loose foundation bolts
- Oil whirl or whip (1/2 or less times shaft speed)
- Worn belts
- Belts and pulleys out of adjustment

TABLE 7-4 (Continued)

Aerodynamically driven galloping and twisting
Changed reciprocating elements that introduce added torsional vibration.

High-frequency vibration

Defective bearings (random or rough vibration)
Inadequate lubrication
Poor gears
Slipping clutches
Rubbing or binding parts
Air leaks
Hydraulic leaks

Impact vibration and rattles

Parts colliding
Broken or loose pieces
Electromagnetically driven loose pieces
Water hammer
Surge

In addition to position, frequency, and charater of the vibration, timing may also furnish an important clue to the nature of the difficulty. Here, stroboscopic observation with a photoelectric pickoff to trigger the stroboscope can be helpful, as illustrated by the cam and follower study previously mentioned.

When stroboscopic observation is not possible, the vibration signal may be observed on an oscilloscope with timing supplied by the photoelectric pickoff.

7.5.6 CONCLUSION. Finally, all vibration problems should be approached to see first if a common-sense, simple, quick solution is available. For example, the whole device that is causing the trouble may be avoided by the use of a totally different kind of device. But if a simple solution is not obvious, the quantitative results of measurements are often essential elements in the efficient analysis and solution of the problem. As various control procedures are used, vibration measurements can show the progress being made and when the attack on the vibration problem must be shifted from one form or place to another.

chapter 8

# SOME CASE HISTORIES

In order to illustrate some of the procedures given in this book, we shall describe in this chapter how some industrial noise problems might be handled. They are taken from actual experience, and where instruments are mentioned, the latest equipment is named, although some of the instruments actually used were earlier models. The principles and techniques illustrated remain unchanged, and the slight departure from authenticity is made up for by the greater usefulness of reference to a current instrument.

## 8.1 NOISE FROM AN AIR COMPRESSOR.

Engineers in a group of offices were annoyed by an intense low-frequency noise whenever an air compressor in another part of the same building was running. The noise was most intense when the office windows were open; the air intake for the compressor was about 50 feet away on the near side of the building. Furthermore, the noise level varied markedly in the office; that is, in the middle of the office the noise was hardly noticeable, but near the windows or the door on the opposite wall the noise was loudest. This standing-wave pattern was confirmed by a quick check on a sound-level meter, with weighting control in the flat position, to show that the maxima were about 162 inches apart. When the windows were closed, the maxima were not obvious because of other background noises. With one or more windows open, the pattern was relatively unaffected by opening or closing the door.

The obvious explanation of this behavior was that the pulses produced at the air intake were propagated through the windows and excited a resonant mode of the office. But one of the engineers suggested that the result might be produced in a different fashion. He suggested that the driving force could be a vibration transmitted through the building and that the windows needed to be open in order for the room resonance to coincide with the frequency of the driving force. (He admitted this explanation was far fetched.)

In order to decide what to do about the problem, some simple measurements were made. Since the annoying noise was low in frequency, it was decided to use the combination of a Type 1560-P40K Preamplifier and Microphone Set driving a Type 1564-A Sound and Vibration Analyzer, which could measure noise components at frequencies as low as 2.5 Hz. A Type 1562-A Sound-Level Calibrator was used to set the level controls. The microphone was set up at one of the maximum level points near the door, and the third-octave analysis shown in Figure 8-1 was obtained. The strong components near 16 and 40 Hz were remeasured with the 1/10-octave bandwidth to be actually at 14 and 37 Hz. The strong component at 37 Hz appeared to be the major offending noise.

A Type 1560-P52 Vibration Pickup was connected to the Type 1564-A. This combination was calibrated by means of a Type 1557-A Vibration Calibrator. Then some exploration of the office floor for a 37 Hz component indicated nothing significant. An analysis of the vibration of the pump structure produced the result shown in Figure 8-2. These measurements satisfied the one engineer that his explanation based on vibration was probably incorrect.

Since the 37-Hz component was so dominant, it could be assessed as a pure-tone. The equal-loudness contours of Figure 3-3 indicated that its loudness level was about 70 phons. Although the rating procedures of Chapter 3 apply generally to broad-band noise, it is obvious from those ratings that a significant drop in level for this very loud tone would be necessary in order to make it acceptable. If it could be lowered to 40 phons, it would probably be unobjectionable. This drop would require a decrease in sound-pressure level to 70 dB.

Many possibilities for correcting the annoying condition were considered, for example, changes in the offices so that they would not resonate at the troublesome frequency, a change in compressor speed, and rerouting of the air intake. The solution adopted was to add a pneumatic filter to the air intake. With the data on the significant components at hand,

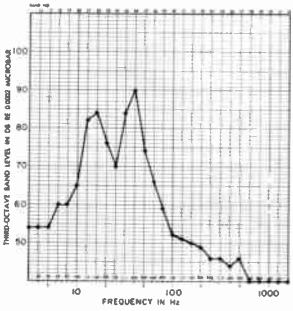


*Figure 8-1. Sound spectrum of noise in office.*

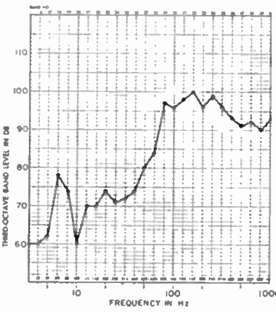


*Figure 8-2. Vibration spectrum at pump.*

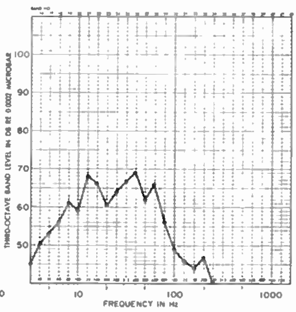


*Figure 8-3. Sound spectrum of office noise after addition of pneumatic filter.*

it was easy to design a proper filter. Thirty feet of pipe was already being used from the air intake to the compressor, and calculations showed that it could form part of the filter. An air tank was added at the center of this pipe, and the noise was so reduced that it was no longer troublesome. The noise analysis in the office after this change is shown in Figure 8-3.

## 8.2 BRAIDING-MACHINE NOISE.

When a manufacturer introduced a process of putting a braided nylon sheath around a cable of wires, the employees in the vicinity of the braiding machine complained about the noise it made. In common with other machines of this type, this was a broad-band noise source, and the obvious instrument to use was an octave-band analyzer.

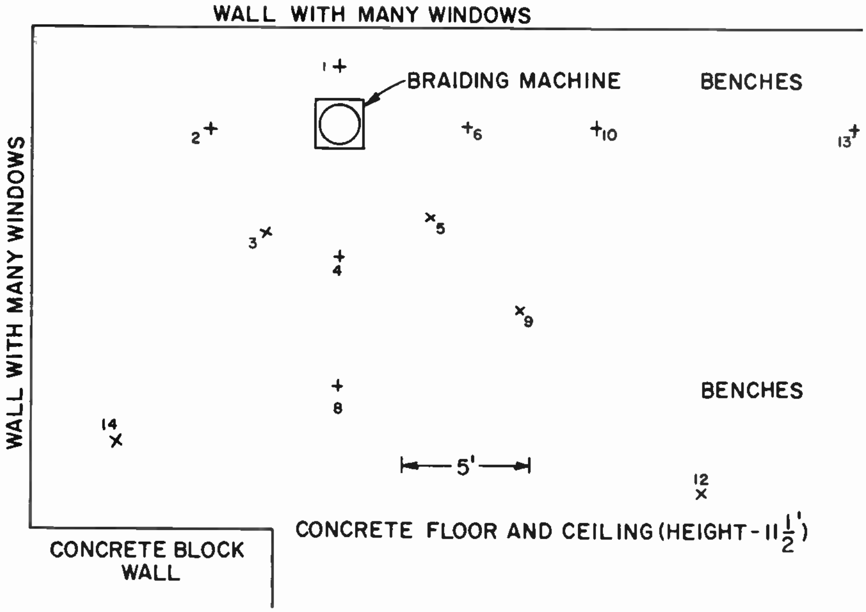
The Type 1558-BP Octave-Band Noise Analyzer with a Type 1560-P6 Microphone Assembly was calibrated with a Type 1562 Sound-Level Calibrator. This equipment was used to analyze the noise at a number of places around the machine. Some of the results are shown in Figure 8-4.

A study of the machine indicated that it would be very difficult to modify it to reduce the level at the operators' ears without reducing the production rate. It was decided therefore to supply protective earmuffs for the operators, since the levels were in the hazardous regions. To protect the other workers, the machine was put in a separate room heavily treated with acoustical tile. In addition, to avoid troubles from open windows in the summer bypassing the wall barriers, the room was air-conditioned. The air conditioning made it unnecessary to open the windows, and it made it possible to wear the earmuffs with comfort even in the summer.

## 8.3 REDUCTION OF FLUTTER IN A TAPE RECORDER.

Measurements of the flutter (variations in tape speed) of a tape recorder showed strong components at 15, 30, and 75 Hz and other minor components. Although it was expected that eccentricities in the drive produced some of this flutter, a check on the effects of vibration was made.

A Type 1560-P54 Vibration Pickup was mounted on the tape deck and connected through a Type 1560-P40 Preamplifier to a Type 1564-A Sound and Vibration Analyzer. The analyzed vibration showed strong components at 30 and 75 Hz, but very little at 15 Hz. The 30 Hz component corresponded to the motor speed. Although the motor and attached flywheel had been balanced before being mounted, the vibration was easily reduced by rebalancing of these in place. After balancing, the flutter component at 30 Hz was negligible, and the 75 Hz component was markedly reduced also.



| Measurement Position | Octave Band-Center Frequency - Hz | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| | Band Levels in dB re $20\mu N/m^2$ | | | | | | | |
| 1 | 65 | 68 | 73 | 86 | 91 | 93 | 94 | 90 |
| 2 | 64 | 65 | 68 | 82 | 86.5 | 90 | 92 | 88 |
| 3 | 63 | 63 | 68 | 81 | 87 | 89 | 91 | 87 |
| 4 | 66 | 76 | 69 | 81 | 86 | 90 | 91 | 87 |
| 5 | 65 | 67 | 69 | 85 | 86 | 89 | 90 | 87 |
| 6 | 65 | 72 | 69 | 83 | 86 | 89 | 91 | 88 |
| 8 | 65 | 69 | 67 | 80 | 84 | 88 | 89 | 86 |
| 9 | 60 | 62 | 66 | 80 | 84 | 88 | 89 | 86 |
| 10 | 65 | 69 | 68 | 80 | 85 | 88 | 89 | 87 |
| 12 | 62 | 60 | 64 | 78 | 83 | 86 | 87 | 84 |
| 13 | 61 | 60 | 65 | 78 | 81 | 85 | 86 | 83 |
| 14 | 65 | 70 | 69 | 81 | 85 | 89 | 90 | 87 |

Microphone on analyzer - 42" above floor.

*Figure 8-4. An octave-band analysis of braiding-machine noise (paragraph 8.2).*

The 15 Hz component corresponded to the capstan speed, and it was the largest remaining component. The fact that there was no appreciable vibration at this frequency seemed surprising at first. The flutter could be reduced significantly by the placing of eccentric weights on the capstan flywheel; but then the vibration of the tape deck increased markedly at 15 Hz. Obviously, this flutter component was caused by eccentricity in the capstan, and the vibration introduced was canceling the effects of eccentricity.

Measurements at the capstan bearing showed that the vibration at 75 Hz was a maximum there. What was happening here, apparently, was that the capstan flywheel and shaft structure had a vibration resonance at 75 Hz that was excited either by the fifth harmonic of the capstan rotation frequency or, more likely, by a combination of a multiple of the motor rotation frequency and the capstan rotation frequency. Because of the resonance, very little energy was required to produce a significant vibration. This mode could be reduced significantly by a change in the resonant frequency, but the balancing of the motor and flywheel had already reduced it so that the 15 Hz component was the only significant one remaining.

## 8.4 AN OIL-PUMP PROBLEM.

An oil pump, used in a production setup to supply oil at high pressure to a number of hydraulic presses, was so noisy that the workmen objected to using it. This pump had been installed to speed up production with new presses, but the men preferred to use an earlier production method because it was not then necessary to use the noisy pump. The problem was to find out what should be done to make the noise less objectionable.

In this example, it was assumed that the pump itself could not be modified to reduce the noise, since correcting basic design faults would be a major problem. Errors in alignment or looseness of mounting, as the source of the high noise levels, however, should be taken into consideration. On that basis, the apparent procedure was to investigate these possibilities, to measure the noise produced by the machine, to measure the background noise level, and then to decide what recommendations should be made.

The following instruments were chosen to take to the factory:

Type 1562-A Sound-Level Calibrator.
Type 1558-A Octave Band Noise Analyzer with Type 1560-P6 Microphone.
Type 1568-A Wave Analyzer.
Type 1560-P11B Vibration Pickup System, comprising Type 1560-P52 Vibration Pickup and Type 1560-P21B

Control Box.
Pair of high-fidelity earphones.
Two sponge-rubber pads.

Before going to the factory each instrument was given a maintenance check to see that it was operating properly, since it is easier to correct any faults at the home office than it is to correct them in a noisy factory where service facilities are limited. The procedure was as follows:

1. All equipment was turned on.
2. Batteries were checked.
3. The analyzers were calibrated by means of their own built-in calibration circuits.
4. A Type 1562 Sound-Level Calibrator was used to check the calibration of the octave-band analyzer.

The instruments were taken in an automobile to the factory, where they were loaded on a rubber-tired cart and taken to the noisy pump on the ground floor. Incidentally, this type of cart is a convenient support for instruments during measurements. At the pump, the obvious data were recorded. It was rated at 5 gallons per minute at 3000 psi, and it was 6 inches long and 5 1/2 inches in diameter with seven knobs projecting from the outer cylinder. These knobs apparently corresponded to the seven cams of the pump. The pump was driven through a three-pronged flexible coupling by a 10-hp, 60 Hz, 1730-rpm induction motor. This motor was air-cooled. The oil storage and heat exchanger tank was about 25 inches long and 15 inches in diameter. These three main items, the pump, the motor, and the tank, as well as a mounting board, some gages and a line switch, were mounted on a 37-inch-square, heavy, steel base. Steel I-beams were welded underneath as a part of this base and these were securely bolted to the floor, which was a reinforced cement slab. Four heavy, brass, pipe lines were connected to the storage tank. Two of these were for water cooling, and the other two were for the oil. These lines ran directly to the heavy masonry wall nearby, and they were securely anchored in many places to the wall as they ran to the different presses.

The factory itself was of heavy reinforced concrete construction with no acoustical treatment. Numerous small machines, benches, storage racks, cartons, and other items were arranged in orderly fashion throughout the large factory space where this pump was located.

When the pump was turned on, it was clear why the men complained. It was very noisy. There were no obvious rattles from loose pieces, however, and there seemed to be no mounting troubles. The floor did not seem to be transmitting vibration, and this conclusion was verified later. The vibration in the oil lines could be felt by touch, but they did not seem to be an important source of noise. For example, a check using Octave-Band Analyzer in the All-Pass position carried along near the lines showed that the noise level dropped noticeably as one went away from the pump. The units mounted on the steel frame appeared to be the main source of noise, and listening nearby indicated that the pump itself was the major source.

A preliminary survey around and over the structure but some 5 feet away was made using the octave-band analyzer. As expected, there was no obvious directional pattern.

The first measurement was made close to the pump. The microphone, only 16 inches from the pump shaft was on the octave-band analyzer, which in turn was set on an empty cardboard packing case on the concrete floor. This first position was selected at this point to make certain that the background noise from other machines would not obscure any significant components.

With the pump turned on, the output from the analyzer was monitored by the pair of earphones. Listening to the output of the various bands showed that the noise in the 600 to 1200 and 1200 to 2400 Hz bands was the dominating part of the annoying, loud noise heard from the machine.

The complete analysis was made at this point as shown in the data sheet of Figure 8-5. Then the pump was turned off, and the background noise was analyzed. In all frequency bands but the lowest (20-75 Hz), this background noise was so low that it could be neglected. It was obvious from this analysis that most of the noise was in the range from 150 to 2400 Hz.

There were no apparent characteristic, pitched sounds in the noise heard from the machine, but it could be expected that some would be present. Just to make sure that nothing important would be overlooked, an analysis of the noise was also made with the Type 1568-A Wave Analyzer on the output of the octave-band analyzer. The only discrete components (definite peaks in response as the analyzer was tuned) that were observed are listed on the data sheet. Of these components, the one at 205 Hz was the basic pumping rate of seven times the rotational speed. A comparison of the levels from this analysis with that in octave-bands showed that most of the energy in the range from 150 to 600 Hz was from discrete components, but above that the noise was generally unpitched.

The next step was to use a vibration test to find out if the mounting was satisfactory. The vibration pickup and control box were connected to the octave-band analyzer. Exploration with the pickup and the analyzer showed the following behavior. The pump itself was vibrating most strongly; the high-frequency components and the low-frequency ones were all present. The driving motor was not vibrating seriously. The storage tank vibrated most strongly at low frequencies. As

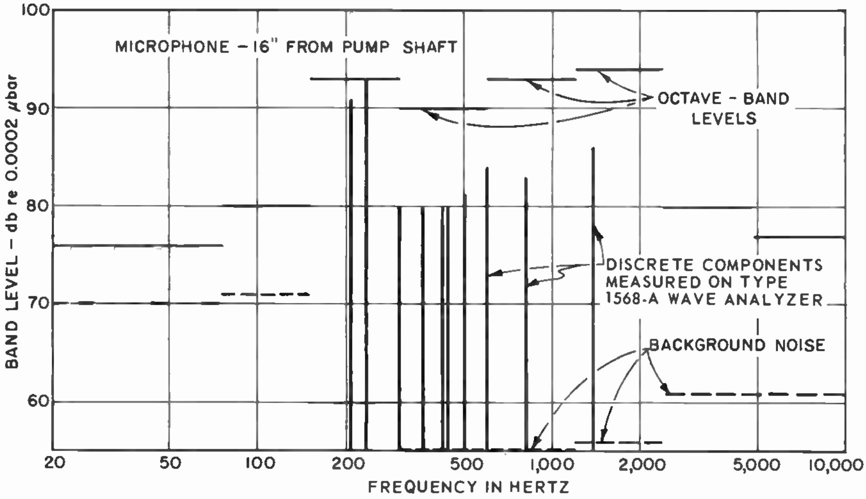


*Figure 8-5. Frequency analysis of the noise produced by a pump. Levels measured with the octave-band analyzer are shown together with components measured on the Type 1568-A Wave Analyzer. Background band levels are shown by horizontal dashed lines; solid horizontal lines represent pump noise plus background.*

the probe was moved about the mounting base toward the concrete floor the amplitude of motion decreased. At the floor the motion was insignificant. This vibration test confirmed that the mounting was not faulty.

The final measurements were octave-band analyses at a number of points 5 feet from the pump and one point 12 feet away. The results of these analyses are shown in the data sheet of Figure 8-6.

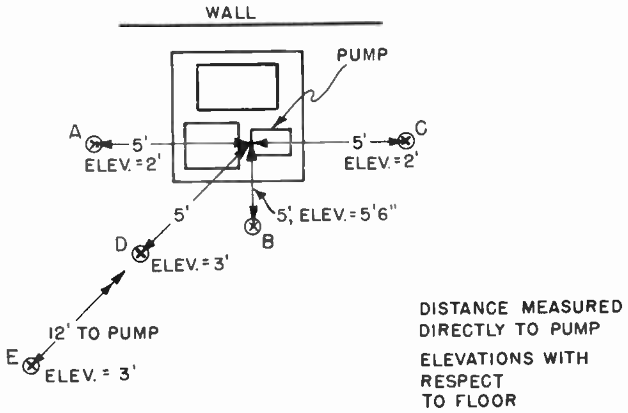
The nearest workmen were about 7 feet from the pump, so that the levels at 5 feet were nearly representative of the conditions they encountered. A comparison of the levels from the pump with the background data and with the speech-interference criteria given in Chapter 8 indicated that a 20-dB reduction in noise level in the bands from 300 to 2400 Hz would have been desirable.

Therefore, as a solution to the problem, the following suggestions were made:

One possible solution is to use a different pump based on a principle of operation that produces less noise as a byproduct.

Another possible solution is to enclose the whole pump in a tight housing with lined ducts for air ventilation. The housing should be treated on the inside with acoustic absorbing materials.

A third solution is to move the pump to another location



| MICROPHONE LOCATION | SOURCE | OVER-ALL | 20 75 | 75 150 | 150 300 | 300 600 | 600 1200 | 1200 2400 | 2400 4800 | 4800 10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | Pump + Bkgd* | 86 | 72-76 | 78 | 76 | 80 | 78 | 81 | 76 | 74 |
| A | Bkgd | 76-78 | 72-76 | 72 | 65 | 61 | 58 | 58 | 62 | 63 |
| B | Pump + Bkgd | 89 | 72-76 | 74-78 | 81 | 85-86 | 81-83 | 82-83 | 76 | 75 |
| B | Bkgd | 76 | 70-74 | 66 | 62 | 61 | 59 | 64 | 70 | 66 |
| C | Pump + Bkgd | 88 | 74-78 | 76-78 | 80 | 84 | 82 | 82-83 | 77-78 | 75 |
| C | Bkgd | 76-78 | 72-74 | 72-74 | 60 | 57 | 56 | 56 | 62 | 62 |
| D | Pump + Bkgd | 87-88 | 72-76 | 75-77 | 82 | 82 | 79 | 82 | 74 | 72 |
| E | Pump + Bkgd | 84-85 | 70-74 | 74 | 78 | 80 | 76 | 76 | 72 | 71 |

*Bkgd = Background

*Figure 8-6. A diagram of the several positions used in making octave-band analyses of pump noise. Results obtained at the various locations are given in the table.*

outside the working area, and this solution was adopted. The pump was moved to a nearby boiler room.

The use of earplugs, sometimes a solution to noise problems, was not adopted here because of the need for communications and the reluctance of personnel to wear such devices except as a last resort.

What had been accomplished by these measurements? First, they had ruled out the possibility of a simple solution, such as isolating the whole structure by vibration mounts, putting flexible couplings in the pipe lines, or using acoustic baffles. Second, they provided the data needed for a preliminary design of a housing, so that its probable cost could be weighed against other possible solutions. In short, these measurements provided the necessary data for a decision by management.

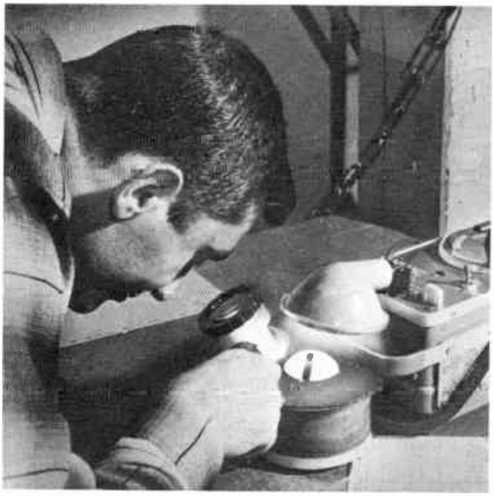


*Figure 8-7. Acoustic Research, Inc. studies acoustic-radiator diaphragms with the Type 1531-A Strobotac® electronic stroboscope. A band of fine flock fiber is applied to the radiator's surface. Under stroboscopic light, nodal points and radiator break-up zones are pinpointed by the degree of fiber vibration along the band of flock. Former methods limited measurements to 1 kHz. The high intensity, short-duration flash of this new stroboscope extends these measurements to 20 kHz.*

*Figure 8-8. At Rotron Manufacturing Company, the Strobotac® electronic stroboscope serves as the principal instrument for analyzing structural weaknesses of air-moving devices. Fan-blade resonances of developmental models are observed under stroboscopic light while the units are subjected to shake-table vibration. Clearance between fan and housing is also noted to ensure that no interference is present.*

## 8.5 SUMMARIES OF SOME EXAMPLES FROM THE LITERATURE.

As an example of vibration isolation, Miller and Dyer[1] report tests on the vibration levels induced in a concrete floor by a printing press. When used with 1/4-inch cork mounting, the press produced such high vibration levels in a concrete floor that the noise in the engineering offices below

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[1] L. N. Miller and I. Dyer, "Printing Machine Isolation," NOISE CONTROL, Vol. 4, No. 4, July, 1958, pp. 21-23.

was excessive. Replacement of these mounts by a much thicker felt mount reduced the vibration amplitudes in the floor to about 1/10 the previous values in the important frequency range of 75 to 600 Hz.

As an example of detection of resonant modes of vibration, Austen and Priede[2] found excessive vibration of the valve cover and the timing cover of a Diesel engine. They found, by exploring with a vibration pickup and by making a narrow-band analysis of the vibration signal, that the valve cover was vibrating strongly at 1150 Hz, while the timing cover had strong components of vibration at 760, 1350, and 2800 Hz. Replacing the cast aluminum covers by "deadened" covers eliminated this excessive vibration.

Feinberg[3] analyzes an interesting example of a gyrocompass mounted in a conventional vibration isolation system. The performance of the gyrocompass was unsatisfactory when subjected to vibration in the frequency range from 220 to 350 Hz. The criterion for acceptable vibration levels was determined by vibrating the gyrocompass as a function of frequency and observing the level at which the performance became unacceptable. This vibration tolerance showed a minimum of 2 $cm/s^2$ rms (66 dB re $10^{-5}$ $m/s^2$ rms) in the frequency range from 240 to 350 Hz. In order to achieve the required low vibration level in this frequency range a tuned two-degrees-of-freedom filter was designed. Compared to the original simple isolation system, the resulting vibration levels at frequencies below 150 Hz were generally higher, but the criterion level was not exceeded, and the levels in the sensitive region from 240 to 350 Hz were, with the new system, sufficiently low that the criterion was satisfied everywhere.

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[2] A. E. W. Austen and T. Priede, "Origins of Diesel Engine Noise," PROCEEDINGS OF THE SYMPOSIUM ON ENGINE NOISE AND NOISE SUPPRESSION, London, Institution of Mechanical Engineers, 24 October 1958, pp. 19-32.

[3] M. Feinberg, "New Methods Simplify Analysis of Vibration-Isolation Systems," Part 1, MACHINE DESIGN, Vol. 37, No. 18, August 5, 1965, pp. 142-149.

# APPENDIXES

appendix I

# DECIBEL CONVERSION TABLES

It is convenient in measurements and calculations to use a unit for expressing a logarithmic function of electric or acoustic power ratios. The decibel (1/10th of the bel) on the briggsian or base-10 scale is in almost universal use for this purpose.

Table I and Table II on the following pages have been prepared to facilitate making conversions in either direction between the number of decibels and the corresponding power and pressure ratios.

Decibel — The number of decibels $N_{dB}$ corresponding to the ratio between two amounts of power $W_1$ and $W_2$ is

$$N_{dB} = 10 \log_{10} \frac{W_1}{W_2} \tag{1}$$

When two pressures $P_1$ and $P_2$ operate in the same or equal impedances.

$$N_{dB} = 20 \log_{10} \frac{P_1}{P_2} \tag{2}$$

## TO FIND VALUES OUTSIDE THE RANGE OF CONVERSION TABLES

Values outside the range of either Table I or Table II on the following pages can be readily found with the help of the following simple rules:

### TABLE I: DECIBELS TO PRESSURE AND POWER RATIOS

Number of decibels positive (+): Subtract +20 decibels successively from the given number of decibels until the remainder falls within range of Table I. To find the pressure ratio, multiply the corresponding value from the right-hand voltage-ratio column by 10 for each time you subtracted 20 dB. To find the power ratio, multiply the corresponding value from the right-hand power-ratio column by 100 for each time you subtracted 20 dB.

Example — Given: 49.2 dB
49.2 dB - 20 dB - 20 dB = 9.2 dB
Pressure ratio: 9.2 dB →
2.884 x 10 x 10 = 288.4
Power ratio: 9.2 dB →
8.318 x 100 x 100 = 83180

Number of decibels negative (-): Add +20 decibels successively to the given number of decibels until the sum falls within the range of Table I. For the pressure ratio, divide the value from the left-hand pressure-ratio column by 10 for each time you added 20 dB. For the power ratio, divided the value from the left-hand power-ratio column by 100 for each time you added 20 dB.

Example — Given: -49.2 dB
-49.2 dB + 20 dB + 20 dB = -9.2 dB
Pressure ratio: -9.2 dB →
.3467 x 1/10 x 1/10 = .003467
Power ratio: -9.2 dB →
.1202 x 1/100 x 1/100 - .00001202

## TABLE II: PRESSURE RATIOS TO DECIBELS

For ratios smaller than those in table — Multiply the given ratio by 10 successively until the product can be found in the table. From the number of decibels thus found, subtract +20 decibels for each time you multiplied by 10.

Example — Given: Pressure ratio = .0131
.0131 x 10 x 10 = 1.31
From Table II, 1.31 →
2.34 dB - 20 dB - 20 dB = -37.66 dB

For ratios greater than those in table — Divide the given ratio by 10 successively until the remainder can be found in the table. To the number of decibels thus found, add +20 dB for each time you divided by 10.

Example — Given: Pressure ratio = 712
712 x 1/10 x 1/10 = 7.12
From Table II, 7.12 →
17.05 dB + 20 dB + 20 dB = 57.05 dB

## USE OF DECIBEL TABLES TO CONVERT VIBRATION READINGS

These decibel tables offer a convenient means of converting decibel vibration readings obtained with the sound-level meter and vibration pickup into displacement in inches, velocity in inches per second, and acceleration in inches per second per second.

Each control box nameplate is inscribed with a conversion table, which applies when that control box is used with the pickup and sound-level meter indicated on the nameplate. The conversion figures appearing on the nameplate of the Type 1560-P21B Control Box are:

| | |
|---|---|
| Displacement | 120 dB → 1 in. rms |
| Velocity | 90 dB → 1 in. per second |
| Acceleration | 50 dB → 1 in. per second per second rms |

N.B. For Types 759-P36 and 1560-P21 Control Boxes, the conversion figures are different from the above. When these control boxes are used, substitute values given on the nameplate for those used below to obtain correct conversion.

NOTE: In Tables I and II, the term "pressure ratio" is equivalent to the term "voltage ratio" as used in the following instructions.

## TO CONVERT DB SOUND-LEVEL METER READINGS INTO RMS AMPLITUDE IN INCHES

1. Note decibel readings of sound-level meter when vibration pickup is in contact with vibrating surface and control box switch is set at DISPlacèment.

2. If reading for Step 1 is below 120 dB: Subtract +20 dB successively from 120 minus dB reading until the remainder falls within the range of Table I of decibel tables. To determine rms amplitude in inches, multiply the voltage ratio (left-hand column) corresponding to the dB remainder by 0.1 for each time you subtracted 20 dB. Figures obtained are expressed directly in inches rms amplitude.

If reading for Step 1 is above 120 dB: Subtract +20 dB successively from dB reading minus 120 dB until the remainder falls within the range of Table I. To determine amplitude in inches, multiply the voltage ratio (right-hand voltage ratio column) corresponding to the dB remainder by 10 for each time you subtracted 20 dB. Figures obtained are expressed directly in inches rms amplitude.

## TO CONVERT DB SOUND-LEVEL METER READINGS INTO RMS VELOCITY IN INCHES PER SECOND

1. Note dB reading of sound-level meter with vibration pickup in contact with vibrating surface and control box switch

set at VELocity.

2. If reading for Step 1 is below 90 dB: Subtract +20 dB successively from 90 minus dB reading until the remainder falls within the range of Table I of decibel tables. To determine rms velocity in inches per second, multiply the voltage ratio (left-hand voltage ratio column) corresponding to the dB remainder by 0.1 for each time you subtracted 20 dB. The value obtained is velocity expressed directly in inches per second rms.

If reading for Step 1 is above 90 dB: Subtract +20 dB successively from dB reading minus 90 until the remainder falls within the range of Table I. To determine rms velocity in inches per second, multiply the voltage ratio (right-hand voltage ratio column) corresponding to the dB remainder by 10 for each time you subtracted 20 dB. The value obtained is velocity expressed in inches per second rms.

## TO CONVERT DB SOUND-LEVEL METER READINGS INTO RMS ACCELERATION IN INCHES PER SECOND PER SECOND

1. Note dB reading of sound-level meter with vibration pickup in contact with vibrating surface and control box switch set at ACCeleration.

2. If reading of Step 1 is below 50 dB: The value obtained from the left-hand ratio column corresponding to 50 minus dB reading is acceleration expressed directly in inches per second per second rms.

If reading for Step 1 is above 50 dB (maximum 132 dB): Subtract +20 dB successively from dB reading minus 50 until the remainder falls within the range of Table I. To determine rms acceleration in inches per second per second, multiply the voltage ratio (right-hand voltage ratio column) corresponding to the dB remainder by 10 for each time you subtracted 20 dB. The value obtained is acceleration expressed directly in inches per second per second rms.

Example:

With the vibration pickup placed in contact with some vibrating surface and the control box switch, let us say, on DISPlacement, a reading of 54 dB is obtained. Then, following outlined procedure:

1. dB reading = 54 dB.
2. 120 - 54 = 66 dB.
   66 - (+20) - (+20) - (+20) = 6 dB remainder.

Voltage ratios corresponding to 6 dB (left-hand column) equal 0.5012; 20 dB was subtracted from 66 dB three times; therefore 0.5012 should be multiplied by 0.1 three times.

Result = 0.0005012 or (to 2 significant figures) 0.00050 inch rms amplitude.

Like procedure should be followed for the calculation of velocity or acceleration.

## Acceleration and Velocity Level

In order to convert the readings obtained with the sound-level meter and vibration pickup system into acceleration level *re* $10^{-3}$ cm/sec$^2$ (often called adB) or velocity level *re* $10^{-6}$ cm/sec (often called vdB), proceed as follows:

When the conversion figures on the nameplate are:

Velocity 90 dB = 1 in./sec
Acceleration 50 dB = 1 in./sec$^2$

add 38.1 dB to sound-level meter reading to get velocity level when the control box is set to velocity, and add 18.1 dB to sound-level meter reading to get acceleration level when the control box is set to acceleration.

# TABLE I

## GIVEN: Decibels TO FIND: Power and Pressure Ratios

### TO ACCOUNT FOR THE SIGN OF THE DECIBEL

**For positive (+) values of the decibel** — Both pressure and power ratios are greater than unity. Use the two right-hand columns.

**For negative (—) values of the decibel**—Both pressure and power ratios are less than unity. Use the two left-hand columns.

**Example**—*Given:* ± 9.1 dB. *Find:*

| | *Power Ratio* | *Pressure Ratio* |
|---|---|---|
| +9.1 dB | 8.128 | 2.851 |
| −9.1 dB | 0.1230 | 0.3508 |

← *- dB +* →

| *Pressure Ratio* | *Power Ratio* | dB | *Pressure Ratio* | *Power Ratio* |
|---|---|---|---|---|
| **1.0000** | **1.0000** | **0** | **1.000** | **1.000** |
| .9886 | .9772 | .1 | 1.012 | 1.023 |
| .9772 | .9550 | .2 | 1.023 | 1.047 |
| .9661 | .9333 | .3 | 1.035 | 1.072 |
| .9550 | .9120 | .4 | 1.047 | 1.096 |
| .9441 | .8913 | .5 | 1.059 | 1.122 |
| .9333 | .8710 | .6 | 1.072 | 1.148 |
| .9226 | .8511 | .7 | 1.084 | 1.175 |
| .9120 | .8318 | .8 | 1.096 | 1.202 |
| .9016 | .8128 | .9 | 1.109 | 1.230 |
| **.8913** | **.7943** | **1.0** | **1.122** | **1.259** |
| .8810 | .7762 | 1.1 | 1.135 | 1.288 |
| .8710 | .7586 | 1.2 | 1.148 | 1.318 |
| .8610 | .7413 | 1.3 | 1.161 | 1.349 |
| .8511 | .7244 | 1.4 | 1.175 | 1.380 |
| .8414 | .7079 | 1.5 | 1.189 | 1.413 |
| .8318 | .6918 | 1.6 | 1.202 | 1.445 |
| .8222 | .6761 | 1.7 | 1.216 | 1.479 |
| .8128 | .6607 | 1.8 | 1.230 | 1.514 |
| .8035 | .6457 | 1.9 | 1.245 | 1.549 |
| **.7943** | **.6310** | **2.0** | **1.259** | **1.585** |
| .7852 | .6166 | 2.1 | 1.274 | 1.622 |
| .7762 | .6026 | 2.2 | 1.288 | 1.660 |
| .7674 | .5888 | 2.3 | 1.303 | 1.698 |
| .7586 | .5754 | 2.4 | 1.318 | 1.738 |
| .7499 | .5623 | 2.5 | 1.334 | 1.778 |
| .7413 | .5495 | 2.6 | 1.349 | 1.820 |
| .7328 | .5370 | 2.7 | 1.365 | 1.862 |
| .7244 | .5248 | 2.8 | 1.380 | 1.905 |
| .7161 | .5129 | 2.9 | 1.396 | 1.950 |
| **.7079** | **.5012** | **3.0** | **1.413** | **1.995** |
| .6998 | .4898 | 3.1 | 1.429 | 2.042 |
| .6918 | .4786 | 3.2 | 1.445 | 2.089 |
| .6839 | .4677 | 3.3 | 1.462 | 2.138 |
| .6761 | .4571 | 3.4 | 1.479 | 2.188 |
| .6683 | .4467 | 3.5 | 1.496 | 2.239 |
| .6607 | .4365 | 3.6 | 1.514 | 2.291 |
| .6531 | .4266 | 3.7 | 1.531 | 2.344 |
| .6457 | .4169 | 3.8 | 1.549 | 2.399 |
| .6383 | .4074 | 3.9 | 1.567 | 2.455 |
| **.6310** | **.3981** | **4.0** | **1.585** | **2.512** |
| .6237 | .3890 | 4.1 | 1.603 | 2.570 |
| .6166 | .3802 | 4.2 | 1.622 | 2.630 |
| .6095 | .3715 | 4.3 | 1.641 | 2.692 |
| .6026 | .3631 | 4.4 | 1.660 | 2.754 |
| .5957 | .3548 | 4.5 | 1.679 | 2.818 |
| .5888 | .3467 | 4.6 | 1.698 | 2.884 |
| .5821 | .3388 | 4.7 | 1.718 | 2.951 |
| .5754 | .3311 | 4.8 | 1.738 | 3.020 |
| .5689 | .3236 | 4.9 | 1.758 | 3.090 |

← *- dB +* →

| *Pressure Ratio* | *Power Ratio* | dB | *Pressure Ratio* | *Power Ratio* |
|---|---|---|---|---|
| **.5623** | **.3162** | **5.0** | **1.778** | **3.162** |
| .5559 | .3090 | 5.1 | 1.799 | 3.236 |
| .5495 | .3020 | 5.2 | 1.820 | 3.311 |
| .5433 | .2951 | 5.3 | 1.841 | 3.388 |
| .5370 | .2884 | 5.4 | 1.862 | 3.467 |
| .5309 | .2818 | 5.5 | 1.884 | 3.548 |
| .5248 | .2754 | 5.6 | 1.905 | 3.631 |
| .5188 | .2692 | 5.7 | 1.928 | 3.715 |
| .5129 | .2630 | 5.8 | 1.950 | 3.802 |
| .5070 | .2570 | 5.9 | 1.972 | 3.890 |
| **.5012** | **.2512** | **6.0** | **1.995** | **3.981** |
| .4955 | .2455 | 6.1 | 2.018 | 4.074 |
| .4898 | .2399 | 6.2 | 2.042 | 4.169 |
| .4842 | .2344 | 6.3 | 2.065 | 4.266 |
| .4786 | .2291 | 6.4 | 2.089 | 4.365 |
| .4732 | .2239 | 6.5 | 2.113 | 4.467 |
| .4677 | .2188 | 6.6 | 2.138 | 4.571 |
| .4624 | .2138 | 6.7 | 2.163 | 4.677 |
| .4571 | .2089 | 6.8 | 2.188 | 4.786 |
| .4519 | .2042 | 6.9 | 2.213 | 4.898 |
| **.4467** | **.1995** | **7.0** | **2.239** | **5.012** |
| .4416 | .1950 | 7.1 | 2.265 | 5.129 |
| .4365 | .1905 | 7.2 | 2.291 | 5.248 |
| .4315 | .1862 | 7.3 | 2.317 | 5.370 |
| .4266 | .1820 | 7.4 | 2.344 | 5.495 |
| .4217 | .1778 | 7.5 | 2.371 | 5.623 |
| .4169 | .1738 | 7.6 | 2.399 | 5.754 |
| .4121 | .1698 | 7.7 | 2.427 | 5.888 |
| .4074 | .1660 | 7.8 | 2.455 | 6.026 |
| .4027 | .1622 | 7.9 | 2.483 | 6.166 |
| **.3981** | **.1585** | **8.0** | **2.512** | **6.310** |
| .3936 | .1549 | 8.1 | 2.541 | 6.457 |
| .3890 | .1514 | 8.2 | 2.570 | 6.607 |
| .3846 | .1479 | 8.3 | 2.600 | 6.761 |
| .3802 | .1445 | 8.4 | 2.630 | 6.918 |
| .3758 | .1413 | 8.5 | 2.661 | 7.079 |
| .3715 | .1380 | 8.6 | 2.692 | 7.244 |
| .3673 | .1349 | 8.7 | 2.723 | 7.413 |
| .3631 | .1318 | 8.8 | 2.754 | 7.586 |
| .3589 | .1288 | 8.9 | 2.786 | 7.762 |
| **.3548** | **.1259** | **9.0** | **2.818** | **7.943** |
| .3508 | .1230 | 9.1 | 2.851 | 8.128 |
| .3467 | .1202 | 9.2 | 2.884 | 8.318 |
| .3428 | .1175 | 9.3 | 2.917 | 8.511 |
| .3388 | .1148 | 9.4 | 2.951 | 8.710 |
| .3350 | .1122 | 9.5 | 2.985 | 8.913 |
| .3311 | .1096 | 9.6 | 3.020 | 9.120 |
| .3273 | .1072 | 9.7 | 3.055 | 9.333 |
| .3236 | .1047 | 9.8 | 3.090 | 9.550 |
| .3199 | .1023 | 9.9 | 3.126 | 9.772 |

# TABLE I (continued)

← −dB+ →

| Pressure Ratio | Power Ratio | dB | Pressure Ratio | Power Ratio |
|---|---|---|---|---|
| **.3162** | **.1000** | **10.0** | **3.162** | **10.000** |
| .3126 | .09772 | 10.1 | 3.199 | 10.23 |
| .3090 | .09550 | 10.2 | 3.236 | 10.47 |
| .3055 | .09333 | 10.3 | 3.273 | 10.72 |
| .3020 | .09120 | 10.4 | 3.311 | 10.96 |
| .2985 | .08913 | 10.5 | 3.350 | 11.22 |
| .2951 | .08710 | 10.6 | 3.388 | 11.48 |
| .2917 | .08511 | 10.7 | 3.428 | 11.75 |
| .2884 | .08318 | 10.8 | 3.467 | 12.02 |
| .2851 | .08128 | 10.9 | 3.508 | 12.30 |
| **.2818** | **.07943** | **11.0** | **3.548** | **12.59** |
| .2786 | .07762 | 11.1 | 3.589 | 12.88 |
| .2754 | .07586 | 11.2 | 3.631 | 13.18 |
| .2723 | .07413 | 11.3 | 3.673 | 13.49 |
| .2692 | .07244 | 11.4 | 3.715 | 13.80 |
| .2661 | .07079 | 11.5 | 3.758 | 14.13 |
| .2630 | .06918 | 11.6 | 3.802 | 14.45 |
| .2600 | .06761 | 11.7 | 3.846 | 14.79 |
| .2570 | .06607 | 11.8 | 3.890 | 15.14 |
| .2541 | .06457 | 11.9 | 3.936 | 15.49 |
| **.2512** | **.06310** | **12.0** | **3.981** | **15.85** |
| .2483 | .06166 | 12.1 | 4.027 | 16.22 |
| .2455 | .06026 | 12.2 | 4.074 | 16.60 |
| .2427 | .05888 | 12.3 | 4.121 | 16.98 |
| .2399 | .05754 | 12.4 | 4.169 | 17.38 |
| .2371 | .05623 | 12.5 | 4.217 | 17.78 |
| .2344 | .05495 | 12.6 | 4.266 | 18.20 |
| .2317 | .05370 | 12.7 | 4.315 | 18.62 |
| .2291 | .05248 | 12.8 | 4.365 | 19.05 |
| .2265 | .05129 | 12.9 | 4.416 | 19.50 |
| **.2239** | **.05012** | **13.0** | **4.467** | **19.95** |
| .2213 | .04898 | 13.1 | 4.519 | 20.42 |
| .2188 | .04786 | 13.2 | 4.571 | 20.89 |
| .2163 | .04677 | 13.3 | 4.624 | 21.38 |
| .2138 | .04571 | 13.4 | 4.677 | 21.88 |
| .2113 | .04467 | 13.5 | 4.732 | 22.39 |
| .2089 | .04365 | 13.6 | 4.786 | 22.91 |
| .2065 | .04266 | 13.7 | 4.842 | 23.44 |
| .2042 | .04169 | 13.8 | 4.898 | 23.99 |
| .2018 | .04074 | 13.9 | 4.955 | 24.55 |
| **.1995** | **.03981** | **14.0** | **5.012** | **25.12** |
| .1972 | .03890 | 14.1 | 5.070 | 25.70 |
| .1950 | .03802 | 14.2 | 5.129 | 26.30 |
| .1928 | .03715 | 14.3 | 5.188 | 26.92 |
| .1905 | .03631 | 14.4 | 5.248 | 27.54 |
| .1884 | .03548 | 14.5 | 5.309 | 28.18 |
| .1862 | .03467 | 14.6 | 5.370 | 28.84 |
| .1841 | .03388 | 14.7 | 5.433 | 29.51 |
| .1820 | .03311 | 14.8 | 5.495 | 30.20 |
| .1799 | .03236 | 14.9 | 5.559 | 30.90 |
| **.1778** | **.03162** | **15.0** | **5.623** | **31.62** |
| .1758 | .03090 | 15.1 | 5.689 | 32.36 |
| .1738 | .03020 | 15.2 | 5.754 | 33.11 |
| .1718 | .02951 | 15.3 | 5.821 | 33.88 |
| .1698 | .02884 | 15.4 | 5.888 | 34.67 |
| .1679 | .02818 | 15.5 | 5.957 | 35.48 |
| .1660 | .02754 | 15.6 | 6.026 | 36.31 |
| .1641 | .02692 | 15.7 | 6.095 | 37.15 |
| .1622 | .02630 | 15.8 | 6.166 | 38.02 |
| .1603 | .02570 | 15.9 | 6.237 | 38.90 |

← −dB+ →

| Pressure Ratio | Power Ratio | dB | Pressure Ratio | Power Ratio |
|---|---|---|---|---|
| **.1585** | **.02512** | **16.0** | **6.310** | **39.81** |
| .1567 | .02455 | 16.1 | 6.383 | 40.74 |
| .1549 | .02399 | 16.2 | 6.457 | 41.69 |
| .1531 | .02344 | 16.3 | 6.531 | 42.66 |
| .1514 | .02291 | 16.4 | 6.607 | 43.65 |
| .1496 | .02239 | 16.5 | 6.683 | 44.67 |
| .1479 | .02188 | 16.6 | 6.761 | 45.71 |
| .1462 | .02138 | 16.7 | 6.839 | 46.77 |
| .1445 | .02089 | 16.8 | 6.918 | 47.86 |
| .1429 | .02042 | 16.9 | 6.998 | 48.98 |
| **.1413** | **.01995** | **17.0** | **7.079** | **50.12** |
| .1396 | .01950 | 17.1 | 7.161 | 51.29 |
| .1380 | .01905 | 17.2 | 7.244 | 52.48 |
| .1365 | .01862 | 17.3 | 7.328 | 53.70 |
| .1349 | .01820 | 17.4 | 7.413 | 54.95 |
| .1334 | .01778 | 17.5 | 7.499 | 56.23 |
| .1318 | .01738 | 17.6 | 7.586 | 57.54 |
| .1303 | .01698 | 17.7 | 7.674 | 58.88 |
| .1288 | .01660 | 17.8 | 7.762 | 60.26 |
| .1274 | .01622 | 17.9 | 7.852 | 61.66 |
| **.1259** | **.01585** | **18.0** | **7.943** | **63.10** |
| .1245 | .01549 | 18.1 | 8.035 | 64.57 |
| .1230 | .01514 | 18.2 | 8.128 | 66.07 |
| .1216 | .01479 | 18.3 | 8.222 | 67.61 |
| .1202 | .01445 | 18.4 | 8.318 | 69.18 |
| .1189 | .01413 | 18.5 | 8.414 | 70.79 |
| .1175 | .01380 | 18.6 | 8.511 | 72.44 |
| .1161 | .01349 | 18.7 | 8.610 | 74.13 |
| .1148 | .01318 | 18.8 | 8.710 | 75.86 |
| .1135 | .01288 | 18.9 | 8.811 | 77.62 |
| **.1122** | **.01259** | **19.0** | **8.913** | **79.43** |
| .1109 | .01230 | 19.1 | 9.016 | 81.28 |
| .1096 | .01202 | 19.2 | 9.120 | 83.18 |
| .1084 | .01175 | 19.3 | 9.226 | 85.11 |
| .1072 | .01148 | 19.4 | 9.333 | 87.10 |
| .1059 | .01122 | 19.5 | 9.441 | 89.13 |
| .1047 | .01096 | 19.6 | 9.550 | 91.20 |
| .1035 | .01072 | 19.7 | 9.661 | 93.33 |
| .1023 | .01047 | 19.8 | 9.772 | 95.50 |
| .1012 | .01023 | 19.9 | 9.886 | 97.72 |
| **.1000** | **.01000** | **20.0** | **10.000** | **100.00** |

← −dB+ →

| Pressure Ratio | Power Ratio | dB | Pressure Ratio | Power Ratio |
|---|---|---|---|---|
| **$3.162\times10^{-1}$** | **$10^{-1}$** | **10** | **3.162** | **10** |
| $10^{-1}$ | $10^{-2}$ | 20 | 10 | $10^2$ |
| $3.162\times10^{-2}$ | $10^{-3}$ | 30 | $3.162\times10$ | $10^3$ |
| $10^{-2}$ | $10^{-4}$ | 40 | $10^2$ | $10^4$ |
| $3.162\times10^{-3}$ | $10^{-5}$ | 50 | $3.162\times10^2$ | $10^5$ |
| $10^{-3}$ | $10^{-6}$ | 60 | $10^3$ | $10^6$ |
| $3.162\times10^{-4}$ | $10^{-7}$ | 70 | $3.162\times10^3$ | $10^7$ |
| $10^{-4}$ | $10^{-8}$ | 80 | $10^4$ | $10^8$ |
| $3.162\times10^{-5}$ | $10^{-9}$ | 90 | $3.162\times10^4$ | $10^9$ |
| **$10^{-5}$** | **$10^{-10}$** | **100** | **$10^5$** | **$10^{10}$** |

# TABLE II

## GIVEN: {Pressure} Ratio TO FIND: Decibels

### POWER RATIOS

**To find the number of decibels corresponding to a given power ratio**—Assume the given power ratio to be a pressure ratio and find the corresponding number of decibels from the table. The desired result is exactly one-half of the number of decibels thus found.

**Example**—*Given:* a power ratio of 3.41. *Find:* 3.41 in the table:

3.41→10.655 dB × ½ = 5.328 dB

| *Pressure Ratio* | .00 | .01 | .02 | .03 | .04 | .05 | .06 | .07 | .08 | .09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **1.0** | **.000** | **.086** | **.172** | **.257** | **.341** | **.424** | **.506** | **.588** | **.668** | **.749** |
| 1.1 | .828 | .906 | .984 | 1.062 | 1.138 | 1.214 | 1.289 | 1.364 | 1.438 | 1.511 |
| 1.2 | 1.584 | 1.656 | 1.727 | 1.798 | 1.868 | 1.938 | 2.007 | 2.076 | 2.144 | 2.212 |
| 1.3 | 2.279 | 2.345 | 2.411 | 2.477 | 2.542 | 2.607 | 2.671 | 2.734 | 2.798 | 2.860 |
| 1.4 | 2.923 | 2.984 | 3.046 | 3.107 | 3.167 | 3.227 | 3.287 | 3.346 | 3.405 | 3.464 |
| 1.5 | 3.522 | 3.580 | 3.637 | 3.694 | 3.750 | 3.807 | 3.862 | 3.918 | 3.973 | 4.028 |
| 1.6 | 4.082 | 4.137 | 4.190 | 4.244 | 4.297 | 4.350 | 4.402 | 4.454 | 4.506 | 4.558 |
| 1.7 | 4.609 | 4.660 | 4.711 | 4.761 | 4.811 | 4.861 | 4.910 | 4.959 | 5.008 | 5.057 |
| 1.8 | 5.105 | 5.154 | 5.201 | 5.249 | 5.296 | 5.343 | 5.390 | 5.437 | 5.483 | 5.529 |
| 1.9 | 5.575 | 5.621 | 5.666 | 5.711 | 5.756 | 5.801 | 5.845 | 5.889 | 5.933 | 5.977 |
| **2.0** | **6.021** | **6.064** | **6.107** | **6.150** | **6.193** | **6.235** | **6.277** | **6.319** | **6.361** | **6.403** |
| 2.1 | 6.444 | 6.486 | 6.527 | 6.568 | 6.608 | 6.649 | 6.689 | 6.729 | 6.769 | 6.809 |
| 2.2 | 6.848 | 6.888 | 6.927 | 6.966 | 7.008 | 7.044 | 7.082 | 7.121 | 7.159 | 7.197 |
| 2.3 | 7.235 | 7.272 | 7.310 | 7.347 | 7.384 | 7.421 | 7.458 | 7.495 | 7.532 | 7.568 |
| 2.4 | 7.604 | 7.640 | 7.676 | 7.712 | 7.748 | 7.783 | 7.819 | 7.854 | 7.889 | 7.924 |
| 2.5 | 7.959 | 7.993 | 8.028 | 8.062 | 8.097 | 8.131 | 8.165 | 8.199 | 8.232 | 8.266 |
| 2.6 | 8.299 | 8.333 | 8.366 | 8.399 | 8.432 | 8.465 | 8.498 | 8.530 | 8.563 | 8.595 |
| 2.7 | 8.627 | 8.659 | 8.691 | 8.723 | 8.755 | 8.787 | 8.818 | 8.850 | 8.881 | 8.912 |
| 2.8 | 8.943 | 8.974 | 9.005 | 9.036 | 9.066 | 9.097 | 9.127 | 9.158 | 9.188 | 9.218 |
| 2.9 | 9.248 | 9.278 | 9.308 | 9.337 | 9.367 | 9.396 | 9.426 | 9.455 | 9.484 | 9.513 |
| **3.0** | **9.542** | **9.571** | **9.600** | **9.629** | **9.657** | **9.686** | **9.714** | **9.743** | **9.771** | **9.799** |
| 3.1 | 9.827 | 9.855 | 9.883 | 9.911 | 9.939 | 9.966 | 9.994 | 10.021 | 10.049 | 10.076 |
| 3.2 | 10.103 | 10.130 | 10.157 | 10.184 | 10.211 | 10.238 | 10.264 | 10.291 | 10.317 | 10.344 |
| 3.3 | 10.370 | 10.397 | 10.423 | 10.449 | 10.475 | 10.501 | 10.527 | 10.553 | 10.578 | 10.604 |
| 3.4 | 10.630 | 10.655 | 10.681 | 10.706 | 10.731 | 10.756 | 10.782 | 10.807 | 10.832 | 10.857 |
| 3.5 | 10.881 | 10.906 | 10.931 | 10.955 | 10.980 | 11.005 | 11.029 | 11.053 | 11.078 | 11.102 |
| 3.6 | 11.126 | 11.150 | 11.174 | 11.198 | 11.222 | 11.246 | 11.270 | 11.293 | 11.317 | 11.341 |
| 3.7 | 11.364 | 11.387 | 11.411 | 11.434 | 11.457 | 11.481 | 11.504 | 11.527 | 11.550 | 11.573 |
| 3.8 | 11.596 | 11.618 | 11.641 | 11.664 | 11.687 | 11.709 | 11.732 | 11.754 | 11.777 | 11.799 |
| 3.9 | 11.821 | 11.844 | 11.866 | 11.888 | 11.910 | 11.932 | 11.954 | 11.976 | 11.998 | 12.019 |
| **4.0** | **12.041** | **12.063** | **12.085** | **12.106** | **12.128** | **12.149** | **12.171** | **12.192** | **12.213** | **12.234** |
| 4.1 | 12.256 | 12.277 | 12.298 | 12.319 | 12.340 | 12.361 | 12.382 | 12.403 | 12.424 | 12.444 |
| 4.2 | 12.465 | 12.486 | 12.506 | 12.527 | 12.547 | 12.568 | 12.588 | 12.609 | 12.629 | 12.649 |
| 4.3 | 12.669 | 12.690 | 12.710 | 12.730 | 12.750 | 12.770 | 12.790 | 12.810 | 12.829 | 12.849 |
| 4.4 | 12.869 | 12.889 | 12.908 | 12.928 | 12.948 | 12.967 | 12.987 | 13.006 | 13.026 | 13.045 |
| 4.5 | 13.064 | 13.084 | 13.103 | 13.122 | 13.141 | 13.160 | 13.179 | 13.198 | 13.217 | 13.236 |
| 4.6 | 13.255 | 13.274 | 13.293 | 13.312 | 13.330 | 13.349 | 13.368 | 13.386 | 13.405 | 13.423 |
| 4.7 | 13.442 | 13.460 | 13.479 | 13.497 | 13.516 | 13.534 | 13.552 | 13.570 | 13.589 | 13.607 |
| 4.8 | 13.625 | 13.643 | 13.661 | 13.679 | 13.697 | 13.715 | 13.733 | 13.751 | 13.768 | 13.786 |
| 4.9 | 13.804 | 13.822 | 13.839 | 13.857 | 13.875 | 13.892 | 13.910 | 13.927 | 13.945 | 13.962 |
| **5.0** | **13.979** | **13.997** | **14.014** | **14.031** | **14.049** | **14.066** | **14.083** | **14.100** | **14.117** | **14.134** |
| 5.1 | 14.151 | 14.168 | 14.185 | 14.202 | 14.219 | 14.236 | 14.253 | 14.270 | 14.287 | 14.303 |
| 5.2 | 14.320 | 14.337 | 14.353 | 14.370 | 14.387 | 14.403 | 14.420 | 14.436 | 14.453 | 14.469 |
| 5.3 | 14.486 | 14.502 | 14.518 | 14.535 | 14.551 | 14.567 | 14.583 | 14.599 | 14.616 | 14.632 |
| 5.4 | 14.648 | 14.664 | 14.680 | 14.696 | 14.712 | 14.728 | 14.744 | 14.760 | 14.776 | 14.791 |
| 5.5 | 14.807 | 14.823 | 14.839 | 14.855 | 14.870 | 14.886 | 14.902 | 14.917 | 14.933 | 14.948 |
| 5.6 | 14.964 | 14.979 | 14.995 | 15.010 | 15.026 | 15.041 | 15.056 | 15.072 | 15.087 | 15.102 |
| 5.7 | 15.117 | 15.133 | 15.148 | 15.163 | 15.178 | 15.193 | 15.208 | 15.224 | 15.239 | 15.254 |
| 5.8 | 15.269 | 15.284 | 15.298 | 15.313 | 15.328 | 15.343 | 15.358 | 15.373 | 15.388 | 15.402 |
| 5.9 | 15.417 | 15.432 | 15.446 | 15.461 | 15.476 | 15.490 | 15.505 | 15.519 | 15.534 | 15.549 |

# TABLE II (continued)

| *Pressure Ratio* | .00 | .01 | .02 | .03 | .04 | .05 | .06 | .07 | .08 | .09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **6.0** | **15.563** | **15.577** | **15.592** | **15.606** | **15.621** | **15.635** | **15.649** | **15.664** | **15.678** | **15.692** |
| 6.1 | 15.707 | 15.721 | 15.735 | 15.749 | 15.763 | 15.778 | 15.792 | 15.806 | 15.820 | 15.834 |
| 6.2 | 15.848 | 15.862 | 15.876 | 15.890 | 15.904 | 15.918 | 15.931 | 15.945 | 15.959 | 15.973 |
| 6.3 | 15.987 | 16.001 | 16.014 | 16.028 | 16.042 | 16.055 | 16.069 | 16.083 | 16.096 | 16.110 |
| 6.4 | 16.124 | 16.137 | 16.151 | 16.164 | 16.178 | 16.191 | 16.205 | 16.218 | 16.232 | 16.245 |
| 6.5 | 16.258 | 16.272 | 16.285 | 16.298 | 16.312 | 16.325 | 16.338 | 16.351 | 16.365 | 16.378 |
| 6.6 | 16.391 | 16.404 | 16.417 | 16.430 | 16.443 | 16.456 | 16.469 | 16.483 | 16.496 | 16.509 |
| 6.7 | 16.521 | 16.534 | 16.547 | 16.560 | 16.573 | 16.586 | 16.599 | 16.612 | 16.625 | 16.637 |
| 6.8 | 16.650 | 16.663 | 16.676 | 16.688 | 16.701 | 16.714 | 16.726 | 16.739 | 16.752 | 16.764 |
| 6.9 | 16.777 | 16.790 | 16.802 | 16.815 | 16.827 | 16.840 | 16.852 | 16.865 | 16.877 | 16.890 |
| **7.0** | **16.902** | **16.914** | **16.927** | **16.939** | **16.951** | **16.964** | **16.976** | **16.988** | **17.001** | **17.013** |
| 7.1 | 17.025 | 17.037 | 17.050 | 17.062 | 17.074 | 17.086 | 17.098 | 17.110 | 17.122 | 17.135 |
| 7.2 | 17.147 | 17.159 | 17.171 | 17.183 | 17.195 | 17.207 | 17.219 | 17.231 | 17.243 | 17.255 |
| 7.3 | 17.266 | 17.278 | 17.290 | 17.302 | 17.314 | 17.326 | 17.338 | 17.349 | 17.361 | 17.373 |
| 7.4 | 17.385 | 17.396 | 17.408 | 17.420 | 17.431 | 17.443 | 17.455 | 17.466 | 17.478 | 17.490 |
| 7.5 | 17.501 | 17.513 | 17.524 | 17.536 | 17.547 | 17.559 | 17.570 | 17.582 | 17.593 | 17.605 |
| 7.6 | 17.616 | 17.628 | 17.639 | 17.650 | 17.662 | 17.673 | 17.685 | 17.696 | 17.707 | 17.719 |
| 7.7 | 17.730 | 17.741 | 17.752 | 17.764 | 17.775 | 17.786 | 17.797 | 17.808 | 17.820 | 17.831 |
| 7.8 | 17.842 | 17.853 | 17.864 | 17.875 | 17.886 | 17.897 | 17.908 | 17.919 | 17.931 | 17.942 |
| 7.9 | 17.953 | 17.964 | 17.975 | 17.985 | 17.996 | 18.007 | 18.018 | 18.029 | 18.040 | 18.051 |
| **8.0** | **18.062** | **18.073** | **18.083** | **18.094** | **18.105** | **18.116** | **18.127** | **18.137** | **18.148** | **18.159** |
| 8.1 | 18.170 | 18.180 | 18.191 | 18.202 | 18.212 | 18.223 | 18.234 | 18.244 | 18.255 | 18.266 |
| 8.2 | 18.276 | 18.287 | 18.297 | 18.308 | 18.319 | 18.329 | 18.340 | 18.350 | 18.361 | 18.371 |
| 8.3 | 18.382 | 18.392 | 18.402 | 18.413 | 18.423 | 18.434 | 18.444 | 18.455 | 18.465 | 18.475 |
| 8.4 | 18.486 | 18.496 | 18.506 | 18.517 | 18.527 | 18.537 | 18.547 | 18.558 | 18.568 | 18.578 |
| 8.5 | 18.588 | 18.599 | 18.609 | 18.619 | 18.629 | 18.639 | 18.649 | 18.660 | 18.670 | 18.680 |
| 8.6 | 18.690 | 18.700 | 18.710 | 18.720 | 18.730 | 18.740 | 18.750 | 18.760 | 18.770 | 18.780 |
| 8.7 | 18.790 | 18.800 | 18.810 | 18.820 | 18.830 | 18.840 | 18.850 | 18.860 | 18.870 | 18.880 |
| 8.8 | 18.890 | 18.900 | 18.909 | 18.919 | 18.929 | 18.939 | 18.949 | 18.958 | 18.968 | 18.978 |
| 8.9 | 18.988 | 18.998 | 19.007 | 19.017 | 19.027 | 19.036 | 19.046 | 19.056 | 19.066 | 19.075 |
| **9.0** | **19.085** | **19.094** | **19.104** | **19.114** | **19.123** | **19.133** | **19.143** | **19.152** | **19.162** | **19.171** |
| 9.1 | 19.181 | 19.190 | 19.200 | 19.209 | 19.219 | 19.228 | 19.238 | 19.247 | 19.257 | 19.266 |
| 9.2 | 19.276 | 19.285 | 19.295 | 19.304 | 19.313 | 19.323 | 19.332 | 19.342 | 19.351 | 19.360 |
| 9.3 | 19.370 | 19.379 | 19.388 | 19.398 | 19.407 | 19.416 | 19.426 | 19.435 | 19.444 | 19.453 |
| 9.4 | 19.463 | 19.472 | 19.481 | 19.490 | 19.499 | 19.509 | 19.518 | 19.527 | 19.536 | 19.545 |
| 9.5 | 19.554 | 19.564 | 19.573 | 19.582 | 19.591 | 19.600 | 19.609 | 19.618 | 19.627 | 19.636 |
| 9.6 | 19.645 | 19.654 | 19.664 | 19.673 | 19.682 | 19.691 | 19.700 | 19.709 | 19.718 | 19.726 |
| 9.7 | 19.735 | 19.744 | 19.753 | 19.762 | 19.771 | 19.780 | 19.789 | 19.798 | 19.807 | 19.816 |
| 9.8 | 19.825 | 19.833 | 19.842 | 19.851 | 19.860 | 19.869 | 19.878 | 19.886 | 19.895 | 19.904 |
| 9.9 | 19.913 | 19.921 | 19.930 | 19.939 | 19.948 | 19.956 | 19.965 | 19.974 | 19.983 | 19.991 |

| *Pressure Ratio* | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **10** | **20.000** | **20.828** | **21.584** | **22.279** | **22.923** | **23.522** | **24.082** | **24.609** | **25.105** | **25.575** |
| 20 | 26.021 | 26.444 | 26.848 | 27.235 | 27.604 | 27.959 | 28.299 | 28.627 | 28.943 | 29.248 |
| 30 | 29.542 | 29.827 | 30.103 | 30.370 | 30.630 | 30.881 | 31.126 | 31.364 | 31.596 | 31.821 |
| 40 | 32.041 | 32.256 | 32.465 | 32.669 | 32.869 | 33.064 | 33.255 | 33.442 | 33.625 | 33.804 |
| 50 | 33.979 | 34.151 | 34.320 | 34.486 | 34.648 | 34.807 | 34.964 | 35.117 | 35.269 | 35.417 |
| 60 | 35.563 | 35.707 | 35.848 | 35.987 | 36.124 | 36.258 | 36.391 | 36.521 | 36.650 | 36.777 |
| 70 | 36.902 | 37.025 | 37.147 | 37.266 | 37.385 | 37.501 | 37.616 | 37.730 | 37.842 | 37.953 |
| 80 | 38.062 | 38.170 | 38.276 | 38.382 | 38.486 | 38.585 | 38.690 | 38.790 | 38.890 | 38.988 |
| 90 | 39.085 | 39.181 | 39.276 | 39.370 | 39.463 | 39.554 | 39.645 | 39.735 | 39.825 | 39.913 |
| **100** | **40.000** | — | — | — | — | — | — | — | — | — |

appendix II

# CHART FOR COMBINING LEVELS* OF UNCORRELATED NOISE SIGNALS

## TO ADD LEVELS

Enter the chart with the NUMERICAL DIFFERENCE BETWEEN TWO LEVELS BEING ADDED. Follow the line corresponding to this value to its intersection with the curved line, then left to read the NUMERICAL DIFFERENCE BETWEEN TOTAL AND LARGER LEVEL. Add this value to the larger level to determine the total.

Example: Combine 75 dB and 80 dB. The difference is 5 dB. The 5-dB line intersects the curved line at 1.2 dB on the vertical scale. Thus the total value is 80 + 1.2 or 81.2 dB.

## TO SUBTRACT LEVELS

Enter the chart with the NUMERICAL DIFFERENCE BETWEEN TOTAL AND LARGER LEVELS if this value is less than 3 dB. Enter the chart with the NUMERICAL DIFFERENCE BETWEEN TOTAL AND SMALLER LEVELS if this value is between 3 and 14 dB. Follow the line corresponding to this value to its intersection with the curved line, then either left or down to read the NUMERICAL DIFFERENCE BETWEEN TOTAL AND LARGER (SMALLER) LEVELS. Subtract this value from the total level to determine the unknown level.

Example: Subtract 81 dB from 90 dB. The difference is 9 dB. The 9-dB vertical line intersects the curved line at 0.6 dB on the vertical scale. Thus the unknown level is 90 - 0.6 or 89.4 dB.

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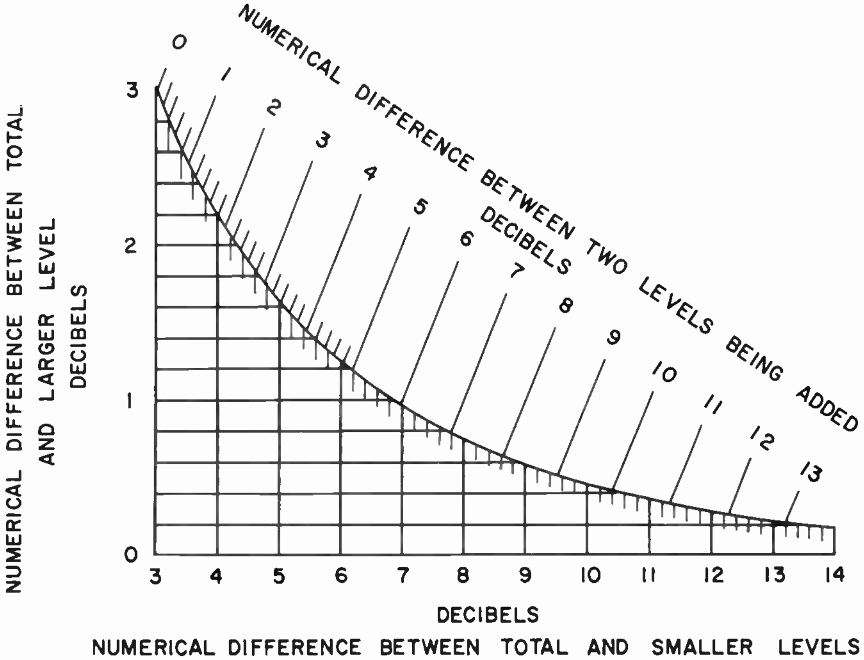
*This chart is based on one developed by R. Musa.


NUMERICAL DIFFERENCE BETWEEN TWO LEVELS BEING ADDED
DECIBELS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
NUMERICAL DIFFERENCE BETWEEN TOTAL AND LARGER LEVEL
DECIBELS
3
2
1
0
3
4
5
6
7
8
9
10
11
12
13
14
DECIBELS
NUMERICAL DIFFERENCE BETWEEN TOTAL AND SMALLER LEVELS

## appendix III

# TABLE FOR CONVERTING LOUDNESS TO LOUDNESS LEVEL

A simplified relation between the loudness in sones and the loudness level in phons has been standardized internationally (ISO/R131-1959). This relation is a good approximation to the psychoacoustical data and is useful for engineering purposes, but it should not be expected to be accurate enough for research on the subjective aspects of hearing.

The relation is

$$S = 2^{(P-40)/10}$$

where S is the loudness in sones and P is the loudness level in phons.

A table of loudness in sones for loudness levels ranging from 20 to 130 phons in increments of 1 phon, calculated from the above relation, is given below.

Examples:

Given - loudness level of 72 phons.
Find - in table under "+2" in the "70" row - 9.2 sones.

|  | LOUDNESS IN SONES |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| Phons | 0 | +1 | +2 | +3 | +4 | +5 | +6 | +7 | +8 | +9 |
| 20 | .25 | .27 | .29 | .31 | .33 | .35 | .38 | .41 | .44 | .47 |
| 30 | .50 | .54 | .57 | .62 | .66 | .71 | .76 | .81 | .87 | .93 |
| 40 | 1 | 1.07 | 1.15 | 1.23 | 1.32 | 1.41 | 1.52 | 1.62 | 1.74 | 1.87 |
| 50 | 2 | 2.14 | 2.30 | 2.46 | 2.64 | 2.83 | 3.03 | 3.25 | 3.48 | 3.73 |
| 60 | 4 | 4.29 | 4.59 | 4.92 | 5.28 | 5.66 | 6.06 | 6.50 | 6.96 | 7.46 |
| 70 | 8 | 8.6 | 9.2 | 9.8 | 10.6 | 11.3 | 12.1 | 13.0 | 13.9 | 14.9 |
| 80 | 16 | 17.1 | 18.4 | 19.7 | 21.1 | 22.6 | 24.3 | 26.0 | 27.9 | 29.9 |
| 90 | 32 | 34.3 | 36.8 | 39.4 | 42.2 | 45.3 | 48.5 | 52.0 | 55.7 | 59.7 |
| 100 | 64 | 68.6 | 73.5 | 78.8 | 84.4 | 90.5 | 97 | 104 | 111 | 119 |
| 110 | 128 | 137 | 147 | 158 | 169 | 181 | 194 | 208 | 223 | 239 |
| 120 | 256 | 274 | 294 | 315 | 338 | 362 | 388 | 416 | 446 | 478 |

appendix IV

# VIBRATION CONVERSION CHARTS

The charts on the following pages illustrate the relationship between frequency, velocity, acceleration, displacement, and jerk (refer to Chapter 2).

Figures IV-1 and IV-2 are general conversion charts for frequency, displacement, velocity, and acceleration. Enter the chart with any two of these parameters to solve for the other two. In Figure IV-1, displacement, velocity, and acceleration are given in inches, inches/second, and inches/second$^2$, respectively, while Figure IV-2 uses metric units.

Figures IV-3 through IV-9 show the direct-reading ranges of the Type 1553-A (inch) and Type 1553-AK (metric) Vibration Meters. Each of these figures is merely a portion of Figure IV-1 or IV-2, expanded and configured to show the range of displacement, velocity, acceleration, or jerk over the frequency range of the instrument.

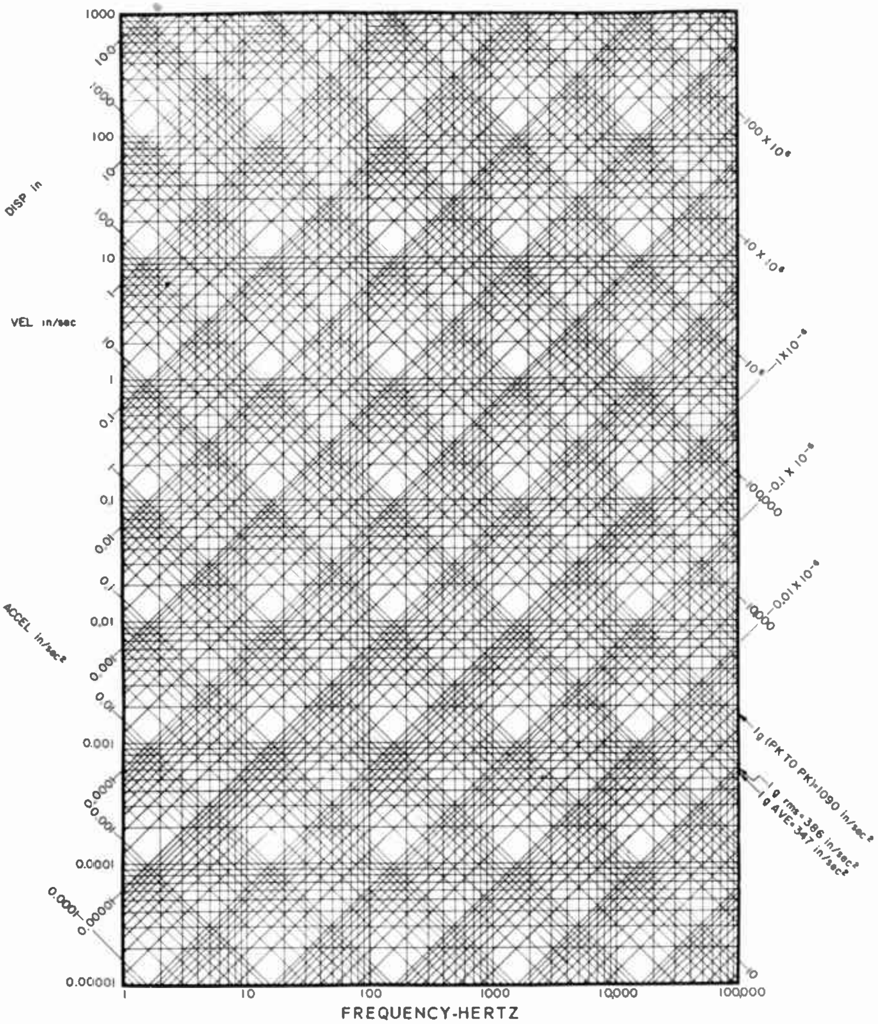


*Figure IV-1. Conversion chart for vibration parameters, for use with Type 1553-A Vibration Meter.*

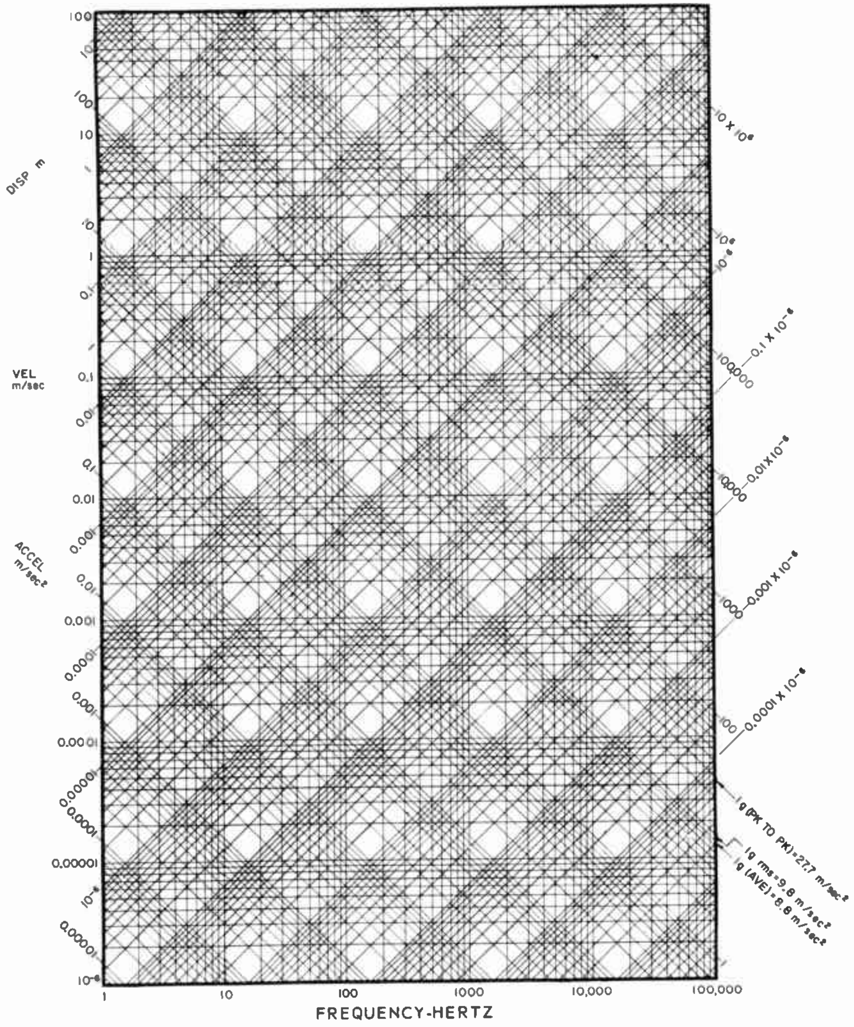


*Figure IV-2. Conversion chart for vibration parameters, for use with Type 1553-AK Vibration Meter.*

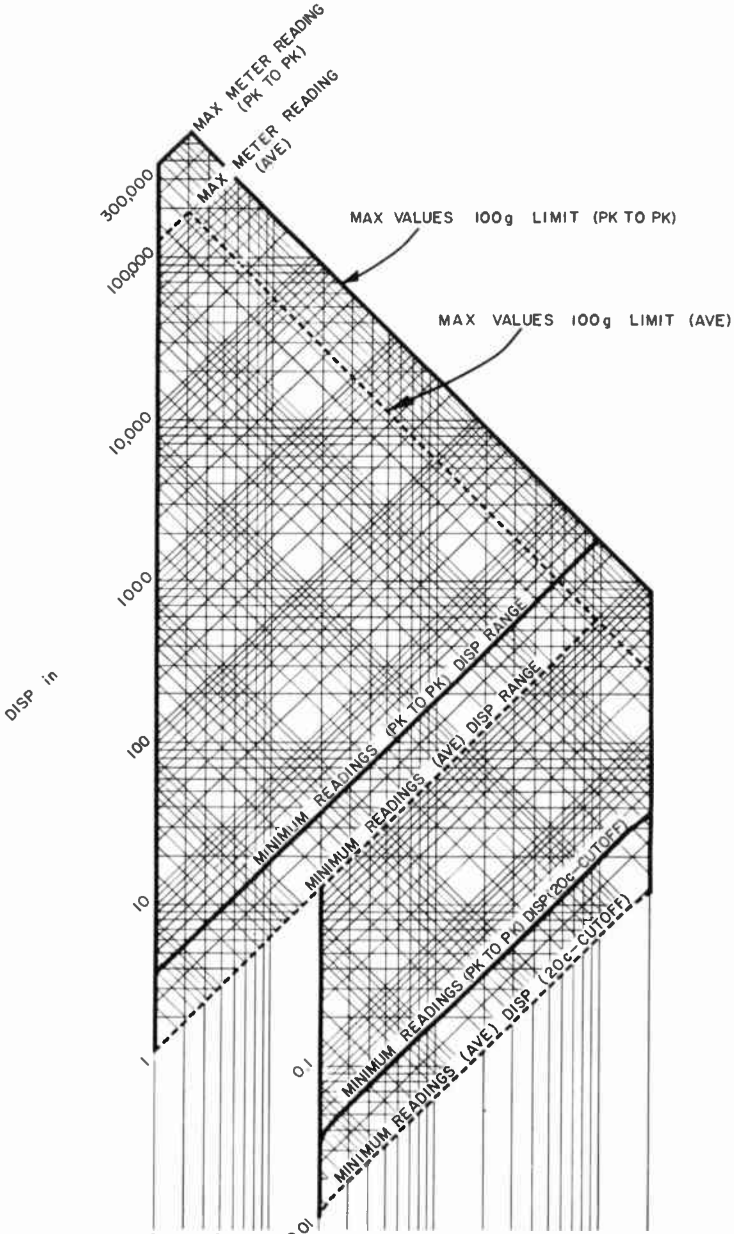


*Figure IV-3. Direct-reading displacement ranges of the Type 1553-A Vibration Meter.*

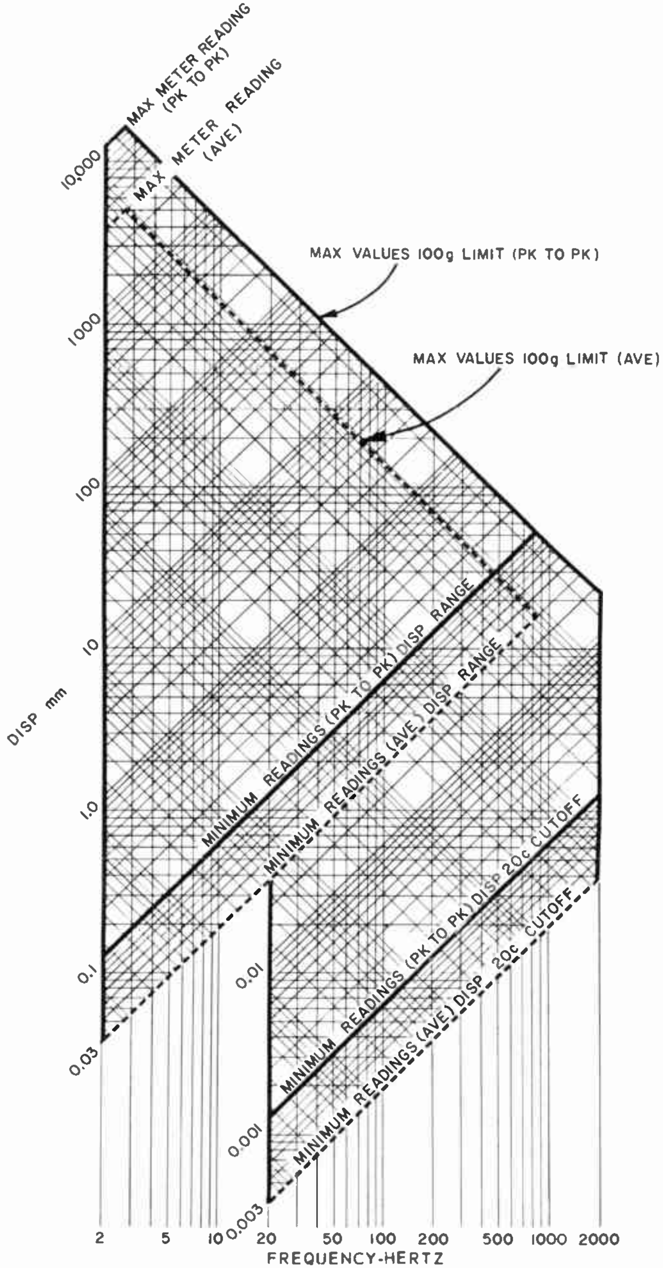


*Figure IV-4. Direct-reading displacement ranges of the Type 1553-AK Vibration Meter.*

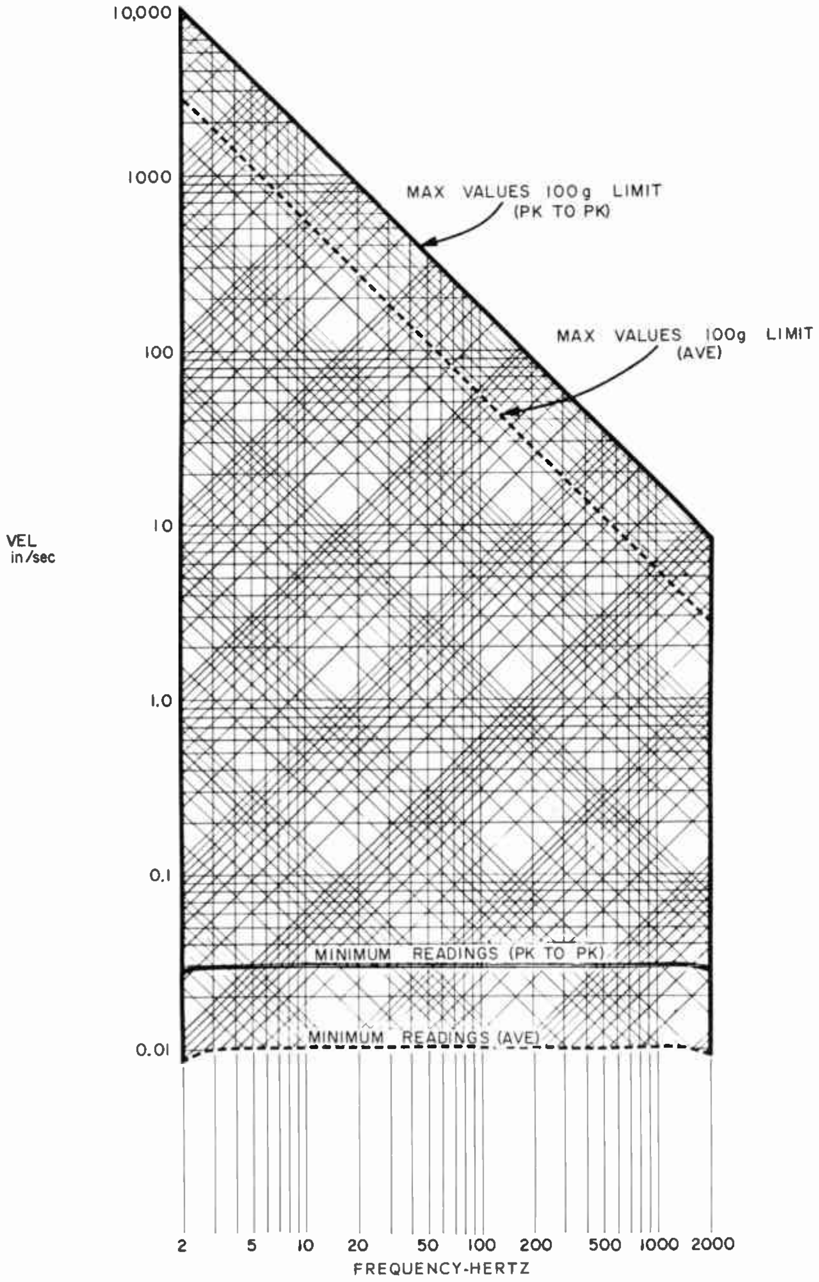


*Figure IV-5. Direct-reading velocity ranges of the Type 1553-A Vibration Meter.*

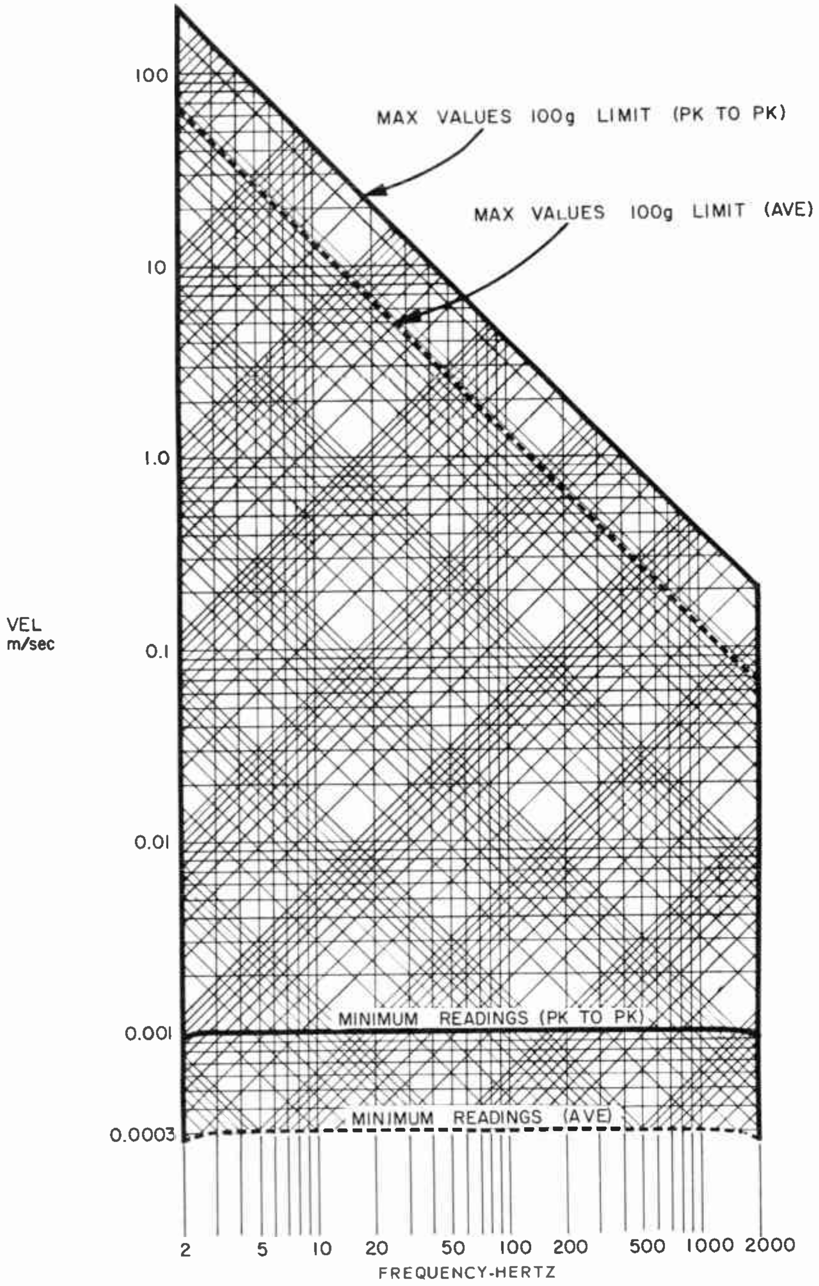


*Figure IV-6. Direct-reading velocity ranges of the Type 1553-AK Vibration Meter.*

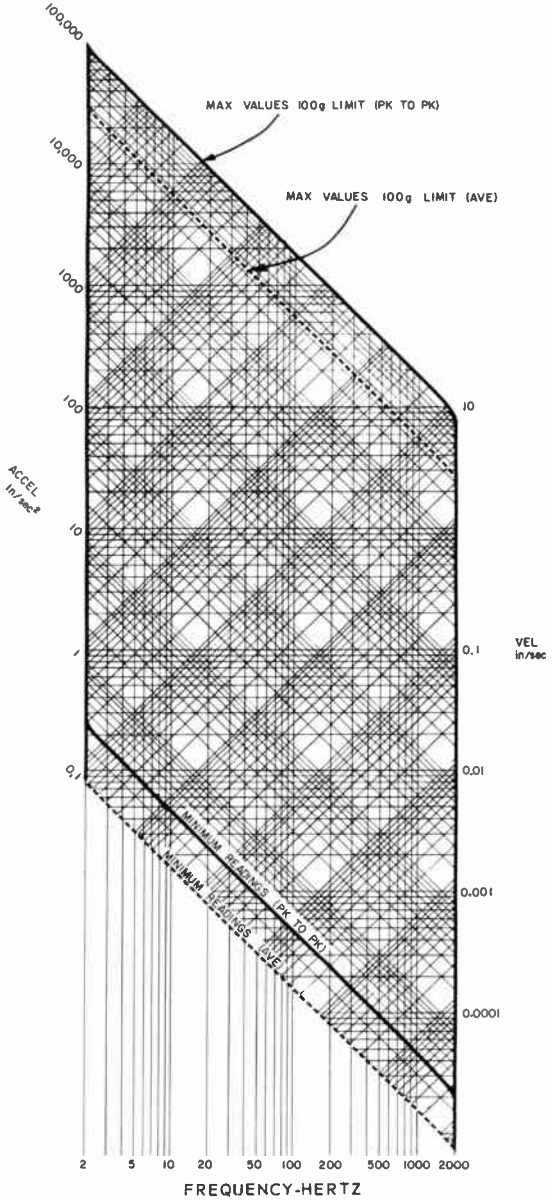


*Figure IV-7. Direct-reading acceleration ranges of the Type 1553-A Vibration Meter.*

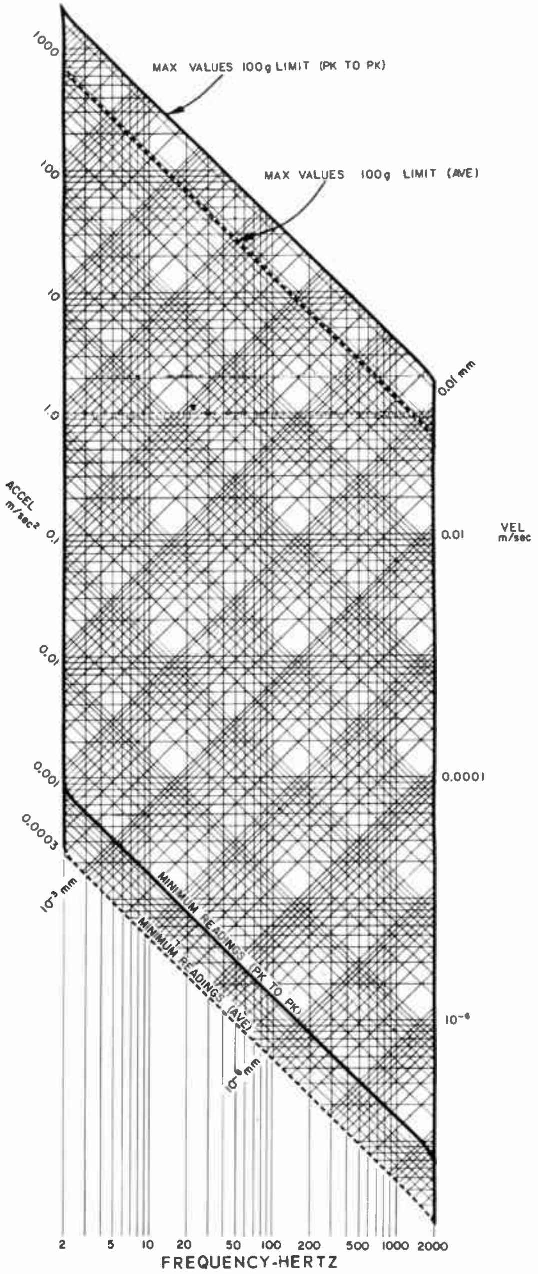


*Figure IV-8. Direct-reading acceleration ranges of the Type 1553-AK Vibration Meter.*

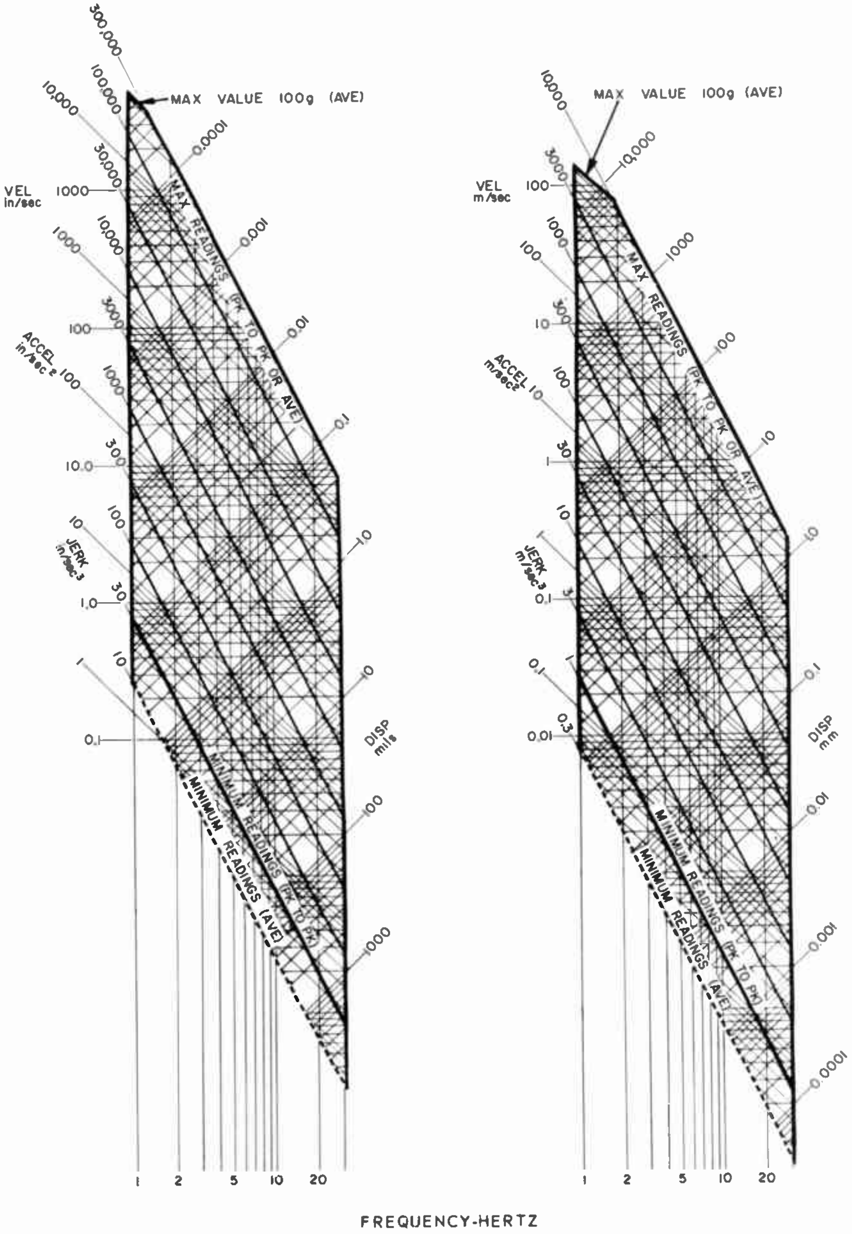


*Figure IV-9. Direct-reading jerk ranges of the Types 1553-A (left) and 1553-AK (right) Vibration Meters.*

## appendix V

# DEFINITIONS

This section on definitions includes most of the technical terms used in this handbook. Most of the definitions are selected from the American Standard Acoustical Terminology (S1.1-1960), and those definitions are marked with an asterisk. The others have been adapted especially for this handbook.

A number of these definitions are very technical in order to be precise. Some readers may then find it easier to refer to the discussion in the main text of this handbook for obtaining a general understanding of some of these terms.

ACCELERATION*

Acceleration is a vector that specifies the time rate of change of velocity.

Note 1: Various self-explanatory modifiers such as peak, average, rms are often used. The time interval must be indicated over which the average (for example) was taken.

Note 2: Acceleration may be (1) oscillatory, in which case it may be defined by the acceleration amplitude (if simple harmonic) or the rms acceleration (if random), or (2) nonoscillatory, in which case it is designated "sustained" or "transient" acceleration.

ANALYZER

An analyzer is a combination of a filter system and a system for indicating the relative energy that is passed through the filter system. The filter is usually adjustable so that the signal applied to the filter can be measured in terms of the relative energy passed through the filter as a function of the adjustment of the filter response-vs-frequency characteristic. This measurement is usually interpreted as giving the distribution of energy of the applied signal as a function of frequency.

ANECHOIC ROOM (FREE-FIELD ROOM)*

An anechoic room is one whose boundaries absorb effectively all the sound incident thereon, thereby affording essentially free-field conditions.

AUDIOGRAM (THRESHOLD AUDIOGRAM)*

An audiogram is a graph showing hearing loss as a function of frequency.

AUDIOMETER*

An audiometer is an instrument for measuring hearing sensitivity.

BAFFLE*

A baffle is a shielding structure or partitions used to increase the effective length of the external transmission path between two points in an acoustic system as, for example, between the front and back of an electroacoustic transducer.

CONFIDENCE LIMITS

Confidence limits are the upper and lower values of the range over which a given percent probability applies. For instance, if the chances are 99 out of 100 that a sample lies between 10 and 12, the 99% confidence limits are said to be 10 and 12.

CRITICAL SPEED*

Critical speed is a speed of a rotating system that corresponds to a resonance frequency of the system.

DEAD ROOM* (See also ANECHOIC ROOM)

A dead room is a room that is characterized by an unusually large amount of sound absorption.

DECAY RATE (See RATE OF DECAY)

DECIBEL*

The decibel is one-tenth of a bel. Thus, the decibel is a unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power.

Note 1: Examples of quantities that qualify are power (any form), sound pressure squared, particle velocity squared, sound intensity, sound energy density, voltage squared. Thus the decibel is a unit of sound-pressure-squared level; it is common practice, however, to shorten this to sound pressure level because ordinarily no ambiguity results from so doing.

Note 2: The logarithm to the base the tenth root of 10 is the same as ten times the logarithm to the base 10: e.g., for a number $x^2$, $\log_{10^{0.1}} x^2 = 10 \log_{10} x^2 = 20 \log_{10} x$. This last relationship is the one ordinarily used to simplify the language in definitions of sound pressure level, etc.

DIRECTIVITY FACTOR*

(1) The directivity factor of a transducer used for sound emission is the ratio of the sound pressure squared, at some fixed distance and specified direction, to the mean-square sound pressure at the same distance averaged over all directions from the transducer. The distance must be great enough so that the sound appears to diverge spherically from the effective acoustic center of the sources. Unless otherwise specified, the reference direction is understood to be that of maximum response.

(2) The directivity factor of a transducer used for sound reception is the ratio of the square of the open-circuit voltage produced in response to sound waves arriving in a specified direction to the mean-square voltage that would be produced in a perfectly diffused sound field of the same frequency and mean-square sound pressure.

Note 1: This definition may be extended to cover the case of finite frequency bands whose spectrum may be specified.

Note 2: The average free-field response may be obtained, for example,

(1) By the use of a spherical integrator

(2) By numerical integration of a sufficient number of directivity patterns corresponding to different planes, or

(3) By integration of one or two directional patterns whenever the pattern of the transducer is known to possess adequate symmetry.

DIRECTIONAL GAIN (DIRECTIVITY INDEX)*

The directional gain of a transducer, in decibels, is 10 times the logarithm to the base 10 of the directivity factor.

DISPLACEMENT*

Displacement is a vector quantity that specifies the change of position of a body or particle and is usually measured from the mean position or position of rest. In general, it can be represented by a rotation vector or translation vector or both.

EARPHONE (RECEIVER)*

An earphone is an electroacoustic transducer intended to be closely coupled acoustically to the ear.

Note: The term "receiver" should be avoided when there is risk of ambiguity.

EFFECTIVE SOUND PRESSURE
(ROOT-MEAN-SQUARE SOUND PRESSURE)*

The effective sound pressure at a point is the root-mean-square value of the instantaneous sound pressures, over a time interval at the point under consideration. In the case of periodic sound pressures, the interval must be an integral number of periods or an interval long compared to a period. In the case of non-periodic sound pressures, the interval should be long enough to make the value obtained essentially independent of small changes in the length of the interval.

Note: The term "effective sound pressure" is frequently shortened to "sound pressure."

FILTER

A filter is a device for separating components of a signal on the basis of their frequency. It allows components in one or more frequency bands to pass relatively unattenuated, and it attenuates components in other frequency bands.

FREE SOUND FIELD (FREE FIELD)*

A free sound field is a field in a homogeneous, isotropic medium free from boundaries. In practice it is a field in which the effects of the boundaries are negligible over the region of interest.

Note: The actual pressure impinging on an object (e.g., electro-acoustic transducer) placed in an otherwise free sound field will differ from the pressure which would exist at that point with the object removed, unless the acoustic impedance of the object matches the acoustic impedance of the medium.

FREQUENCY (IN CYCLES PER SECOND OR HERTZ)

Frequency is the time rate of repetition of a periodic phenomenon. The frequency is the reciprocal of the period.

g*

The quantity "g" is the acceleration produced by the force of gravity, which varies with the latitude and elevation of the point of observation. By international agreement, the value 980.665 cm/s$^2$ = 386.087 in./s$^2$ = 32.1739 ft./s$^2$ has been chosen as the standard acceleration of gravity.

HEARING LOSS (HEARING LEVEL)
(HEARING-THRESHOLD LEVEL)*

The hearing loss of an ear at a specified frequency is the amount, in decibels, by which the threshold of audibility for that ear exceeds a standard audiometric threshold.

Note 1: See American Standard Specification for Audiometers for General Diagnostic Purposes, Z24.5-1951, or the latest approved revision.

Note 2: This concept was at one time called Deafness; such usage is now deprecated.

Note 3: Hearing Loss and Deafness are both legitimate qualitative terms for the medical condition of a moderate or a severe impairment of hearing respectively. Hearing Level, however, should only be used to designate a quantitative measure of the deviation of the hearing threshold from a prescribed standard.

IMPACT*

An impact is a single collision of one mass in motion with a second mass which may be either in motion or at rest.

ISOLATION*

Isolation is a reduction in the capacity of a system to respond to an excitation attained by the use of a resilient support. In steady-state forced vibration, isolation is expressed quantitatively as the complement of transmissibility.

JERK*

Jerk is a vector that specifies the time rate of change of the acceleration; jerk is the third derivative of the displacement with respect to time.

LEVEL*

In acoustics, the level of a quantity is the logarithm of the ratio of that quantity to a reference quantity of the same kind. The base of the logarithm, the reference quantity, and the kind of level must be specified.

Note 1: Examples of kinds of levels in common use are electric power level, sound-pressure-squared level, voltage-squared level.

Note 2: The level as here defined is measured in units of the logarithm of a reference ratio that is equal to the base of logarithms.

Note 3: In symbols

$$L = \log_r (q/q_o)$$

where L = level of kind determined by the kind of quantity under consideration, measured in units of $\log_r r$

r = base of logarithms and the reference ratio

q = the quantity under consideration

$q_o$ = reference quantity of the same kind.

Note 4: Differences in the levels of two quantities $q_1$ and $q_2$ are described by the same formula because, by the rules of logarithms, the reference quantity is automatically divided out:

$$\log_r(q_1/q_o) - \log_r(q_2/q_o) = \log_r(q_1/q_2)$$

LIVE ROOM*

A live room is a room that is characterized by an unusually small amount of sound absorption.

LOUDNESS*

Loudness is the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud.

Note: Loudness depends primarily upon the sound pressure of the stimulus, but it also depends upon the frequency and wave form of the stimulus.

LOUDNESS CONTOUR*

A loudness contour is a curve that shows the related values of sound pressure levels and frequency required to produce a given loudness sensation for the typical listener.

LOUDNESS LEVEL*

The loudness level of a sound, in phons, is numerically equal to the median sound pressure level, in decibels, relative to 0.0002 microbar, of a free progressive wave of frequency 1000 Hz presented to listeners facing the source, which in a number of trials is judged by the listeners to be equally loud.

Note: The manner of listening to the unknown sound, which must be stated, may be considered one of the characteristics of that sound.

LOUDSPEAKER (SPEAKER)*

A loudspeaker is an electroacoustic transducer intended to radiate acoustic power into the air, the acoustic waveform being essentially equivalent to that of the electrical input.

MASKING*

(1) Masking is the process by which the threshold of audibility for one sound is raised by the presence of another (masking) sound.

(2) Masking is the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. The unit customarily used is the decibel.

MECHANICAL IMPEDANCE*

Mechanical Impedance is the impedance obtained from the ratio of force to velocity during simple harmonic motion.

MECHANICAL SHOCK*

Mechanical shock occurs when the position of a system is significantly changed in a relatively short time in a non-periodic manner. It is characterized by suddenness and large displacement, and develops significant inertial forces in the system.

MEL*

The mel is a unit of pitch. By definition, a simple tone of frequency 1000 Hz, 40 decibels above a listener's threshold, produces a pitch of 1000 mels. The pitch of any sound that is judged by the listener to be n times that of a 1-mel tone is n mels.

MICROBAR, DYNE PER SQUARE CENTIMETER*

A microbar is a unit of pressure commonly used in acoustics. One microbar is equal to 1 dyne per square centimeter.

Note: The term "bar" properly denotes a pressure of $10^6$ dynes per square centimeter. Unfortunately, the bar was once used to mean dyne per square centimeter, but this is no longer correct.

MICROPHONE*

A microphone is an electroacoustic transducer that responds to sound waves and delivers essentially equivalent electric waves.

NNI

NNI is the noise and number index based on perceived noise level, and it is used for rating airplane flyby noise.

NOISE*

(1) Noise is any undesired sound. By extension, noise is any unwanted disturbance within a useful frequency band, such as undesired electric waves in any transmission channel or device.

(2) Noise is an erratic, intermittent, or statistically random oscillation.

Note 1: If ambiguity exists as to the nature of the noise, a phrase such as "acoustic noise" or "electric noise" should be used.

Note 2: Since the above definitions are not mutually exclusive, it is usually necessary to depend upon context for the distinction.

NOISE LEVEL*

(1) Noise level is the level of noise, the type of which must be indicated by further modifier or context.

Note: The physical quantity measured (e.g. voltage), the reference quantity, the instrument used, and the bandwidth or other weighting characteristic must be indicated.

(2) For airborne sound unless specified to the contrary, noise level is the weighted sound pressure level called sound level; the weighting must be indicated.

NOYS

Noys is a unit used in the calculation of perceived noise level.

OCTAVE*

(1) An octave is the interval between two sounds having a basic frequency ratio of two.

(2) An octave is the pitch interval between two tones such that one tone may be regarded as duplicating the basic musical import of the other tone at the nearest possible higher pitch.

Note 1: The interval, in octaves, between any two frequencies is the logarithm to the base 2 (or 3.322 times the logarithm to the base 10) of the frequency ratio.

Note 2: The frequency ratio corresponding to an octave pitch interval is approximately, but not always exactly, 2:1.

OSCILLATION*

Oscillation is the variation, usually with time, of the magnitude of a quantity with respect to a specified reference when the magnitude is alternately greater and smaller than the reference.

PEAK-TO-PEAK VALUE*

The peak-to-peak value of an oscillating quantity is the algebraic difference between the extremes of the quantity.

PERCEIVED NOISE LEVEL

Perceived noise level is the level in dB assigned to a noise by means of a calculation procedure that is based on an approximation to subjective evaluations of "noisiness."

PHON*

The phon is the unit of loudness level. (See "Loudness Level.")

PITCH*

Pitch is that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch depends primarily upon the frequency of the sound stimulus, but it also depends upon the sound pressure and wave form of the stimulus.

Note 1: The pitch of a sound may be described by the frequency or frequency level of that simple tone, having a specified sound pressure level, which is judged by listeners to produce the same pitch.

POINT SOURCE

See "Simple Sound Source."

POWER LEVEL*

Power level, in decibels, is 10 times the logarithm to the base 10 of the ratio of a given power to a reference power. The reference power must be indicated. [The reference power is taken as $1.0 \times 10^{-12}$ watt in this handbook.]

PRESBYCUSIS

Presbycusis is the condition of hearing loss specifically ascribed to aging effects.

PRESSURE SPECTRUM LEVEL*

The pressure spectrum level of a sound at a particular frequency is the effective sound pressure level of that part of the signal contained within a band 1 cycle per second wide, centered at the particular frequency. Ordinarily this has significance only for sound having a continuous distribution of energy within the frequency range under consideration. The reference pressure should be explicitly stated.

PRIMITIVE PERIOD (PERIOD)*

The primitive period of a periodic quantity is the smallest increment of the independent variable for which the function repeats itself.

Note: If no ambiguity is likely, the primitive period is simply called the period of the function.

PURE TONE

See "Simple Tone."

RANDOM NOISE*

Random noise is an oscillation whose instantaneous magnitude is not specified for any given instant of time. The instantaneous magnitudes of a random noise are specified only by probability distribution functions giving the fraction of the total time that the magnitude, or some sequence of magnitudes, lies within a specified range.

Note: A random noise whose instantaneous magnitudes occur according to the Gaussian distribution is called "Gaussian random noise."

RATE OF DECAY*

The rate of decay is the time rate at which the sound pressure level (or other stated characteristic) decreases at a given point and at a given time. A commonly used unit is the decibel per second.

RESONANCE*

Resonance of a system in forced oscillation exists when any change however small in the frequency of excitation causes a decrease in the response of the system.

Note: Velocity resonance, for example, may occur at a frequency different from that of displacement resonance.

RESONANCE FREQUENCY
(RESONANT FREQUENCY)*

A resonance frequency is a frequency at which resonance exists.

Note: In case of possible confusion the type of resonance must be indicated: e.g., velocity resonance frequency.

RESPONSE*

The response of a device or system is the motion (or other output) resulting from an excitation (stimulus) under specified conditions.

Note 1: Modifying phrases must be prefixed to the term response to indicate kinds of input and output that are being utilized.

Note 2: The response characteristic, often presented graphically, gives the response as a function of some independent variable such as frequency or direction. For such purposes it is customary to assume that other characteristics of the input (for example, voltage) are held constant.

REVERBERATION*

1. Reverberation is the persistence of sound in an enclosed space, as a result of multiple reflections after the sound source has stopped.

2. Reverberation is the sound that persists in an enclosed space, as a result of repeated reflection or scattering, after the source of sound has stopped.

Note: The repeated reflections of residual sound in an enclosure can alternatively be described in terms of the transient behavior of the modes of vibration of the medium bounded by the enclosure.

REVERBERATION TIME*

The reverberation time of a room is the time that would be required for the mean squared sound pressure level therein, originally in a steady state, to decrease 60 dB after the source is stopped.

SIMPLE SOUND SOURCE*

A simple sound source is a source that radiates sound uniformly in all directions under free-field conditions.

SIMPLE TONE (PURE TONE)*

1. A simple tone is a sound wave, the instantaneous sound pressure of which is a simple sinusoidal function of the time.

2. A simple tone is a sound sensation characterized by its singleness of pitch.

Note: Whether or not a listener hears a tone as simple or complex is dependent upon ability, experience, and listening attitude.

SONE*

The sone is a unit of loudness. By definition, a simple tone of frequency 1000 Hz, 40 decibels above a listener's threshold, produces a loudness of 1 sone. The loudness of any sound that is judged by the listener to be n times that of the 1-sone tone is n sones.

Note 1: A millisone is equal to 0.001 sone.

Note 2: The loudness scale is a relation between loudness and level above threshold for a particular listener. In presenting data relating loudness in sones to sound pressure level, or in averaging the loudness scales of several listeners, the thresholds (measured or assumed) should be specified.

SONICS*

Sonics is the technology of sound in processing and analysis. Sonics includes the use of sound in any noncommunication process.

SOUND*

1. Sound is an oscillation in pressure, stress, particle displacement, particle velocity, etc., in a medium with internal forces (e.g. elastic, viscous), or the superposition of such

propagated alterations.

2. Sound is an auditory sensation evoked by the oscillation described above.

Note 1: In case of possible confusion the term "sound wave" or "elastic wave" may be used for concept (1), and the term "sound sensation" for concept (2). Not all sound waves can evoke an auditory sensation: e.g. ultrasound.

Note 2: The medium in which the source exists is often indicated by an appropriate adjective: e.g. airborne, waterborne, structureborne.

SOUND INTENSITY (SOUND POWER DENSITY) (SOUND-ENERGY FLUX DENSITY)*

The sound intensity in a specified direction at a point is the average rate of sound energy transmitted in the specified direction through a unit area normal to this direction at the point considered.

SOUND LEVEL*

Sound level is a weighted sound pressure level obtained by the use of metering characteristics and the weighting specified in the American Standard Sound Level Meters for Measurement of Noise and Other Sounds, Z24.3-1944, or the latest approved revision thereof. The weighting employed must always be stated. The reference pressure is 0.0002 microbar.

Note: A suitable method of stating the weighting is, for example, "The A sound level was 43 dB."

SOUND LEVEL METER*

A sound level meter is an instrument including a microphone, an amplifier, an output meter, and frequency weighting networks for the measurement of noise and sound levels in a specified manner.

Note: Specifications for sound level meters for measurement of noise and other sounds are given in American Standard Sound Level Meters for Measurement of Noise and Other Sounds, S1.4-1961, or the latest approved revision thereof.

SOUND PRESSURE LEVEL*

The sound pressure level, in decibels, of a sound is 20 times the logarithm to the base 10 of the ratio of the pressure of this sound to the reference pressure. The reference pressure shall be explicitly stated.

Note 1: The following reference pressures are in common use;

(a) $2 \times 10^{-4}$ microbar

(b) 1 microbar

Reference pressure (a) is in general use for measurements concerned with hearing and with sound in air and liquids, while (b) has gained widespread acceptance for calibrations of transducers and various kinds of sound measurements in liquids.

[The reference pressure used in this handbook is $2 \times 10^{-4}$

microbar = $20 \mu N/m^2$.]

Note 2: Unless otherwise explicitly stated, it is to be understood that the sound pressure is the effective (rms) sound pressure.

Note 3: It is to be noted that in many sound fields the sound pressure ratios are not the square roots of the corresponding power ratios.

SPECTRUM*

1. The spectrum of a function of time is a description of its resolution into components, each of different frequency and (usually) different amplitude and phase.

2. "Spectrum" is also used to signify a continuous range of components, usually wide in extent, within which waves have some specified common characteristic; e.g., "audio-frequency spectrum."

Note 1. The term spectrum is also applied to functions of variables other than time, such as distance.

SPEECH INTERFERENCE LEVEL (SIL)

The speech interference level of a noise is the average, in decibels, of the sound pressure levels of the noise in the three octave bands of center frequency 500, 1000 and 2000 Hz.

STANDING WAVE*

A standing wave is a periodic wave having a fixed distribution in space which is the result of interference of progressive waves of the same frequency and kind. Such waves are characterized by the existence of nodes or partial nodes and antinodes that are fixed in space.

THRESHOLD OF AUDIBILITY
(THRESHOLD OF DETECTABILITY)*

The threshold of audibility for a specified signal is the minimum effective sound pressure level of the signal that is capable of evoking an auditory sensation in a specified fraction of the trials. The characteristics of the signal, the manner in which it is presented to the listener, and the point at which the sound pressure is measured must be specified.

Note 1: Unless otherwise indicated, the ambient noise reaching the ears is assumed to be negligible.

Note 2: The threshold is usually given as a sound pressure level in decibels, relative to 0.0002 microbar.

Note 3: Instead of the method of constant stimuli, which is implied by the phrase "a specified fraction of the trials," another psychophysical method (which should be specified) may be employed.

THRESHOLD OF FEELING (OR TICKLE)*

The threshold of feeling (or tickle) for a specified signal is the minimum sound pressure level at the entrance to the external auditory canal which, in a specified fraction of the trials, will stimulate the ear to a point at which there is a sensation of feeling that is different from the sensation of hearing.

TIF (TELEPHONE INFLUENCE FACTOR)

TIF is an index of the potential interfering effect of a particular power circuit on a telephone circuit. (See AIEE Trans. Vol. 79, Part I, 1960, pp. 659-664.)

TONE*

(a) A tone is a sound wave capable of exciting an auditory sensation having pitch.

(b) A tone is a sound sensation having pitch.

TRANSDUCER*

A transducer is a device capable of being actuated by waves from one or more transmission systems or media and of supplying related waves to one or more other transmission systems or media.

Note: The waves in either input or output may be of the same or different types (e.g., mechanical, or acoustic).

TRANSIENT VIBRATION*

Transient vibration is temporarily sustained vibration of a mechanical system. It may consist of forced or free vibration or both.

ULTRASONICS*

Ultrasonics is the technology of sound at frequencies above the audio range.

Note: Supersonics is the general subject covering phenomena associated with speed higher than the speed of sound (as in the case of aircraft and projectiles traveling faster than sound). This term was once used in acoustics synonomously with "ultrasonics;" such usage is now deprecated.

VELOCITY*

Velocity is a vector that specifies the time rate of change of displacement with respect to a reference frame.

Note: If the reference frame is not inertial, the velocity is often designated relative velocity.

VIBRATION*

Vibration is an oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

VIBRATION ISOLATOR*

A vibration isolator is a resilient support that tends to isolate a system from steady-state excitation.

VIBRATION METER (VIBROMETER)*

A vibration meter is an apparatus for the measurement of displacement, velocity, or acceleration of a vibrating body.

WHITE NOISE

White noise is a noise whose noise power per unit frequency is substantially independent of frequency over a specified range.

Note: White noise need not be random.

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## appendix VI

# WORDS COMMONLY USED TO DESCRIBE SOUNDS

The words listed below are commonly used to describe sounds of various types. Such words are often helpful in conveying information on the general nature of a sound.

BANG
BARK
BEEP
BELLOW
BLARE
BLAST
BLEAT
BONG
BOOM
BRAY
BUZZ
CACKLE
CHEEP
CHIME
CHIRP
CLACK
CLANG
CLANK
CLAP
CLATTER
CLICK
CLINK
CLUCK
CLUNK
CRACK
CRACKLE
CRASH
CREAK
DINGDONG
DRIP
DRUMMING
FIZ
GNASHING
GOBBLE
GRATING
GRINDING
GROAN
GROWL
GRUMBLE
GRUNT
GURGLE
HISS
HOOT
HOWL
HUM
JINGLE
JANGLE
KNOCK
MEW
MOAN
MOO
MURMUR
NEIGH
PATTER
PEAL
PEEP
PING
POP
POW
POUNDING
PULSING
PURR
RAP
RATTLE
RING
RIPPLING
ROAR
RUMBLE
RUSTLE
SCREAM
SCREECH
SCRUNCH
SHRIEK
SIZZLE
SLAM
SNAP
SNARL
SNORT
SPLASH
SQUAWK
SQUEAK
SQUEAL
SQUISH
STAMP
SWISH
TAP
TATTOO
THROB
THUD
THUMP
THUNDER
TICK
TINKLE
TOOT
TRILL
TWANG
TWITTER
WAIL
WHEEZE
WHINE
WHIR
WHISPER
WHISTLE
YAP
YELP
ZAP

## appendix VII

# REFERENCES

## STANDARDS

The following standards in acoustics and mechanical shock and vibration can be purchased from the United States of America Standards Institute, 10 East 40th Street, New York 17, New York:

| | |
|---|---|
| S1.1-1960 | Acoustical Terminology |
| S1.2-1962 | Physical Measurement of Sound |
| S1.4-1961 | General-Purpose Sound Level Meters |
| S1.5-1963 | Loudspeaker Measurements |
| S1.6-1967 | Preferred Frequencies and Band Numbers for Acoustical Measurements |
| S1.10-1966 | Calibration of Microphones |
| S1.11-1966 | Octave, Half-Octave, and Third-Octave Band Filter Sets |
| S1.12-1966 | Specification for Laboratory Standard Pressure Microphones |
| S2.1-1961 | Shock Testing Machine |
| S2.2-1959 | Calibration of Shock and Vibration Pickups |
| S2.4-1960 | Specifying the Characteristics of Auxiliary Equipment |
| S2.5-1962 | Specifying the Performance of Vibration Machines |
| S2.6-1963 | Mechanical Impedance of Structures |
| S2.7-1964 | Terminology for Balancing Rotating Machinery |
| S3.1-1960 | Criteria for Background Noise in Audiometer Rooms |
| S3.2-1960 | Measurement of Monosyllabic Word Intelligibility |
| S3.3-1960 | Electroacoustical Characteristics of Hearing Aids |
| S3.4 | Computation of the Loudness of Noise |
| S3-W-39 | Effects of Vibration on Man |
| S4.1-1960 | Mechanically Recorded Lateral Frequency Records |
| Z24.5-1951 | Audiometers for General Diagnostic Purposes |
| Z24.9-1949 | Coupler Calibration of Earphones |
| Z24.12-1952 | Pure-Tone Audiometers for Screening Purposes |
| Z24.13-1953 | Speech Audiometers |
| Z24.15-1955 | Specifying the Characteristics of Analyzers |

| | |
|---|---|
| Z24.17-1955 | Class H I (High-Impact) Shock-Testing Machine |
| Z24.19-1957 | Laboratory Measurement of Air-Borne Sound Transmission Loss of Building Floors and Walls |
| Z24.21-1957 | Specifying the Characteristics of Pickups for Shock and Vibration Measurements |
| Z24.22-1957 | Measurement of the Real-Ear Attenuation of Ear Protectors at Threshold |
| Z24.24-1957 | Calibration of Electroacoustical Transducers (Particularly Those for Use in Water) |

as well as the following recommendations of the International Organization for Standardization:

| | |
|---|---|
| ISO/R131-1959 | Expression of the physical and subjective magnitudes of sound or noise |
| ISO/R140-1960 | Field and laboratory measurements of airborne and impact sound transmission |
| ISO/R226-1961 | Normal equal-loudness contours for pure tones |
| ISO/R266-1962 | Preferred frequencies for acoustical measurements |
| ISO/R354-1963 | Measurement of Absorption Coefficients in a Reverberation Room |
| ISO/R357-1963 | Power and Intensity Levels of Sound or Noise |
| ISO/R362-1964 | Measurement of Noise Emitted by Vehicles |
| ISO/R389-1964 | Reference Zero for Pure-Tone Audiometers |
| ISO/R31/Part VII-1965 | Quantities and Units of Acoustics |
| ISO/R495-1966 | Test Codes for Measuring the Noise Emitted by Machines |

and the following standards of the International Electrotechnical Commission

| | |
|---|---|
| IEC/118 (1959) | Measurements of Hearing Aids |
| IEC/123 (1961) | General Purpose Sound Level Meters |
| IEC/126 (1961) | Reference Coupler |
| IEC/178 (1965) | Pure Tone Screening Audiometers |
| IEC/179 (1965) | Precision Sound Level Meters |

Representative List of Other Standards and Test Codes

Air Conditioning and Refrigeration Institute (ARI)

| | |
|---|---|
| STD 443 | Rooms Fan-Coil Air Conditioners |

Air Diffusion Council

| | |
|---|---|
| AD-63 | Room-to-Room Sound Transmission in Plenum Systems |

Air Moving & Conditioning Association (AMCA)

| | |
|---|---|
| Bulletin 300 | Sound Testing of Air Moving Devices |

American Gear Manufacturers Association (AGMA)

| | |
|---|---|
| AGMA 295.02 | Sound of High Speed Helical and Herringbone Gears |

American Society of Heating, Refrigeration & Air Conditioning Engineers (ASHRAE)

| | |
|---|---|
| 36-62 | Sound Power Radiated From Equipment |
| 36A-63 | Sound Power of Ductless, Through the Wall Equipment |
| 36B-63 | Acoustic Performance of Air Control & Terminal Devices |

American Society for Testing and Materials (ASTM)

| | |
|---|---|
| C423-65T | Acoustic Absorption of Materials in Reverberant Room |
| C384-58 | Acoustic Impedance and Absorption by Tube Method |
| E90-66T | Acoustic Transmission Loss of Floors and Walls |

Compressed Air and Gas Institute (CAGI)

Portable Pneumatic Tool Noise Measurement

Institute of Electrical and Electronics Engineers (IEEE)

| | |
|---|---|
| IEEE85 | Airborne Noise Measurements on Rotating Electric Machinery (1965) |

Society of Automotive Engineers

| | |
|---|---|
| J6A | Ride and Vibration Data Manual |
| J919 | Measurement of Sound Level at Operator Station |
| J952 | Maximum Sound Levels for Engine Powered Equipment |

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Acoustical Materials Association (59 East 55th Street, New York 22, New York), Sound Absorption Coefficients of Architectural Acoustical Materials.

National Bureau of Standards, US Department of Commerce, "Sound Absorption Coefficients of the More Common Acoustic Materials," Letter Circular, LC 870.

National Bureau of Standards, US Department of Commerce, "Sound Insulation of Wall and Floor Constructions," Building Materials and Structures Report BMS144, February 25, 1955. Supplement, February 27, 1956.

C. Zwikker and C. W. Kosten, Sound Absorbing Materials, Elsevier: New York, 1949.

appendix VIII

# CATALOG SECTION

The following pages include detailed specifications for General Radio sound- and vibration-measuring instruments and accessories. Further information may be obtained from General Radio, which maintains sales engineering offices in West Concord, Mass., and in the following metropolitan areas: New York, Philadelphia, Washington, Orlando, Dallas, Chicago, Los Angeles, San Francisco, Syracuse, and Toronto. Overseas, General Radio is represented by its wholly owned subsidiary, General Radio Company (Overseas), Zurich, Switzerland, and by representatives in many countries.

Prices and specifications given are subject to change without notice.

# SOUND-LEVEL METER

## Type 1565-A

- conforms to USA and international standards
- 44- to 140-dB measurement range
- ceramic microphone
- solid-state circuits

Sound-Level Meter in leather carrying case.

Although not so versatile in application as the Type 1551, this instrument is a standard sound-level meter capable of accurate noise measurements, in conformity with national and international standards. It is particularly useful for rapid surveys, for periodic checks on noisy environments, and for production testing of manufactured products.

The 1565-A Sound-Level Meter is a pocket-sized, lightweight instrument that can be held and operated with one hand. It includes most of the features usually found only in larger, more expensive instruments. With an adaptor in place of the microphone, the 1565 will accept a connector from a vibration pickup or other transducer or from a cable to a remotely placed microphone.

— See **GR Experimenter** for October-November 1964.

## specifications

**Sound-Level Range:** 44 to 140 dB (re 20 $\mu$N/m²).

**Weighting:** A, B, and C weighting in accordance with USA Standard S1.4-1961 and IEC Publication 123, 1961.

**Microphone:** Lead-zirconate-titanate ceramic unit.

**Output:** At least 1.5 V behind 20 kΩ when meter reads full scale. Output can be used to drive a 1556 Impact-Noise Analyzer, 1558 Octave-Band Noise Analyzer, 1521 Graphic Level Recorder, or headphones. Harmonic distortion, 1% or less for frequencies above 100 Hz and 2% or less for frequencies below 100 Hz (panel meter at full scale).

**Meter:** Rms response, and fast and slow meter speeds, in accordance with USA S1.4-1961 and IEC Publication 123, 1961.

**Auxiliary Input Provision:** A 1560-P96 Adaptor is available to allow connection to any source fitted with a male 3-terminal microphone connector. Input impedance is approximately 13 MΩ in parallel with 25 pF. For correct weighting, source impedance must be 380 pF ±5%.

**Calibration:** Sound-level meter can be pressure calibrated at 125, 250, 500, 1000, and 2000 Hz with a 1562 Sound-Level Calibrator or at any frequency from 20 to 2000 Hz with a 1559-B Microphone Reciprocity Calibrator.

**Operating Temperature Range:** 0 to 50°C.

**Storage Temperature Range:** −20° to 70°C (battery removed).

**Operating Humidity Range:** 0 to 90% R.H.

**Temperature Coefficient of Sensitivity:** Approx +0.03 dB/°C.

**Effect of Magnetic Field:** Equivalent C-weighted sound level of a 1-oersted (80 A/m) 60-Hz field is about 47 dB when meter is oriented for maximum indication.

**Power Supply:** One 1½-V size C flashlight cell. Battery life approx 35 hours for 2 h/day service.

**Accessories Available:** 1565-P1 Leather Carrying Case, 1562-A Sound-Level Calibrator, 1560-P96 Adaptor to adapt input to mate with three-terminal male microphone connector necessary for connection to vibration pickup, 1560-P95 Adaptor Cable to connect output to 1521-B Graphic Level Recorder or other devices fitted with jack-top binding posts on ¾-in. centers.

**Dimensions (width x height x depth):** 3¹⁄₁₆ x 7⅜ x 2⅛ in. (78 x 190 x 54 mm).

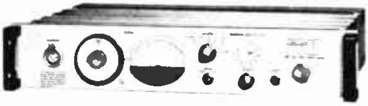
**Weight:** Net, 1¾ lb (0.8 kg); shipping, 5 lb (2.3 kg).

| Catalog Number | Description |
|---|---|
| 1565-9701 | **1565-A Sound-Level Meter** |
| 1565-9601 | **1565-P1 Leather Carrying Case** |
| 8410-9899 | **Replacement Battery** |

# PRECISION SOUND-LEVEL METER

## Type 1561

- meets IEC 179 and USASI S1.4
- rechargeable-battery operation
- rack model available
- external-filter connections



Rack Model

Industry standards for acoustical measurements are becoming more stringent. IEC Publication 179, 1965 requires greater accuracy of sound-level meters, particularly at frequencies above 1 kHz. The 1561 was designed to meet this requirement and the tighter low-frequency requirements of USA Standard S1.4-1961. It has the weighting characteristics, wide sound-level range, internal calibration facility, high-level output, and other capabilities of proven value in all the GR sound-level meters.

### SPECIAL FILTERING

For special needs, the 1561 has provisions for the connection of an external filter to shape the frequency response as required. The new GR 1952 Universal Filter is designed for such service.

### CHOICE OF MOUNTING

For many applications, a rack-mounted sound-level meter is more appropriate than a portable instrument, e.g., in complete measuring systems. The 1561 is offered in both versions.

### RECHARGEABLE BATTERY OPERATION

Either model of the 1561 can be powered by nickel-cadmium batteries; the portable model is available with two sets and separate battery charger or with dry cells; the rack model will operate from an ac line or from rechargeable batteries for which a charging circuit is built in.

## specifications

**Sound-Level Range** (rms, dB re 20 $\mu$N/m$^2$):

| Frequency Characteristic | With 1560-P7 Microphone and 10-ft cable | With 1560-P7 Microphone and 1560-P40 Preamplifier* |
|---|---|---|
| Flat | 35 to 150 dB | 31 to 130 dB |
| C Weighting | 32 to 150 dB | 27 to 130 dB |
| B Weighting | 31 to 150 dB | 26 to 130 dB |
| A Weighting | 31 to 150 dB | 27 to 130 dB |

*Min obtained with ×10 preamp gain, max with ×1

Max peak levels about 11 dB higher; at least 5-dB signal-to-noise ratio for lower values given above.

**Frequency Characteristics:** A, B, and C weighting in accordance with USA Standard S1.4-1961, IEC Publication 123, 1961 and IEC Publication 179, 1965 for precision sound-level meters Also provided is a flat response from 20 Hz to 20 kHz to permit measurement of sound-pressure level. Jacks are provided for insertion of an external filter.

**Microphones:** The GR 1560-P7 Precision Microphone is supplied with portable models with a 10-ft cable to permit microphone to be located away from instrument and observer to minimize diffraction effects (1561 gain is set to compensate for cable loss).

**Sound-Level Indication:** Reading is sum of meter and attenuator setting. Meter calibrated −6 to +10 dB; attenuator calibrated 30 to 140 dB in 10-dB steps.

**Output** (full-scale meter reading): 1.25 V behind 5500 Ω; harmonic distortion <0.5%.

**Input Impedance:** >100 MΩ, across 40 pF in portable model, across 90 pF in rack model.

**Meter:** Rms response; fast and slow meter speeds in accordance with above USASI and IEC standards.

**Calibration:** Absolute calibration of the 1561 is set acoustically at 500 Hz and a level of 114 dB re 20 $\mu$N/m$^2$. Microphone response and sensitivity are measured in a free field 20 Hz to 15 kHz by comparison with a WE 640AA Laboratory Standard microphone with calibration traceable to the National Bureau of Standards. Complete electrical frequency-response measurements are made on each instrument. Panel adjustment provided for standardizing gain with internal calibration circuit, which has adjustment to permit calibration in terms of microphone sensitivity (control is internal and accessible through case of portable models, on front panel of rack models). The 1562 Sound-Level Calibrator or 1559 Microphone Reciprocity Calibrator can be used for making periodic over-all acoustic checks.

**Temperature and Humidity Effects:** The instrument will operate within specifications, for meter indications above 0 dB, over a range of 10 to 50°C and 0 to 90% relative humidity, when standardized by its internal calibration circuit or an external calibrator. No damage to microphone from −30 to +60°C and 0 to 100% relative humidity.

**Magnetic-Field Effects:** In a 60-Hz, 1-oersted (80 A/m) magnetic field and oriented for max reading, the rack model will indicate about 42 dB, the portable model about 53 dB (C weighting).

**Accessories Supplied:** Portable models include Precision Microphone Type 1560-P7, 10-ft microphone cable, and either one set of dry-cell batteries or two sets of rechargeable batteries and Battery Charger Type 1560-P60. Rack model includes power cord and spare fuses.

**Accessories Available:** 1952 Universal Filter and 1560-P40 Preamplifier (power supplied by 1561).

**Power Required:** The rack-mount 1561-R contains ac power supplies for operating the instrument and for recharging the batteries (not supplied) that can be used to power the instrument. This model operates from 100 to 125 or 200 to 250 V, 50 to 60 Hz, 2.5 W max.

The portable 1561 is supplied with either 3 Burgess type PM6 dry-cell batteries (or equivalent), which give about 15-h average operation, or with 2 sets of rechargeable nickel-cadmium batteries and the 1560-P60 Battery Charger. This unit will simultaneously recharge two sets of batteries (one set in the 1561, the other in the charger) from a power line of 105 to 125 or 210 to 250 V, 50 to 60 Hz, 5 W.

The nickel-cadmium batteries will provide about 20-h of operation and recharge in about 15-h; dry-cells about 15 h.

**Mounting:** The 1561-R is in a rack-mount cabinet, the portable model in a Flip-Tilt case; the charger in an aluminum case.

**Dimensions** (width x height x depth): Portable, 10¾ x 6⅛ x 5¾ in. (275 x 160 x 150 mm); rack, 19 x 3½ x 15 in. (485 x 89 x 385 mm); Battery Charger, 4¼ x 3¾ x 8 in. (110 x 96 x 205 mm).

**Net Weight:** Portable, 5½ lb (2.5 kg); rack, 15 lb (7.0 kg).

**Shipping Weight** (est): Portable, 20 lb (4.6 kg); rack, 23 lb (10.5 kg).

| Catalog Number | Description |
|---|---|
| | **1561 Precision Sound-Level Meter** |
| | Portable Models, incl precision microphone and 10-ft cable |
| 1561-9700 | with dry-cell batteries |
| | with 2 sets rechargeable batteries and recharger |
| 1561-9701 | for 115 volts |
| 1561-9702 | for 230 volts |
| 1561-9703 | **1561-R Precision Sound-Level Meter**<br>Rack Model (no battery or microphone) |
| 8410-3000 | **Replacement Dry Cell, 3 req'd** |
| 8410-1040 | **Rechargeable Battery, 2 req'd** |

# SOUND-LEVEL METER

## Type 1551-C

- 24- to 150-dB measurement range
- meets common standards:
  - USA Standards S1.4-1961
  - IEC Publication 123, 1961
- 20-Hz to 20-kHz amplifier response
- internal calibration system

The 1551-C is not only a convenient, highly accurate sound-level meter but is also the key instrument in a wide variety of sound and vibration measuring systems. In use as a sound-level meter alone, the 1551 is compact and easy to handle, rugged enough for severe environments, and simple to use.

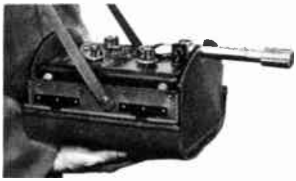
A highly versatile instrument, it will, for example, serve as a calibrated preamplifier in combination with other, related instruments such as spectrum analyzers, special-purpose microphones, calibrators, and vibration pickups. Many other accessories, such as graphic level recorders and tape recorders, can be operated from the sound-level-meter output.

This sound-level meter can also be used as a portable amplifier, attenuator, and voltmeter for laboratory measurements in the audio-frequency range.

Many of its applications are described in detail in the Handbook of Noise Measurement, a copy of which is available to each user.

**Description**

The 1551-C consists of an omnidirectional microphone, a calibrated attenuator, an amplifier, standard weighting networks, and an indicating meter. The complete instrument, including batteries, is mounted in an aluminum case. The microphone can be used in several positions and, when not in use, folds down into a storage position, automatically disconnecting batteries. An ac power-supply unit is available.



(Left) Microphone in the storage position (batteries automatically disconnected). (Center) The sound-level meter operated in its leather carrying case, microphone in the horizontal operating position. (Right) The sound-level meter ac-operated with the Type 1262-B Power Supply, which plugs directly into the base of the sound-level meter.

## specifications

**Sound-Level Range:** From 24 to 150 dB (re 20 $\mu$N/m²).

**Frequency Characteristics:** Four response characteristics, A, B, C, or 20 kHz, as selected by panel switch. The A-, B-, and C-weighting positions are in accordance with USA Standard S1.4-1961 and IEC Publication 123, 1961. Frequency response for the 20-kHz position is flat from 20 Hz to 20 kHz, so that complete use can be made of very wide-band microphones such as the 1551-P1 Condenser Microphone Systems.

**Microphone:** GR Type 1560-P5. Accessory condenser microphone is available.

**Sound-Level Indication:** Sound level is indicated by the sum of the meter and attenuator readings. The clearly marked, open-scale meter covers a span of 16 dB with calibration from −6 to +10 dB. The attenuator is calibrated in 10-dB steps from 30 to 140 dB above 20 $\mu$N/m².

**Calibration Accuracy:** When amplifier sensitivity has been standardized, the absolute accuracy of sound-level measurements at 500 Hz is within ± 1 dB and at all frequencies is in accordance with the USA Standard.

Panel adjustment is provided for standardizing amplifier gain with internal calibration circuit.

Absolute acoustic sensitivity is factory calibrated at 500 Hz. Microphone response and sensitivity are measured in a free field from 20 Hz to 15 kHz by comparison with a WE 640AA laboratory-standard microphone with calibration traceable to the National Bureau of Standards. Complete electrical frequency-response measurements are made on each instrument.

The 1562-A Sound-Level Calibrator or the 1559-B Microphone Reciprocity Calibrator can be used for making periodic over-all acoustic checks.

**Output:** 1.4 V behind 7000 Ω (panel meter at full scale). The output can be used to drive analyzers, recorders, oscilloscopes, and headphones. Harmonic distortion (panel meter at full scale) <1%.

**Input Impedance:** 25 MΩ in parallel with 50 pF.

**Meter:** Rms response, and fast and slow meter speeds in accordance with USA S1.4-1961 and IEC 123, 1961.

### Environmental Effects

**Temperature and Humidity:** Microphone is not damaged at temperatures from −30 to +95°C and relative humidities from 0 to 100%. When standardized by its internal calibration system or a 1562 Sound-Level Calibrator, the instrument will operate within catalog specifications (for panel-meter indications above 0 dB) over the temperature range of 0 to 60°C and the relative humidity range of 0 to 90%.

**Magnetic Fields:** When exposed to a 60-Hz, 1-oersted (80 A/m) field, the sound-level meter will indicate 60 dB (C weighting) when oriented for maximum sensitivity to the magnetic field.

**Electrostatic Fields:** Aluminum case provides sufficient shielding, so that normally encountered electrostatic fields have no effect.

**Vibration:** Case is fitted with soft rubber feet and amplifier is resiliently mounted for vibration isolation. When the instrument is set on its feet on a shake table and vibrated at 10 mils pk-pk displacement over the frequency range of 10 to 55 Hz, the unwanted signals generated do not exceed an equivalent C-weighted sound-pressure level of 45 dB when motion is vertical, 60 dB when motion is lengthwise, or 40 dB when motion is sidewise.

### GENERAL

**Power Supply:** Two 1½-V size D flashlight cells and one 67½-V battery (Burgess XX45 or equivalent) are supplied. An ac power supply, the Type 1262-B, is available.

**Accessories Supplied:** Telephone plug.

**Accessories Available:** 1551-P2 Leather Case (permits operation of instrument without removal from case), 1562 Sound-Level Calibrator, 1560-P95 Adaptor Cable for connecting output to 1521-B Graphic Level Recorder.

**Mounting:** Aluminum cabinet.

**Dimensions (width x height x depth):** 7¼ x 9¼ x 6⅛ in. (185 x 235 x 160 mm).

**Weight,** Net, 7¾ lb (3.6 kg); shipping, 16 lb (7.5 kg), batteries incl. Add 2 lb for leather case.

### 1262-B POWER SUPPLY

Attaches to the 1551-C Sound-Level Meter for ac-line operation.

**Power Required:** 105 to 125 or 210 to 250 V, 50 to 400 Hz, 2 W.

**Dimensions (width x height x depth):** 5 x 7¼ x 3⅛ in. (130 x 185 x 80 mm).

**Weight:** Net, 2½ lb (1.2 kg); shipping, 8 lb (3.7 kg).

| Catalog Number | Description |
|---|---|
| 1551-9703 | **1551-C Sound-Level Meter** |
| 8410-9499 | **Set of Replacement Batteries** |
| 1551-9602 | **1551-P2 Leather Carrying Case** |
| 1262-9702 | **1262-B Power Supply** |

PATENT NOTICE. See Note 12.

# VIBRATION METER

## Type 1553

- direct reading in acceleration, velocity, displacement, and jerk
- 2 to 2000 Hz (120 to 120,000 rpm) to 20,000 Hz with suitable pickup
- portable, battery operated, simple to use

Vibration in a machine can cause faulty production, premature wear, structural fatigue, and human discomfort and fatigue.

The 1553, portable and simple to use and to read, is well suited to making rapid, repetitive measurements against vibration criteria, such as required in quality control product testing and preventive maintenance programs. With the 1553, periodic measurements of over-all vibration in a machine will quickly show any deteriorating performance trends and lead to early preventive maintenance.

This instrument gives readings in quantities that are physically meaningful: displacement (for clearance problems), velocity (for a criterion in preventive maintenance of machines), acceleration (a measure of the possibility of mechanical failure), and jerk (related to vehicular riding comfort).

Its excellent low-frequency response permits the study of the operation of belt drives and of the effectiveness of mountings designed to reduce vibrations in adjacent structures.

Frequency analysis of vibrations aids in identifying their mechanical sources, diagnosing causes, and measuring the effect of remedies. The GR 1564-A Sound and Vibration Analyzer or the 1568-A or 1900-A Wave Analyzer is of great value in making such frequency analyses.

The 1553 Vibration Meter consists of an inertia-operated, lead-zirconate-titanate ceramic pickup, which delivers a voltage proportional to the acceleration of the vibratory motion; an adjustable attenuator; an amplifier; and an indicating meter. Networks can be switched to convert the output of the vibration pickup to a voltage proportional to displacement, velocity, or jerk (time rate of change of acceleration).

The 1553-A indicates directly in inches, in./s, in./s$^2$, or in./s$^3$. The 1553-AK indication is in metric units: mm, m/s, m/s$^2$, and m/s$^3$.

Filter jacks on the panel allow the use of external high-pass filters where it is desired to eliminate the frequency components below 30 or 70 Hz.

The vibration meter is portable and is mounted in a Flip-Tilt cabinet, which serves as protective cover and case in transit, and as a base on which the instrument can be operated in almost any position from vertical to horizontal.

Accessories include various tips and a metal probe for the pickup to facilitate measurements in normally inaccessible places. Available at additional cost is the 1560-P35 Permanent-Magnet Clamp, which replaces the probe or tip when measurements are made under conditions where hand-held operation would not be satisfactory.

## specifications

**Ranges of Measurement:**

| Type No. | Quantity | Peak to Peak Min | Peak to Peak Max | Average Min | Average Max | Units | Frequency Range (Hz) |
|---|---|---|---|---|---|---|---|
| **1533-A** | Acceleration | 0.3 | 300,000 | 0.03 | 30,000 | in./s² | 2-2000 |
| | Velocity | 0.03 | 30,000 | 0.003 | 3,000 | in./s | 2-2000 |
| | Displacement | 3 | 300,000 | 0.3 | 30,000 | mils | 2-2000 |
| | Displacement | 0.03 | 30,000 | 0.003 | 3,000 | mils | 20-2000 |
| | Jerk | 30 | 300,000 | 3 | 30,000 | in./s³ | 2-20 |
| **1553-AK** | Acceleration | 0.01 | 10,000 | 0.001 | 1,000 | m/s² | 2-2000 |
| | Velocity | 0.001 | 1,000 | 0.0001 | 100 | m/s | 2-2000 |
| | Displacement | 0.1 | 10,000 | 0.01 | 1,000 | mm | 2-2000 |
| | Displacement | 0.001 | 1,000 | 0.0001 | 100 | mm | 20-2000 |
| | Jerk | 1 | 10,000 | 0.1 | 1,000 | m/s³ | 2-20 |

Vibration pickup with permanent-magnet clamp

**Accuracy:** ±10% of full scale.

**Input Impedance:** 25 MΩ.

**Voltage at Output Jack:** 5 V rms, behind 75 kΩ for full-scale deflection.

**Attenuators:** A 10-step attenuator changes the meter-scale range by a factor of 100,000 to 1. Window readout indicates full-scale values and units (10 times full-scale for AVERAGE readings).

**Calibration:** Internal.

**Allowable Pickup Sensitivity for Direct Reading:** 30 to 150 mV/g.

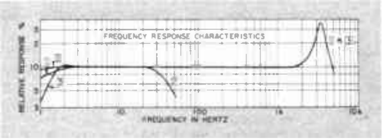
**Terminals:** A panel jack is provided for plugging in earphones, 1564-A Sound and Vibration Analyzer, 1556-B Impact-Noise Analyzer, 1538 or 1531 Strobotac® electronic stroboscope, 1568-A or 1900-A Wave Analyzer, or an oscilloscope.

**Power Supply:** Portable model, 3 size-D cells and one 67½-V battery (Burgess Type XX45 or equivalent) supplied. Typical battery life, 7 days at 8 h per day. For ac operation, use Type 1262-C Power Supply (listed below). Rack model, Type 1262-C Power Supply is included.

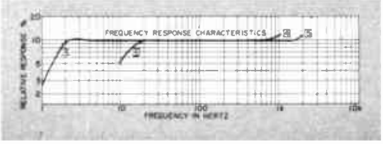
**Accessory Supplied:** 1560-P52 Vibration Pickup.

**Accessories Available:** 1560-P35 Permanent-Magnet Clamp; 1557-A Vibration Calibrator, high-frequency pickup 1560-P53, and high-sensitivity pickup 1560-P54.

**Mounting:** Flip-Tilt Case. Rack-mount versions also available.



Response characteristics for constant applied (1) acceleration, (2) jerk, (3) velocity, (4) displacement, 2-Hz cutoff, and (5) displacement, 20-Hz cutoff.



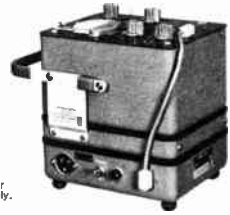
**Dimensions (width x height x depth):** Portable model, 8 x 9¼ x 7½ in. (205 x 235 x 190 mm); rack model, 19 x 10½ x 5 in. (485 x 270 x 130 mm).

**Net Weight:** Portable model, 10½ lb (4.8 kg); rack model, 14 lb (6.5 kg).

**Shipping Weight:** Portable model, 14 lb (6.5 kg); rack model, 31 lb (14.5 kg).

## Type 1262-C

## Power Supply



Vibration meter with power supply.

Attaches to 1553 for ac operation. Included with rack model.

## specifications

**Power Required:** 105 to 125 V, 50 to 400 Hz, 3 W, or 195 to 250 V, 50 Hz, 6 W.

**Dimensions (width x height x depth):** 7¼ x 9¼ x 3¼ in. (185 x 235 x 83 mm).

**Weight:** Net, 2¼ lb (1.1 kg); shipping, 8 lb (3.7 kg).

| Catalog Number | Description |
|---|---|
| | **Vibration Meter** |
| 1553-9701 | **1553-A (English Units)**<br>Portable model |
| 1553-9550 | **1553-A (English Units)**<br>Rack model (with ac supply) |
| 1553-9819 | **1553-AK (Metric Units)**<br>Portable model |
| 1553-9560 | **1553-AK (Metric Units)**<br>Rack model (with ac supply) |
| 1262-9703 | **1262-C Power Supply** |
| 8410-9799 | **Set of Replacement Batteries** |
| 1560-9652 | **1560-P52 Replacement Vibration Pickup** |
| 1560-9635 | **1560-P35 Permanent-Magnet Clamp** |

PATENT NOTICE. See Note 12.

# DATA RECORDER

## Type 1525-A

- 15 Hz to 16 kHz
- built-in sound-level meter
- 2 channels, 2 speeds
- wide dynamic range

Tailored by GR specifically for acoustic-noise measurements, this instrument is both a sound-level meter and audio tape recorder. With it you can make on-location measurements and calibrated recordings for unhurried and detailed laboratory analysis later or make a permanent record of once-only events. The 1525-A permits recording with a flat frequency-response characteristic, recommended for recording noise and not available with speech and music recorders. Dual channels, simultaneous playback and recording, two-speed drive, and accessory tape-loop guides add versatility.

**MAIN CHANNEL**

The main-channel recording amplifier doubles as the sound-level-meter amplifier and, for its dual role, contains an accurate step attenuator and several weighting networks: those prescribed by USASI for a sound-level meter, NAB equalization, and constant-current (flat) response. The high input impedance of this amplifier will accommodate a variety of high-impedance transducers. The GR 1560-P5 Microphone is recommended; with it, sound-level-meter performance conforms to American Standard S1.4-1961 and IEC 123-1961. The 1562 Sound-Level Calibrator is recommended as a source of standard sound level for the calibration of recording levels.

The GR 1560-P40 Preamplifier can be used to drive either channel; power for its operation is supplied at both input connectors.

**SECOND CHANNEL**

The second channel lets you record timing signals or a narration of test program and conditions. Or you can play back a prerecorded test signal (e.g., swept tone, tone bursts, or filtered noise) into a system whose output is being recorded on the main channel. This method simplifies many measurements, room reverberation for one. Acoustical noise, too, can be recorded on channel 2 with the aid of an external sound-level meter or preamplifier.

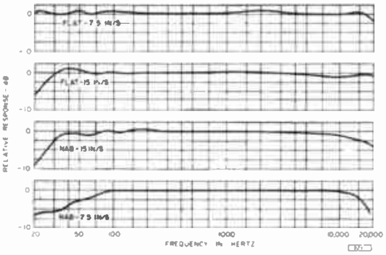
**PLAYBACK AND MONITORING**

Identical playback amplifiers monitor both channels and provide outputs that are always available, even during recording. In addition, the monitor amplifier that drives the panel meter and supplies an additional output can be switched to monitor the output of any of the recording or playback amplifiers. A peak-responding monitor light, sensing recording levels in the main channel after equalization, warns you against saturating the tape, with resultant distortion.

### VERSATILE OPERATION

In addition to recording and storing data for later use, the 1525-A can serve many other purposes. Short-duration, varying, or once-only sounds can be made continuous or repetitive by playback of the recording as a tape loop, guides for which are supplied. Frequency of a noise may be doubled or halved by playback at a tape speed that is twice or half that used for recording, thus similarly scaling the effective bandwidth of an analyzer and of the recorder itself. Time can also be scaled or reversed, a convenience in graphic recording of transients.

— See **GR Experimenter** for October 1966.



Typical over-all frequency response characteristics.

## specifications

**Frequency Response (over-all):**

At 15 in./s (38.1 cm/s)
Constant Current: ±2 dB, 50 to 15,000 Hz.
+2, −4 dB, 30 to 18,000 Hz.
NAB equalization: ±2 dB, 50 to 15,000 Hz.
At 7½ in./s (19.05 cm/s)
Constant Current: ±2 dB, 20 to 10,000 Hz.
+2, −4 dB, 15 to 16.000 Hz.
NAB equalization: +2, −4 dB, 50 to 15,000 Hz.

**Signal-to-Noise Ratio:**

NAB equalization: Over 54 dB below 2% distortion point as measured according to NAB standard (A weighting).

Constant Current: Over 45 db below 2% distortion point for noise band from 20 to 15,000 Hz (over 65 dB for octave band at 1 kHz) with input channel #1 more than 10 mV.

**INPUT**

**Channels:** 2 channels with separate record and playback amplifiers and separate channel erase.

**Measurement Range (Input Level):** 10 μV to 1 V on channel #1 (40 to 140 dB sound-pressure level for microphone sensitivity of −66 dB re 1 V/μbar). About 0.7 V on channel #2 for full-scale meter indication. (For high sensitivity, channel #2 can be driven by the output of a separate sound-level meter.)

**Impedance:** Channel #1: approx 20 pF shunted by 400 MΩ.
Channel #2: > 100 kΩ.

**Weighting Characteristics:** NAB, constant current, A, B, and C weighting (standard sound-level-meter characteristic) and D weighting (decreasing response with increasing frequency above 1 kHz of 20 dB per decade of frequency) for record channel #1. Constant current for record channel #2.

**RECORDING**

**Flutter and Wow:** Below 0.2%, rms.

**Bias and Erase Frequency:** 95 kHz nominal; separate erase for each channel; cleans tape greater than 60 dB.

**Tape Speeds:** 15 in./s (38.1 cm/s).
7½ in./s (19.05 cm/s).

**OUTPUT**

**Weighting Characteristics:** NAB and constant current for both playback amplifiers.

**Monitoring:** Electronic voltmeter with 16-dB range and sound-level-meter ballistic characteristics, switchable to monitor record or playback level on either channel. Peak monitor on record channel #1.

**Levels:** When meter reads +10 dB, monitor output is approx 1.5 V, open circuit, and playback outputs are approx 0.5 V, open circuit.

**Impedance:** Source impedance for monitor output is 330 Ω; for playback outputs it is 10,000 Ω. Any load can be connected to the output.

**GENERAL**

**Tapes:** ¼-inch, professional quality, 7-inch reel (max).

**Power Required:** 105 to 125 V, 60 Hz, 135 W.

**Accessories Supplied:** Guides for tape loop: 1560-P99 Adaptor Cable; line power cord; transport power cord; roll of tape; take-up reel; 2 reel-lock knobs; maintenance kit; rack-mount accessories.

**Accessories Available:** 1562-A Sound-Level Calibrator, 1560-P5 Microphone and 1560-P34 Tripod and Extension Cable for sound measurements and recording. 1560-P40K Preamplifier and Microphone Set for sound measurements and recording at levels below 50 dB where the best signal-to-noise ratio must be maintained (the recorder supplies the necessary power to operate a 1560-P40 Preamplifier). For sound and noise analysis, 1900-A Wave Analyzer, 1564-A Sound and Vibration Analyzer, 1568-A Wave Analyzer, 1558 Octave-Band Noise Analyzers.

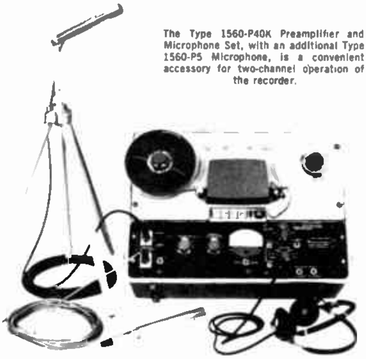
**Mounting:** Luggage carrying case or rack.

**Dimensions (width x height x depth):** Portable, 21 x 16 x 9 in, (540 x 410 x 230 mm); rack, 19 x 14 x 7 in. (485 x 355 x 180 mm).

**Net Weight:** Portable, 53 lb (25 kg); rack, 50 lb (23 kg).

**Shipping Weight:** 60 lb (28 kg).

| Catalog Number | Description |
|---|---|
| 1525-9701 | **1525-A Data Recorder** |



The Type 1560-P40K Preamplifier and Microphone Set, with an additional Type 1560-P5 Microphone, is a convenient accessory for two-channel operation of the recorder.

acoustics

# MICROPHONE RECIPROCITY CALIBRATOR

## Type 1559-B

- accuracy ±0.3 dB
- NBS traceable via WE 640AA microphone
- direct readout without calculations

This unique instrument employs the recognized method of performing the absolute calibration of laboratory standard microphones*: the closed-coupler (cylindrical cavity) reciprocity-calibration procedure. It will also serve as a sound-level calibrator or precision acoustical source for making rapid checks on microphones and sound-level meters or setting reference levels in analyzing systems.

The 1559-B contains the acoustic cavity and two transducers used in reciprocity calibration, interconnecting circuits and switching that obviate the need for physically moving the microphones during calibration, and an analog calculator that directly reads out microphone sensitivity after a simple 4-step voltage-matching procedure. A sound-level meter and nearly any general-purpose audio oscillator will serve as the required external detector and signal source.

### BASIC PRINCIPLES

The analog calculator solves for the sensitivity of the unknown microphone from two quantities that the 1559-B measures by voltage matching: the ratio and the product of the sensitivities of the unknown and the internal reciprocal microphone.

— See GR Experimenter for December 1964.

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* General Radio Types 1560-P3, 1560-P4, 1560-P5, 1560-P6, Western Electric 640AA or equivalent, and (with special adaptor) GR Type 1551-P1L.

## specifications

### AS MICROPHONE CALIBRATOR

**Range:** For microphone sensitivities between −35 dB and −75 dB re 1 V/μbar.

**Accuracy:**

| Microphone Type | Accuracy | Frequency Range |
|---|---|---|
| GR 1560-P5, -P6 and WE 640AA | ±(0.2 + 0.1 $f_{\text{kHz}}$) dB | 20 Hz to 2.5 kHz |
| | ±0.7 dB | 2.5 to 6 kHz* |
| GR 1560-P3, -P4 | ±(0.2 + 0.1 $f_{\text{kHz}}$) dB | 20 Hz to 2.5 kHz |
| | ±0.7 dB | 2.5 to 7 kHz* |
| GR 1551-P1L† | ±(0.2 + 0.1 $f_{\text{kHz}}$) dB | 20 Hz to 2.5 kHz |
| | ±0.7 dB | 2.5 to 5 kHz |

* To 8 kHz with corrections. † Requires special adaptor.

### AS PRECISION ACOUSTICAL SOURCE

**Frequency Range:** 20 Hz to 7 kHz.

**Output:** 92 dB re 20 μN/m² for excitation of 50 V.

**Accuracy:** At 92 dB, ±0.2 dB + error in determining microphone sensitivity.

### AS SOUND-LEVEL CALIBRATOR

**Frequency Range:** 20 Hz to 2.5 kHz.

**Output:** 92 dB re 20 μN/m² when the input level in dB meter reads 92 dB.

**Accuracy:** ±0.7 dB at standard atmospheric pressure.

**Note:** The above specifications apply when the cavity is properly sealed. It may be necessary to apply a sealing compound (grease, etc) to the rim of the unknown microphone.

### GENERAL

**Accessories Required:** Generator and detector. Generator to supply 5 V or more into a 2000-pF load, and 2.5 V or more into a 600-Ω load. The 1304-B Beat-Frequency Audio Generator, the 1210-C Unit R-C Oscillator, and the 1310-A Audio Oscillator are recommended. The 1551 or 1561 Sound-Level Meter, 1558 Octave-Band Analyzer, or 1564 Sound and Vibration Analyzer is recommended for the detector.

**Accessories Supplied:** 274-NP Patch Cord and an extension cable for connection to generator and detector; and adaptors for reciprocity and comparison calibration of the 1560-P5, 1560-P6, and Western Electric 640AA or equivalent microphones.

**Mounting:** Flip-Tilt Case. Also available in rack-mount version.

**Dimensions (width x height x depth):** Portable model, 10 x 8 x 7½ in. (255 x 205 x 190 mm); rack model, 19 x 10½ x 5 in. (485 x 270 x 130 mm).

**Net Weight:** Portable model, 13 lb (6 kg); rack model, 14 lb (6.5 kg).

**Shipping Weight:** Portable model, 16 lb (7.5 kg); rack model, 25 lb (11.5 kg).

| Catalog Number | Description |
|---|---|
| | **1559-B Microphone Reciprocity Calibrator** |
| 1559-9702 | Portable Model |
| 1559-9842 | Rack Model |

PATENT NOTICE. See Notes 15 and 22.

# SOUND-LEVEL CALIBRATOR

## Type 1562-A

- 125 to 2000 Hz
- ±0.3-dB accuracy
- fits many microphones

The 1562 is a self-contained unit for making accurate field calibrations on microphones and sound-measuring instruments. It generates a precisely known sound-pressure level at five USASI-preferred frequencies. With its several frequencies, improved accuracy, and built-in oscillator, the 1562 supersedes the 1552-1307 two-instrument combination.

The 1562 will calibrate the Western Electric 640AA and the GR 1560-P5, -P6, and -P7 microphones used with current instruments, the GR 1551-P1 Condenser Microphone System, and the older Types 1560-P3 and 1560-P4. Thus sensitivity and response tests can be made at several frequencies on a variety of instruments with microphones, including Types 1551, 1561, and 1565-A Sound-Level Meters, 1558 Octave-Band Analyzers, 1564-A Sound and Vibration Analyzer, 1555-A Sound-Survey Meter, and 1525-A Data Recorder.

An electrical signal output is provided for tests on instruments without microphones. An indicator lamp is provided to check for adequate battery voltage.

For even greater accuracy and NBS traceability, use the 1559-B Microphone Reciprocity Calibrator.

— See **GR Experimenter** for May-June 1967.

## specifications

**ACOUSTIC OUTPUT**

**Frequencies:** 125, 250, 500, 1000, and 2000 Hz, ±3%.

**Sound-Pressure Level:** 114 dB re 20 $\mu N/m^2$.

**Accuracy** (at 23°C and 760 mm Hg):

| | at 500 Hz | other frequencies |
|---|---|---|
| WE 640AA or equivalent | ±0.3 dB | ±0.5 dB |
| other microphones | ±0.5 dB | ±0.7 dB |

**Temperature Coefficient:** Between 0 and −0.012 dB/°C.

**Pressure Correction:** Chart supplied.

**ELECTRICAL OUTPUT**

**Voltage:** 1.0 V ±20% behind 6000 Ω.

**Frequency Characteristic:** Output is flat ±2%.

**Distortion:** <0.5%.

**Connector:** Standard telephone jack.

**GENERAL**

**Operating Environment:** 0 to 50°C, 0 to 95% relative humidity.

**Accessories Supplied:** Carrying case, adaptors for 15/16-in. and 5/8-in. diameter microphones. (Fits 1⅛-in. microphones without adaptor.) Battery included.

**Battery:** One 9 V Burgess PM6 or equal. 120 hours use.

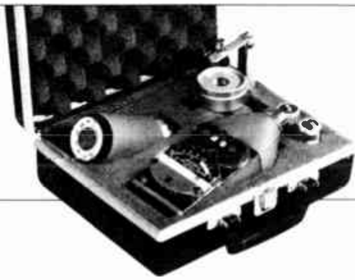
**Dimensions:** Length, 5 in. (130 mm); diameter, 2¼ in. (55 mm).

**Weight:** Net, 1 lb (0.5 kg); shipping, 4 lb (1.9 kg).

| Catalog Number | Description |
|---|---|
| 1562-9701 | **1562-A Sound-Level Calibrator** |

# AUDIOMETER CALIBRATION SET

## Type 1565-Z



A set of three GR acoustical-measuring instruments comprises an accurate, portable, and inexpensive system for the field calibration of audiometers. The importance of periodic calibration to ensure accurate, defensible audiometric data is being increasingly emphasized. Many of the recent articles on the subject are referred to in the October 1966 **GR Experimenter.**

The 1565-Z calibration set contains the GR 1565-A Sound-Level Meter to measure the response of the audiometer, the 1560-P82, a Type 1 earphone coupler that fits the 1565's microphone, the 1562-A Sound-Level Calibrator to ensure accurate reading from the sound-level meter, and a calibration chart, all in a convenient carrying case.

**EARPHONE COUPLERS**

GR offers two couplers that will meet the requirements of a Type 1 coupler in the American Standard Method Z24.9-1949 on "Coupler Calibration of Earphones."

The 1560-P82 coupler fits ¹⁵⁄₁₆-in. diameter microphones, including the GR 1560-P5 and -P6 and the Type L laboratory standard microphones like the Western Electric 640AA. The 1560-P81 coupler fits 1⅛-in. microphones such as the older GR 1560-P3 and -P4 Microphones.

— See **GR Experimenter** for October 1966.

### specifications — couplers only

**Type Coupler:** USASI Type 1.

**Volume:** 6 $cm^3$ including equivalent volume of microphone (Type 1560-P5 Microphone for Type 1560-P82 Coupler; Type 1560-P3 Microphone for the Type 1560-P81 Coupler).

**Axial Holding Force:** 500 grams.

**Frequency Range:** 100 Hz to 8000 Hz; ±1 dB from 100 Hz to 6000 Hz, increasing to ±3 dB at 8000 Hz (with corrections for pressure response of microphone).

**Dimensions:** Coupler (diameter x height), 2¼ x 1¹⁄₃₂ in. (57 x 26 mm); over-all (width x height x depth), 2¼ x 3 x 3 in. (57 x 76 x 76 mm).

**Weight:** Net, 8 oz (230 g); shipping, 2 lb (1 kg).

### specifications — 1565-Z

**Comprises:** 1565-A Sound-Level Meter, 1560-P82 Earphone Coupler, 1562-A Sound-Level Calibrator, storage case.

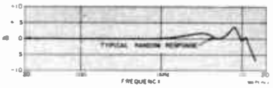
**Dimensions** (width x height x depth): 11¼ x 4¼ x 10 in. (290 x 110 x 255 mm).

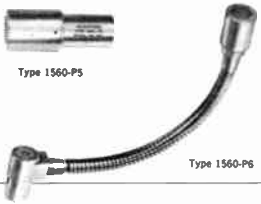
**Weight:** Net, 5 lb (2.3 kg); shipping (est), 12 lb (5.5 kg).

| Catalog Number | Description |
|---|---|
| 1565-9900 | **1565-Z Audiometer Calibration Set** |
| 1560-9682 | **1560-P82 Earphone Coupler** |
| 1560-9681 | **1560-P81 Earphone Coupler** |

# MICROPHONES

## Type 1560-P5
## Type 1560-P6





Type 1560-P5

Type 1560-P6

These GR-manufactured microphones are piezoelectric ceramic units, whose characteristics closely approach those of condenser microphones used as laboratory standards. They require no polarizing voltage and their impedance is lower by an order of magnitude. Thus, leakage due to high humidity is less of a problem than with the condenser type. Its stable capacitance makes the cable correction relatively independent of temperature. The 1560-P5 and the 1560-P6 Microphones use the same cartridge, which is the same diameter as the Western Electric 640AA laboratory standard microphone.

— See **GR Experimenter** for May-June 1967.

### specifications

**Frequency Response:** Typical response is shown in the accompanying plot. Deviations of individual units from the typical response are approx ±0.3 dB from 20 to 1000 Hz and ±1 dB up to about 7000 Hz.

**Sensitivity:** −60 dB re 1 V/μbar nominal.

**Temperature Coefficient of Sensitivity:** Approx −0.01 dB/°C.

**Internal Impedance:** Capacitive; 1560-P5, 390 pF at 25°C, nominal; 1560-P6, 425 pF at 25°C, nominal. Temperature coefficient of capacitance: 2.2 pF/°C over range of 0 to 50°C.

**Environmental Effects:** Microphone is not damaged by temperatures from −40 to +60°C and relative humidities of 0 to 100%.

**Terminals:** Microphones fit 3-terminal microphone cable connector. For hum reduction both microphone terminals may be floated with respect to ground.

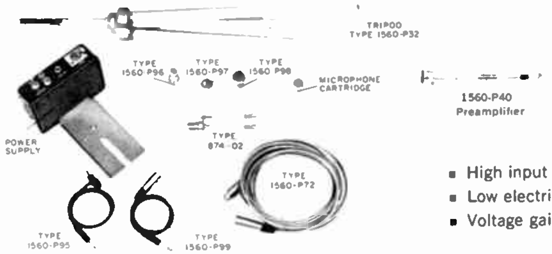
**Cartridge Dimensions:** Diameter 0.936 ± 0.002 in. (23.7 mm), length 1⅛ in. (29 mm).

**Net Weight:** 1560-P5, 2 oz (60 g); 1560-P6, 8 oz (0.3 kg).

| Catalog Number | Description |
|---|---|
| 1560-9605 | **1560-P5 Microphone** |
| 1560-9606 | **1560-P6 Microphone Assembly** |

# PREAMPLIFIER

## Type 1560-P40



- High input impedance; low output impedance
- Low electrical noise level
- Voltage gain of 1 or 10

The 1560-P40 Preamplifier is a high-input impedance, low-noise preamplifier. It is particularly well suited for amplifying the output of piezoelectric transducers, such as microphones and vibration pickups, and for use with GR sound-level meters and analyzers when a long cable (up to 1 mile) must be used between microphone and instrument. It is also a useful probe amplifier for other electrical signals where its high input impedance and low noise are necessary. For example, it can increase the sensitivity and input impedance of analyzers, recorders, amplifiers and null detectors, counters and frequency meters, voltmeters, and low-frequency oscilloscopes.

### DESCRIPTION

The 1560-P40 is a three-stage negative-feedback amplifier that makes full use of the low-noise and high-input-impedance characteristics of a unipolar transistor (FET). The feedback can be switched by the user to obtain a voltage gain of either 1:1 or 10:1. A 1560-P5 or P7 microphone cartridge plugs directly onto the input end of the case. Adaptors are available for connecting the preamplifier to the cartridge of the GR 1560-P3 Microphone, to GR874 connectors, and to 3-terminal microphone connectors. Output from the preamplifier is through a 3-terminal shielded connector. The required dc supply voltage is applied from one of these terminals to ground. This voltage can be obtained directly from the 1558, 1568, or 1564 Analyzers, the 1525 Recorder, 1561 Precision Sound-Level Meters, or from the rechargeable-battery power supply listed below.

### THREE SETS

**The 1560-P40H Preamplifier and Power Supply Set** is self-powered and independent of any external supply so that it can be used with the 1900-A Wave Analyzer as well as with all the other instruments mentioned above.

**The 1560-P40J Preamplifier and Adaptor Set** is dependent for its power on the instrument to which it is connected, so that it should be used with the analyzers, recorder, and sound-level meters mentioned above. If the connector from the source is not one of those for which an adaptor is supplied, GR874 adaptors can be used with almost all standard coaxial connectors.

**The 1560-P40K Preamplifier and Microphone Set** is for use with the sound-level meters, analyzers, or recorder when an acoustical measurement is needed at low levels and the microphone must be mounted at the end of a cable.

— **See GR Experimenter for June 1965.**

## specifications

**Gain:** 1:1 or 10:1 (20 dB) ±0.3 dB at 25°C; <±0.3 dB gain change −50°C to +55°C.

**Input Capacitance:** 6 pF.

**Input Resistance:** >500 MΩ at low audio frequencies.

**Output Resistance:** 1:1 gain — approx 10 Ω in series with 3.3 μF.
10:1 gain — approx 100 Ω in series with 3.3 μF.

**Noise:** ≤2.5 μV equivalent input voltage (400-pF source impedance, C-weighted, 10-kHz effective bandwidth).

**Frequency Response** (at 0.5 V pk-pk open-circuit output):

1:1 gain

| | | |
|---|---|---|
| 0°C to 55°C | ±1.5 dB<br>±0.25 dB | 1 Hz to 500 kHz<br>3 Hz to 500 kHz |
| −30°C to 55°C | ±1 dB<br>±0.25 dB | 5 Hz to 500 kHz<br>20 Hz to 500 kHz |
| 10:1 gain | | |
| −30°C to 55°C | ±3 dB<br>±1.5 dB<br>±0.25 dB | 3 Hz to 500 kHz<br>5 Hz to 500 kHz<br>20 Hz to 250 kHz |

**Harmonic Distortion at Audio Frequencies:**
Open circuit, at 1 V pk-pk: <0.25%.
Capacitor load of 0.01 μF (equivalent to a cable over 200 ft long): Max output (pk-pk) at 1% distortion is 5 V for 1 kHz, 2 V for 10 kHz.

**Accessories Available** (supplied in combinations listed below): Power supply, includes two 9.6-V nickel-cadmium rechargeable batteries, a charging circuit, a battery-check light, and a power cord.

Types 1560-P96, 1560-P97, and 1560-P98 Adaptors for converting the input pin connections to 3-terminal shielded microphone connectors, to the pin sockets necessary for the cartridge of a 1560-P3 Microphone, and to a GR874 connector, respectively.

Types 1560-P72 (25-ft), 1560-P72B (100-ft), and 1560-P72C (4-ft) cables for supplying power to and transferring the signal from the preamplifier.

Type 1560-P95 Adaptor Cable for connecting the signal from the power supply through a cable to a double plug.

Type 1560-P99 Adaptor Cable for connection from phone plug to microphone plug.

**Power Required:** 15 to 25 V, 1 to 2 mA, dc; available from power supply listed below, or from 1558, 1568, and 1564 analyzers, 1525 Recorder, and 1561 Sound-Level Meter.

**Dimensions:** Length 6⅞, diameter 1.155 by 1 in. (175 x 30 x 26 mm).

**Weight:** Net, 9 oz (0.3 kg); shipping, 3 lb (1.4 kg), preamplifier only.

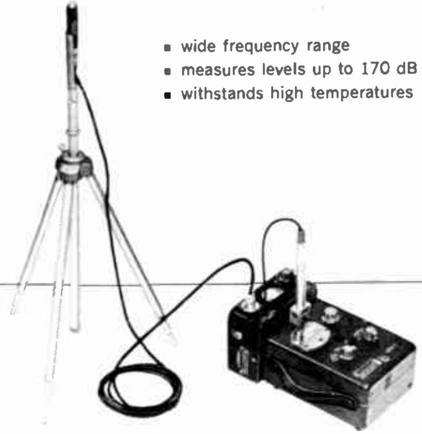
| | 1560-P40H | 1560-P40J | 1560 P40K |
|---|---|---|---|
| 1560-P40 Preamplifier | X | X | X |
| Power Supply | X | | |
| Microphone Cartridge | | | X |
| 1560-P32 Tripod | | | X |
| 1560-P72 Cable (25 ft) | | | X |
| 1560-P72C Cable (4 ft) | X | X | X |
| 1560-P95 Adaptor Cable | X | | |
| 1560-P96 Adaptor | X | X | |
| 1560-P97 Adaptor | | X | |
| 1560-P98 Adaptor | X | X | |
| 1560-P99 Adaptor Cable | X | | |
| 874-Q2 Adaptor | X | | |
| **Shipping Weight:** | 10 lb (4.6 kg) | 4 lb (1.9 kg) | 14 lb (6.5 kg) |

| Catalog Number | Description |
|---|---|
| 1560-9640 | **1560-P40 Preamplifier** |
| 1560-9500 | **1560-P40H Preamplifier and Power Supply Set** |
| 1560-9510 | **1560-P40J Preamplifier and Adaptor Set** |
| 1560-9520 | **1560-P40K Preamplifier and Microphone Set** |

# CONDENSER MICROPHONE SYSTEM

## Type 1551-P1

- wide frequency range
- measures levels up to 170 dB
- withstands high temperatures



1551-P1 with 1551-C Sound-Level Meter

Applications include:

Measurement of high-frequency and high-level noises produced by such noise sources as air streams, woodworking and metalworking machinery, turbines, and jet engines.

General-purpose sound-level measurements where ambient temperature and sound level are high.

Measurements on high-fidelity sound systems over the full audio spectrum.

### DESCRIPTION

The 1551-P1L Condenser Microphone System uses an Altec 21-BR-150 microphone and measures sound-pressure levels up to 155 dB; the 1551-P1H, which uses a 21-BR-180 microphone, measures levels up to 170 dB.

The microphone base houses a subminiature pre-amplifier tube. A battery-operated power supply provides power and polarizing voltage. An extension cable, a tripod, and a leather carrying case are supplied.

## specifications

**Frequency Response:** 20 Hz to 18 kHz with either microphone. Typical response curves are shown.

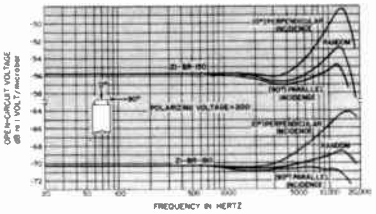
**Calibration:** Output level vs frequency is measured in our laboratory by comparison with a standard microphone. The measured level at 500 Hz and a calibration curve are supplied.

**Output Impedance:** 6500 Ω (typical).

**Direct Use with Analyzers:** These assemblies can supply a signal directly to the 1558 Octave-Band Noise Analyzer or the 1564-A Sound and Vibration Analyzer, provided that the levels of the measured components are above the following indicated values:

| | 1551-P1H | 1551-P1L |
|---|---|---|
| 1558-A, -BP | 65 dB | 50 dB |
| 1564-A | 65 dB | 50 dB |

A 1562 Sound-Level Calibrator is necessary for absolute level calibration.



Typical response vs frequency.

**Max Sound-Pressure Level:**

| Frequency | Up to 1.5 kHz | | At 15 kHz | |
|---|---|---|---|---|
| **Distortion** | <1% | <10% | <10% | <1% |
| **1551-P1L** | 135 dB | 155 dB | 125 dB | 135 dB |
| **1551-P1H** | 150 dB | 170 dB | 140 dB | 150 dB |

**Minimum Measurable Sound-Pressure Level:**

1551-P1L—50 dB (re 20 μN/m²) } with 10-dB
1551-P1H—65 dB (re 20 μN/m²) } signal-to-noise ratio

**Temperature and Humidity:** Max recommended operating temperature of the microphone in its probe is 100°C. Microphone is not damaged by exposure to high humidity, but prolonged exposure may render it temporarily inoperative.

**Batteries:** One 1½-V size D flashlight cell and one 300-V B battery (Eveready 493, Burgess V-200 or equivalent) are supplied. Batteries should last at least 150 hours under normal use.

**Mounting:** The microphone on its base plugs into one end of a 10-ft cable and will slip into a receptacle on the tripod. The other end of the cable is connected to the power-supply unit, which fastens to one end of the sound-level meter.

**Components and Accessories Supplied:** Microphone base assembly, cable assembly, power supply, microphone, microphone cap, carrying case, and tripod.

**Dimensions:** In carrying case, 7 x 5½ x 8½ in. (180 x 140 x 220 mm).

**Weight:** Net, in carrying case, 7¼ lb (3.3 kg); shipping, 15 lb (7 kg).

| Catalog Number | Description |
|---|---|
| | **Condenser Microphone System** |
| 1551-9866 | **1551-P1L (Normal Level)** |
| 1551-9865 | **1551-P1H (High Level)** |
| 8410-9599 | **Set of Replacement Batteries** |

The 1560-P11B Vibration Pickup System with the 1551-C Sound-Level Meter

- accessories for sound-level meters
- select for:
  - high-frequency performance
  - high sensitivity
  - general application, economy

# VIBRATION PICKUPS AND SYSTEMS

For the measurement of solid-borne vibrations with the sound-level meter a vibration pickup is used in place of the microphone.

Each of these Vibration Pickup Systems consists of a vibration pickup, a control box, and a connection cable. The vibration pickup is an inertia-operated, ceramic device, which generates a voltage proportional to the acceleration of the vibrating body. By means of integrating networks in the control box, voltages proportional to velocity and displacement can also be delivered to the sound-level meter. The desired response is selected by means of a three-position switch on the control box. Conversion data are supplied for translating the decibel indications of the sound-level meter into the vibration parameters of displacement, velocity, and acceleration.

Three models are offered, differing in frequency range, sensitivity, and price.

## TYPE 1560-P11B

This system uses a lead-zirconate-titanate pickup, identical with that used on the 1553-A Vibration Meter. Probe and probe tips are provided. A permanent-magnet mount is also available.

## TYPE 1560-P13

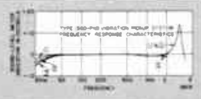
For measurements at higher frequencies than the -P11B system affords, the -P13 combination is recommended, consisting of the 1560-P53 Vibration Pickup and the 1560-P23 Control Box. A small holding magnet is included.

This system with the Type 1551-C or -B Sound-Level Meter provides the flat frequency response and low-noise operation required by MIL-STD-740 (SHIPS) for vibration measurement. (The holding magnet is not used for measurements according to that standard.)

## TYPE 1560-P14

The vibration pickup used in this system has approximately 10 times the sensitivity and 10 times the impedance of the 1560-P52.

**Pickup Systems**

| | **General Purpose 1560-P11B Vibration Pickup System** | **High Frequency 1560-P13 Vibration Pickup System** | **High Sensitivity 1560-P14 Vibration Pickup System** |
|---|---|---|---|
| **Ranges of Measurement Rms Acceleration (in./s²)** | 0.1 to 39,000 (100 g)† | 0.3 to 390,000 (1000 g)† | 0.01 to 3900 (10 g)† |
| **Rms Velocity (in./s)** | 0.001 to * | 0.001 to 1000 | 0.0001 to * |
| **Rms Displacement (in.)** | 0.00003 to * | 0.00003 to 30 | 0.000003 to * |
| **Frequency Range**<br>Response characteristics for constant applied (1) acceleration, (2) velocity, and (3) displacement. |  |  |  |
| **Net Weight of System (lb)** | 1¾ (0.8 kg) | 1¾ (0.8 kg) | 2 (1 kg) |
| **Shipping Weight (lb)** | 5 (2.3 kg) | 5 (2.3 kg) | 5 (2.3 kg) |
| **Catalog Number** | 1560-9922 | 1560-9613 | 1560-9614 |

**Pickup Characteristics**

| **Pickup Type Number** | 1560-P52 | 1560-P53 | 1560-P54 |
|---|---|---|---|
| **Sensitivity (mV/g), nominal** | 70 | 70 | 700 |
| **Temp Coeff of Sens (dB/°C)** | <−0.01 | <0.02 | 0.01 |
| **Resonant Frequency (Hz)** | 3200 | 27,000 | 5000 |
| **Capacitance (pF)** | 10,000 | 350 | 700 |
| **Temperature Range (°C)** | −18 to 100 | −54 to 177 | −18 to 120 |
| **Relative Humidity Range (%)** | 0 to 100 | 0 to 100 | 0 to 100 |
| **Cable Length (ft)** | 5 (1.55 m) | 8 (2.5 m) | 8 (2.5 m) |
| **Dimensions (in.)** | 1⅝ × 1⁷⁄₁₆ × ⁹⁄₁₆ | ⅝ (hex) × 0.7 | 1³⁄₁₆ (dia) × 1¹⁄₁₆ |
| **(mm)** | 42 × 37 × 15 | 15.5 × 18 | 31 × 27 |
| **Net Weight (oz)** | 1.6 (45 grams) | 1.1 (31 grams) | 3.1 (90 grams) |
| **Catalog Number** | 1560-9652 | 1560-9653 | 1560-9654 |

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* Upper limit of displacement and velocity measurements depends upon frequency and is determined by the maximum acceleration possible before nonlinearity occurs (100 g for 1560-P11B, 10 g for 1560-P14).

† g = acceleration of gravity.

# VIBRATION CALIBRATOR

## Type 1557-A

- calibrates vibration pickups, meters
- generates 1 g at 100 Hz
- portable, battery-operated

The calibrator provides a single-frequency (100 Hz), single-level (1 g) check on the GR Vibration Pickups, the 1553 Vibration Meter, or any pickup whose total mass is 300 grams or less. It can provide on-the-spot calibration of vibration-measuring systems immediately before and after important measurements and can also be used to compare transducers or to calibrate working transducers against a standard transducer.

Operation of the calibrator is simple. A pickup of known mass is attached to the shaker, either in place of one of the removable 50-gram disks or to one of the disks by double-faced, pressure-sensitive tape. The user adjusts the LEVEL control until the panel meter, calibrated in grams, indicates the mass of the pickup. The pickup will then be automatically subjected to an acceleration of 1 g at 100 Hz.

The 1557-A is a small, battery-operated unit consisting of a transistorized electromechanical oscillator and a cylindrical shaker. The acceleration output of the calibrator appears at two pillbox-shaped, 50-gram disks mounted on an internal cylinder that projects through the sides of the instrument.

View of the calibrator with Type 1560-P52 Vibration Pickup attached.

## specifications

**OUTPUT**

**Acceleration:** 1 g rms ±10%. 1 g = 386 in./s² (9.81 m/s²).

**Velocity:** 0.614 in./s (15.6 mm/s) rms.

**Displacement:** 0.000978 in. (0.0248 mm) rms; 0.00277 in. (0.0704 mm) pk-pk.

**Frequency:** 100 Hz ±1% for 50-gram load; 100 Hz +0, −2% for 300-gram load.

**GENERAL**

**Batteries:** Four RM-4 (or equivalent) mercury cells. Battery life is 100 hours of continuous operation. (Dry cells optional; please specify.)

**Accessory Supplied:** Leather carrying case.

**Mounting:** Aluminum case.

**Dimensions** (width x height x depth): 4 x 8 x 4 in. (105 x 205 x 105 mm).

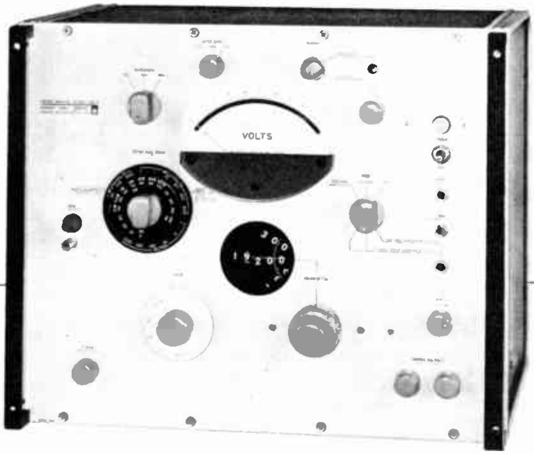
**Weight:** Net, 3¼ lb (1.5 kg); shipping, 5¼ lb (2.4 kg)

| Catalog Number | Description |
|---|---|
| 1557-9701 | **1557-A Vibration Calibrator** |

# WAVE ANALYZER

## Type 1900-A

- 20 to 54,000 Hz, linear frequency scale
- 3-, 10-, and 50-Hz bandwidths
- 30 $\mu$V to 300 V, full scale — 3 $\mu$V with preamp
- 80-dB recording analyzer with 1521 recorder
- outputs: filtered or BFO, 100 kHz and dc recorder
- 1-megohm input impedance on all ranges



The wave analyzer is used for measuring the components of, or analyzing the spectra of, complex electrical signals, acoustic noise, or mechanical vibrations

Individual components of periodic complex waveforms such as harmonic or intermodulation distortion are readily separated and measured, owing to the excellent selectivity.

Automatic frequency control enables the 1900-A to remain tuned to a slowly varying component that might otherwise drift out of the 50-Hz bandwidth.

This analyzer is particularly suited for analyzing noise, because its bandwidth in hertz is independent of the center frequency. The required averaging time is, therefore, constant, and the calculation of spectrum level is simple. Furthermore, when the 50-Hz bandwidth is used, the averaging time required is reasonably short.

For automatic analysis, outputs are provided for driving the 1521 Graphic Level Recorder as well as dc recorders.

The 1560-P40H Preamplifier and Power Supply Set is available to extend the full-scale sensitivity to 3 microvolts and to increase the input impedance.

### TUNABLE FILTER USE

The analyzer can also be used as a tunable filter, so that the individual components of a complex input signal can be used to drive other instruments, such as frequency counters, when a highly accurate measure of the component frequencies is desired, or to drive earphones. When a wide-band noise generator drives the analyzer, the output is a tunable narrow band of noise. Such a signal is useful in a number of psychological and architectural-acoustics tests.

### AS A TRACKING GENERATOR

In the "tracking generator" mode of operation the output is a sine-wave signal tunable over the 54-kHz range and always in tune with the analyzer. When this signal is used to drive a bridge or other network, the output can be measured by the analyzer, whose selectivity reduces the interference from extraneous noise, hum, and distortion.

### DESCRIPTION

The 1900-A is a heterodyne type of voltmeter. The intermediate-frequency amplifier at 100 kHz includes a highly selective quartz-crystal filter whose bandwidth can be switched to 3, 10, and 50 Hz. The use of a heterodyne system makes it possible to vary the response frequency although the filter frequency is fixed. The 100-kHz output of the filter is indicated on a meter and is also available at the panel. In one mode of operation the output is also heterodyned back to the original frequency. In another mode the local oscillator beats with a 100-kHz quartz-crystal oscillator to function as a beat-frequency oscillator. These two outputs are also available at panel terminals as FILTERED INPUT COMPONENT and INDICATED FREQUENCY, respectively.

— See **GR Experimenter** for April 1964.

## specifications

### FREQUENCY

**Range:** 20 to 54,000 Hz. The frequency is indicated on a counter and a dial with a linear graduation, 10 Hz per division.

**Accuracy of Calibration:** ±(½% + 5 Hz) up to 50 kHz; ±1% beyond 50 kHz.

**Incremental-Frequency Dial (ΔF):** ±100 Hz. Accuracy is ±2 Hz below 2 kHz, ±5 Hz up to 54 kHz.

**Automatic Frequency Control:** At frequencies below 10 kHz, total range of frequency lock is 400 Hz for the 50-Hz band and 150 Hz for the 10-Hz band, as defined by 3-dB drop in response from full-scale deflection. At 50 kHz, the lock ranges decrease to one-half of these values.

**SELECTIVITY** Three bandwidths (3, 10, and 50 Hz).

Effective bandwidth for noise equal to nominal bandwidth within ±10% for 10- and 50-Hz bands and ±20% for 3-Hz band.

**3-Hertz Band:** At least 30 dB down at ±6 Hz from center frequency, at least 60 dB down at ±15 Hz, at least 80 dB down at ±25 Hz and beyond.

**10-Hertz Band:** At least 30 dB down at ±20 Hz, at least 60 dB down at ±45 Hz, at least 80 dB down at ±80 Hz and beyond.

**50-Hertz Band:** At least 30 dB down at ±100 Hz, at least 60 dB down at ±250 Hz, at least 80 dB down at ±500 Hz and beyond.

### INPUT

**Impedance:** 1 MΩ shunted by 30 pF on all ranges.

**Voltage Range:** 30 μV to 300 V, full scale, in 3, 10 series. A decibel scale is also provided.

**Voltage Accuracy:** After calibration by internal source, the accuracy up to 50 kHz is ±(3% of indicated value + 2% of full scale) except for the effects of internal noise when the attenuator knob is in the maximum-sensitivity position. From 50 to 54 kHz, the above 3% error becomes 6%.

**Residual Modulation Products and Hum:** At least 75 dB down.

### OUTPUT

**100-kHz Output:** Amplitude is proportional to amplitude of selected component in analyzer input signal. With the 1521 Graphic Level Recorder connected, full-scale output is at least 3 V. Dynamic range from overload point to internal noise is >80 dB with attenuator knob fully clockwise.

**Recording Analyzer:** See the 1910-A Recording Analyzer and 1521-B Graphic Level Recorder.

**DC Output:** 1 mA in 1500 Ω, full scale, one side grounded.

**Filtered Input Component:** Output at least 1 V across 600-Ω load for full-scale meter deflection with output control at max.

**Tracking Analyzer (Indicated Frequency):** 20 Hz to 54 kHz; output is at least 2 V across 600-Ω load with output control at max.

### GENERAL

**Terminals:** Input, binding posts; output, telephone jacks.

**Power Required:** 105 to 125 or 210 to 250 V, 50 to 60 Hz, 40 W.

**Accessories Supplied:** 1560-P95 Adaptor Cable, phone plug, power cord, spare fuses.

**Accessories Available:** 1900-P1 and 1900-P3 Link Units for coupling to 1521 Graphic Level Recorder, 1560-P40H Preamplifier and Power Supply Set.

**Mounting:** Rack-Bench Cabinet.

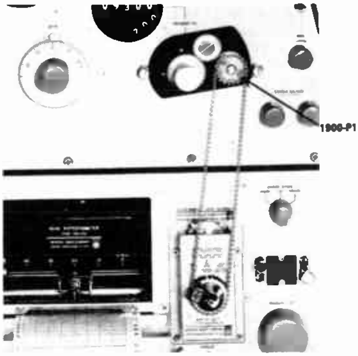
**Dimensions (width x height x depth):** Bench model, 19 x 16¼ x 15¼ in. (485 x 415 x 390 mm); rack model, 19 x 15¾ x 13¼ in. (485 x 400 x 340 mm).

**Weight:** Net, 56 lb (26 kg); shipping, 140 lb (64 kg).

| Catalog Number | Description |
|---|---|
| 1900-9801 | **1900-A Wave Analyzer, Bench Model** |
| 1900-9811 | **1900-A Wave Analyzer, Rack Model** |

PATENT NOTICE. See Notes 1, 15, and 18.

## AUTOMATIC WAVE ANALYSIS



The 1900-A Wave Analyzer can be used in conjunction with the GR 1521 Graphic Level Recorder to produce, automatically, permanent graphic records of high-resolution spectrum analyses. The necessary coupling mechanisms and chart papers are available for frequency scales of 50, 500, or 5000 Hz per inch. A choice of 3 recorder potentiometers permits selection of 20, 10, or 5 dB per inch, so that virtually any combination of horizontal and vertical scale resolution is possible.

The 1900-P1 and 1900-P3 Link Units mount on the wave analyzer in place of the manual frequency-tuning dial providing mechanical coupling to the recorder. The 1900-P3 permits selection of 500 or 50 Hz per inch scale factors with a lever; the 1900-P1 provides 5000 or 500 Hz per inch by the interchanging of sprocket wheels.

An assembly of the 1900-A Wave Analyzer, 1900-P1, and 1521-B Graphic Level Recorder is available as the 1910-A Recording Wave Analyzer.

| Catalog Number | Description | Chart Paper |
|---|---|---|
| 1900-9601 | **1900-P1 Link Unit** | 1521-9464, 500 Hz/in.<br>1521-9465, 5000 Hz/in. |
| 1900-9603 | **1900-P3 Link Unit** | 1521-9464 |

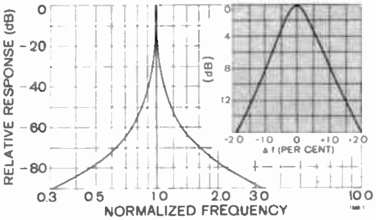
# WAVE ANALYZER

## Type 1568-A

- 20 Hz to 20 kHz
- 1% constant-percentage bandwidth
- portable, battery-operated
- 85-db rejection

The 1568-A is an important new instrument for high-resolution frequency analyses, whether for measuring vibration and noise components or the spectrum of a complex electrical signal. Recent design advances combine the excellent filter shape of a wave analyzer with the convenient, simple operation of constant-percentage-bandwidth analyzers in a portable, low-cost instrument.

The voltage sensitivity and input impedance, adequate for most uses, can be improved to 10 microvolts full-scale and > 500 megohms, respectively, by the use of a 1560-P40 Preamplifier. Power for it is supplied at the input connector.



Attenuation characteristics of the filter.

### HIGH RESOLUTION

Narrow bandwidth permits separation of closely spaced frequencies; wide dynamic range, high stop-band attenuation, and low distortion allow measurement of small components in the presence of components up to 80 dB larger. These capabilities are vital to the identification of unwanted vibration and noise components and to the measuring of discrete frequencies in complex electrical waveforms. At low frequencies bandwidth is narrower, stability better, and calibration more accurate than those of fixed-bandwidth heterodyne wave analyzers.

The 1568 will excell in such applications as

- harmonic distortion measurements at low frequencies
- harmonic analysis — 1% bw yields 50 components
- detailed analysis of machinery noise and vibration
- separation of close, discrete, low frequencies

### AUTOMATIC ANALYSIS

In combination, the 1568-A and 1521-B Graphic Level Recorder produce spectrum plots with as much as a 70-dB recording range. Automatic range switching is included for ease and speed in making spectrum analyses. The analyzer and recorder are available mounted in a cabinet, interconnected, and mechanically coupled as a complete system, the 1913 Recording Wave Analyzer.

— See **GR Experimenter** for September 1966.

## specifications

### FREQUENCY

**Range:** 20 Hz to 20 kHz in six half-decade bands.

**Dial Calibration:** Logarithmic.

**Accuracy of Frequency Calibration:** 1%.

**Filter Characteristics:** Bandwidth between 3-dB points on selectivity curve is one percent of selected frequency.

Attenuation at 20% above and at 20% below selected frequency is greater than 50 dB referred to the level at the selected frequency. Attenuation at twice and at one-half the selected frequency is at least 75 dB referred to the level at the selected frequency. Ultimate attenuation is greater than 85 dB.

Uniformity of filter peak response with tuning is ±1 dB from 20 Hz to 6.3 kHz and ±2 dB from 20 Hz to 20 kHz.

### INPUT

**Impedance:** 100 kΩ.

**Voltage Range:** 100 µV to 300 V, full scale, in 3 10 series steps. Power is supplied at input socket for the 1560-P40 Preamplifier, which extends the sensitivity to 10 µV, full scale, and increases the input impedance to more than 500 MΩ.

**Distortion:** Input-circuit distortion is lower than —80 dB relative to input-signal level.

### OUTPUT

**Impedance:** 6000 Ω. Any load can be connected.

**Voltage:** At least one volt open circuit when meter reads full scale.

**Crest-Factor Capacity:** Greater than 13 dB.

**Output Meter:** In addition to normal-speed mode, meter has slow-speed mode for manual measurements of noise.

### GENERAL

**Analyzing Range:** 80 dB. Components of an input signal that differ in amplitude by as much as 80 dB can be measured.

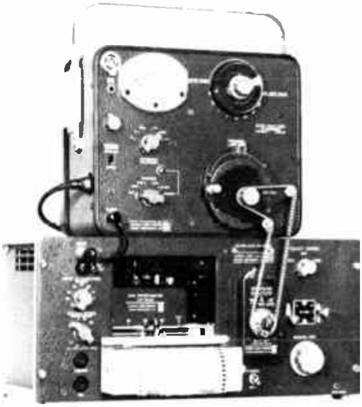
**Automatic Recording:** Automatic range switching is provided to allow convenient, continuous spectrum plotting when the 1521 Graphic Level Recorder is used. Medium-speed motor is recommended. Chart paper is Catalog No. 1521-9475. Frequency scale is logarithmic, 10 inches per decade; vertical scale is 4 inches for 20, 40, or 80 dB, depending on the potentiometer used in the recorder.

**Amplitude Calibrator:** A built-in, feedback-type calibration system permits amplitude calibration at any frequency.

**Accessories Supplied:** Power cord; 1568-2090 Detented Knob and Dial Assembly, used to facilitate measuring the components of an input signal as a percentage or in decibels with an arbitrary voltage reference.

**Accessories Available:** Preamplifier and Adaptor Set 1560-P40J; Link Unit 1521-P15, with Sprocket Kit 1521-P16 for mechanical coupling to 1521-B Graphic Level Recorder equipped with Drive Unit 1521-P10B; Chart Paper 1521-9475.

**Power Supply:** 100 to 125 or 200 to 250 V, 50 to 60 Hz. 2 W for normal operation, 3.5 W for battery charging. A rechargeable nickel-cadmium battery is supplied. Battery provides about 20 hours of operation when fully charged and requires 16 hours for charging. Internal charger operates from the power line.



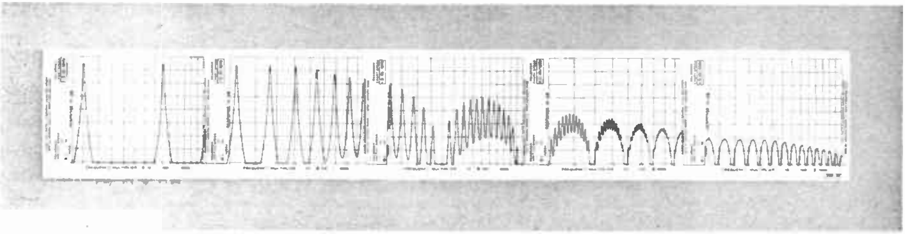
The analyzer coupled to the Type 1521-B Graphic Level Recorder for the automatic plotting of frequency spectra. The chart paper has a logarithmic frequency scale, and frequency ranges on the analyzer are changed automatically.

**Mounting:** Flip-Tilt case, rack model available.

**Dimensions** (width x height x depth): Portable, with case closed, 13¼ x 13 x 8¼ in. (340 x 330 x 210 mm); rack, 19 x 12¼ x 5 in. (485 x 310 x 130 mm).

**Weight:** Net, 21½ lb (10.0 kg); shipping, 27 lb (12.5 kg).

| Catalog Number | Description |
|---|---|
| 1568-9701 | **1568-A Wave Analyzer, Portable Model** |
| 1568-9820 | **1568-A Wave Analyzer, Rack Model** |
| 1560-9510 | **1560-P40J Preamplifier and Adaptor Set** |



Frequency spectrum analysis of a 1.0-ms pulse at a 70-Hz repetition rate. The 1% bandwidth yields high resolution at low frequencies, shows the envelope at high frequencies.

# SOUND AND VIBRATION ANALYZER

## Type 1564-A

- 2.5 Hz to 25 kHz
- 2 bandwidths: 1/3- and 1/10-octave
- use direct from microphone or vibration pickup
- ac or portable battery operation
- automatic spectrum plots with 1521 recorder

The 1564-A Sound and Vibration Analyzer is designed primarily for measuring the amplitude and frequency of the components of complex sound and vibration spectra. Its 1/3-octave (23%) and 1/10-octave (7%) noise bandwidths provide the flexibility needed for analysis of both the noise and its causes.

### INPUT SOURCES

The high input impedance of the analyzer permits direct connection of piezoelectric transducers for measuring sound pressures from 44 to 150 dB re 20$\mu$N/m$^2$ and acceleration from 0.0007 g to 100 g.

The 1560-P40 preamplifier is available to extend the full scale sensitivity of the analyzer by 20 dB (10:1) and to allow use of the transducer at the end of a long extension cable. Alternatively, for higher sensitivity, the analyzer can be driven from a sound-level meter or vibration meter.

### AUTOMATIC ANALYSIS

Automatic range switching is provided so that the 1521-B Graphic Level Recorder can record automatically the spectrum of a signal under analysis. The combination of analyzer and recorder is available as the 1911-A Recording Sound and Vibration Analyzer for continuous spectrum plots. For both stepped and continuous 1/3-octave analysis, the recorder and analyzer are coupled by the 1564-P1 Dial Drive; this system is available as the 1912 Third-Octave Recording Analyzer.

### NOISE FILTER

The analyzer can be used in conjunction with the 1390-B, 1381, or 1382 random-noise generators for transfer and reverberation measurements using 1/3- or 1/10-octave bands of random noise.

### DESCRIPTION

The 1564-A consists of a high impedance amplifier, a continuously tunable filter having a noise bandwidth of either 1/3 or 1/10 octave, an output amplifier, and a meter. The center frequency of the filter is continuously adjustable. An all-pass, or flat, characteristic permits measurement of the over-all signal amplitude.

— See **GR Experimenter** for September-October 1963.

## specifications

### FREQUENCY

**Range:** 2.5 Hz to 25 kHz in four decade ranges.

**Dial Calibration:** Logarithmic.

**Accuracy of Calibration:** ±2% of frequency-dial setting.

**Filter Characteristics:** Noise bandwidth is either ⅓ octave or 1/10 octave. One-third-octave characteristic has at least 30-dB attenuation at one-half and twice the selected frequency. One-tenth-octave characteristic has at least 40-dB attenuation at one-half and twice the selected frequency. Ultimate attenuation is 70 dB or greater for both characteristics. For both bandwidths, peak response is uniform ±1 dB from 5 Hz to 10 kHz and ±1.5 dB from 2.5 Hz to 25 kHz. An ALL-PASS, or flat, characteristic is also included.

### INPUT

**Impedance:** 25 MΩ in parallel with 80 pF (independent of attenuator setting).

**Voltage Range:** 0.3 mV to 30 V full scale in 10-dB steps.

**Microphone:** 1560-P6 Microphone Assembly or the 1560-P40K Preamplifier and Microphone Set is recommended.

**OUTPUT**

**Voltage:** At least 1.0 V open circuit, when meter reads full scale.

**Impedance:** 6000 Ω. Any load can be connected.

**Meter:** Three scales, 0 to 3 V; 0 to 10 V; −6 to +10 dB.

**Recording Analyzer:** Automatic range switching at the end of each frequency decade allows convenient continuous recording of spectra with the 1521-B Graphic Level Recorder.

**GENERAL**

**Amplitude Calibration:** Built-in, feedback-type calibration system permits amplitude calibration at any frequency.

**Detector:** Rms with three averaging times. Faster two speeds conform with USA standard for sound-level meters.

**Power Required:** Operates from 105 to 125 or 210 to 230 V, 50-60 Hz, or from nickel-cadmium battery supplied. Battery provides 25 h of operation when fully charged and requires 14 h for charging.

**Accessories Supplied:** Power cord, shielded cable, and detented knob and dial assembly.

**Accessories Available:** 1560-P6 Microphone Assembly, 1560-P52, -P53, -P54 Vibration Pickups, 1560-P40 Preamplifier (power for preamp available at input connector), 1564-P1 Dial Drive for coupling to 1521 recorder for stepped third-octave analysis.

**Mounting:** Flip-Tilt Case. Rack-mount version also available.

**Dimensions (width x height x depth):** Portable model, 10¼ x 8⅛ x 8 in. (260 x 210 x 205 mm); rack model, 19 x 10½ x 6 in, (485 x 270 x 155 mm).

**Net Weight:** Portable model, 14½ lb (7 kg); rack model, 15½ lb (7.5 kg).

**Shipping Weight:** Portable model, 17 lb (8 kg); rack model, 28 lb (13 kg).

| Catalog Number | Description |
|---|---|
| | **1564-A Sound and Vibration Analyzer** |
| 1564-9701 | Portable Model |
| 1564-9820 | Rack Model |

PATENT NOTICE. See Notes 12, 15, and 22.

# DIAL DRIVE

## Type 1564-P1

Noise and vibration measurement criteria often call for "stepped" frequency analysis in which the analyzer, rather than sweeping continuously through its frequency range, dwells briefly at each specified frequency. Stepped one-third-octave analysis is widely used for noise measurements to check compliance with various criteria such as Military Standard-740B(SHIPS), ASHRAE 36A-63, and others.

The 1564-P1 synchronizes the 1564 analyzer and the 1521-B Graphic Level Recorder for producing automatic third octave-analysis plots. This complete system is available as the 1912 Third-Octave Recording Analyzer, or the 1564-P1 can be added to existing units.

The dial drive automatically sets the analyzer to the one-third-octave center frequencies designated by USASI as Preferred Frequencies for Acoustical Measurements in Standard S1.6-1960 and in S1.11-1966.

The dwell time in each band is adjustable to permit averaging the noise level over a desired time interval and is controlled by an internal timer (set by front-panel control) or by a synchronizing signal. This signal is normally generated by the contactor attached to the graphic level recorder. Alternately, a tape loop containing a recorded signal for analysis could trigger a sensing device to generate the synchronizing signal, thus making the dwell time equal to the time for one "pass" of the tape loop.

The 1564-P1 also permits the analyzer frequency to be continuously swept for more detailed analysis of a noise.

— See GR Experimenter for May-June 1967.

## specifications

**STEPPING CHARACTERISTICS**

**Stepping Motion:** 0.75°/step; 40 steps (30°) per one-third octave; controlled to step in sequence of 4 pulses = 3°.

**Stepping Time:** Stepped positions, approx 0.35 s/30°; continuous positions, 6 s/30° or 20 s/30°, both synchronized to 60-Hz line.

**Dwell Time (per ⅓-octave band):** Dwell time plus stepping time is 1, 3, 10 or 30 s, when controlled by 1521-B Graphic Level Recorder with medium-speed motor installed. These times can be increased by a factor of 2 or 4 with cam adjustment. Dwell time can also be controlled by front-panel knob over a range of about 1 to 60 s.

**GENERAL**

**Temperature Range:** Operating, 0 to 50°C; storage, −40 to +70°C.

**Humidity Range:** 0 to 95% relative humidity.

**Synchronization:** To 1521 Graphic Level Recorder in both stepped and continuous modes.

**Recording System:** Output from 1564-A Sound and Vibration Analyzer can be connected to any recording system with an input impedance of 10 kΩ or more and a sensitivity of at least 10 mV.

**Power Required:** 100 to 125 or 200 to 250 V, 60 Hz.

**Accessories Supplied:** Adaptor-cable assembly, power cord, spare fuses; end-frame set (bench model), or rack support set (rack model).

**Accessories Available:** Chart paper for use with 1521 Graphic Level Recorders: 1521-9460 for stepped analysis and 1521-9469 for continuous analysis.

**Dimensions (width x height x depth):** Relay-rack section, 19 x 3½ x 12½ in. (485 x 89 x 320 mm); stepper motor, 4¼ (dia) x 5⅛ in. (110 x 135 mm); contactor assembly, 3 x 4 1/16 x 2⅛ in. (77 x 105 x 54 mm).

**Weight:** Total shipping, 36 lb (16.5 kg); net, relay-rack section, 14½ lb (7 kg); stepper motor, 1½ lb (0.7 kg); contactor assembly, 8 oz (230 g).

| Catalog Number | Description |
|---|---|
| 1564-9771 | **1564-P1 Dial Drive, Bench Model** |
| 1564-9772 | **1564-P1 Dial Drive, Rack Model** |

# OCTAVE-BAND NOISE ANALYZER

## Type 1558

- 44 to 150 dB direct from microphone to 24 dB with preamplifier
- meets USASI Standards
- A-weighting available in 1558-BP
- portable, battery-operated
- internal calibration circuit

The 1558-BP Octave-Band Noise Analyzer (with the 1560-P40K preamplifier)

The 1558 is used for the rapid analysis of broadband noises, where a knowledge of individual frequency components is not required. For the measurement of octave-band sound-pressure levels above 44 dB re 20 $\mu$N/m$^2$ the analyzer can be used directly with a piezoelectric microphone. For lower levels, it can be operated from the output of the 1560-P40 Preamplifier or a sound-level meter.

It is particularly useful for:

- Studies of environmental noise as related to hearing damage.
- Measurement of environmental noise, as in offices and factories, where speech-interference level is important.
- Measurement of aircraft, vehicle, and machinery noise.
- Production testing and noise-level acceptance tests.
- Loudness determinations.
- Acoustical studies of rooms and materials.

Two models of the octave-band noise analyzer are available. The 1558-BP has octave bands centered at USASI Preferred Frequencies (USA Standard S1.6-1960*) and includes an A-weighted filter characteristic that eliminates the need for a separate sound-level meter in some applications. It also conforms to the current American Standard Specification for Octave, Half-Octave, and Third-Octave-Band Filter Sets S1.11-1966 for Type E, Class II octave-band filters. The 1558-A has octave bands as specified by the older USASI Standard for Octave-Band Filters Z24.10-1953, as well as bandpass filters that extend the range at both ends beyond that specified in the standard.

Essentially, the analyzer consists of a high-impedance preamplifier, a filter, an output amplifier, and a meter. The preamplifier frequency response can be internally set to be either "flat" or C-weighted. A built-in reference allows calibration for microphones ranging in sensitivity from −52 to −62 dB re 1 volt/$\mu$bar. RC active filters are used, resulting in small size, light weight, and lack of interference from stray magnetic fields. The high input impedance and preamplification permit the use of piezoelectric microphones and vibration pickups. The analyzer is portable and powered by rechargeable nickel-cadmium batteries.

— See **GR Experimenter** for October 1962.

### Accessory Microphone and Preamplifier

The 1560-P6 Microphone Assembly, recommended for use with the 1558, consists of a ceramic microphone unit attached to a short length of flexible conduit, which in turn mounts on a swivel base. The microphone assembly plugs into the MIKE input connector on the panel of the octave-band analyzer.

It has a flat response to sounds of random incidence from 20 Hz to 8 kHz. It will withstand temperatures from −40 to +60°C and relative humidity from 0 to 100%. It shows little change in sensitivity and internal impedance with temperature.

Another microphone assembly that also extends the sensitivity of the 1558 to 24 dB is the 1560-P40K Preamplifier and Microphone Set. The preamplifier also allows the microphone to be used at the end of a long extension cable without loss in sensitivity.

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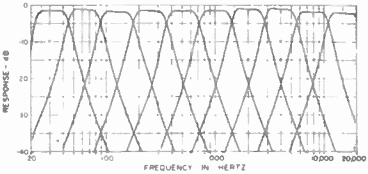
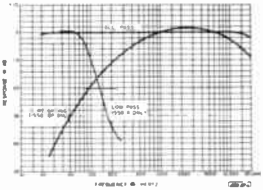
* Also specified by ISO Recommendation 266 and German Standard DIN45-401.



(Left) Filter characteristics of the 1558-BP. The 1558-A characteristics are similar, except that the center frequencies are different as specified in the data below. (Right) Lowpass and allpass characteristics of the 1558.



## specifications for 1558-BP (1558-A similar)

**Filter Characteristics** (measured with signal applied at INPUT (SLM) terminals): Level at center frequency in bands from 63 to 8000 Hz is uniform ±1 dB. Max deviation from ALL PASS level at center frequency in any band is 1 dB. For bands from 63 to 8000 response at nominal cutoff frequency is (3.5 ±1) dB below response at center frequency. Attenuation is at least 30 dB at one-half the lower nominal cutoff frequency and twice the upper nominal cutoff frequency for all octave bands. Attenuation is at least 50 dB at one-fourth the lower nominal cutoff frequency and four times the upper nominal cutoff frequency for all octave bands. The 75-Hz low-pass filter in 1558-A has at least 35-dB attenuation at 200 Hz and at least 50-dB attenuation at 400 Hz.

**Bands:** 1558-BP, center frequencies of bands are 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz; also ALL PASS, and A-weighting characteristic conforming to USASI specification S1.4-1961 for sound-level meters.

1558-A, filter bands conform to USASI specification Z24.10-1953 for octave-band filters and are 18.75 to 37.5, 37.5 to 75, 75 to 150, 150 to 300, 300 to 600, 600 to 1200, 1200 to 2400, 2400 to 4800, 4800 to 9600, and 9600 to 19200 Hz; also ALL PASS, and low-pass with 75-Hz upper cutoff frequency.

**Sound-Pressure-Level Range:** 44 to 150 dB re 20 $\mu N/m^2$ in any band when 1560-P6 Microphone is used, 24 to 130 dB with 1560-P40K Preamplifier and Microphone Set.

**Input:** Impedance at MIKE terminals is approx 50 pF in parallel with 50 MΩ. It is intended for use with high-impedance transducers such as the 1560-P6 Microphone Assembly.

Impedance at INPUT (SLM) terminals, intended for connection to output of a sound-level meter, is approx 100 kΩ. Max input is 3 V.

**Amplifier Frequency Characteristic:** Can be set to be either C-weighting, which is specified by USASI (S1.4-1961, Sound-Level Meters), or 20 kHz, an essentially flat response.

**Output:** Output is at least 1 V behind 6000 Ω (panel meter at full scale). Any load can be connected across the output terminals.

**Meter:** Rms response and FAST and SLOW meter speeds in accordance with USASI S1.4-1961.

**Internal Calibration:** A built-in reference allows the gain of the analyzer to be calibrated for use with piezoelectric microphones having sensitivities from −52 to −62 dB re 1 V/μbar. The absolute accuracy for ALL PASS is then within 1 dB over a wide range of atmospheric conditions.

**Batteries:** An 19.2-V rechargeable nickel-cadmium battery gives 30-h operation. It is recharged from a 25- to 60-Hz power line. Full charge takes about 14 h.

**Accessories Supplied:** Carrying strap, power cord for charging battery, shielded cable for connection to sound-level meter.

**Accessories Available:** 1560-P6 Microphone Assembly. 1560-P40K Preamplifier and Microphone Set. Power is available for the 1560-P40 Preamplifier at the MIKE connector.

**Mounting:** Flip-Tilt Case. Rack-version also available.

**Dimensions** (width x height x depth): Portable model, 10¼ x 9¼ x 7¼ in. (260 x 235 x 185 mm); rack model, 19 x 8¾ x 5 in. (485 x 225 x 130 mm).

**Net Weight:** Portable model, 8¾ lb (4 kg); rack model, 9 lb (4.1 kg).

**Shipping Weight:** Portable model, 12 lb (5.5 kg); rack model, 22 lb (10 kg).

| Catalog Number | Description |
|---|---|
| | **Octave-Band Noise Analyzer** |
| | **1558-BP, Current Standard Frequencies** |
| 1558-9890 | Portable Model |
| 1558-9848 | Rack Model |
| | **1558-A, Old Standard Frequencies** |
| 1558-9701 | Portable Model |
| 1558-9820 | Rack Model |
| 1560-9606 | **1560-P6 Microphone Assembly** |
| 1560-9520 | **1560-P40K Preamplifier and Microphone Set** |

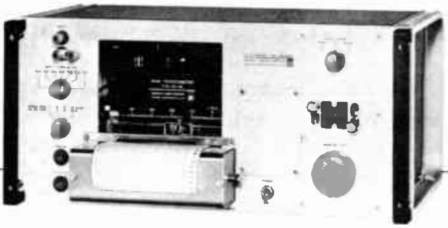
PATENT NOTICE. See Notes 15 and 22.

Relay-rack model is adapted from portable model.

# GRAPHIC LEVEL RECORDER

## Type 1521-B

- 4.5 Hz to 200 kHz
- 1-mV ac sensitivity
- linear dB plot of rms ac-voltage level
- 20-, 40-, or 80-dB range
- convenient, disposable pens



The 1521-B is a completely transistorized, single-channel, servo-type recorder. It produces a permanent, reproducible strip-chart record of ac-voltage level as a function of time or some other quantity.

Most often these are records of the frequency response of a device or the frequency spectrum of noise or of a complex electrical signal. The Graphic Level Recorder can be mechanically or electrically coupled to various GR analyzers and oscillators to synchronize the frequency scale of the chart record with the instrument's calibrated tuning-control dial. Such combinations of instruments are available factory assembled or as individual components to add to existing equipment. (See preceding pages.)

Owing to the high stability of its reference voltage and amplifier gain, the 1521 can be calibrated and used as a recorder of absolute level.

With a sound-level meter, the recorder can plot sound levels over a wide dynamic range as a function of time. The writing speed is sufficiently high for the measurement of reverberation time and other transient phenomena.

The wide range of paper speed facilitates long-period studies of the noise produced by traffic and machinery, as well as of short-duration transients.

The frequency response can be extended downward to 4.5 Hz at the slower writing speeds. Writing speeds and low-frequency cutoff are selected by a single switch.

Changes of range are easily accomplished by use of a 20-dB or an 80-dB potentiometer in place of the standard 40-dB unit. With the 80-dB unit, the maximum writing speed is 300 dB/second. The slow writing speeds filter out abrupt level variations, yielding a smoothed plot without loss of accuracy.

A linear potentiometer is available, which can be used for dc recording and is easily substituted for the logarithmic ac potentiometers.

— See **GR Experimenter** for September 1964.

## specifications

**Recording Range:** As supplied, 40 dB full-scale; 20-dB and 80-dB ranges are also available. For dc recording, 0.8 to 1 V (0.8 to 1.0 mA) full-scale, with zero position adjustable over full scale.

**Frequency Response and Writing Speed**

**Level Recording:** High-frequency response ±2 dB to 200 kHz. Low-frequency sine-wave response depends on writing speed, as shown in following table:

| Writing Speed (approx) in./s with 0.1-inch overshoot | Low-Frequency Cutoff Hz (less than 1 dB down) |
|---|---|
| 20 | 100 |
| 10 | 20 |
| 3 | 7 (3 dB down at 4.5 Hz) |
| 1 | 7 (3 dB down at 4.5 Hz) |

**Dc Recording:** 3 dB down at 8 Hz (pk-pk amplitude less than 25% of full scale).

**Potentiometer Linearity**

**20-, 40-, 80-dB Potentiometers:** ±1% of full-scale dB value plus a frequency error of 0.5 dB at 100 kHz and 1.5 dB at 200 kHz.

**Linear Potentiometer:** ±1% of full scale.

**Resolution** ±0.25% of full scale.

**Max Input Voltage:** 100 V ac.

**Input Attenuator:** 60 dB in 10-dB steps.

**Input Impedance:** 10,000 Ω for ac level recording; 1000 Ω for dc recording.

**Max Sensitivity:** 1 mV at 0 dB for level recording; 0.8 or 1 V full-scale for dc recording.

**Paper Speeds**

**High-speed motor (normally supplied):** Paper speeds of 2.5, 7.5, 25, 75 in./min. Used for high-speed-transient measurements and with Type 1304 Beat-Frequency Audio Generator.

**Medium-speed motor (supplied on request):** Paper speeds of 0.5, 1.5, 5, 15 in./min. Used with analyzers and in level-vs-time plots.

**Low-speed motor (supplied on request):** Paper speeds of 2.5, 7.5, 25, 75 in./h. Used for level-vs-time measurements from 1 to 24 h.

**External Dc Reference:** An external dc reference voltage of from 0.5 to 1.5 V can be applied internally to correct for variations of up to 3 to 1 in the signal source of the system under test.

**Detector Response:** Rms within 0.25 dB for multiple sine waves, square waves, or noise. Detector operating level is 1 V.

**Chart Paper:** 4-inch recording width on 5-inch paper. All rolls are 100 feet long. See full list of charts below.

**Accessories Supplied:** 40-dB potentiometer, 12 disposable pens with assorted ink colors, 1 roll of 1521-9428 chart paper, power cord, spare fuses, 1560-P95 Adaptor Cable (phone to double plug).

**Accessories Available:** Potentiometers, chart paper, pens, high-, medium-, and low-speed motors, drive and link units.

**Power Required:** 105 to 125 or 210 to 250 V, 50 or 60 Hz, 35 W.

**Mounting:** Rack-Bench Cabinet.

**Dimensions** (width x height x depth): Bench model, 19 x 9 x 13½ in. (485 x 230 x 345 mm); rack model, 19 x 8¾ x 11¼ in. (485 x 225 x 290 mm).

**Weight:** Net, 50 lb (23 kg); shipping, 62 lb (29 kg).

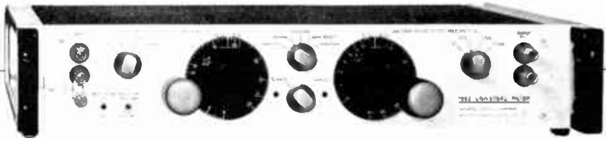
| Catalog Number | Description |
|---|---|
| | **Graphic Level Recorder** |
| 1521-9812 | 1521-B, Rack Model (for 60-Hz supply) |
| 1521-9802 | 1521-B, Bench Model (for 60-Hz supply) |
| 1521-9507 | 1521-BQ1, Rack Model (for 50-Hz supply) |
| 1521-9506 | 1521-BQ1, Bench Model (for 50-Hz supply) |

PATENT NOTICE. See Notes 1 and 18.

# UNIVERSAL FILTER

## Type 1952

- 4-Hz to 60-kHz tuning
- low-pass or high-pass,
  band-pass or band-reject, ganged for easy tuning
- high attenuation rate — 30 db/octave
- line or battery operation



The 1952 Universal Filter will perform as a low-pass, high-pass, band-pass, or band-reject filter at the turn of a panel switch. It consists of a low-pass and a high-pass filter that can be employed singly, in cascade, or in parallel, to provide the assortment of over-all characteristics. The cut-off frequencies of the two filters can be controlled independently or ganged together to provide constant-percentage bandwidth for band-pass or band-reject tuning.

This filter is of value in many signal-conditioning applications. For example, it can be used to control system bandwidth for reduction of extraneous signals or to evaluate the effect of limited bandwidth upon signal intelligibility and data-transmission accuracy. As a high-pass filter it can reduce power-line-related components, as a low-pass filter control high-frequency noise, or as a notch filter eliminate single-frequency components. The 1952 can also act as part of a spectrum analyzer or distortion meter and, with a random-noise generator, produce controlled bands of noise as test signals. It is recommended as an accessory for the GR 1142 Frequency Meter and Discriminator and the 1561-R Precision Sound-Level Meter.

## specifications

### FREQUENCY RANGE

**Cut-off Frequencies:** Adjustable 4 Hz to 60 kHz in four ranges.

**Pass-Band Limits:** Low-frequency response to dc (approx 0.7 Hz with ac input coupling) in LOW PASS and BAND REJECT modes. High-frequency response uniform ±0.2 dB to 300 kHz in HIGH PASS and BAND REJECT modes.

**Controls:** Log frequency-dial calibration; accuracy ±2% of cut-off frequency (at 3-dB points).

### FILTERS

**Filter Characteristics:** Filters are fourth-order (four-pole) Chebyshev approximations to ideal magnitude response. The nominal pass-band ripple is ±0.1 dB (±0.2 dB max); nominal attenuation at the calibrated cut-off frequency is 3 dB; initial attenuation rate is 30 dB per octave. Attenuation at twice or at one-half the selected frequency, as applicable, is at least 30 dB.

**Tuning Modes:** Switch selected, LOW PASS, HIGH PASS, BAND PASS, and BAND REJECT.

**Ganged Tuning:** The two frequency controls can be ganged in BAND PASS and BAND REJECT modes so the ratio of upper to lower cut-off frequencies remains constant as controls are adjusted. Range overlap is sufficient to permit tuning through successive ranges without the need to reset frequency controls if ratio of upper to lower cut-off frequencies is 1.5 or less.

**Minimum Bandwidth:** 25% (approx ½ octave) in BAND PASS mode.

**Null Tuning:** In BAND REJECT mode, setting the frequency controls for a critical ratio of upper to lower cut-off frequency (indicated on dials) gives a null characteristic (point of infinite attenuation) that can be tuned from 5 Hz to 50 kHz.

### INPUT

**Gain:** 0 or −20 dB, switch selected. Accuracy of gain is ±1 dB, of 20-dB attenuator is ±0.2 dB.

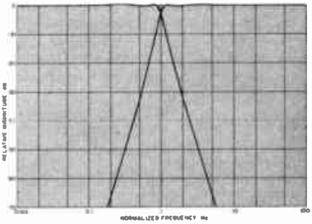
**Impedance:** 100 kΩ.

**Coupling:** Ac or dc, switch selected. Lower cut-off frequency (3 dB down) for ac coupling is about 0.7 Hz.

**Max Voltage:** Max sine-wave input is 3 V rms (8.4 V pk-pk) or 30 V rms with input attenuator at 20 dB. Max peak input voltage for dc coupling is ±4.2 V. For ac coupling max peak level of ac component must not exceed ±4.2 V and dc component must not exceed 100 V. Input can tolerate peak voltages of ±100 V without damage. An LC filter at input limits bandwidth to 300 kHz, thus reducing danger of overloading active circuits at frequencies above normal operating range.

### GENERAL

**Output:** 600-Ω impedance. Any load can be connected without affecting linear operation of output circuit. Temperature coefficient of output offset voltage is between 0 and +4 mV/°C.



Low-pass and high-pass filter characteristics.

**Noise:** <100 μV in an effective bandwidth of 50 kHz.

**Distortion:** Max harmonic distortion, with all components in the pass band, for a linear load, is less than 0.25% for open-circuit voltages up to 3 V and frequencies up to 50 kHz.

**Power Required:** 100 to 125 or 200 to 250 V (switch selected), 50 to 60 Hz, 2.5 W. Or 19.2 V, approx 20 mA from rechargeable nickel-cadmium batteries (not supplied), about 10-h operation. Connections for external battery.

**Accessories Supplied:** Power cord, spare fuses, bench- or rack-mount hardware.

**Accessories Available:** Rechargeable batteries (two required) and 1560-P60 Battery Charger.

**Dimensions** (width x height x depth): Bench, 19 x 3⅞ x 15 in. (485 x 99 x 385 mm); rack, 19 x 3½ x 11¾ in. (485 x 89 x 300 mm); charger, 4¼ x 3¾ x 8 in. (110 x 96 x 205 mm).

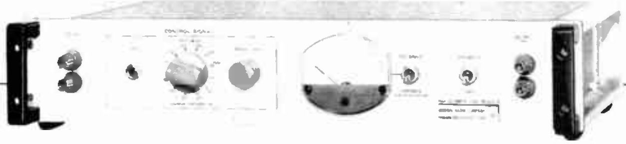
**Weight:** Net, 20½ lb (9.5 kg); shipping, 25 lb (11.5 kg).

| Catalog Number | Description |
|---|---|
| | **1952 Universal Filter** |
| 1952-9801 | Bench Model |
| 1952-9811 | Rack Model |
| 8410-1040 | **Rechargeable Battery (2 req'd)** |
| | **1560-P60 Battery Charger** |
| 1560-9660 | 115 volts |
| 1560-9661 | 230 volts |

# AUTOMATIC LEVEL REGULATOR

## Type 1569

- 2 Hz to 100 kHz
- 50-dB control range
- acoustic-system accessory



The 1569 Automatic Level Regulator is intended as an accessory for an oscillator or for a source of narrow-band noise. Its primary function is to control the signal level in swept-frequency sound and vibration tests.

The regulator senses a control voltage from a microphone, accelerometer, or other transducer monitoring the sound or vibration to be controlled and adjusts its output to maintain constant level (see diagram). Output level is indicated by a panel meter with a linear-dB scale, showing the operator where in its 50-dB control range the regulator is operating. Regulation is such that a level variation (without the regulator) of 25 dB, for instance, is compressed to a variation of 1 dB. The control rate is adjustable by means of a panel control to suit the operating frequency and magnitude-phase conditions in the control loop.

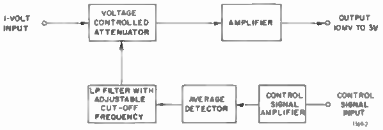


Diagram of 1569 Automatic Level Regulator

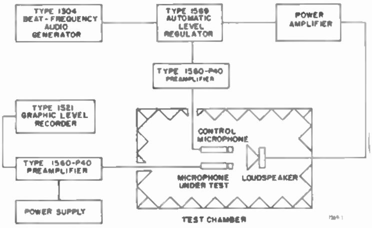
The 1569 can also be used to regulate voltage from an oscillator or other signal source. In this mode, the control range is limited to 15 dB.

## specifications

**Frequency Range:** 2 Hz to 100 kHz.
**Control Range:** 50 dB.
**Compression Ratio:** 25 (0.04 dB per dB).

**DRIVE (INPUT)**
**Voltage Required** (for normal operation): 1 V.
**Impedance:** 100 kΩ.

**OUTPUT**
**Voltage:** 3 V max to 10 mV min.
**Impedance:** 600 Ω. Any load impedance can be connected without affecting linear operation of output circuit.



Typical Measurement System Using 1569

**Noise:** Typically better than 65 dB below 3 V in 100-kHz band.
**Harmonic Distortion:** <1% total for <1-V output level.
**Automatic "Shut-Down":** A loss of drive (input) voltage from signal source causes the output voltage to drop to zero to protect equipment connected to output.

**CONTROL-SIGNAL INPUT**
**Voltage:** 5 mV to 4 V required.
**Impedance:** 25 MΩ.
**Control Rates and Corresponding Min Operating Frequencies:**

| 1000 dB/s | 300 dB/s | 100 dB/s | 30 dB/s | 10 dB/s | 3 dB/s |
|---|---|---|---|---|---|
| 600 Hz | 200 Hz | 60 Hz | 20 Hz | 6 Hz | 2 Hz |

**Power Required:** 100 to 125 or 200 to 250 V (switch selected), 50 to 60 Hz, 4 W.
**Accessories Supplied:** Power cord, spare fuses, bench- or rack-mount hardware.
**Accessories Available:** GR 1560-P40 Preamplifier (power for preamplifier available at rear-panel input connector); 1304 Beat-Frequency Audio Generator, 1521 Graphic Level Recorder; microphones and vibration pickups.
**Mounting:** Rack-Bench Cabinet.
**Dimensions** (width x height x depth): Bench model, 19 x 3⅞ x 13 in. (485 x 99 x 330 mm); rack model, 19 x 3½ x 10½ in. (485 x 89 x 275 mm).
**Weight:** Net, 13 lb (6 kg); shipping, 30 lb (14 kg).

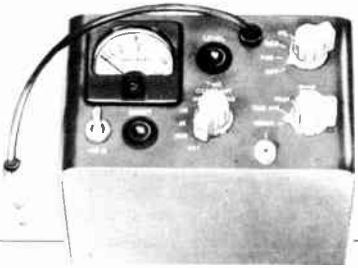
| Catalog Number | Description |
|---|---|
| | **1569 Automatic Level Regulator** |
| 1569-9700 | Bench Model |
| 1569-9701 | Rack Model |

# IMPACT-NOISE ANALYZER

## Type 1556-B

- measures electrical and acoustical noise peaks
- stores transient peak and time-average values
- 50-μs rise-time response

The 1556-B Impact-Noise Analyzer attaches to the 1551-C Sound-Level Meter as shown here.



This device evaluates the characteristics of impact-type sounds and electrical noise impulses, which cannot be satisfactorily measured with conventional noise-meters.

**Impact Noises** include those produced by punch presses, forging hammers, fire alarms, pile drivers, office machinery, and similar equipment. From the standpoint of hearing damage, some of these sounds constitute a serious problem for industry. They have hitherto been measurable only by complicated methods employing oscilloscopes.

The two characteristics of impact sounds that seem most significant are the peak amplitude and the duration, or decay time. This analyzer measures the:

- peak value, the maximum level reached by the noise,
- "quasi-peak", a continuously indicating measure of the high levels reached just before the time of indication, and
- time-average, a measure of the average level over a predetermined period of time, which, when subtracted from peak level, is a measure of the duration of the impact.

For these applications, the 1556-B operates from the output of a 1551, 1561, or 1565-A Sound-Level Meter or 1558 Octave-Band Noise Analyzer and, when a vibration pickup is used in place of the microphone, will measure vibration impacts. It will also operate from tape recorders, and vibration meters.

**Electrical Noise Peaks** in a wire communication circuit can be measured with this instrument as one of the tests to determine the adequacy of the circuit for transmitting data pulses. In such measurements, many peaks may be measured in a short time, and, after each peak, the stored signal must be erased before the next pulse occurs. To facilitate this a RESET pushbutton is provided, which can also be operated by an ordinary camera cable release.

**Circuit.** A battery-operated, degenerative, transistor amplifier simultaneously drives three ac voltmeter circuits, which comprise rectifiers, storage capacitors, and a dc electronic voltmeter. The electrical storage system (a capacitor charged by a rectifier) makes it possible to measure three characteristics of an impulse — peak, quasi-peak, and time-average — with a single meter.

## specifications

**Input:** Any voltage from 1 to 10 V for normal range. Inputs below 1 V reduce the range of reading.

**Input Impedance:** Between 25,000 and 100,000 Ω, depending on the setting of the LEVEL control.

**Frequency Range:** 5 Hz to 20 kHz.

**Level Indication:** Meter calibrated in dB from −10 to +10. Attenuator switch increases range by 10 dB.

**Peak Reading:** Rise time is less than 50 μs for a value within 1 dB of peak value (for rectangular pulses). Storage time at normal room temperature is greater than 10 s for a 1-dB change in value.

**Quasi-Peak Reading:** Rise time of less than ¼ ms and decay time of 600 ±120 ms for rectifier circuit.

**Time-Average Reading:** Charge time of rectifier circuit selected by seven-position switch, having times of 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, and 0.2 s for the resistance-capacitance time constant. Storage time at normal room temperature is greater than 1 min for a 1-dB change in value.

**Input Terminals:** Cord with phone plug at one end.

**Accessory Required:** A sound-level meter, analyzer, or other calibrated amplifier to supply 1556 input.

**Batteries:** One 1½-V size-D flashlight cell and one 45-V battery are supplied. Typical battery life is 100 hours.

**Mounting:** Aluminum cabinet; leather carrying case supplied. Cabinet can be fastened directly to one end of a 1551 Sound-Level Meter.

**Dimensions** (width x height x depth): 7½ x 6½ x 4½ in. (190 x 170 x 110 mm).

**Weight:** Net, 4½ lb (2.1 kg); shipping, 12 lb (5.5 kg).

| Catalog Number | Description |
|---|---|
| 1556-9702 | **1556-B Impact-Noise Analyzer** |

# INDEX

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