Convention Record of the I·R·E

1953 NATIONAL CONVENTION

Part 3—Audio

SESSIONS ON . . .

Seminar: Acoustics for the Radio Engineer — I

Seminar: Acoustics for the Radio Engineer — II

Audio

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The Institute of Radio Engineers

CONVENTION RECORD OF THE I.R.E.

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PART 3 - AUDIO

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FUNDAMENTAL THEORY

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ABSTRACT

This seminar, comprising the above three papers, presents the engineering aspects of the science of acoustics and those fundamental principles which have a direct bearing on acoustical engineering in terms which the Radio Engineer can understand, and which will assist him in his daily work. Leading experts in the field discuss fundamental theory with emphasis on equivalent electrical circuits, the engineering use of microphones, loudspeakers, and the characteristics which are of importance to their users.

PHONOGRAPH REPRODUCTION

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INTRODUCTION

The art of phonograph reproduction represents the accumulation of numerous experiences which begin with the placement of the artists and microphones in the studio and end with the complaints from the neighbors when a 50 watt system shakes the building. We largely omit experiences of the first type, which are outside the scope of this discussion. Experiences of the second type can be grouped together with the other problems in mechanics and human relations which need not be treated here because they are well understood by radio engineers. Likewise, we omit catalog information which is available at the exhibits. This session is limited to the theory of phonograph reproduction, and especially to those topics which have an important bearing upon the quality of reproduction. Obviously, only the briefest treatment can be given to such an extensive subject in the alloted space and time. Therefore, the reader will be referred to other published works for detailed treatment, whenever possible.

The first section is broadly termed "Grooves and Needles". It deals with the problems encountered by the needle in attempting to follow the undulations of the record groove. It covers such subjects as groove modulation, distortions, stresses, and needle wear.

The second section deals with pickup cartridges and the features which have bearing upon fidelity and efficiency.

The third section deals with phonograph arms -- the geometry of arm design, the optimum placement with respect to the record, and the interrelations between the dynamic properties of arms and the characteristics of cartridges.

The fourth and last section deals with the subject of recording characteristics, reproducing characteristics, and the playback objective characteristic required to reproduce correctly any given recording characteristic.

1. GROOVES AND NEEDLES

1.1 Geometry of Grooves and Needles

Basic to the theory of phonograph reproduction are the interrelations between grooves and needles. The groove has the function of retaining the needle tip and causing it to follow the groove undulations firmly and without side-play. A V cross section has been found to be the most convenient for this purpose. Because of manufacturing techniques, the bottom of the V is rounded -- not sharp -- and a sufficiently large rounded needle tip is desirable so as to be supported principally by the side walls rather than by the bottom of the groove. Most needle tips have a spherical shape when they are new, because a spherical tip can be specified, manufactured, and inspected with comparative ease.

Fig. 1 shows the theoretical profile of a standard RTMA needle for 78 rpm records in a typical old-style coarse groove. The needle has a radius of 2.7 mils (1 mil = 0.001"); the groove has an approximate width of 6 mils, an included angle of 90°, and a bottom radius of about 2 to 2.3 mils. In actual practice, the arm load upon the needle causes the elastic groove material to be deformed. Therefore, the needle often rides upon the bottom as well as the side walls of the groove.

Fig. 2 shows the profile of a standard needle for slow speed records placed in a typical fine groove. The needle has a radius of 1 mil; the groove has an approximate width of 2.7 mils, an included angle of 90°, and a bottom radius of 0.2 to 0.5 mils.

The necessity of using two different needles has presented the record player industry with a host of problems, which have not had a satisfactory solution to this date. High fidelity requirements, where cost is no object, can be met with two separate pickups or plug-in pickup cartridges. The next best popular approach consists of the provision of dual needle pickups with shifting mechanisms which permit one or the other needle to be brought into play. Technically speaking, this is a good solution. Operationally speaking, it is far from ideal entirely aside of mechanical complications, because it requires active cooperation on the part of the user without immediate and obvious penalty for non-cooperation. Since the average user in the home is apt to be forgetful of operating details, the choice of needle often turns out to be entirely fortuitous.

Another solution has been the introduction of all-purpose needles[1] intended to work with both the coarse and the fine grooves. The most popular of these is similar to a conventional needle, but with a tip radius of about 2 mils. Record engineers often frown upon this approach even if it is operationally good. A 2 mil needle will ride at the corners of the fine groove, and, therefore, it will tend to pick up the noise from small surface imperfections, while, in a coarse groove, it will ride at the bottom and have imperfect support from the sides. Fortunately, the groove is elastic, and it yields under the needle load, so that neither of these conditions is apt to be present to a fatal degree. In actual practice, creditable results have been obtained with this type of needle by judicious curtailment of the high frequency response of the system. Other all-purpose needles have been used to a lesser degree with varying success.

Another solution which we believe is imminent is for the record manufacturers to provide the coarse grooves with a smaller bottom radius so that all records might be played with a single small-radius needle. We have received information that at least two leading record manufacturers are already providing a 1.5 mil radius at the bottom of their 78 rpm grooves. This new coarse groove and a typical fine groove are shown in Fig. 3. A 1.6 mil radius needle is already in use as an all-purpose needle for these two grooves. The performance is satisfactory since a 1.6 mil radius needle receives support from the side walls of the new coarse groove and it rides within the confines of a fine groove. When this new coarse groove becomes adopted by other record manufacturers for 78 rpm records, the problems created by the two groove sizes in home record players will be greatly alleviated. For high fidelity use in lightweight pickups, the 1 mil needle will continue to offer advantages because it "traces" the groove better than the larger needles, as shown in 1.2 and 1.4.

1.2 Modulated Grooves

Information is stored in a record groove by modulating (or more correctly, undulating) the groove in the recording process. Here we are concerned with the lateral recording process, where modulation is in the plane of the record as shown in Fig. 4. In this figure, a modulated groove is shown between two unmodulated grooves. To make the most of the available medium and gain a large signal-to-noise ratio, the recording engineer is apt to impose the largest possible modulation upon the groove consistent with the limitations of the recording process. Some of these limitations are of interest.

First, we recognize the amplitude ξ. From the recording standpoint, ξ_{max} is limited by the possibility of cutting into the adjacent grooves. Coarse grooves have a land 4 mils (0.01 cm) wide. Fine grooves are recorded with variable pitch and may have a land 1 to 2 mils wide (0.0025-0.005 cm). The limits of modulation amplitude may be expected to approximate these values.

The second important quantity is the maximum modulation velocity or the rapidity of the lateral motion of the recording stylus. Lateral velocity u equals U $d\xi/dx$, where U is the linear groove velocity and $d\xi/dx$ equals the slope of the modulated groove. The principal limitation upon u resides in the clearance angle of the recording stylus which is approximately 45°. Tan 45° = 1; therefore, one can expect the maximum velocity of modulation not to exceed the minimum linear groove velocity which is about 11.5 inches per second (29 cm/sec) for fine groove records and 16 inches per second (40 cm) for 78 rpm records.

The third important quantity is acceleration. Acceleration equals $U^2 d^2\xi/dx^2$. At the crest of the wave, $d^2\xi/dx^2 = 1/r_m$, where r_m is the radius of curvature of the groove modulation. Of even greater interest is the radius of curvature in the plane normal to the groove wall and which we designate as $r_w = \sqrt{2}\, r_m$. It is evident that as the radius of curvature of modulation becomes comparable to the radius of the needle r_n, the latter can no longer faithfully follow the motion of the recording stylus. A discriminal situation occurs when $r_w = r_n$. Beyond this discriminant, the needle will contact the crest of the groove at two points and instead of following a smooth path, it will turn a sharp corner. Obviously, this effect is most likely to occur at the inner grooves where U is smallest and wavelengths are short.

The maximum acceleration at the inner grooves of fine groove records which can be traced by a 1 mil radius stylus without "hitting a corner" can be calculated as follows:

$$a_{max} = \sqrt{2}\, U^2/r_n = 1.41 \times 29^2/0.00254$$
$$= 468{,}000 \text{ cm/sec}^2 = 475 \text{ "G" units} \qquad (1)$$

For 78 rpm records,

$$a_{max} = 1.41 \times 40^2/0.0027 = 833{,}000 \text{ cm/sec}^2$$
$$= 850 \text{ "G" units} \qquad (2)$$

At this time it is well to remark that the acceleration of the needle, a_n may be greatly in excess of the acceleration of modulation. When the modulation has a small radius of curvature, the path of the needle may exhibit a cusp resulting in very high acceleration. Distortion also may be present. Measurements prove that this situation exists in loud recordings.

1.3 Measurement of Modulation

Modulation can be measured by means of the setup shown in Fig. 5. A calibrated displacement-responsive pickup (such as a piezoelectric pickup) will measure displacement; adding one stage of CR differentiation measures velocity, and a second stage of CR differentiation measures acceleration. A frequency meter may be used as a rough guide of the frequency range. The modulation peaks are read on the oscilloscope. The peak values of modulation which have been measured in this manner are given in Table I.

Table I

Record Approx. Freq. Range	Displacement Peaks Cm. (200-2000 cps)	In.	Velocity Peaks Cm/Sec. (1000-3000 cps)	In/Sec.	Acceleration Peaks "G" units (3000-8000 cps)
33-45 rpm Fine groove Records	.004-.005	.0015-.002	20-35	11-14	700-800
78 rpm Coarse Groove Records	.0010-.0012	.004-.005	38-50	15-20	2000-2500

1.4 Tracing Distortion

The fact that acceleration peaks exceed the calculated value indicates that radius of curvature of the groove becomes comparable to or is less than the radius of the needle tip. This results in the generation of distortion. The amount of harmonic distortion which occurs with sinusoidal waves has been calculated by DiToro,[2] Pierce and Hunt,[3] Hunt and Lewis,[4] Sepmeyer[5] and others. Of principal concern is third harmonic which is given by the equation:

$$H.D._3 = (1/16)\ (r_n/r_m)^2 \qquad (3)$$

where r_n is the needle radius and r_m is the radius of modulation curvature at the crest of the sine wave. When the modulation curvature equals the needle radius, the third harmonic distortion is 6.25%. When the needle path comes to a cusp, the modulation curvature is 1/1.41 of the needle radius. In that instance, therefore, $H.D._3 = (1/16)(1.41)^2 = .125 = 12.5\%$. Additionally, there is the inevitable intermodulation distortion which has been calculated by Hunt and Lewis[4] and measured by Roys.[6] Unfortunately, the climax of the finale occurs at the inner grooves where the linear groove velocity U is low. These factors conspire to produce distortion in highly modulated records which is clearly audible on an extended range system.

1.5 Pinch Effect

Another factor of importance is known as the "pinch effect".[3] In Fig. 6 is shown a modulated groove. Because the groove is cut with a flat faced tool, the radial distances between the groove walls remain constant, but the normal distances at the points of highest velocity are narrowed down. The cross section of the maximum and minimum groove width is shown in Fig. 7. At left is shown the position of the needle in an unmodulated groove. At right is a point of high velocity where the groove is "pinched", forcing the needle to move upward. This effect takes place twice per cycle. Pinch effect is partially cushioned by the elastic properties of the groove wall,[21] but nevertheless, it is important that the needle have sufficient vertical compliance and a low mass to execute at least a part of the motion. Failure in this respect will result in excessive needle chatter as a result of direct radiation of sound by the record and the pickup owing to the high frequency vertical forces which are developed. Record and needle wear will also be adversely affected.

1.6 Groove Wall Deformation

All of the previous analyses have been based upon the assumption that the needle has a point contact with the undistorted surface of the groove. Actually the record material is elastic and the needle penetrates slightly into the surface of the material owing to the pickup load. Upon removal of the load the surface springs back if the elastic limit of the material has not been exceeded. Beyond the elastic limit, the groove will be permanently embossed or it may crumble or tear. Groove wall deformation has a bearing upon (1) response, (2) damage resulting from stresses, and (3) needle wear measurements.

With regard to response, the effects of groove wall deformation were studied by Kornei[7] and measured by Reiskind[8] and others. Reiskind reports 3-10 db loss at the inner grooves of 33 rpm records at 9 kc. Frequently, diameter equalization is added in recording to diminish this loss at the expense of tracing distortion. Often there is a resonant effect between the needle mass and the compliance of the record material which may cause a peak in the high frequency region.

With regard to record damage, we shall report briefly on experiments regarding groove wall deformation and stresses, which are summarized in Fig. 8 in tabulated form. To ascertain the diameter of needle penetration, the width of the traces made upon the uncut portion of records by needles of various diameters were measured under various loads. Portions of record surface were previously stained by application of a diluted soap solution which, upon drying, left an extremely thin film of soap upon the record. As the records were turned, the film of soap was removed at the points of contact with the needle leaving a trace equal in width to the diameter of needle penetration d_n. The loads used were 3-1/2, 7, 14, and 28 grams. Since in normal use, two equal forces L_n combine at 90° due to the pickup load, these figures have been multiplied by $\sqrt{2}$ to represent the vertical pickup load L_v. The first column gives the radius of the needles r_n in mils, and the first column under each load figure gives the diameter of penetration in mils. The record surface was inspected for scratching or scoring. The uncircled diameter figures indicate that there has been no visible scoring or permanent deformation. The broken line circle indicates a slight amount of scoring and a full circle indicates heavy damage to the surface. The data is obviously not sufficiently complete to draw final conclusions. In general terms, however, it may be said that 5 gram loads would not result in appreciable damage to the groove; 10 gram loads would cause damage with 1 mil radius needles but no damage with 1.8 mil radius needles. A 20 gram load or higher is apt to result in damage with all needles.

From load and diameter it is easy to calculate the average vertical stress S_c which is also shown in Fig. 8. It is interesting to note that the material can momentarily support stresses which are greatly in excess of the published yield points which were established with static tests. Another observation which can be made is that a given stress which causes damage with a small radius needle can be supported without damage with a large radius needle. This apparent anomaly can be related to a recent suggestion by Mr. Reiskind of RCA that shear stresses in addition to compression stresses might be important in causing damage to record grooves. Shear stresses would appear to be greater with smaller needles for a given diameter of penetration.

1.7 Needle Wear

In a recent survey, "needle wear" was listed as the foremost cause of the loss in quality in phonograph reproduction. The progressive stages of needle wear are shown in Fig. 9. Beginning with a theoretical profile of a new needle at a, after a moderate amount of wear, the needle takes on the shape shown at b. It will be noted that wear is unequal because of side thrust which is referred to later. After prolonged wear, the edges of the groove begin to wear into the needle forming a shoulder. The shoulder will interfere with the free up-and-down motion due to pinch effect. While authorities may argue about tolerable wear, practically no one will disagree that a needle should be replaced upon the formation of a shoulder.

Needle wear results in the formation of flats at the point of contact with the groove. As shown in Fig. 10, a flat begins to form by gradual removal of material pressed into the record surface. During these early stages of wear, measurements of the length of flat have little meaning. After a definite flat has been formed, the length of the flat can be measured by reflecting a beam of light from it and measuring the length of the reflected line of light by means of a microscope. Fig. 11 shows the side view of a needle which has had considerable wear, the heavy line portraying the appearance of the reflected line of light.

It has been demonstrated previously that the spherical tip is unable to follow the modulation of the groove shape accurately at short wavelengths, which results in tracing distortion. The formation of flats will cause a further deterioration in quality. The theoretical motion executed by a worn needle sliding over a sinusoidally modulated groove is shown in Fig. 12. Instead of moving along a sinusoidal path, the needle will travel the modified path shown in heavy line.

This motion of the needle may be analyzed in terms of its harmonic components and this analysis shows that distortion of the order of 30% may result. Additionally, a worn needle causes a loss in the high frequency response.[9]

1.8 Permissible Wear

There has been much discussion and little agreement regarding the maximum needle flat which may be tolerated before the needle is discarded. Some listeners are truly possessed with golden ears and they are able to discern the increase in distortion resulting from the initial formation of a flat -- say 3/4 mils on fine groove records and 1 mil on 78 rpm records. At the opposite pole, we have a report of listening tests in which a jury pronounced that distortion produced by worn needles on 78 rpm records became appreciable when the needle flats attained 4.7 mils (for speech) and 8.5 mils (for popular music). In view of these extremes of opinion, it is not feasible to establish hard-and-fast rules regarding needle life.

The maximum permissible flat length will obviously affect the useful life of the needle. The length of flat D of a needle under given conditions of wear is a function of the radius of the needle r_n, the vertical needle load L_v, and the time of wear t. In previous experiments, we have established that these quantities are connected approximately by the following equation:[10]

$$D = k\, r_n^{[1/(2n+2)]}\, L_n^{[n/(2n+2)]}\, t^{[1/(2n+2)]} \qquad (4)$$

where k and n are constants depending upon the needle and record material and n takes on values from 1/3 to 1 with an average n = 3/4. From this equation, it is seen that the size of flat D varies with the third to fourth root of the time of use t. Obviously, needle life can be greatly prolonged by a relatively small compromise in the quality of reproduction. Where an expert may discard a needle after ten hours of use, a "hep-cat" may find it still "playable" after 1000 hours.

1.9 Needle Wear vs. Record Wear

One phase of the problem is the rate of needle wear as a function of record wear. New records are much less damaging to needles than used records. An example of this type of data is shown in Fig. 13. The ordinates denote the size of flat developed on new osmium and sapphire needles on filled vinylite records as a function of the average plays per record side. It is seen, for example, that 377 minutes of play with a 1 mil sapphire-tipped needle on records which have been used on the average 10 times produced a flat of approximately 1/2 mil; the same playing time on records which had been played 50 times on the average produced flats of 9 mils. From equation 4, it can be estimated that needles will last six to ten times as long on new records as they would on records which had been previously played 50 times. This is one of many variables that makes it difficult to predict how long a needle will last before requiring replacement.

This effect is also evident -- although to a lesser degree -- on other record compositions.

1.10 Needle Wear vs. Time of Wear

It has been shown that record wear tests require careful control of the number of times each record is played. In conducting needle wear tests, we have chosen the figure 100 as the number of times the record is to be used before discarding. Examples of the results obtained with osmium-tip needles on 78 rpm records are shown in Fig. 14.

A 2.7 mil osmium needle played 2000 minutes at 1/4 oz. load (33 hours) developed a 1.5 mil flat, which would be the cause for discarding in true high fidelity use. The same needle in a moderate fidelity system where a 2.5 mil flat might be permissible would have lasted 200 to 250 hours. The price for high fidelity is indeed a high one.

As a last example of needle wear tests, Fig. 15 shows the size of flats developed in 1 mil radius sapphire and osmium needles on filled vinylite fine groove records. A needle load of 7 grams was used. A 0.75 mil flat developed after 1300 minutes of play which is equivalent to 22 hours. However, from previously stated data, if the record had been used on the average only 10 times, the life would have been 6 to 10 times longer, or about 180 hours. A 1 mil osmium needle developed a 1.3 mil flat for 1300 minutes of play under similar conditions. Since a sapphire needle was played 5200 minutes before a 1.3 mil flat was developed, we conclude that sapphires have an advantage over osmium in a ratio of 4:1.

1.11 Diamond Needles

Recently there has been a considerable amount of discussion and publication regarding the merits of diamond needles. Few of these articles are sufficiently documented to draw sound conclusions, but naturally, diamonds wear much longer than osmium or sapphire tips. A recent report which appears to be based on comprehensive data supplied by the users has been published by Maximilian Weil[11] which indicates that diamonds should last approximately 10 times as long as sapphires. Others have claimed life ratios as great as 20 or 30 to 1 in favor of diamonds.

2. PICKUP CARTRIDGES

2.1 Mechanical Characteristics

The needle is fixed or removably installed in a pickup cartridge, which is our next subject of interest. It makes very little difference from the viewpoint of final results what principle of transduction is used in the cartridge. The cartridge characteristics which are of interest are the mechanical impedance which determines the ability of the needle to follow the groove modulation, and the electrical response and impedance.

In this section we consider mechanical impedance. It will be remembered that the needle is driven by a groove wall which is inclined at 45°. The groove modulation drives the needle laterally against the impedance of the needle point. The force-reaction which is developed tends to push the needle up the side wall. If this force exceeds the pickup load, the needle will be in contact with one groove wall only, or it may even be ejected from the groove. In studying the mechanical characteristics of pickups, we will keep this criterion in mind and assume that the lateral force developed must not exceed the vertical pickup load.

2.2 Compliance

An important characteristic of pickup cartridges is the lateral needle point compliance, which is the flexibility of the needle point for lateral motions. The groove displacement ξ, the compliance and the force are related by the following equation:

$$F = \xi / C \qquad (5)$$

where F is the lateral force, dynes
ξ is the displacement, cm.
C is the compliance, cm/dyne

A simple instrument to measure pickup compliance is shown in Fig. 16. It consists of a non magnetic vise to clamp the pickup to be measured and a block magnet which bears upon the needle tip and which is magnetically held against the adjustable knife edge.[12] A piece of soft plastic has been cemented to the bottom of the block to engage the needle tip. The magnet is actuated by a coil connected to a variable frequency oscillator. In this mechanical system, the magnet constitutes the principal mass and the pickup furnishes the principal compliance. The resonant frequency of the system is determined by measuring the pickup output with a vacuum tube voltmeter. The compliance can be easily determined from the equation:

$$\omega_o^2 MC = 1 \qquad (6)$$

where ω_o is 2π x resonant frequency
M is the effective mass of the magnet at the needle point, grams
C is the compliance of the pickup, cm/dyne

To visualize the compliance required for proper tracking, equation 6 has been represented graphically at the top of Fig. 17. The slanted straight lines represent the pickup compliance. It will be remembered that the displacement peaks in 78 rpm records were between 0.010 and

0.012 cm. If the pickup load is 10 grams, compliance must be between 1 and 1-1/2 x 10^{-6} cm/dyne for proper tracking. With fine groove records, amplitudes rarely exceed 0.005 cm., and assuming a pickup load of 5 grams, the compliance of 1 x 10^{-6} should suffice.

Another factor of importance is vertical compliance, which should be sufficient to permit the needle to follow the up-and-down motion generated by the pinch effect. However, excessive vertical compliance is apt to cause a "flutter" due to vertical resonance of the arm and needle.

2.3 Resistance

Mechanical resistance must be low enough to avoid the generation of excessive forces owing to the high modulation velocity peaks. A moderate amount of resistance will have some beneficial effects upon the damping of the arm resonance. Low frequency mechanical resistance of a pickup cartridge can be estimated by means of the instrument in Fig. 16.[12]

2.4 Mass

Another important characteristic is the effective mass at the needle tip. Effective mass equals the moment of inertia divided by the perpendicular radius squared. Force developed between the needle and the groove is given by the equation $F = ma_m$. This equation is plotted at the lower part of Fig. 17, where the slanted lines represent the mass of the pickup. For example, in 78 rpm records the peak accelerations were found to be between 2000 and 2500 g which, with a 10 gram pickup force, requires the moving mass not to exceed 5 mg. On the other hand, the 700 to 800 G accelerations in fine groove records with a 5 gram pickup load would require the effective needle mass not to exceed 5 to 7 mg. The effective mass should be equally small to follow the vertical acceleration generated by the pinch effect. This leads to the observation that 78 rpm records present greater tracking problems than do fine groove records, when the same needle force is employed.

3. PICKUP ARMS

3.1 The Function of the Pickup Arm

The pickup arm has two principal functions. The first is to support the cartridge in the proper geometric relation with respect to the record grooves. The second is to act as a high pass filter preventing the translation motion and rumble frequency from entering the cartridge, but passing through the desired signal frequency. We discuss them in that order.

3.2 Geometry of Pickup Arms

The importance of proper alignment between the cartridge and the groove can be seen from Fig. 18. A sinusoidally modulated groove is denoted by the solid line. If the line of motion of the needle is perpendicular to the groove, the needle point will trace the groove modulation faithfully. However, if the cartridge is slanted so that the needle is constrained to move along the slanted line, it will be found that the needle is tracing the distorted wave which is shown in dashed line.

Mathematical analysis of the distorted wave shows that there is generation of second harmonic.[13] The per cent second harmonic is given approximately by the equation $(u_{max}/U) \times \alpha$, where α is the angle of inclination of the line of motion of the needle from the vertical line measured in radians. We have seen that the ratio u_{max}/U approaches unity at the inside grooves, and, therefore, the second harmonic distortion peaks will be approximately equal to the angle of slant α in radians. There is also the inevitable intermodulation distortion.[13] These distortions may become considerable if the arm is improperly designed or improperly placed.

The angular relations between the groove and the arm are shown in Fig. 19. Consider the distance between the vertical arm pivot and the needle which is labeled ℓ. If the arm is straight, the line of motion of the needle is perpendicular to ℓ. However, the line tangent to the groove at the point of contact with the needle is displaced by the tracking angle ϕ from the line ℓ. By the way of example, at the bottom of Fig. 19, the angle ϕ is plotted as a function of groove radius and arm placement for an arm 7-1/2" long. If the arm is placed so that the needle passes through the center of the turntable, the tracking angle ϕ varies as shown by the line A. ϕ is 6° at the inner groove and 23° at the outer groove. In a straight arm, $\alpha = \phi \simeq 0.1$ radian at the inner groove, and 10% distortion will occur at modulation peaks.

If the arm is moved closer to the record so that it passes beyond the center, the tracking angle becomes greater, but it is also more uniform over the record. For example, if the amount of overhang equals 1/2", the tracking angle varies from 25° at the inner groove down to 20° at some intermediate groove and up to 29° at the outer grooves. Therefore, if the arm is bent or offset at an angle β of 23.5°, the error at the inner groove will become 1.5°, and at the outer groove it will be 6°. The reduction in tracking error over our first example is now better than 3:1.

It can be shown[13,14] that the optimum offset angle is:

$$\beta_o = \frac{r_1\left(1 + \frac{r_1}{r_2}\right)}{\ell\left[1/4\left(1 + \frac{r_1}{r_2}\right)^2 + \frac{r_1}{r_2}\right]} \qquad (7)$$

and optimum overhang D is:

$$D_o = \frac{r_1^{\ 2}}{\ell\left[1/4\left(1 + \frac{r_1}{r_2}\right)^2 + \frac{r_1}{r_2}\right]} \qquad (8)$$

where r_1 is the innermost groove radius and r_2 is the outermost groove radius.

3.3 Placement of Arms

Equations are also available[15] to ascertain how to best mount an existing arm which may have a length ℓ and an offset angle β radians other than that given by the previous equation. This may be done by calculating a discriminal angle given by the equation:

$$\beta_i = \frac{1}{\ell\left[\left(\frac{1}{r_1} + \frac{1}{r_2}\right) - \frac{r_1}{2}\left(\frac{1}{r_1^{\ 2}} + \frac{1}{r_2^{\ 2}}\right)\right]} \qquad (9)$$

If the arm offset angle β is less than β_i, the overhang distance D is given by the equation:

$$D = \frac{\beta\left(\frac{1}{r_1} + \frac{1}{r_2}\right) - \frac{1}{\ell}}{\frac{1}{r_1^{\ 2}} + \frac{1}{r_2^{\ 2}}} \qquad (10)$$

If β lies between β_i and β_o,

$$D = \frac{r_2}{2}\left(\frac{r_2}{\ell} - \beta\right)\left[\left(1 + \frac{\beta^2}{\left(\frac{r_2}{\ell} - \beta\right)^2}\right)^{1/2} - 1\right] \qquad (11)$$

If β is greater than β_o, the mounting distance D is found from:

$$D = \frac{r_1}{2}\left(\beta - \frac{r_1}{\ell}\right)\left[\left(1 + \frac{\beta^2}{\left(\beta - \frac{r_1}{\ell}\right)^2}\right)^{1/2} + 1\right] \qquad (12)$$

By careful design and placement of the arm, the tracking error distortion may be reduced to 3 or 4%, even for the heavily modulated inner grooves, which is negligible in comparison with the tracing distortion and other distortions in the system.

3.4 Side Thrust

Analysis of the load and friction forces at the needle tip indicates the existence of a radial force F_r which is proportional to the tracking angle ϕ.[15] This force is usually directed towards the center of the record and it must be borne by the inner record groove. This force is known as side thrust, and it is responsible for the unequal wear of the two sides of a needle.

3.5 Dynamics of Pickup Arms

It has been stated that a pickup arm must act as a high pass filter to permit the transmission of the recorded information into the cartridge, but to prevent turntable rumble and the steady state motion of the spiral record groove. This is achieved approximately by placing the lateral resonance of the arm mass and cartridge compliance at the lower end of the frequency spectrum. A resonant frequency of 40 cps is often found to be satisfactory since it is located between the 30 and 60 cps rumble components, and, at the same time, it prevents the attenuation of signals above 40 cps. To this end, if the pickup cartridge had a compliance of 1×10^{-6} cm/dyne, the lateral mass of the arm and cartridge should be 16 grams. The lateral mass equals the moment of inertia divided by ℓ^2.
The resonant rise of the arm will be damped to a certain extent by the resistive components of the impedance of the pickup cartridge. It is not feasible, however, to damp the arm completely in this manner. A good alternative solution to this problem is that proposed by Mr. Bachman in his design of the viscous damped arm described recently in the TRANSACTIONS of the IRE-PGA.[16]

The arm resonance is utilized in low cost phonograph players to improve the low frequency response, thereby compensating for the deficiencies of some of the other components in the system. For example, if the compliance of the cartridge is 0.5×10^{-6}, a relatively light arm having a lateral mass of 8 grams will resonate at approximately 80 cps giving a substantial amount of bass boost. This approach is obviously justified only when cost is the primary consideration.

4. RESPONSE CHARACTERISTICS

4.1 Recording Characteristics

The subject of response characteristics is heavily weighted by artistic and commercial considerations and is the subject of many arguments. We have attempted to avoid them as far as possible by dealing with response characteristics largely from the technical viewpoint.

The typical recording arrangement is shown in Fig. 20[17] -- 1 is the studio, containing microphones, etc.; 2 represents the mixers and microphone amplifiers which feed the monitor loudspeaker. The only artistic element which we consider in this discussion is the musical director. His job is to determine the placement of the artists and microphones, and otherwise to alter the musical content until the sounds coming over the monitor loudspeaker system convey the artistic message which he wishes his public to hear. The monitor system is presumed to be constructed in accordance with the best practice to reproduce the incoming signal faithfully. After this artistic result is achieved, the signal is switched to the recording bus, and in turn to the recording amplifier and compensating networks, 3, which drive the cutter mechanism. We shall limit our discussion to the means of providing a playback system, 4, which will reproduce the message to the listener in the form originally heard by the recording director. This objective can be achieved if we know the "recording characteristic", which is defined as the frequency response of the recording system between the recording bus and the final pressing. Having this knowledge, all one has to do is to provide the reverse recording characteristic in the playback system to achieve our technical objective.

The "recording characteristic" is plotted in terms of the velocity of the record groove which is obtained by feeding a constant voltage into the recording bus. This characteristic includes the high frequency pre-emphasis and other modifications used in the recording process. The recording characteristics of three record manufacturers are shown in Fig. 21. The solid line represents the recording characteristics employed by Columbia for LP records. The dotted line is the recording characteristic employed by Capitol. The dashed line is the RCA "New Orthophonic" characteristic used in RCA recordings.

At one time, there was quite a bit of difference in recording characteristics of various manufacturers. As seen in Fig. 21, the present-day characteristics are beginning to overlap each other and the day when a single standardized characteristic will be adopted may not be too remote. A single recording characteristic which seems to represent the present-day recording practice is shown in Fig. 22. This curve may well be considered for purposes of standardization.

4.2 Reproducing Characteristic

A reproducing characteristic may be defined as the electrical response into the loudspeaker of the reproducing system vs. the frequency when playing a record having a constant groove velocity over the frequency range of interest. If the reproducing characteristic is the inverse of the recording characteristic, and if the loudspeaker system is constructed in accordance with the best practice to reproduce the incoming signal faithfully, the listener will hear essentially the message as intended by the musical director. The inverse of Fig. 22 may be taken as a satisfactory reproducing characteristic for present day recordings. The 50 cycle point of this characteristic would be at +15 db and the 10,000 cycle point at -13 db. A slightly different reproducing characteristic was adopted some time ago by the Audio Engineering Society, the 50 cycle point being at +18 db and the 10,000 cycle point at -12 db.[18]

Reproducing characteristic is difficult to measure directly because constant velocity records are not available. Some manufacturers have provided records which are intended to be representative of their particular recording characteristic, and which, when reproduced "flat", indicate compliance with the particular recording characteristic. The majority of test records available in the laboratory have an approximately "constant displacement" characteristic at low frequency and an approximately "constant velocity" characteristic at high frequency. Therefore, what is of interest in the design of a playback system is not the "reproducing characteristic", but a playback characteristic in terms of a given recording characteristic and a given test record.[19] We call it the "playback objective characteristic". The proper procedure for obtaining this characteristic is outlined in 4.3.

4.3 Playback Objective Characteristic

The playback objective characteristic must always include the recording characteristic and the velocity-frequency characteristic of the test record to be employed. The velocity calibration of test records may be obtained from the manufacturer, or it may be measured by means of "light patterns".[20] For example, in Fig. 23, the curve indicated by the round dots represents the relative velocity-frequency characteristic in db of the RCA test record 12-5-29 (45 rpm). Of course, any other test record with known velocity-frequency characteristic may be used.

Let the solid line in Fig. 23 represent the recording characteristic in db for which it is desired to adjust the reproducing system. The recording characteristic is subtracted point-by-point from the velocity-frequency characteristic of the test record. The resulting curve, indicated by the square dots, is the "playback objective characteristic", or the playback response required to match the particular recording characteristic. It should be carefully noted that the ordinates of the recording characteristic are added when they are negative, and subtracted when they are positive from the test record characteristic to yield the correct "playback objective characteristic".

After the playback system has been adjusted to provide this playback objective characteristic, it will then, by definition, possess the desired "reproducing characteristic" to complement the given "recording characteristic".

This does not preclude, however, the necessity of providing suitable controls for adjusting the low and the high frequency response to compensate for the differences of loudness of reproduction. On the contrary, such controls greatly enhance the ability of the playback system to provide pleasing and realistic reproduction.

ACKNOWLEDGMENT

The author wishes to acknowledge with thanks the suggestions and information furnished for the purpose of this Seminar session by the following individuals and organizations: Mr. W. S. Bachman of Columbia Records, Inc.; Mr. R. Dally of General Electric Company; Mr. C. J. LeBel of Audio

Devices, Inc.; Mr. H. I. Reiskind of RCA; and Mr. E. H. Uecke of Capitol Records, Inc.

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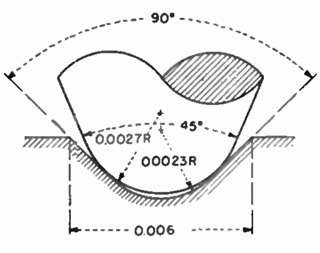


Fig. 1
Profile of "old-style" 78 rpm groove with standard RTMA needle for 78 rpm grooves.

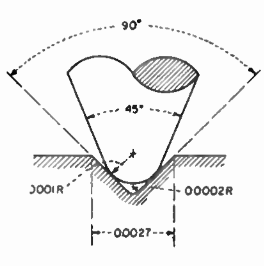


Fig. 2
Profile of standard fine groove with standard RTMA needle for fine grooves.

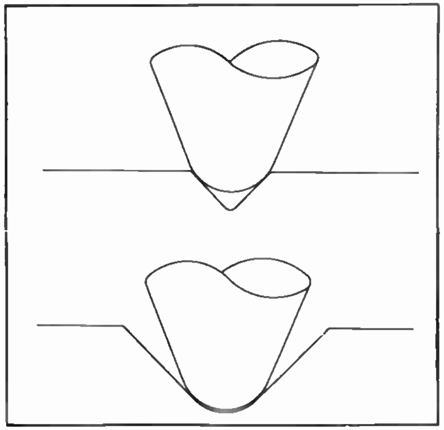


Fig. 3
1.6-mil radius all-purpose needle in a fine groove (above) and in the "new-style" 78 rpm groove used by some record manufacturers.

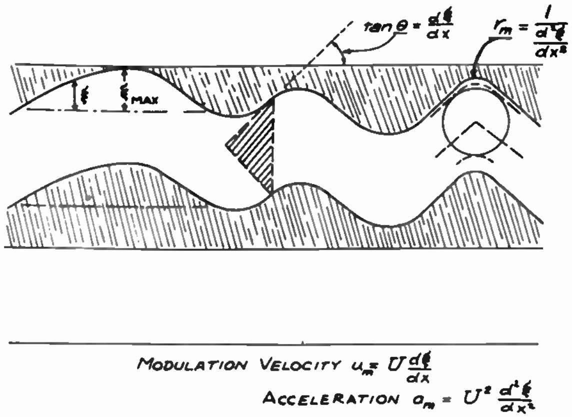


Fig. 4
The elements of modulation: the maximum displacement, velocity, and acceleration of modulation.

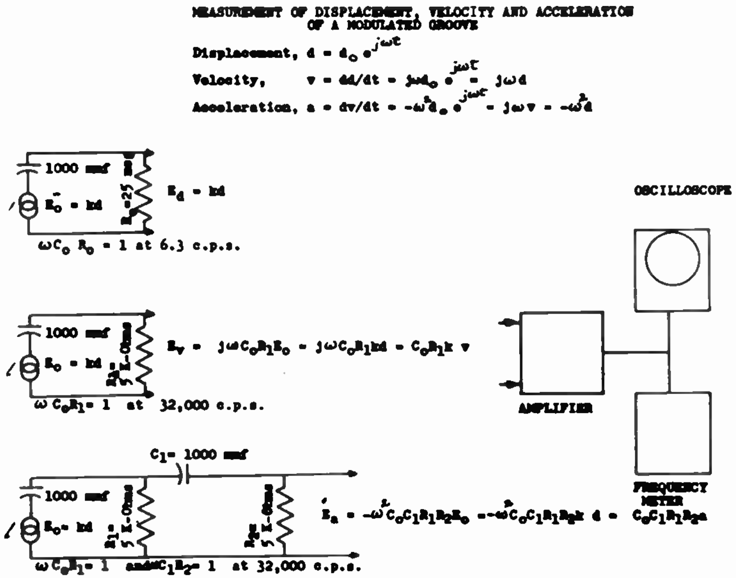


Fig. 5
Setup for measurement of modulation elements.

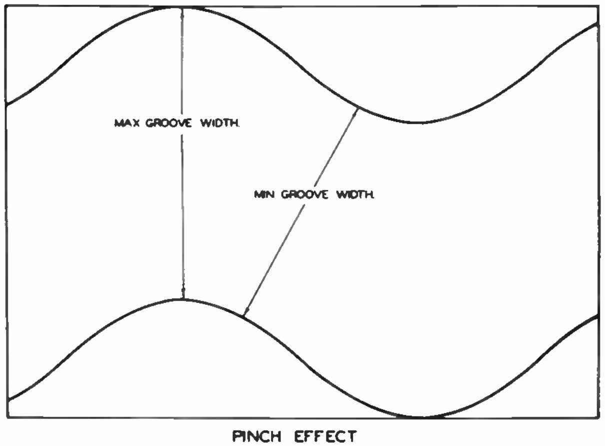


Fig. 6
Constriction of modulated groove.

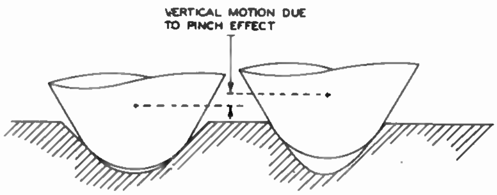


Fig. 7
Vertical displacement of needle owing to groove constriction.

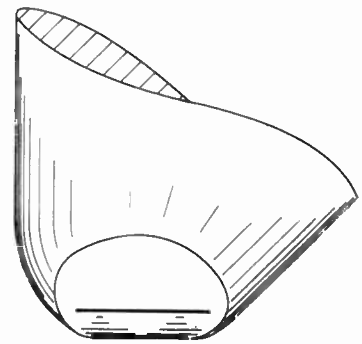


Fig. 11
Side view of a worn needle.

	L_v →	5 grams		10 grams		20 grams		40 grams	
	r_n mils	d_n mils	S_c lbs/□"	d_n mils	S_c lbs/□"	d_n mils	S_c lbs/□"	d_n mils	S_c lbs/□"
Shellac	1.1	.6	27000	.8	31000	1.0	40000		
	1.8	.6	27000	.8	31000	1.0	40000	1.4	40000
	2.5	.8	16000	9	25000	1.1	33000	1.4	40000
Red Vinylite	1.1	.9	20000	1.0	20000	1.2	28000		
	1.8	.8	16000	1.0	20000	1.2	28000	1.6	31000
	2.5	.8	16000	1.0	20000	1.3	24000	1.8	25000

Fig. 8 - Needle penetration, stresses and damage.

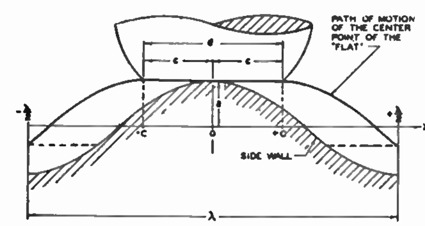


Fig. 12
Theoretical motion of worn needle tracing a sinusoidally modulated groove.

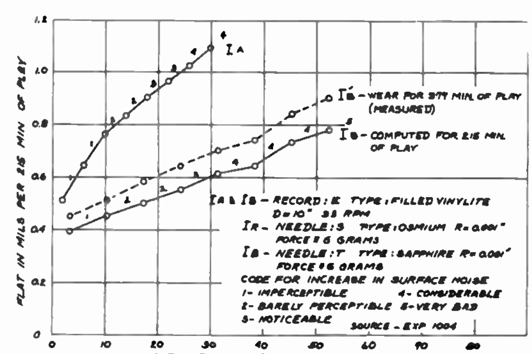


Fig. 13
Increase in the rate of needle wear as a function of record wear.

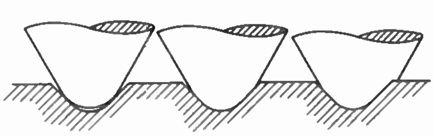


Fig. 9
Theoretical profile of needle during progressive stages of needle wear.

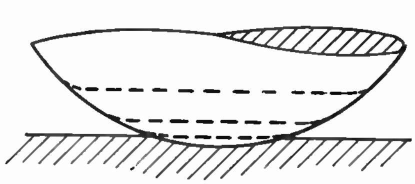


Fig. 10
Progressive stages in the formation of a needle flat.

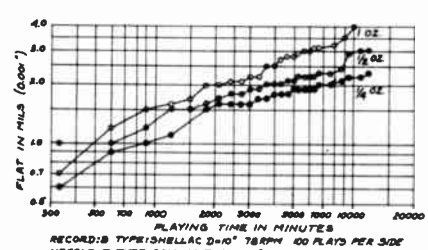


Fig. 14
Needle wear vs. the time of wear. Osmium-tipped needles on 78 rpm shellac records.

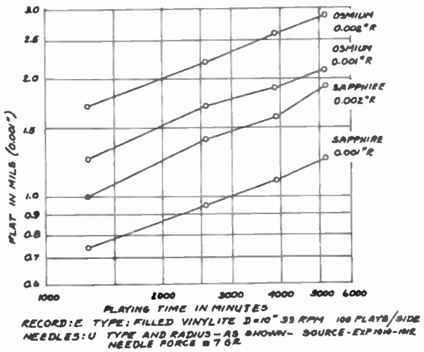


Fig. 15
Needle wear vs. the time of wear.
Osmium and sapphire-tipped needles
on filled vinylite 33 rpm records.

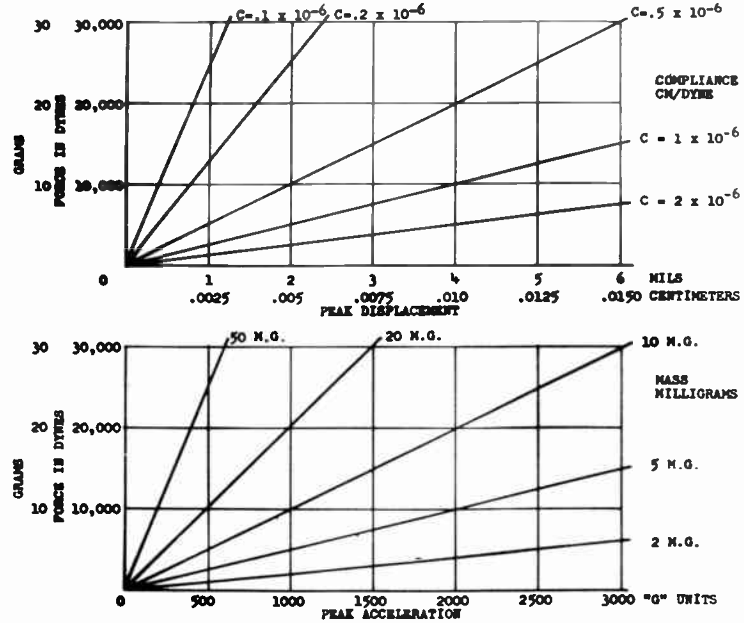
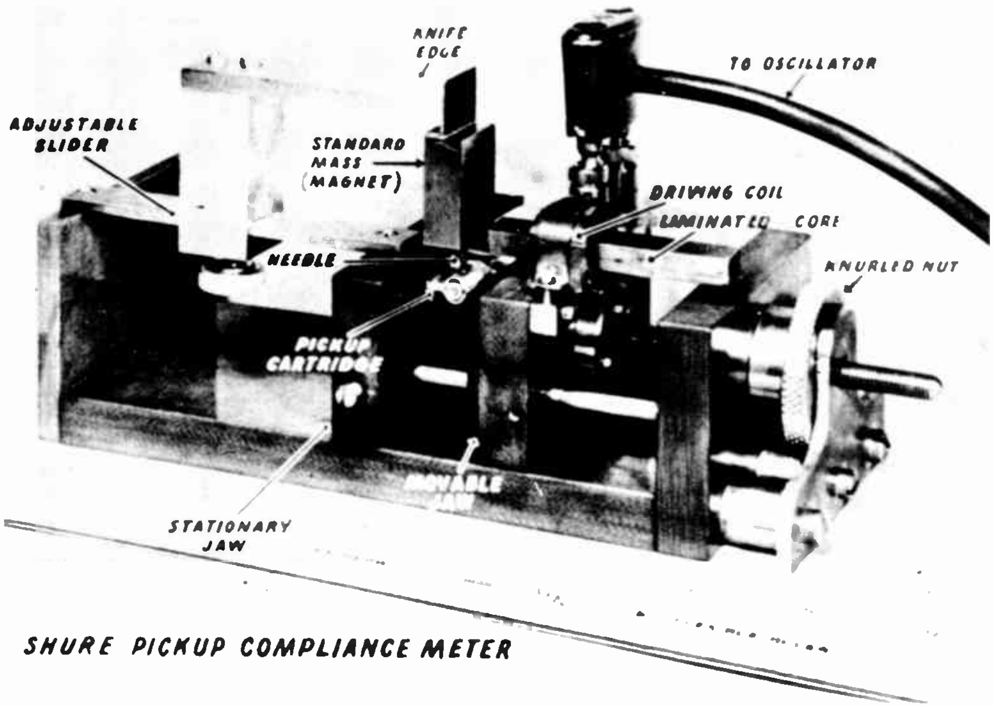


Fig. 17
Chart for selecting pickup compliance and mass
as a function of elements of modulation.



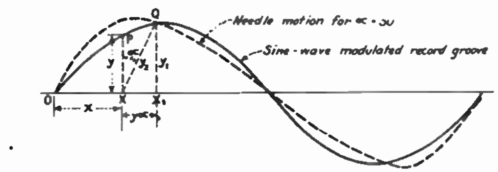


Fig. 18
Manner in which a sinusoidal wave form
is distorted owing to tracking error.

Fig. 16
Instrument for measuring low frequency compliance and damping of pickup cartridges.

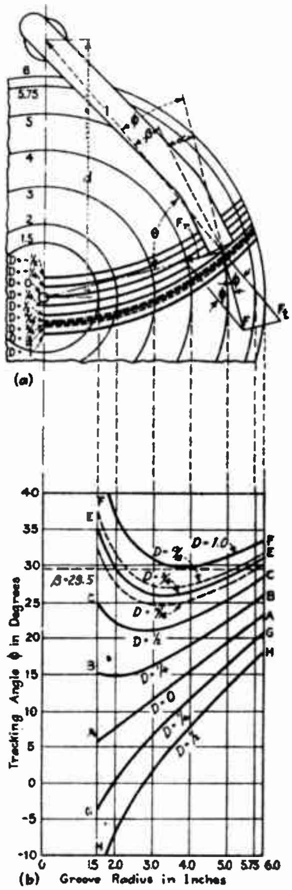


Fig. 19
Dimensions and angles
involved in tone-arm design.

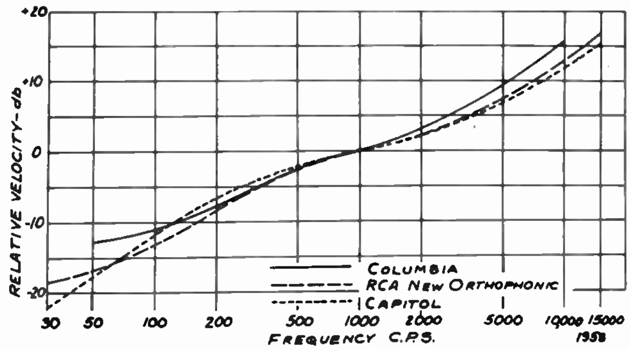


Fig. 21
Recording characteristics
of three record manufacturers (1953).

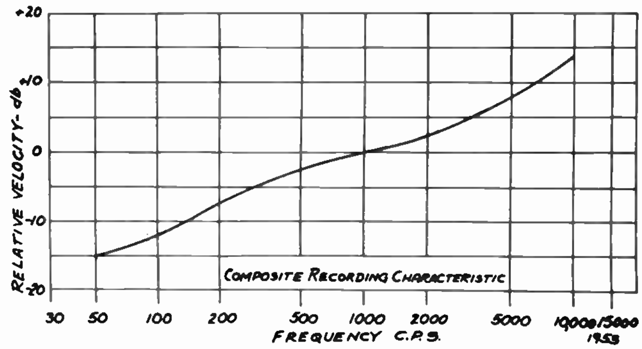


Fig. 22
A composite of characteristics
shown in Fig. 21.

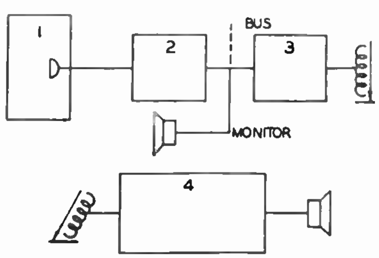


Fig. 20
Typical recording arrangement.

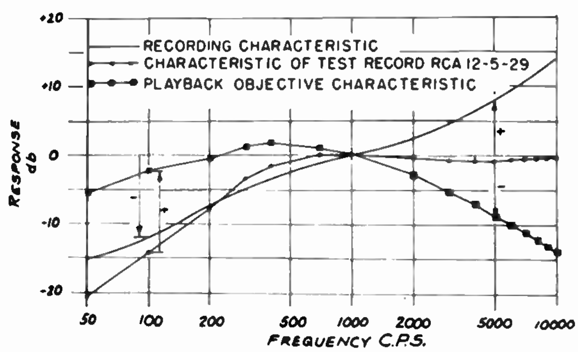


Fig. 23
Derivation of the
"Playback Objective Characteristic."

MAGNETIC RECORDING

Marvin Camras
Armour Research Foundation
of Illinois Institute of Technology
Chicago, Illinois

Sound recording can be thought of as a long time-delay element, that we put into a circuit, but it differs from other delay elements in several ways:

1. The delay is measured in hours or days, rather than fractions of a second.
2. The delay is usually longer than the entire program.
3. Time delay can be controlled after the event.
4. The sound can be repeated.

The most convenient way to produce the above characteristics is to take the sound pattern which varys in both time and space, and convert it into a fixed space pattern on a suitable record medium. Whenever we want to re-create the sound, we move the fixed pattern relative to a pickup device, and change it back into a time and space varying pattern.

Comparison of Recording Methods

The most common recorded pattern is a mechanical phonograph groove with lateral or vertical dimensions that vary from an average position according to the original acoustic waves. A second widely used record is an optical strip with a visual pattern which transmits light in accordance with the original acoustic waves. The third method, which has grown most rapidly in recent years, is a magnetic pattern on a wire, tape or other magnetizable material.

Each system has advantages. In the field of home entertainment, especially for short popular records, the phonograph disc is unsurpassed. For theater projection, optical sound on film is most convenient. Popularity of magnetic recording is based on several unique features:

1. Fidelity - no vibrating mechanical parts are required either in recording or playback.
2. Reliability - no critical adjustments as in a cutter stylus or a recording galvanometer - immediate monitoring.
3. Economy - low initial cost - erasibility - ease of editing.

Fundamentals of Magnetic Recording - The Record Medium

Those of us who are familiar with magnets only in the form of bi-polar horseshoe or bar shapes, may be surprised to find that magnets with multiple poles are possible. Figure 1 pictures one of these. We can go even further and show that the degree of magnetization may be continuously variable, according to any desired function within limits of recording resolution. Figure 2 is an arbitrary wave shape, and the corresponding magnetic flux pattern. The flux surrounding a magnetic record can be made visible by settling fine iron particles on its surface. This was done to a wire recording in Figure 3 and to a half-width tape recording in Figure 4. (Irregularities of the recording gap show up so well that crime detection laboratories could prove that a record was made on a certain recorder.)

Magnetic Records

Magnetic records have been made in the form of round wires, flat wires, threads, tapes, films, discs, belts, cylinders, and flat sheets. Any or all of these can be solid, plated, coated, or impregnated with the active material, so we have a sizeable number of combinations to choose from. Some of the more common forms are shown in Figures 5 and 6.

Most magnetic recording wire is a stainless steel alloy of about 18% chromium, 9% nickel, and 73% iron. It is interesting that this alloy is from the class of "non-magnetic stainless steels". Though non-magnetic as it comes in ingot form, the alloy takes on the desired magnetic properties after a series of carefully controlled heating and cold-working treatments. Recording wire is available on standard spools about 2 3/4 inches in diameter by 5/8 inch high, containing up to an hour (7200 feet) of .0036 or .004 inch diameter wire.

Most magnetic tape is a thin coating of active material on a plastic film base. The tan or brown coating is an iron oxide of formula Fe_2O_3, with magnetic properties including a coercive force of about 275, and a residual magnetization of about 800. The oxide is a fine powder, with particles about .00004 inch or smaller in size, uniformly dispersed in a binder which adheres to the film base. Black coatings for tape are generally iron oxides of formula Fe_3O_4, with a coercive force of about 350, and with the same physical characteristics as the brown oxide. Recently a "high output" tape has become available. It has practically double the magnetic energy of ordinary brown tape, but is otherwise interchangeable with it.

A standard tape package contains 600 or 1200 feet of 1/4 inch wide by .002 inch thick tape, on a 5 or 7 inch plastic reel which resembles an 8 mm film spool. Wider tapes, flat sheets, discs and motion picture films coated with the magnetic oxide dispersion are also available.

A comparison of the magnetic properties of certain recording materials shows the progress made in recent years. Carbon steel wire in early recorders had a hysteresis loop as in Figure 7, with coercive force of 30 oersteds or less. The modern stainless alloy of Figure 8 has a coercive force of 245, which enables it to operate at a fraction of the speed of the old wire. Similarly, the earliest types were made with carbonyl iron. A specimen of this material had the poor magnetic properties of Figure 9. Later tapes using iron oxides were a great improvement, as shown in Figure 10, but still did not compare to present day materials of Figure 11.

Figure 12 shows the improvement in frequency response (before equalization) resulting from the substitution of high-coercive stainless for medium coercive carbon steel wire. Similar improvements are noted in comparing tapes. Differences of this order make it possible to slow down the record by a factor of two or three, and still get equal or better response.

Recording Heads

The recording process impresses a magnetic pattern on to the record medium by passage of the medium over a head, where each element in turn is acted on by a magnetic field, and become permanently magnetized according to the field it encounters. An important problem is to make the recording field as sharp as possible so that it affects a small portion of the record. The shorter the wavelength we can record, the slower we can run the record for a given frequency response.

One of the simplest recording heads is a bar electromagnet, with one pole contacting the record. This has a broad magnetic field and poor resolution. A better design is shown in Figure 13A where the field is concentrated by a pair of opposed polepieces sharpened to a point. This design is unsuitable for wire recording because rotation of the wire gives fluctuating output. Staggering the polepieces as in Figure 13B helps overcome this trouble, but at the expense of resolving power. A much better arrangement is shown in Figure 13C which uses a narrow gap between flat faces to concentrate the field, instead of sharpened poles. The modified form of Figure 13D substitutes a slot for the hole through the poles, for convenience in threading.

The recording head for tape in Figure 14, consists of a high permeability magnetic core with a narrow air gap (about .0005 inches). It is difficult to take full advantage of very small gaps because the field is not sharply defined at the gap boundaries, but extends for a distance as we approach and leave the gap. There is also a problem caused by the decrease in field as we move in an upward direction, away from the gap (Figure 14). This makes the magnetizing field non-uniform through the cross section of the tape. In some designs the tape also encounters undesirable, spurious fields as it enters or leaves the head. We also notice that the head is rather wasteful of flux, since most of it passes across the gap faces, rather than through the tape.

Heads have been designed to avoid these shortcomings. One promising type is the cross-field head of Figure 15. To the gap field of an ordinary head (A) we add a vertical field as in (B). Vector addition of the field components gives a resultant as in Figure 16 which is more concentrated at one pole edge and dies away more rapidly at the other. The result is a sharper recording field, more uniform through the cross section of the record medium. Other heads are shown in Figure 17. To the right is a microhead, about 1/8 inch in diameter which is more efficient than standard sizes. In the center is a combination erase-record-playback head built on a single core. At the left is a turn-in-gap head which has no conventional winding, but is energized by current sent through a high conductivity spacer in the gap itself.

Biasing

When we make a record using audio only in the head, the recording is a distorted version of the input current. Investigation shows a relation between applied field and retained magnetization as in Figure 18, which is an inherent property of the recording medium. We would like a straight line relationship between these quantities. One way of obtaining it would be to apply d-c bias to shift the operating point to P. This is wasteful since we now use only half of the magnetization curve. Another way is to pre-saturate the record and then subject it to a recording field containing a component opposite to the saturated direction, plus the audio to be recorded. This action is shown in Figure 19. At the zero cycle of audio, the bias brings the magnetization down to 0, and leaves a retained magnetism 0' after the record leaves the head. At the positive and negative audio peaks the magnetization reaches A and C respectively, and results in a final state A' and C'. The chief faults of d-c bias are even-harmonic distortion, and noise.

High frequency bias has so many advantages that it is used almost exclusively at present. Here a supersonic flux, usually between 20 kc and 300 kc is superimposed on the audio flux to be recorded. In magnitude this bias flux reaches to the points x,y, where the B_r-H curve of Figure 20 is rising rapidly. When we filter the high frequency component from the output, there remains an audio flux which is a faithful reproduction of the input audio component. In practice, the filtering is automatic, since the high frequency component is beyond the resolving power of the head-tape system. We notice two important advantages of high frequency bias: (1) When the audio is zero the record is demagnetized, and has a very low noise level. (2) Recording is symmetrical, so that even harmonic distortion is absent.

Recording Circuits

Typical recording circuits are shown in Figure 21. Four methods of introducing the high frequency bias are shown. The parallel connection of A is simple, but introduces the bias voltage into the audio amplifier. The series connection (B) makes isolation easier. With both A and b the number of turns on the recording head is limited because high bias voltages might result in breakdown. This is avoided in arrangement (C), where bias is introduced by a few auxiliary turns on the recording head placed in series with the erase head. In some designs, as in (D), we can obtain sufficient bias in the recording head by induction from the erase head in close proximity.

The Playback Process

A pickup head for a magnetic tape record is shown in Figure 22. In construction it is similar to a recording head; in fact the same head is often switched so that it serves either function. A typical recorded element is shown in (A). When such an element passes over the gap, a portion of the flux (B) goes through the magnetic core and links the coil. But much of the flux is lost. For example, portions (C) and (D) are shunted across the pickup gap, while (E) completes its circuit in air.

The voltage induced in the voice coil is given by:

$$E = KCGfN\phi_r, \qquad (1)$$

where E is the induced voltage.

K is a coefficient that takes into account the incomplete coupling of tape to head, conversion factors, etc.

C is a coefficient that decreases with rising frequency because of core losses.

G is a coefficient that decreases at shorter wavelengths because of finite size of the gap.

f is the recorded frequency.

N is the number of turns on voice coil.

ϕ_r is the residual flux in the tape.

In specific problems the best results are obtained by graphical treatment, but analytical studies are valuable in giving an insight of the processes involved. From equation (1) we see the output voltage is directly proportional to frequency, so we expect the output voltage to rise 6 db for every octave increase in frequency. This is borne out in the response curve of Figure 23. Here the playback of a tape, recorded with constant current in the head, rises about 6 db per octave in the range from 100 to 1000 cycles. Above 1000 cycles the losses tends to reduce C, G, and ϕ_r of equation (1):

(A) Eddy currents, hysteresis losses, and skin effects in the core reduce flux in the voice coil.

(B) When the effective gap size (g) becomes comparable to the recorded wavelength (λ), the output is further reduced by

$$G = \frac{\sin \pi g/\lambda}{\pi g/\lambda} \qquad (2)$$

(C) At short wavelengths the mutual demagnetizing effects of closely adjacent poles reduce the residual flux. Core losses and partial erasure during the recording process also reduce the ϕ_r. These factors stop the rise in output voltage with rising frequency. Above 3000 cycles the output in Figure 2 falls off, until at 10 kc it is 15 db below the peak.

At low frequencies, if wavelengths become longer than the head itself, the magnetic coupling of tape to head becomes inefficient and the output falls more rapidly than 6 db per octave. We begin to notice this effect in Figure 23 below 100 cycles.

According to Equation (2), we note that when the recorded wavelength equals the effective gap, the output is zero, but if we decrease the wave, length still further the output rises again. We get another null at $g = 2\lambda, 3\lambda, 4\lambda$ .... etc. This is shown in Figure 24, where a record was played back with gaps of different sizes. With an 0.1 gap we get a null at intervals of about 700 cycles. In special applications we can make use of these outputs which are supposedly beyond the resolving power of the heads. But in most cases we use the region to the left of the first null point and try to increase its upper limit by means of short gaps. Spurious pickup of the recorded flux at points other than the gap will also give rise to peaks and valleys resembling the response of Figure 24, and the designer may have to take precautions to prevent them.

Equalization

The characteristic of Figure 23 must be corrected at both high and low frequencies if a flat response curve is desired. We can apply correction either during recording (pre-equalization), or during playback (post-equalization) or both. If we do all our equalization in recording, we must boost the input level of low frequencies 20 or 30 db with respect to the peak at about 3000 cycles. We then find that the low frequencies would saturate or overload the tape long before its capabilities at medium or high frequencies were exceeded. On the other hand, if we did all our equalization on playback we would require 15 or 20 db boost at 10 kc with respect to the 3 kc peak, and this would emphasize the amplifier and tape hiss unduly.

Studies of the frequency spectra of speech and music show that components above 3000 cycles occur at lower levels than medium frequencies, and that at 10 kc we can boost the response as much as 15 db, without exceeding the medium frequency peaks. We can thus correct the high frequency response of our tape characteristic completely by pre-equalization, and this is common practice in most magnetic recorders.

Most of the low frequency equalization must be done in playback. Many of the high quality machines do all of it in playback. But when the response extends down to 30 or 50 cycles, the heads and pre-amplifiers must be carefully designed to avoid hum, because the hum as well as the head output is boosted about 25 db. Recorders which cut off at 100 or 200 cycles do not require as much boost and are insensitive at hum frequencies, so their design is not difficult. A compromise is often used where half of the equalization is done on record, and half on playback. This reduces hum, and also simplifies switching because the equalizer is left in the circuit all the time.

Erasing

The erase head usually resembles the recording head, but the gap is five or ten times as large, and the winding is energized with enough input power to erase completely the highest level recordings. High frequency erase heads which operate at bias frequencies leave the record in a demagnetized condition and give the maximum signal to noise ratio. Direct current and permanent magnet heads are sometimes used for economy or for extra strong fields. Some of these are made to approximate a-c erasure by subjecting the tape to a series of opposite poles, each weaker than the preceding one. Direct current heads are generally noisier than a-c types.

Record media that saturate slowly at high fields and have high coercive force are more difficult to erase than record media that saturate rapidly at moderate fields and have lower coercive force. To erase the more difficult materials special measures are taken, including multiple gap heads, turn-in-gap heads, d-c heads, etc. Erase efficiency of heads can be evaluated by plotting the erase effect on a saturated signal against the input power to the head. (Since power is difficult to measure at high frequencies, the voltampere input is usually taken for comparative purposes.) Figure 25 is a set of such curves, comparing three different designs.

Problems in Magnetic Recording

Flutter remains one of the most important problems in high quality magnetic recording. The ear can detect as little as 0.001 per cent flutter under favorable conditions, while the best mechanical systems operate at levels of about 0.1 per cent. In most cases, the mechanical designs "just grow" on the drafting board without taking advantage of what is known about optimum capstan and flywheel sizes, compliances, etc. However, even with the best designs a very high order of precision is required in manufacture.

Noise is also a problem, for even when it is 50 to 60 db below the signal level, a careful listener can detect it. With the best modern systems, noise level is almost the only feature by which the recorded program can be distinguished from the direct program. Noise can be reduced by better tapes and better heads, but we soon reach a point where tube noise of high gain amplifiers is the limiting factor. High output tapes and high output heads offer a solution, because they do not require as much amplification.

Frequency response improvements are always welcome. Even if we do not need the better high frequency response we can always drop the speed. One thing that is often overlooked is the importance of good contact between tape and head. It can be shown that when a tape is separated a slight distance (d) from the head, the playback of a wavelength (λ) is reduced by a factor: db loss = $56 d/\lambda$, which can be a tremendous amount at high frequencies. This considers only the playback loss. Recording loss as great or greater must be added. At the present time we can record about 2000 cycles per second per inch-per-second of tape speed. Figure 26 shows some trends of the past. With better tapes, better heads, and better ways for keeping them in mutual contact we may expect further improvement, but extrapolation into the future, as by the dashed line of Figure 26, is always uncertain.

Transfer of recordings from layer to layer of a reel has been a problem in the past. This can be reduced to a negligible value by working with a record material of proper magnetic characteristics, by avoiding recording levels that approach saturation, and by storing the record away from high temperatures and magnetic fields.

Distortion is very low in magnetic records. It can be kept at a minimum by proper setting of the high frequency bias. The setting for lowest distortion is usually at a bias current considerably higher than the adjustment for maximum response, especially at high frequencies. An unusual type of distortion often occurs when supersonic bias is used, where the high frequency oscillator beats against harmonics of the recorded audio frequencies. This can be minimized by selecting a bias frequency at least five times as high as the highest audio to be recorded.

"Drop-outs" are a nuisance in recording for instrumentation purposes, where loss of a single pulse may upset the entire system. It has been found that drop-outs can result from lumps in the coating which cause a slight momentary separation between tape and head. Special tapes are now available which are so carefully made that drop-outs are practically non-existant.

Future Developments

Many of the things considered in the last section as "problems" give a clue to "future developments" when the problems are solved. For example, high outputs, narrower tracks, lower speeds, and better response are in the offing, not necessarily as spectacular sudden developments, but as evolution of present trends.

New heads now in the experimental stage, are made of magnetic ferrite materials. They can be used at very high frequencies, and are so hard that they are virtually wear-proof.

Binaural and stereophonic sound, which reach their highest state of perfection in magnetic recording, are logical adjuncts to three dimensional movies that have been introduced lately.

Video recording, with present standards, requires frequencies about 100 to 1000 times as high as the upper limit of conventional recorders. One system now being developed is a multiplexer that extends the response by using a number of parallel channels. Video recording on a tape 1/2 inch to 1 inch wide, running at 100 inches per second is promised.

Alternative methods for recording intelligence are frequency modulation, carrier currents, pulse width and pulse time modulation, etc. All of these have been uneconomical for audio use in view of the limited channel width available in magnetic recording. However, they are quite practical for instrumentation, and are widely used. Now that magnetic recorders with a channel width of 100 kc or more available, we can expect further uses for these newer forms of modulation.

Magnetic recording is also ideal for memory devices in computers and for business machines because of its rapid response, permanence, and erasibility. The field is developing so fast that it is difficult to keep track of all the new applications.

Motion picture film carrying a narrow

magnetic strip is now beginning to be used for the sound track on films ranging from the 35mm professional class to the 8 mm amateur.

As magnetic recording becomes more widespread, there is a demand for pre-recorded music, and for duplicating methods. Duplication by magnetic contact printing is a rapid and economical process.

Among the most recent developments are magnetic playback heads which respond to the magnetic flux of the recording, rather than to its rate of change. Such heads give faithful reproductions of waveforms at very slow speeds; in fact, the tape can be stopped at any part of a recorded cycle and the amplitude of that point can be read. They also give outputs in the order of volts, rather than millivolts, so that our ideas about amplification and equalization will have to be revised.

From all of these considerations we can conclude that magnetic recording is changing more rapidly than ever. We might compare its present state with that of vacuum tube art when the 201A tube was standard; and we can look forward to many new and interesting developments in the future.

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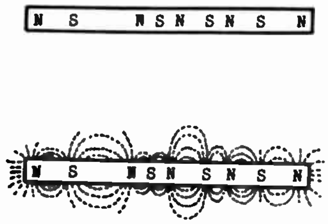


Fig. 1
Multi-polar bar magnet. A bar magnet can be magnetized so as to have multiple poles (top). Field patterns surrounding a multi-polar bar magnet (bottom).

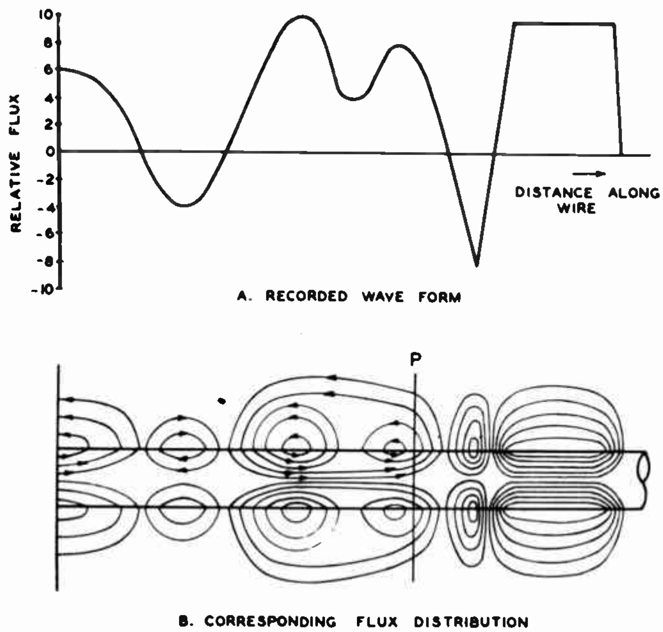


Fig. 2
Flux distribution around a wire record.

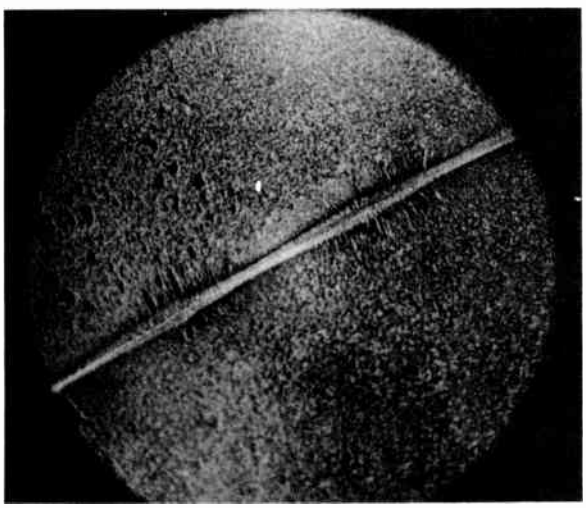


Fig. 3
Field patterns surrounding a magnetic recording wire. Wire .004 inches diameter. Recorded frequency 100 cycles. Iron dust suspended in mineral oil was used to form these patterns. (Taken by Mr. A. V. Appel, Armour Research Foundation).

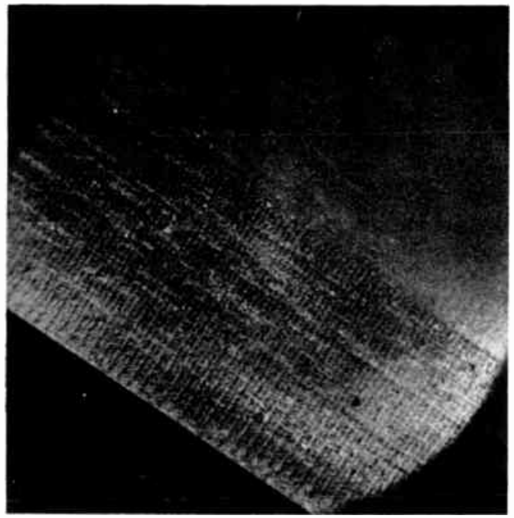


Fig. 4
Field patterns of a recorded tape.

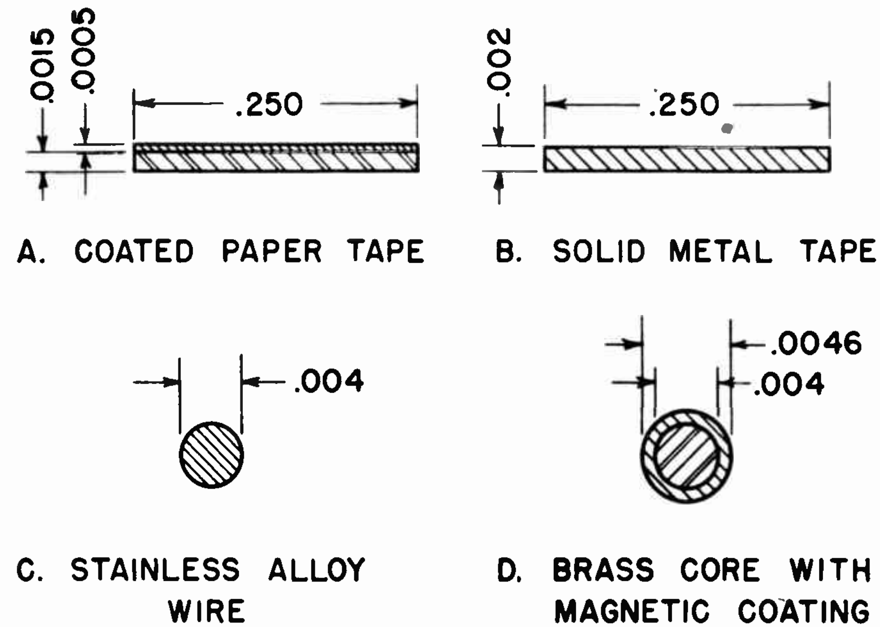


Fig. 6
Cross section of some magnetic recording media.

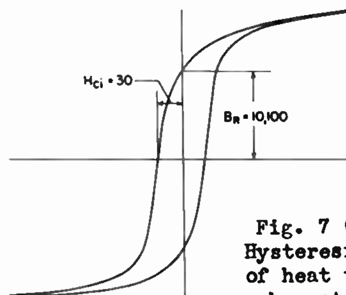


Fig. 7 (left)
Hysteresis loop of heat treated carbon steel tape.

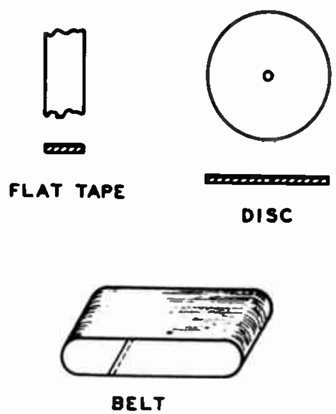


Fig. 5
Coated magnetic records.

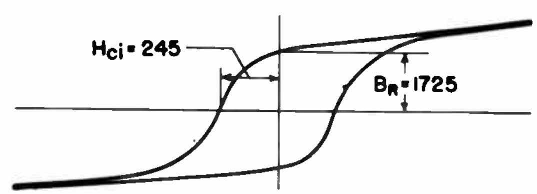


Fig. 8
Hysteresis loop of stainless alloy tape.

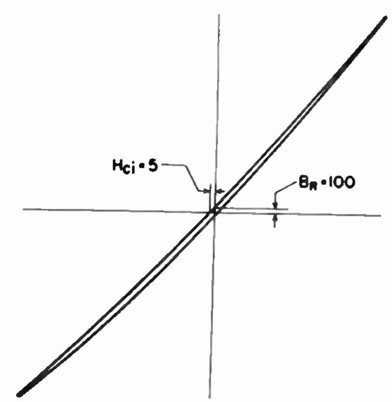


Fig. 9
Hysteresis loop of carbonyl iron coated tape.

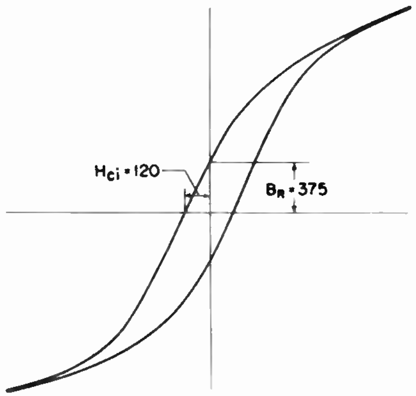


Fig. 10
Hysteresis loop
of magnetite coated tape.

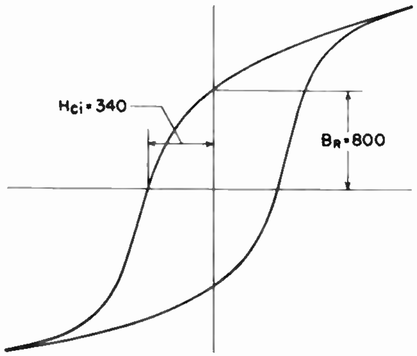


Fig. 11
Hysteresis loop
of 140A coated tape.

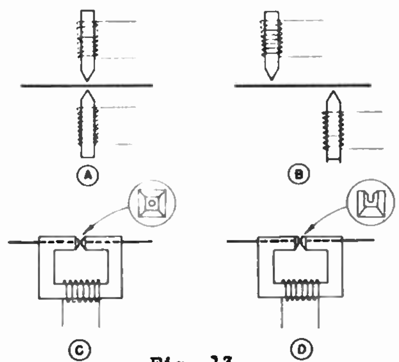


Fig. 13
Magnetic recording heads.

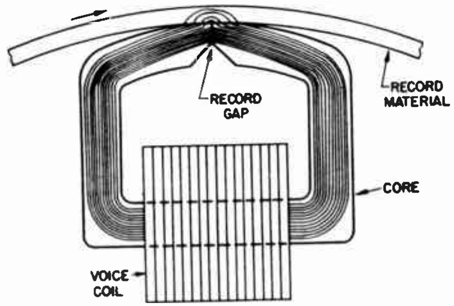


Fig. 14
Flux paths in a magnetic
head during recording.

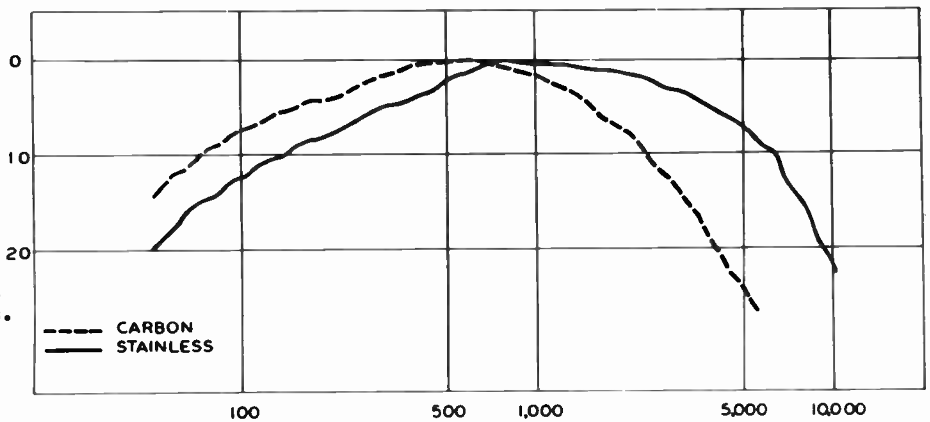
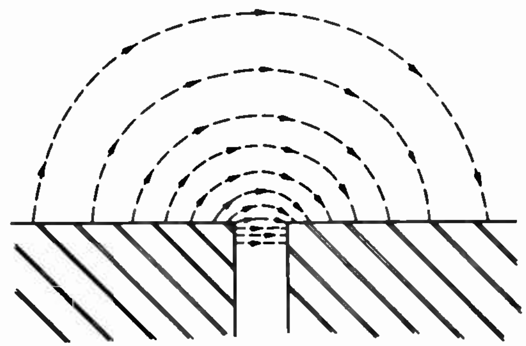
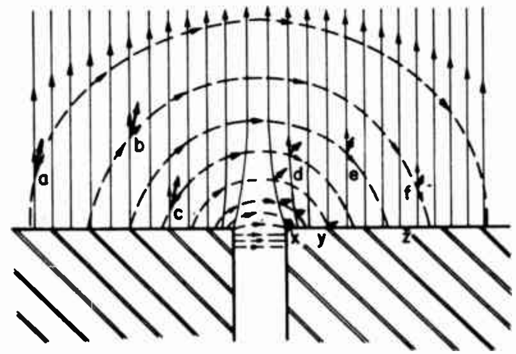


Fig. 12 (right)
Response of carbon steel
and stainless steel wires.



A. MAGNETIC FIELD PRODUCED BY GAP



B. SUPERPOSED CROSS FIELD ADDS VECTORIALLY
TO THE GAP FIELD

Fig. 15
Flux paths in an X-field head.

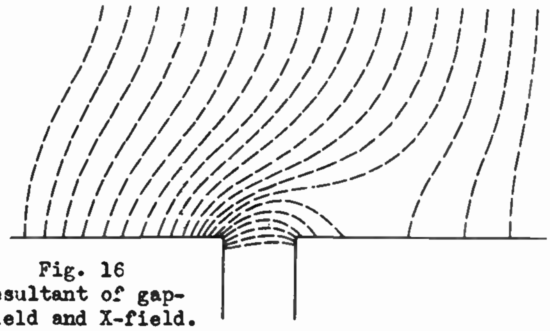


Fig. 16
Resultant of gap-field and X-field.

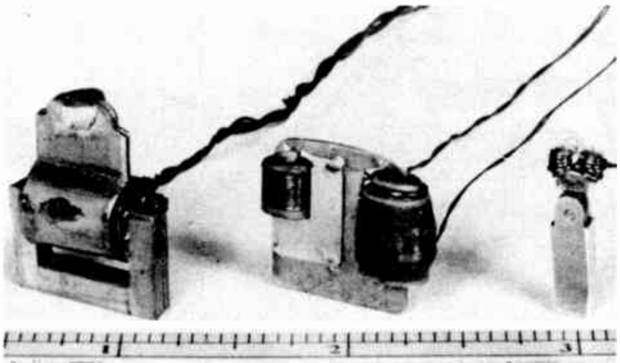


Fig. 17
Types of magnetic heads.

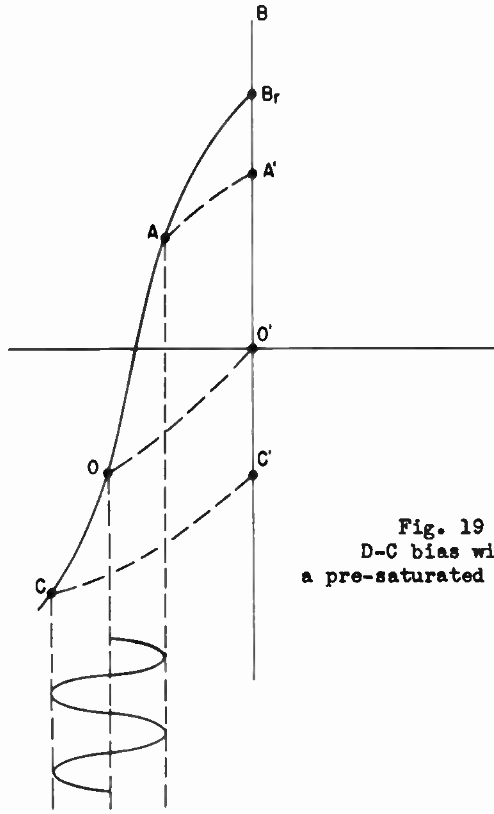


Fig. 19
D-C bias with a pre-saturated record.

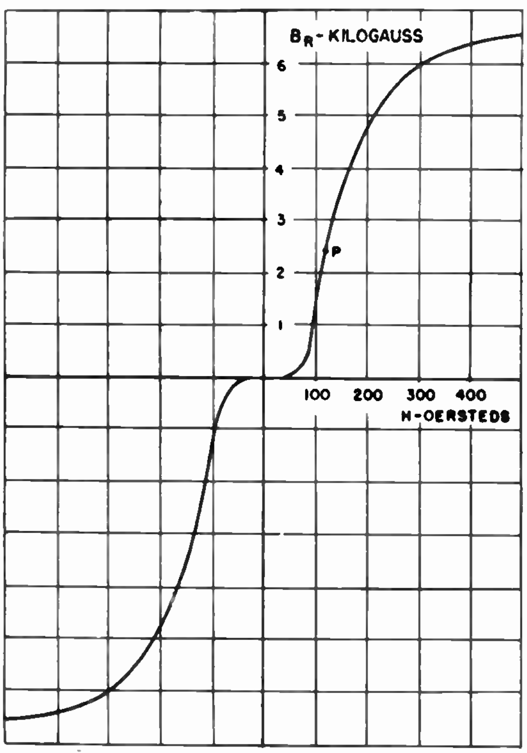


Fig. 18
Retained flux density vs. field for typical magnetic recording medium.

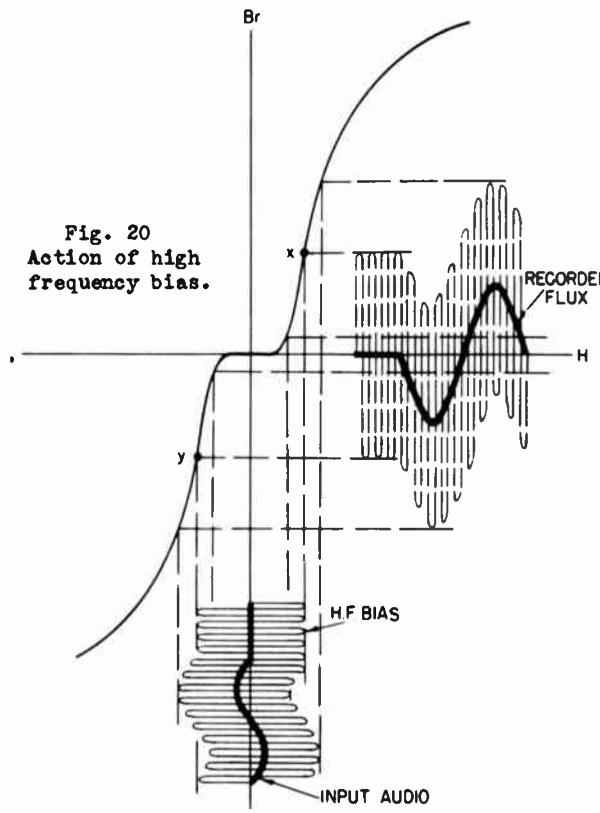


Fig. 20
Action of high frequency bias.

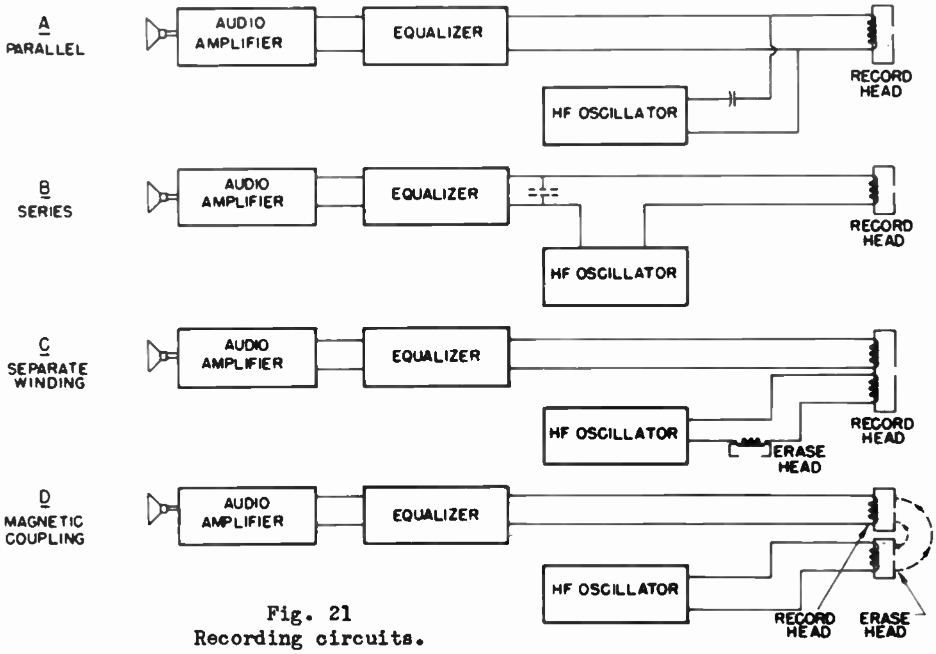


Fig. 21
Recording circuits.

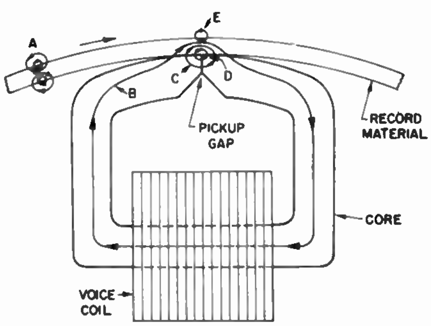


Fig. 22
Flux paths in a magnetic head on playback.

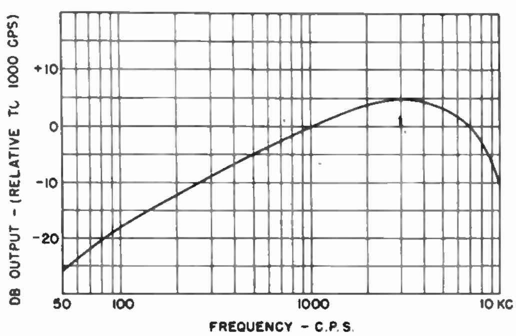


Fig. 23
Constant current response of 140A recording tape.

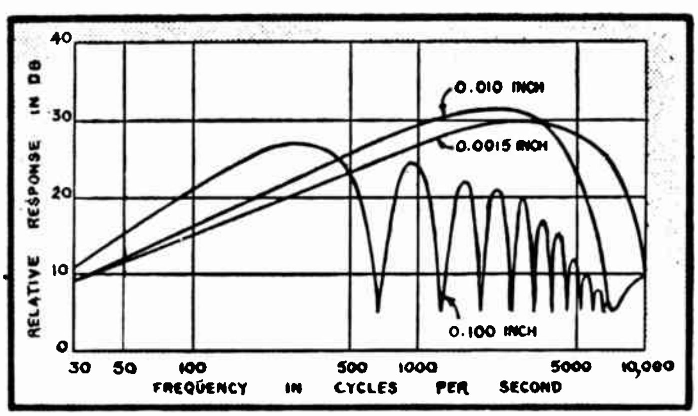


Fig. 24
Effect of gap length on frequency response (Holmes & Clark).

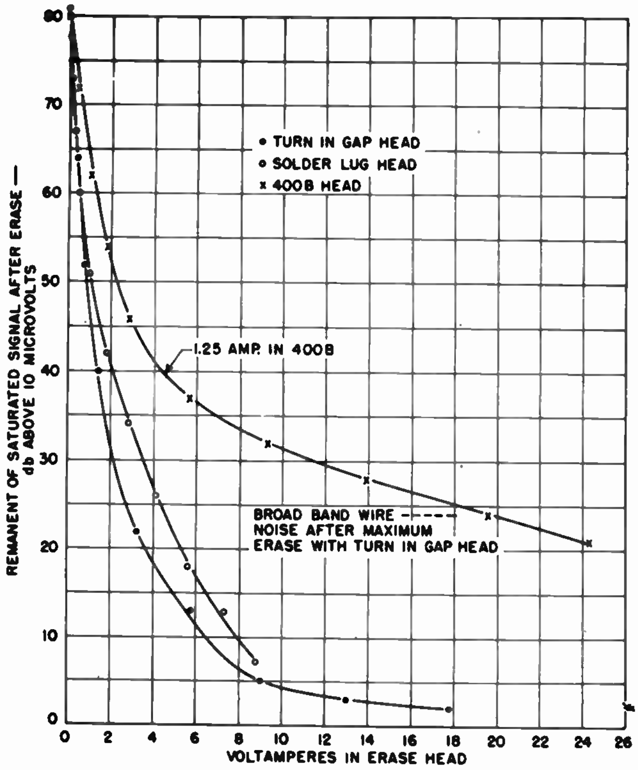


Fig. 25 (left)
Erase curves, basis of volt-ampere input to heads.

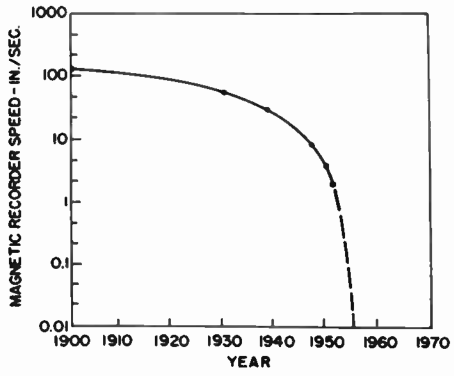


Fig. 26
Trend of typical magnetic recorder speeds.

STUDIO ACOUSTICS

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Neither the full paper nor the abstract was available at the time of publication.

SOUND SYSTEM FOR PLENARY HALL
OF
UNITED NATIONS GENERAL ASSEMBLY BUILDING

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SUMMARY

The sound reinforcing system for the Plenary Hall of the General Assembly Building of the United Nations, New York, was especially designed to function properly in the unusual style of architecture of that room. The principal design requirements were intelligibility, naturalness, concealment, and freedom from feedback when operated at required sound levels. Satisfactory speech intelligibility is obtained by faithful reproduction of the frequency range between 300 and 6000 cps, freedom from non-linear distortion, uniform coverage of the hall at all frequencies, and by a suitable employment of time delay systems. Design data and measured performance characteristics are presented in this paper.

1. Introduction

The Permanent Headquarters of the United Nations in New York comprise three main structural units - the Secretariat Building, the Conference Building, and the General Assembly Building. The Plenary Hall of the General Assembly Building, with a capacity of 1,500,000 cubic feet and a seating capacity of 2300, is the largest meeting area provided on the site.

The general considerations governing optimum acoustic performance in an enclosed space are well known. However, in the practical case architectural considerations are of prime importance, particularly in large structures of this kind. This frequently entails problems of special interest in obtaining optimum performance from the area concerned.

The Plenary Hall was designed with a view to provide the delegates with an area in which to meet which was not simply, in feeling, the front part of a large auditorium, but rather an integral entity visually and acoustically, with the public and press seating subsidiary to the main delegates area.

A number of basic acoustical problems were presented by this architectural plan: the circular dome, the conical front walls of the booths at the side of the delegates' area, the reflecting glass panels on the rear wall, the placement of the loudspeakers to meet the degree of concealment required.

2. Acoustics of the Hall

The principal design criteria to be met for the acoustics of the hall are three-fold. First, the reverberation time should be low enough so that successive syllables of speech are not masked by preceding syllables. Second, the noise background should be controlled so that there is no interference with the required speech level. Third, the placement of the loudspeakers should be such that the sound seems to come naturally from the person speaking.

The principles governing successful sound reinforcement influence both the choice of equipment and the acoustical design of the hall. It was shown in an earlier paper[1] that successful speech intelligibility is achieved if the spectrum level of the background noise is, on the average, more than 25 db below speech peak levels in the frequency range between 200 and 6000 cps. If this frequency range is divided into four parts of equal importance to speech intelligibility, the parts are 200 to 840, 840 to 1660, 1660 to 2820 and 2820 to 6100 cps.[2] Also, it was shown in Reference 1 that, if the loudspeaker system has a directivity index of between 5 and 10 db, the maximum reverberation time should be less than 1.5 seconds on the average throughout the above frequency range to avoid masking effects. The loudspeaker should be placed between 20 and 30 feet above the head of the speaker, with the principal axis of the horn pointed downward so as to keep as much sound off the sidewalls and ceiling as possible. Data published by Haas[3], and by Bolt and Doak[4] indicate that, if the subjective impression that the voice is reaching the listener from the direction of the speaker rather than from the loudspeakers of the sound reinforcing system is to be maintained, the arrival of the reinforced sound should be delayed by a short interval (5 - 35 milliseconds) either by a suitable location of the loudspeakers behind the speaker, or by the introduction of acoustic delay in the sound reinforcing chain.

3. Auditorium Design

The acoustical materials for the auditorium were chosen to produce a reverberation time of approximately 1.4 seconds in the vicinity of 500 cps. Above 500 cps the reverberation time decreases with increasing frequency as a result of air absorption. No particular attempt was made to maintain absorption at the very low frequencies as the purpose of the hall is primarily for parliamentary meetings, and for this use, speech frequencies below 300 cycles are deliberately attenuated in the audio system.

4. Reverberation Time

The measured reverberation time for the empty hall is shown in Figure 1. With normal occupancy the reverberation time throughout the speech frequency range will be considerably lower than shown.

An effort was made to reduce to a minimum the area of all surfaces that might produce echoes. This was achieved with the exception of part of the glass panel areas at the rear of the hall (Figure 2) where only partial heavy curtaining was possible owing to the presence of the entrance doors.

5. Noise Background

The measured ambient noise in the hall when empty is shown in Figure 3, and is due essentially to ventilation noise. Previous work[5] has indicated that if the noise levels are known in the three octave frequency bands, 600 to 1200, 1200 to 2400 and 2400 to 4800 cps, the effect of the noise in reducing speech intelligibility can be estimated. These three bands are a fair approximation to the upper three of the four equal-contribution bands given above. In estimating the effect, we define Speech Interference Level as the simple average of the noise levels in the three octave bands just named. The peaks of the speech sounds, as read on a sound level meter with an octave band analyzer, should, when calculated in the same manner as the speech interference level, lie 25 decibels above the speech interference level. In this hall, the Speech Interference Level is 32 db, which is considered satisfactory for a room of this type. This means, therefore, that to maintain the required margin of 25 db previously quoted between the reinforced speech level and the background noise, the average of the peak speech levels in these three frequency bands should be 57 db or higher.

6. Loudspeaker Design

The principal design criteria for the loudspeaker system are (1) uniform distribution of reinforced sound throughout the hall, (2) level of sound reinforcing to be within 65 - 70 db with a minimum margin against feedback of 6 db at this level, (3) substantially uniform frequency response between 300 and 6000 cps, (4) satisfactory concealment of loudspeakers.

The architectural design required that the main loudspeaker system be concealed in the rear wall above the podium. The loudspeaker vault can be seen from Figures 4, 6 and 7. It is located behind the United Nations emblem, Figure 8. The vault is approximately 20 feet behind and 15 feet above the microphones on the speaker's lectern. Other locations were considered for the loudspeakers in the hall that would provide greater freedom from acoustic feedback to the microphones, but were not deemed feasible for architectural reasons. An advantage of the present loudspeaker location is the desirable delay in arrival of the reinforced sound at the listener in relation to the direct sound. In order to prevent feedback of sound it was recognized that the main loudspeakers could not be tilted down steeply enough to provide reinforcement at the seats directly in front of the lectern. To cover these seats, an additional loudspeaker was placed in the lectern as shown in Figures 9 and 10.

In Figures 4 and 5, the region of influence of each of the loudspeaker groups is indicated by the shaded regions. Loudspeakers 1 and 2 supply the public and press areas at the rear of the hall and the rear part of the main floor area where the delegates are seated. Loudspeakers 3 and 4 supply the center part of the delegates' area. Loudspeaker 6 supplies the first rows of delegates seats in front of the lectern. The sound coverage from loudspeakers 1 and 2 overlap throughout the rear-center area of the hall, while coverage from loudspeakers 3 and 4 overlap throughout the front-center part of the hall. The region served by loudspeaker 6 is shown by the small fan-shaped area on the plan.

In addition to the main area so far discussed it will be seen from Figure 5 that seats are provided on either side of the main delegates' area. These seats, reserved for important guests, are under a balcony and are shielded from the radiation pattern of the main loudspeakers. It was necessary, therefore, to provide four ceiling loudspeakers on each side as shown by the double circles.

The loudspeaker units located in the front wall are of the multi-cellular type illustrated in Figures 6 and 7. One low frequency unit, No. 5, is provided for motion picture sound. The directivity pattern of the high frequency units, as estimated from data taken in free field conditions, is shown in Figure 11. It is seen by comparing the two curves that the loudspeakers are more directional at high frequencies in the plane involving two cells, while they are more directional at low frequencies in the plane involving four cells. It was anticipated that the principal difficulties from feedback in the hall would occur at high frequencies because of exposed wood and glass surfaces. Accordingly, the orientation of the speakers was so planned that a minimum of high frequency energy was radiated to the upper side walls by placing loudspeakers 1 and 2 as shown in Figure 7. By providing a shelf covered with sound absorbing material in front of the lower edge of the loudspeaker vault (Figure 6) and by placing the loudspeakers as far back in the vault as the required radiation pattern would permit, acoustic feedback to the microphones by direct path was minimized. The loudspeaker vault was also lined with sound absorbing material.

The ornamental shield mounting the United Nations emblem in front of the loudspeaker vault is constructed of metal and cloth of sufficiently open mesh to be substantially transparent to sound. Measurements up to a frequency of 6000 cps indicated no measurable attenuation.

7. Lectern Design

The lectern design is shown in Figures 9, 10 and 12. The three microphones move with the reading table, which is provided with a push-button raise and lower mechanism. In view of the proximity of the main loudspeaker vault behind the lectern, special care was exercised in the lectern design to avoid reflecting surfaces which, by forming standing wave patterns, could increase acoustic feedback. The absorbent lining is indicated in Figure 9.

Feedback from the loudspeaker due to mechanical vibration of the lectern is eliminated by a sound absorbing container and mounting as indicated.

8. Audio Input Equipment

In accordance with the general policy of decentralization of equipment for the numerous meeting areas in the building, the audio equipment for the Plenary Hall is located in one of the booths overlooking the hall. The control console and audio racks provide the technical facilities for sound re-inforcing, simultaneous interpretation, and feeds to the central master control.

A block diagram of the basic audio and sound reinforcing system is shown in Figure 13. In general, the system follows conventional design practice.

Particular consideration has been given to assuring uninterrupted operation of the audio chain in the circumstances that individual components fail.

The three microphones on the speaker's lectern are associated with separate preamplifiers and keys and, while the normal procedure is to use the two side microphones, the center microphone can be switched in if required. On the President's Table the individual microphones for each of the three officials are on desk stands which can be moved should a microphone fail.

The normal amplifier chain is backed up by a standby chain brought into the circuit by a key on the control console. As the sound reinforcing is provided through four channels and is not interrupted by the failure of a single amplifier, the normal procedure of a patching operation to insert a spare amplifier is used in this case. Spare amplifiers are, of course, provided in all cases, which are patched into the circuit to recover the standby facilities should an amplifier fail.

A limiting amplifier is incorporated as part of the main amplifier chain. The purpose of the limiter is essentially to restrict the input to the sound reinforcing system in view of the high reserve audio power capacity of the amplifier system (175 watts) - as, for example, when the Chairman's gavel is used. A compression of 3 db on occasional peaks is considered normal. Further, where it is desired to obtain the maximum margin between the operating point and the feedback point of such a system it is necessary to restrict limiting action. The margin to the feedback point is governed by the condition of maximum gain in the audio channel (i.e. without limiter action). The possible sound reinforcement level for a given protection against feedback is, therefore, reduced to the extent that limiter action reduces the gain of the audio channel.

The acoustic delay for the east and west wing speakers is given by the travel time of a magnetic tape band from the recording head to the reproducing head of a tape machine. The magnitude of the delay is adjusted by varying the tape speed. The delay unit is located in the circuit as shown in Figure 13.

The equalizer element provides the necessary correction in the overall frequency response from amplifier input to acoustic power output from the loudspeakers to maintain a substantially flat response up to 6000 cps. The Speech/Music filter in the Speech position provides the required attenuation in the system below 300 cycles. The filter is operated in the Music position, giving a substantially flat low frequency response, only in the eventuality that motion picture sound is required in the hall.

9. Adjustment of System

The desired orientation of the four high frequency horns in the main vault was first accurately established by replacing the driver units by a light source and lining up with an observer standing at the required point in the hall. The two horns that feed the delegates' area 3 and 4 are tilted in such a way as to provide nearly uniform coverage at all seats in the delegates' area except those near the speaker's lectern. Measurement of the sound level distribution showed an increase of approximately 6 db down the center aisle of the delegates' area due largely to an overlap of the coverage area from the two horns. A reduction of this level was accomplished by plugging two cells on each of loudspeakers 3 and 4 as shown in Figure 7. Satisfactory sound distribution was obtained from loudspeakers 1 and 2 in the press and public area. However, the upper two cells of each loudspeaker are plugged to prevent radiation of unnecessary high frequency energy into the dome as shown in Figure 7.

As finally established, the sound distribution pattern is uniform within ± 3 db over the delegates, press and public area of the hall. Under these conditions the power level in loudspeakers 1 and 2 feeding the back of the hall is 10 db higher than for loudspeakers 3 and 4.

10. Acoustic Delay System

With the two groups of four loudspeakers in the ceiling above the visitors' section (Figure 5) adjusted to provide adequate sound reinforcing for this special area, the initial tests showed serious echo effects in a zone extending along the side delegates' seats from front to back of the hall on each side, and noticeable back to the press area. In this zone the difference in time of arrival of the reinforced sound from the loudspeaker groups 7 and 8 and the sound from the main vault is in the region of 50 - 60 milliseconds. Subjective measurements have shown that echo effects are present when a second sound source exists with a time delay exceeding 35 milliseconds and an amplitude within 10 db of the original sound. These conditions are met in the zone concerned. Accordingly time delay was introduced in the audio channel feeding the wing loudspeakers (Figure 13).

By introducing a time delay of 65 milliseconds, somewhat greater than the previous time difference, not only was echo effect eliminated, but the apparent source of sound, which previously came from the side speakers for delegates sitting in the echo zone, shifted to the area of the speaker's lectern thus recovering the impression of naturalness. Under these time delay conditions, the auxiliary wing loudspeakers may be used to augment the main sound reinforcing energy up to 6 db in this zone without losing the desired apparent point of origin of the sound.

11. Microphone Arrangements

For the initial installation, small non-directional condenser microphones were used for the lectern and President's Table. The feedback point of the system with these non-directional microphones was found to be limited by reverberant sound pickup from the hall. This effect was aggravated as the area in which these microphones are located is to some degree the natural focus point of the hall resulting from the physical configuration (Figure 5). Experiments with microphones off the center line of the hall showed a reduction of feedback by 6 - 8 db.

The maximum improvement against reverberant sound pickup was given by using two cardioid pattern microphones on either side of the lectern with their principal axes facing each other. Although this orientation would result in loss of level if the speaker stepped far back from the lectern, a study of the directivity characteristic reveals that performance is highly satisfactory for normal talking positions. The center condenser microphone is provided as a standby, or is used as a separate sound pickup microphone independent of the normal audio channel. The use of the cardioid pattern microphone oriented as shown gives an improvement of 4 - 6 db against acoustic feedback. Under these operating conditions the acoustic feedback at the lectern microphones is determined approximately equally by reverberant sound pickup and direct pickup from the loudspeaker vault. The sound reinforcing level in the hall is normally maintained at approximately 68 db (sound level with "B" Network) with a margin of 6 db or greater against the singing point, depending upon the occupancy of the hall.

12. System-Frequency Response

The overall frequency response characteristic provided for the main sound reinforcing system is shown in Figure 14. This is measured from amplifier input to acoustic power output at the front of the press seating. Curve B relates to loudspeakers 3, 4 and 5 with the Speech/Music key in the Speech position. Curve C is the response of loudspeakers 1 and 2. The wing loudspeaker groups 7 and 8 are adjusted to a similar performance as the main system. The lectern loudspeaker 6 is compensated to give more rapid bass attenuation, as its purpose is to contribute only high frequency energy in the nearby area falling in the high frequency shadow of the main-vault loudspeakers.

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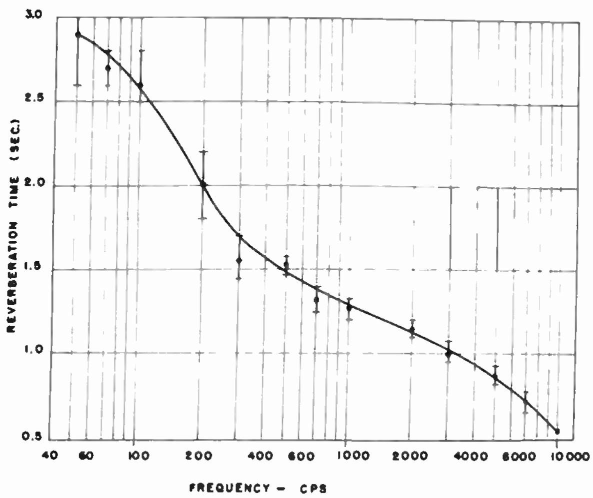

Fig. 1
Reverberation times measured in General Assembly Plenary Hall using warble-tones and graphic level recorder.

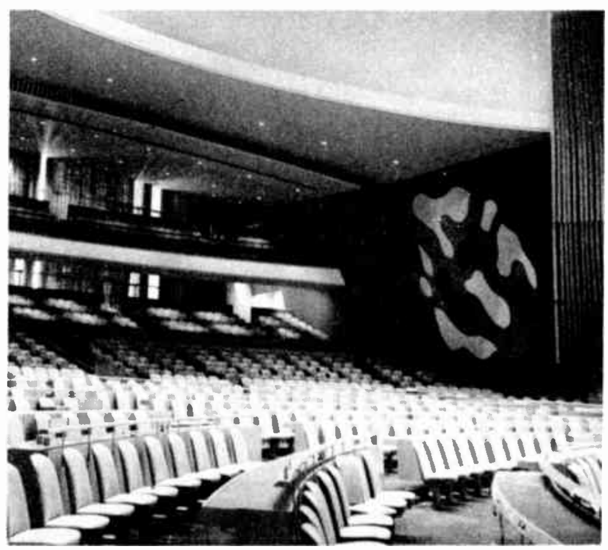

Fig. 2
View to the rear of the Plenary Hall. The nearby seats are in the delegates' area beneath the great dome. The intermediate seats are for representatives of the press. The distant seats and the balcony seats are for the public.

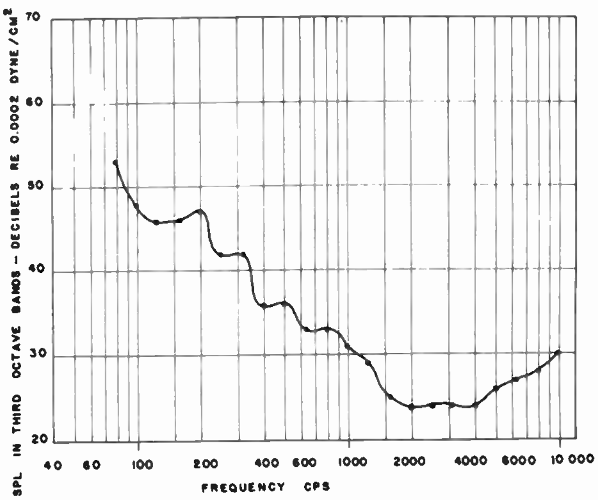

Fig. 3
Sound pressure levels of the ambient noise in the Plenary Hall measured in one-third octave bands. There was no audience, but the air-conditioning system was in full operation. The Speech Interference Level is about 32 decibels.

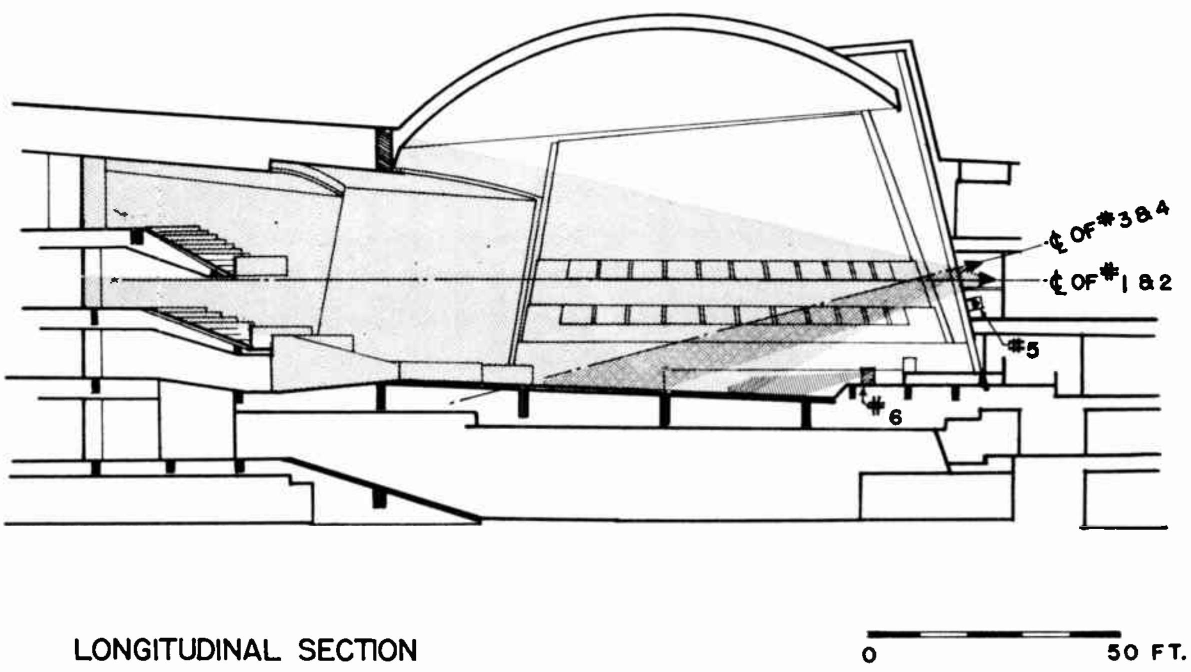

Fig. 4
Longitudinal section of the hall showing, by the shading, the regions served by the three principal groups of the main loudspeakers. Loudspeakers 1 and 2 serve the rear two-thirds of the hall. Loudspeakers 3 and 4 serve the front one-third of the hall, except for a few seats directly in front of the lectern that are served by loudspeaker 6.

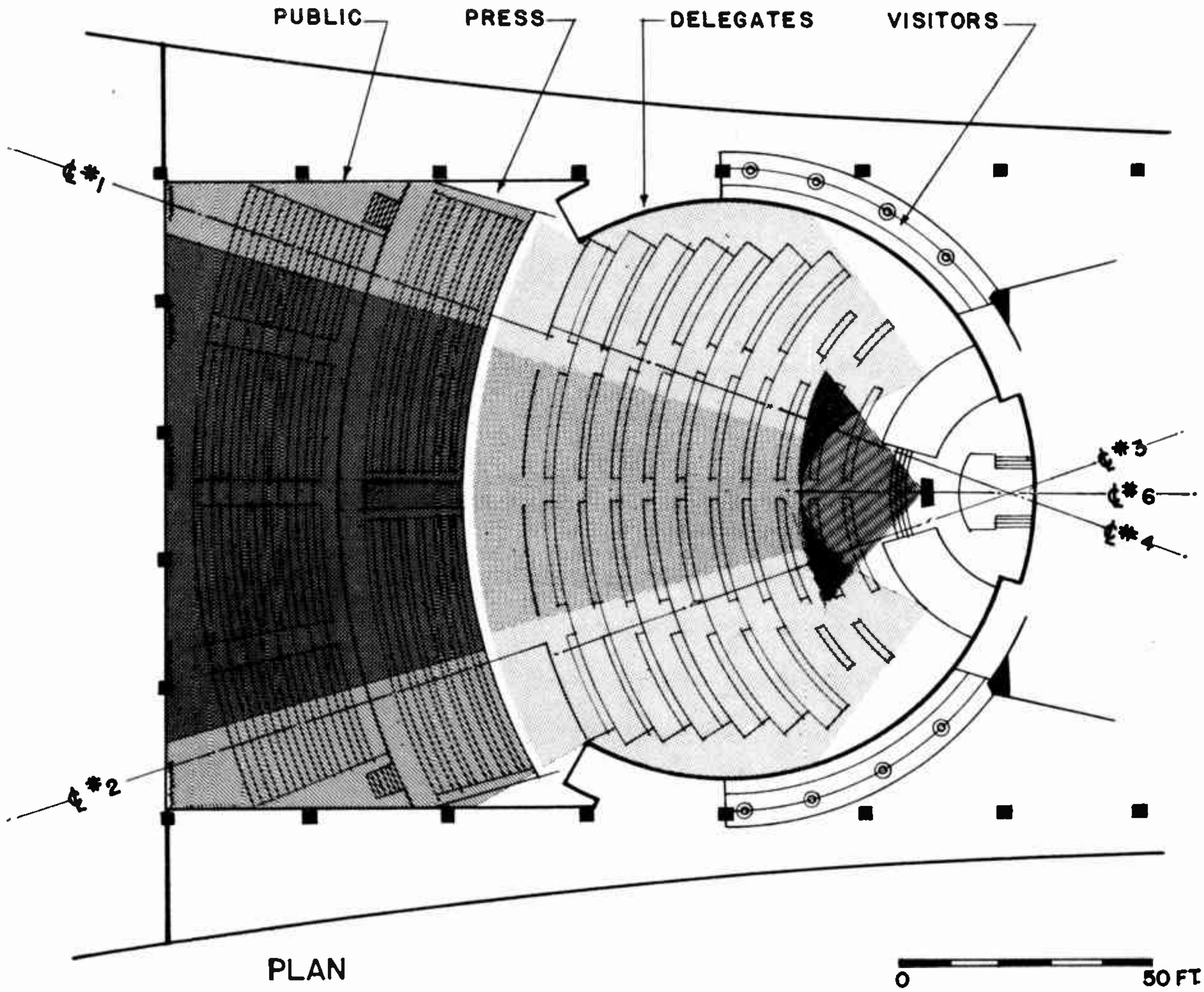

Fig. 5
Plan view of the hall showing, by the shading, the regions served by the various loudspeakers. The visitors' sections are served by eight low-level overhead loudspeakers indicated by the double circles.

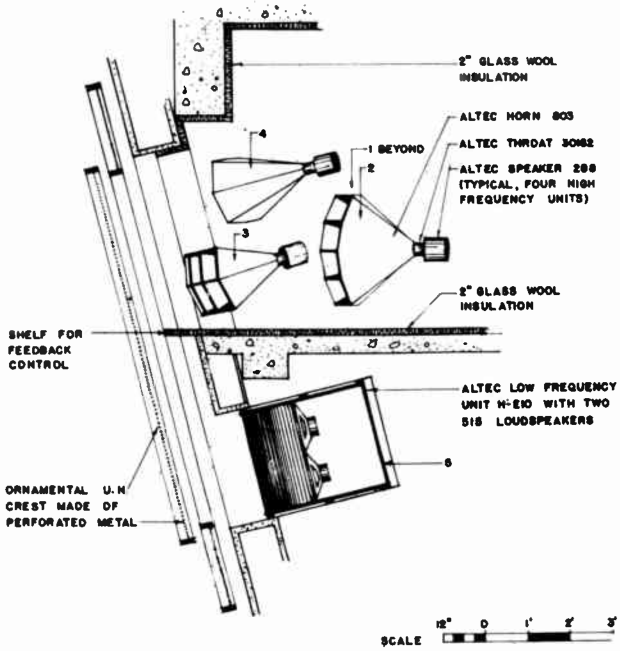

Fig. 6
Transverse section of the front-wall loudspeaker vault showing the location of loudspeakers 1 to 5.

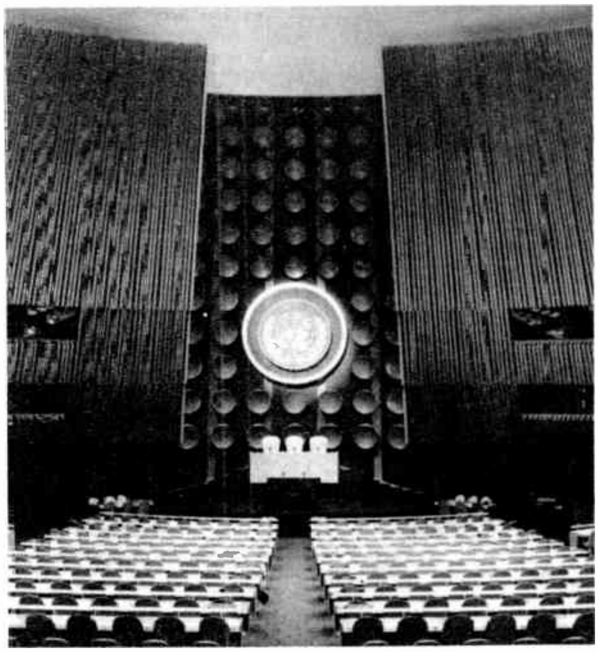

Fig. 8
View of the front of the hall. The loudspeakers are located behind the United Nations emblem.

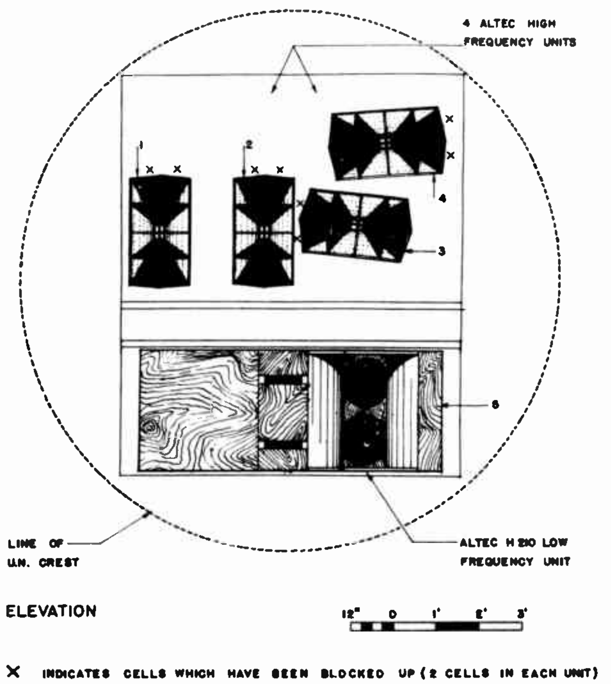

Fig. 7
Front elevation of the front-wall loudspeaker vault showing the location of loudspeakers 1 to 5.

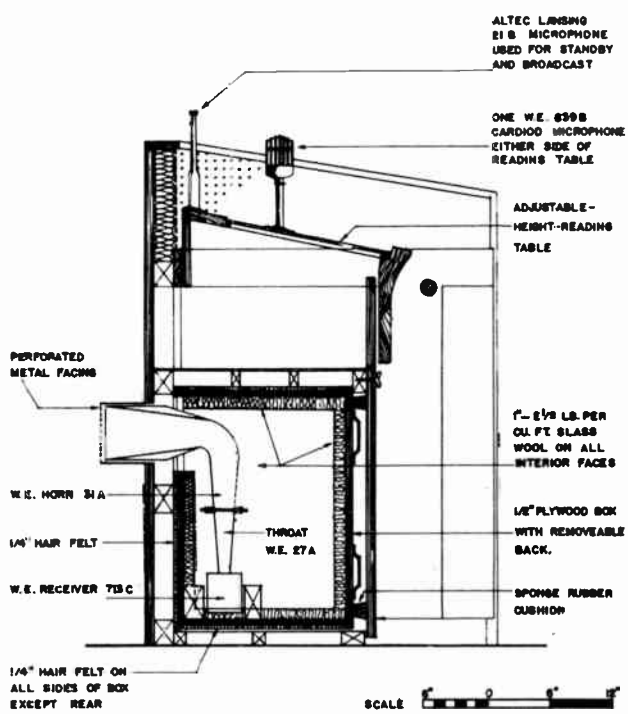

Fig. 9
Transverse section of the lectern showing the locations of the loudspeaker and the microphones.

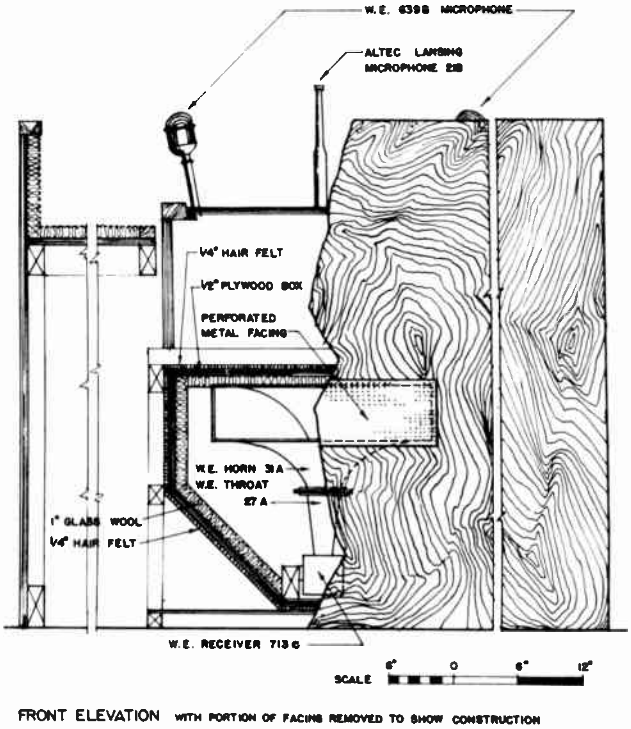

Fig. 10
Front elevation of the lectern. The W. E. 639-B microphones are at present vertical instead of slanted as shown.

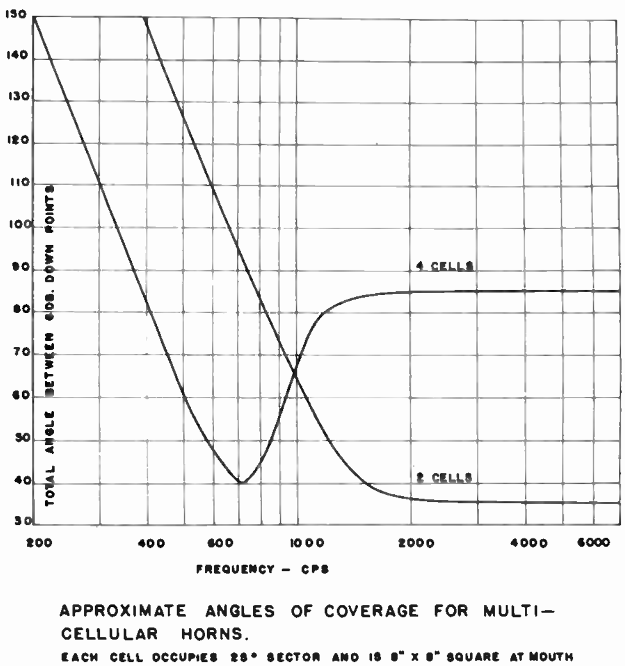

Fig. 11
Approximate widths of directivity pattern for 2 x 4 cell horns measured in the planes of the 4 cells and the 2 cells respectively.

Fig. 12
View showing arrangement of microphones on the speaker's lectern and the President's Table.

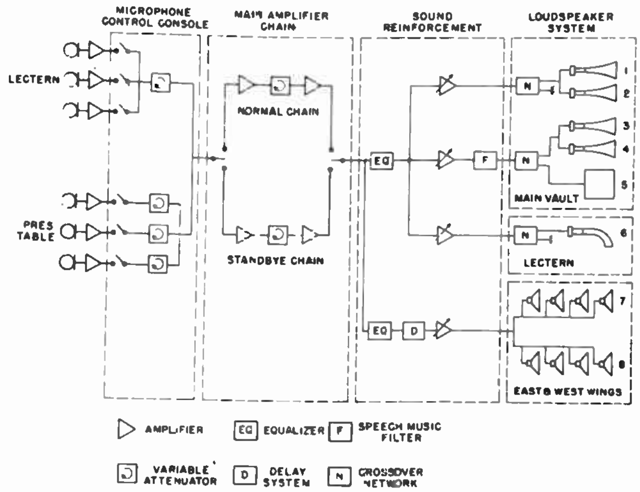

Fig. 13
Block diagram of the audio and sound reinforcing system.

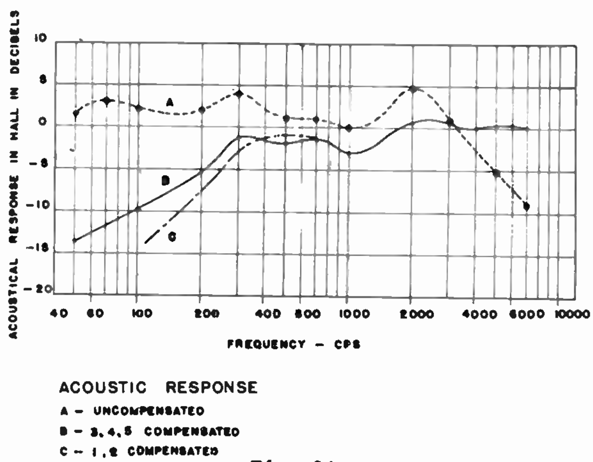

Fig. 14
Relative frequency response of the overall sound system with constant electrical power input to the main amplifier, measured at the rear of the delegates' seating area.

THE DEVELOPMENT OF A VARIABLE TIME DELAY

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INTRODUCTION

Applications

There are many applications in acoustics and allied fields for a variable time delay of the type described in this paper. Probably foremost among these applications is the use of a precision variable time delay as a component in analog electronic correlators for use in acoustical measurements. A time delay can also be used as an auxiliary to a sampling analog correlator to speed up the computation of correlation functions for large values of τ. The original work of Haas and Myer[1] and later work of Bolt and Doak[2] and Parkin[3] show that the use of time delays can help to preserve realism in speech reinforcement systems. The applications of time delays also include sound ranging, speech scrambling and producing artificial reverberation.

Methods of delaying audio frequency electrical signals might be listed in three general catagories: 1. purely electrical, 2. electro-acoustical, and 3. electro-mechanical. Real and artificial transmission lines make up the first catagory and are generally useful only for delays of less than a few microseconds. The transmission of sound between transducers separated by solid, liquid or gaseous media characterizes the electro-acoustical methods. These methods afford longer delays but their performance is frequently limited by the transducers, and the attenuation and frequency response are functions of the magnitude of the delay.

The development of magnetic recording during recent years has made possible the use of a magnetic material as the medium in the electro-mechanical type of delay. The magnetic material is commonly in the form of a continuous loop of recording tape or a disc or drum plated or coated with a magnetic material.

The system described in this paper is of the electro-mechanical type utilizing a drum coated with magnetic material as the moving medium. A drum was chosen instead of a loop of tape to avoid the dimensional instability of the tape.

The applications listed earlier require that the delay system have a uniform frequency response throughout most of the audio spectrum and that the relative time delay between its output signals be adjustable from zero to a few tenths of a second.

Outline of the System Employed

The processes of recording, reproducing and erasing employed in this system are similar to those of a conventional tape recorder. In the case of a drum, however, the length of a magnetic track is the drum's circumference, and with continuous erasing and recording any part of the signal remains recorded for less than the period of rotation of the drum. By the end of one period of rotation the signal has been recorded, reproduced and erased.

In order to obtain a relative time delay, τ, which can go through zero, the system uses two tracks around the periphery of the drum, and the operations of recording, reproducing and erasing go on simultaneously on both tracks. Figure 1 shows cross sections of the tracks and a block diagram of the remainder of the system. The input $f(t)$ is recorded on both tracks which rotate with the angular velocity ω of the drum. The outputs from channels 1 and 2 are $f(t - \alpha/\omega)$ and $f(t - \beta/\omega)$ where α and β represent the angular separations of the respective record and reproduce heads. If only relative delays are of interest, let $t' = t - \alpha/\omega$. Then the output of channel 1 becomes $f(t')$ and the output of channel 2 becomes $f(t' - \tau)$ where $\tau = (\beta - \alpha)/\omega$. If α and ω are held constant and β is varied from β_1 to β_2 by rotating either the record head or reproduce head of channel 2 around the periphery of the drum, τ will vary from $(\beta_1 - \alpha)/\omega$ to $(\beta_2 - \alpha)/\omega$.

It can be seen from the relations given above that the accuracy with which τ can be adjusted for a given mechanical accuracy of the system depends upon the magnitude of ω. In order to permit adjustments of short time delays without requiring unreasonable mechanical accuracy, a movement of one mil (0.001 inch) along the surface of the drum was made to represent a change in τ of 10 microseconds. This set the surface velocity at 100 inches per second. The diameter chosen for the drum was 8 inches, and therefore the angular velocity was required to be approximately 8 π radians per second.

The recording, reproducing and erasing heads were spaced from the surface of the drum to prevent wear. Spacing the heads from the surface of the drum also reduced the mechanical load on the drum drive to that of bearing friction alone, which made it possible to design a mechanical coupling system more effective in reducing fluctuations in the relative time delay.

THE MECHANICAL SYSTEM

The Drum and Magnetic Surface

Figure 2 shows the drum and its supports. The drum was made 6 inches wide to allow for the addition of other recording tracks in the future. The bearings were placed at one end so that the inside surface of the drum could also be used. A pair of precision, pre-loaded bearings were located directly under the left-hand edge of the drum proper. A single precision bearing was located at the extreme left-hand end of the assembly beside the flywheel, which, as will be explained later, is on a separate bearing. The entire drum was machined from 17 ST aluminum alloy, and the 8 inch diameter outer surface has a runout of less than ± 0.1 mil. This accuracy is required in order to reduce variation in the head-to-medium spacing and the attendant amplitude modulation of the output signals.

A coating of magnetic material consisting of a dispersion of iron oxide was sprayed onto the surface of the drum. The oxide coating has the advantage that it may be readily applied and removed without dismounting the drum.

The spraying process is similar to that used by the Harvard Computation Laboratory for coating drums used to store digital data by pulse recording. A small artist's spray gun was used to apply the coating. The ring supporting the heads was removed and the remainder of the drum assembly was placed on the table of a milling machine. The spray gun was clamped to the frame of the milling machine and was fed a very dilute dispersion on the iron oxide held in suspension by the constant stirring of a small electric motor. The drum was then rotated by its normal drive and moved back and forth in front of the spray gun by the power feed of the milling machine until the desired number of coats was obtained. A few coats of an adhesive were applied to the drum before and after the dispersion to seal the aluminum surface and protect the final surface.

Standard commercial dispersions of black iron oxide and red iron oxide were obtained. Each dispersion was tested by applying 40 coats to the drum resulting in layers approximately 0.4 mils thick. The data thus obtained indicates that although there is little difference in either the output versus frequency or the output versus bias characteristics for the two media, the black oxide, because of its higher coercivity, requires approximately twice as much erase power as the red oxide to decrease the recorded signal by a given number of decibels. Since the higher velocity of the medium and the spacing between erase head and medium make adequate erasing difficult, the lower coercivity of the red oxide was sufficient reason for its choice.

These coatings were sufficiently uniform to produce no measured change in the drum runout. It was found, however, that a larger signal-to-noise ratio was obtained by applying approximately the same thickness of coating in more layers. The coating now in use on the drum is approximately 0.5 mils thick and resulted from 225 passes under the spray gun.

The Mechanical Drive System

In order to eliminate fluctuations in τ, the velocity of the drum should be constant. Both belts and idler wheels were tried as coupling devices between the motor and the drum in an effort to reduce variations in the drum velocity. The idler wheel showed two distinct advantages over the belt. 1. The idler wheel can be operated so that increased load pulls it into tighter contact with the capstan and driven surface, thus making it partially self adjusting. 2. The idler wheel can be operated so that speed fluctuations introduced by its irregularities are of much high frequency than those introduced by a belt. These high frequency fluctuations are more highly attenuated by the low-pass, inertia controlled system. This smoothing or filtering action can be further enhanced by increasing the compliance of the drum-idler wheel coupling. The driving system shown in Fig. 2 and 3 is one way of increasing this compliance while also adding inertia to the system in the form of a flywheel. The flywheel runs on an independent bearing concentric with the drum and is rim driven by the idler wheel as shown in Fig. 3. The idler wheel is disengaged from the flywheel and capstan when the motor is turned off in order to prevent any plastic deformation that might result from prolonged contact. Figure 2 shows the spring coupling between the flywheel and the drum. The stop pins prevent excessive stretching of the springs as the drum is being accelerated to full speed.

Figure 4 shows an electrical circuit analogous to the mechanical driving system. Current is analogous to torque and voltage is analogous to angular velocity. The motor to idler wheel and idler wheel to flywheel speed-ratios have been used to refer all velocities, torques and component values to the drum side of the system.

The sychronous drive motor shown in Fig. 3 is of the hysteresis type and has an almost constant torque characteristic during starting. This enables it to accelerate the system to sychronous speed without stalling or causing excessive slipping of the idler wheel. After the system reaches the steady state the motor can be considered as the constant velocity source ω_o shown in Fig. 4.

The fluctuations in speed caused by irregularities in the idler wheel are represented by the velocity source $\omega_1(t)$. The rotational compliance K_1^{-1} and rotational resistance B_1 represent the compliance of the idler wheel and motor suspension and the slippage of the idler wheel; B_f and J_f represent the viscous bearing friction and moment of inertia of the flywheel, the rotational compliance K_c^{-1} represents the coupling springs between the flywheel and the drum, and J_d represents the moment of inertia of the drum. The drum bearings are pre-loaded to such a pressure that their behavior is more nearly that of rolling friction than that of viscous friction. τ_d in Fig. 4 is a torque, constant in magnitude and always opposing the motion so as to represent the rolling friction of the drum bearings. B_d represents the viscous bearing friction. The complex, natural angular frequencies of the analog circuit of Fig. 4 are approximately $-2 \pm j0$ and $-0.22 \pm j7.5$. These values indicate an underdamped resonance of frequency 1.2 cps with a decay time of 4.5 seconds.

The period of rotation of the idler wheel is approximately 1/14 second and thus the lowest frequency component of $\omega_1(t)$ is approximately 14 cps. To evaluate the usefulness of placing the compliant coupling K_c^{-1} between the flywheel and the drum, the ratio of the ac component of the drum velocity ω_d to ω_1 was calculated for both the normal coupling springs and for rigid coupling between the drum and flywheel ($K_c^{-1} \longrightarrow 0$). These calculations show that the compliant coupling gives a 43 db reduction in the 14 cps component of ω_d as compared to rigid coupling.

Variations in the velocity of the drum such as those just discussed have two effects upon the operation of the system:

1. The frequencies of the reproduced signals are modulated.

2. The magnitude of the relative time delay is modulated.

The first effect is a function only of the ratio of the instantaneous velocity of the drum as a given point passes under a recording head to the velocity when it passes under the reproducing head of the same channel. The magnitude of this frequency modulation is given directly by data such as that shown in Fig. 5 which is a plot of the instantaneous frequency of the reproduced signal versus time for a 4 kc input signal.* These curves show the effectiveness of adding the coupling springs. The conditions for both curves were the same except that for curve (a) the flywheel was rigidly coupled to the drum and for curve (b) the normal coupling was employed. The predominant component remaining in Fig. 5(b) is a 4 cps fluctuation corresponding to the period of rotation of the drum.

The modulation in τ is dependent upon the variations in drum velocity between the time the signal is reproduced from channel 1 and the time it is reproduced from channel 2. Figure 6 is a plot of the phase angle between the two outputs of the system for a relative delay of 100 milliseconds and a frequency of 1 kcps, and thus gives a measure of the modulation of τ. Curve 6(b) shows that by operating the drum drive motor from a steady source of 60 cps, the variations in τ are reduced to $\pm$ 0.02 per cent. This remaining fluctuation is composed of random variations plus 4 cps and 1.2 cps components. The random variations are caused by changes in idler wheel slippage (changes in B_1 of Fig. 4). The 4 cps and 1.2 cps components correspond respectively to the frequency of rotation of the drum

* The frequency deviations shown in Fig. 5 were measured by the axis-crossing internal meter (ACIM) developed in the M.I.T. Acoustics Laboratory and described in the Acoustics Laboratory Quarterly Progress Report for July-September, 1951, pp. 32-34.

and the underdamped natural frequency of the mechanical filter.

Figure 1 shows that the record head of channel 2 was chosen as the head to be moved around the periphery of the drum to vary the magnitude of the time delay. This choice was made because the mechanism for rotating the head causes small variations in its spacing from the medium, and, as will be shown, the performance of the recording process can be made almost independent of small variations in head to medium spacing.

The mechanism for rotating the head around the drum is shown in Fig. 2. The gearing is such that the mechanical revolution counter indicates τ directly in milliseconds.

THE RECORDING, REPRODUCING AND ERASING SYSTEM

Choice and Mounting of Heads

The heads used for the operations of recording, reproducing and erasing are all modified versions of a half-track erase head. These heads are 0.125 inches wide and originally had front and back gaps of approximately 5 mils. The surfaces along the pole pieces where the tape would normally run were ground flat for about 50 mils on either side of the gap. This permits a more uniform area of relative contact with the magnetic medium and assures that these surfaces are exactly perpendicular to the side of the head used for mounting. The heads were mounted around the periphery of the drum from a ring support as shown in Fig. 2. A fine-thread set-screw and spring are used to permit adjustment of the head to drum spacing. The heads have been operated with spacings of approximately 1 mil for several months without requiring adjustment.

The Recording Process

In order to investigate the effect upon the recording process of spacing between the record head and the magnetic material, data for Fig. 7 were taken on a red oxide coating. The wavelength, λ, of the recorded signal is given by $\lambda = v/f$ and is in mils if v, the velocity of the medium, is in inches per second, and f, the recorded frequency, is in kcps. For wavelengths long compared to ℓ, the width of the gap, and d, the spacing, the principal effect of the spacing is causing a flux division between the paths ℓ and ℓ' of Fig. 7. For this approximation the division is dependent primarily upon the reluctance of the two paths, and the magnitude of the flux going through the record medium (path ℓ') is a function of the ratio of d to ℓ.

Variations in the record head to medium spacing cause corresponding changes in both the signal and bias intensities in the medium. In order to separate the effects of the changes in bias and signal fields, data for the dashed curves of Fig.7 were taken with the bias readjusted for maximum output for each value of spacing. It can be seen that the effect of increasing the spacing is the same on the 100 and 1000 cps signals (λ = 0.1 and 0.01 inches respectively).

For shorter wavelengths, this simple approximation must be revised to include the effect of broadening the magnetic field with increasing spacing. The graphical analysis of the field of the recording head given by Begun[4] is applicable to this refinement. While Dr. Begun's analysis was made for the flux distribution within powdered iron oxide in contact with the record head, it would not be appreciably different for air since the permeability of the iron oxide was only 3. This analysis shows that the field is much less sharply defined even at a relatively short distance from the record head. Dr. Begun then shows by a graphical analysis of the recording process employing ac bias that this broadening of the field causes a loss in high frequency response and thus in the present case a departure from the frequency independence discussed earlier. In the broken curves of Fig. 7, this effect is illustrated by the fact that the curve for 10 kc (λ = 10 mils) has a steeper slope than the curves for 100 and 1000 cps.

It should be noted as stated before that the reduction in the signal field illustrated by the broken curves of Fig. 7 is only a part of the total effect of spacing upon the recording process. For a constant bias mmf applied to the record gap, the bias field as well as the signal field in the magnetic medium decreases as the spacing increases. The effect of an ac bias upon the recording process is covered from several points of view in the literature.[5,6,7] In general, the process of linearly superimposing the signal amplitude makes it possible to obtain a remanent induction in the magnetic material that is very nearly proportional to the instantaneous intensity of the signal field at the trailing edge of the record-head gap. As a compromise between high output and low distortion it is frequently recommended that the bias be adjusted to a value 20 to 30 per cent greater than the value yielding maximum output for medium wavelengths.[8] Since the output versus bias-mmf curves have a negative slope in this region, the decrease in bias intensity in the recording medium caused by an increase in the record head to medium spacing tends to produce an increase in output. The solid curves of Fig. 7, taken for a fixed bias level at the record head, show this effect tends to cancel the effect owing to division of flux discussed earlier giving approximately zero slope for values of spacing in the vicinity of 1 mil.

When the zero-slope spacing is used, this method appears to give the same freedom from signal amplitude fluctuations owing to variations in record head-to-medium spacing that would be given by boundary-displacement recording[9] without the necessity for maintaining a saturated medium with the accompanying high noise level.

The Reproducing Process

A sinusoidal signal recorded in a longitudinal manner on a magnetic material can be thought of as a series of half wave-length magnets end to end along the direction of motion as shown in Fig. 8. As stated before, the recorded wavelength is given by $\lambda = v/f$. Thus, as the frequency increases, in the length of these half-wavelength magnets decreases and their field decays more rapidly with distance from the surface. The head-to-medium spacing for the reproducing process is therefore more effectively expressed in terms of wavelengths (d/λ in Fig. 8).

The curve shown in Fig. 8 agrees quite well with theoretical and experimental values given in the literature.[11, 12] It has an almost constant slope of -56 db per unit of d/λ, or ($56\ f/v$) db/mil of spacing in the units used above. It can thus be seen that the amplitude modulations of the signal produced by variations in the reproduce head-to-medium spacing will increase directly with frequency. For the drum run-out of approximately $\pm$ 0.1 mils, v = 100 inches per second as given before, and f = 10 kcps, the amplitude modulations of the signal owing to the reproducing process would be approximately $\pm$ 0.5 db. If the bias and record head to medium spacing are adjusted for cancellation of the amplitude modulation in the recording process, the total amplitude modulation of a 10 kcps signal is $\pm$ 0.5 db. This is illustrated in Fig. 9 which shows the overall frequency response of the system. The amplitude modulations appear to begin suddenly at 8 kcps because the graphic level recorder used to plot the curve could not respond to changes of less than 0.5 db.

The length of relative contact between the reproduce heads and the medium is approximately 0.1 inch. Thus, below about 200 cps (λ = 0.5 inch) only the leakage flux from the magnetized medium passes through the reproduce head and the unequalized response changes from a 6 db per octave to a 12 db per octave slope.[13] The low frequency limit of the system was set at 100 cps because the post-emphasis necessary to equalize the response for lower frequencies would cause a prohibative increase in the hum and noise level.

Many of the factors that affect the amplitude-frequency response of the system produce no corresponding phase-frequency characteristic. Thus, when the overall amplitude response is equalized by a minimum phase network the phase-frequency characteristic is not flat. This phenomena is characteristic of magnetic recorders utilizing the high frequency region of their response and restricts the application of the system to operations not requiring waveform preservation. This is not detrimental to the performance of the delay as a component of a correlator because in this application only the relative phase shift between the two channels is of importance. Departure of this relative phase shift from that of a pure time delay can be minimized by careful circuit symmetry in the two channels.

The Erasing Process

The front gaps of the erase heads were increased to 23 mils in order to obtain a sufficiently broad spatial field distribution to give adequate erasing action. The same source of 40 kcps ac was used for both bias and erase to eliminate the possibility of audio frequency beats between the two.

The Electronic Circuits

The electronic circuits are quite conventional with several high-Q traps inserted at strategic points to reduce the 40 kc signal resulting from erase and bias leakage to approximately the level of the hum and noise. A meter switch makes it possible to monitor the recording level, playback levels of both channels, the bias level and the B+ supply voltage.

Summary of Performance Characteristics

The mechanical filter in the driving system makes it possible to hold the peaks of the fluctuations in τ to approximately 0.02 per cent of τ or less for all values of τ. The rejection of the flutter components due to irregularities in the idler wheel is so high that the performance is relatively independent of the condition of the idler wheel.

The relative time delay between channels 1 and 2 is continuously variable from -15 milliseconds to 190 milliseconds. The mechanical revolution counter shown in Fig. 2 indicates the value of τ directly in tenths of a millisecond. As mentioned before, variations in line frequency cause a drift of approximately $\pm$ 0.1 per cent in τ. The overall fluctuation in τ can be reduced to approximately $\pm$ 0.02 per cent by using a more stable 60 cps source. The factors mentioned above, together with inaccuracies in the gears used to rotate the record head, limit the calibration of the revolution counter in absolute values of τ to approximately $\pm$ 0.2 per cent.

The overall frequency response of the system is shown in Fig. 9. It is within $\pm$ 2 db from 100 cps to 10 kcps and drops rapidly below 70 cps. Noises owing to nonuniformity of the magnetic material, hum pickup in the reproduce heads, circuit noise and bias leakage are all at about the same level. The total noise measured with a Ballantine 300 VTVM is 45 db below the reproduced signal corresponding to the recording level causing overall system distortion of 3 per cent at 400 cps. The relative phase shift between channels for zero τ is less than 1° for frequencies from 500 cps to 5 kcps, and gradually increases to approximately 4° at 100 cps and 10 kcps.

Applications of the System

The performance characteristics of this system appear to be satisfactory for a wide range of laboratory applications. This system has been used in conjunction with a sampling analog correlator to compute the autocorrelation functions of various types of music, and to compute the crosscorrelation function between stimulus and brain waves. It has also been used briefly in psychoacoustical studies. Upon completion of the remaining components of an analog correlator it is hoped that this time delay system can be used in applying correlation techniques to some of the problems of room acoustics.

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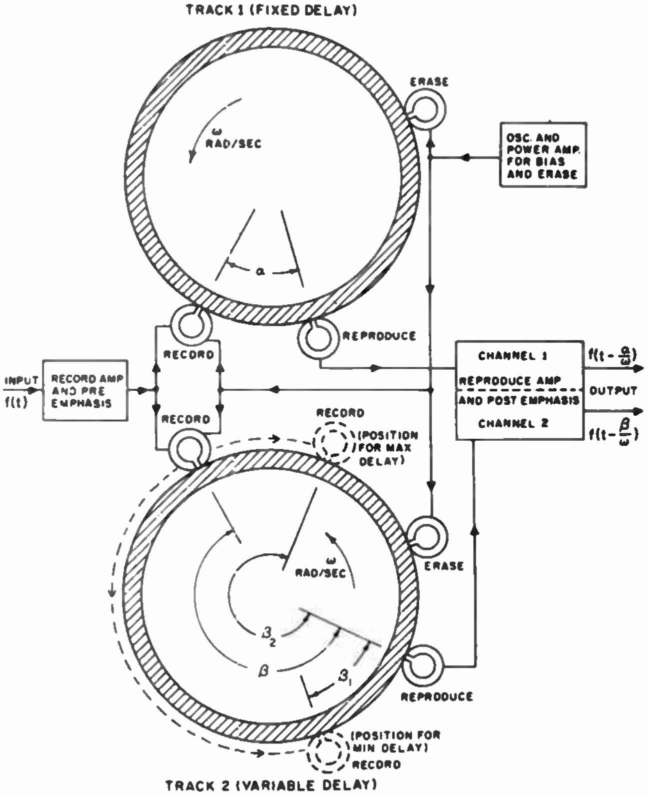

Fig. 1
Block diagram of the system.

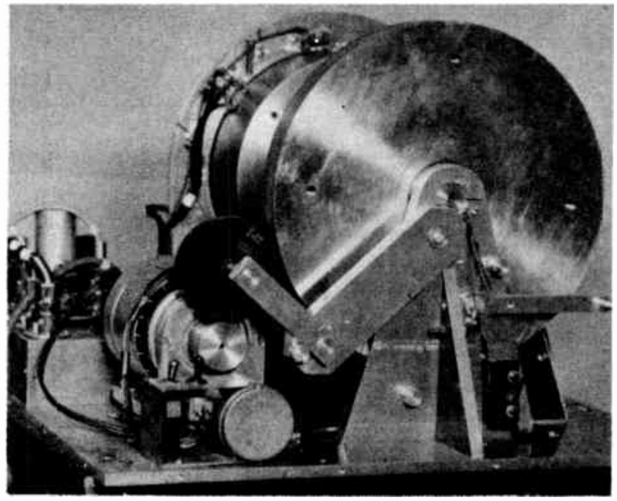

Fig. 3

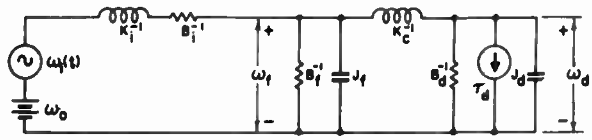

Fig. 4
Analogous electrical circuit of the mechanical driving system.

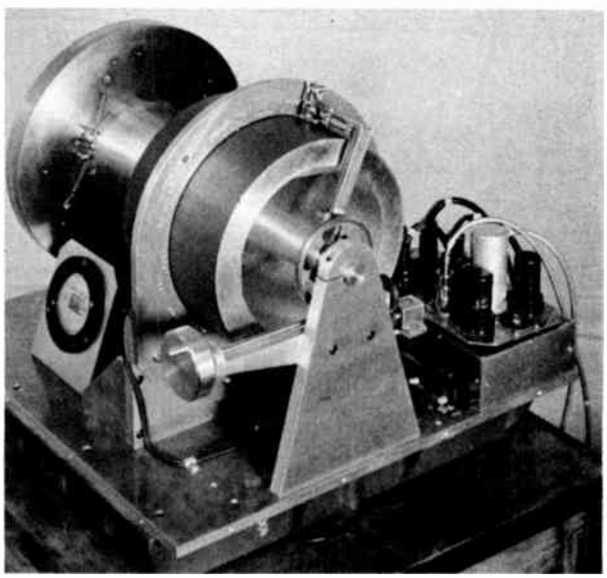

Fig. 2

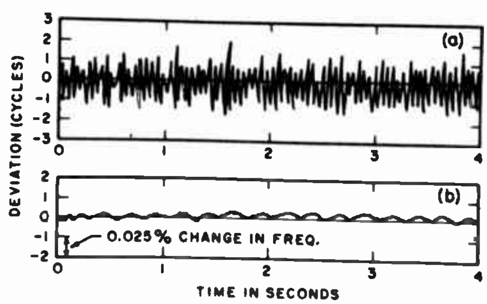

Fig. 5
Frequency modulation of the output for 4 kc input signal: (a) rigid coupling and (b) normal compliant coupling between flywheel and drum.

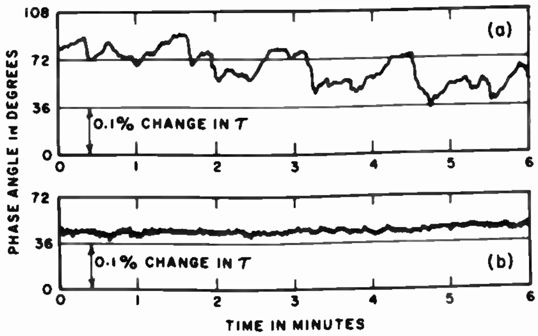

Fig. 6
Modulation of the relative time delay, τ: (a) 60 cps power line and (b) constant 60 cps source used to operate drive motor.

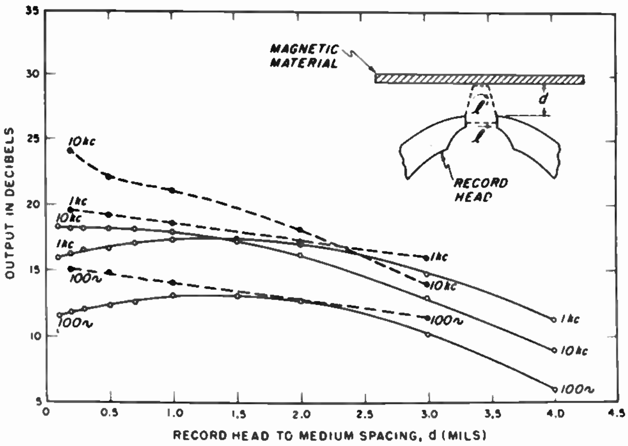

Fig. 7
Output versus spacing of the recording head. Bias set at one value for solid curves. Bias adjusted for maximum output at each value of spacing for broken curves.

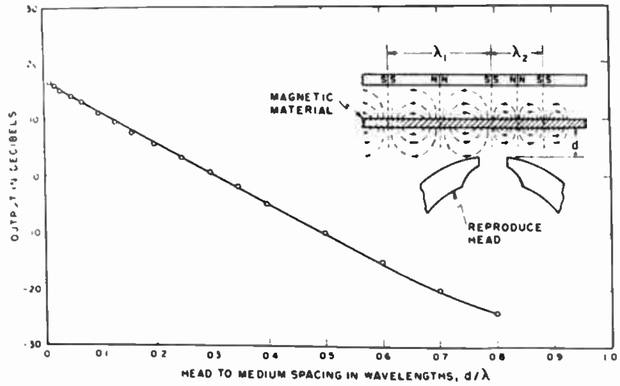

Fig. 8
Output versus spacing of the reproducing head in wavelengths. Insert is a cross-section of the reproduce head together with flux distribution in magnetic material on which two frequencies have been longitudinally recorded.[10]

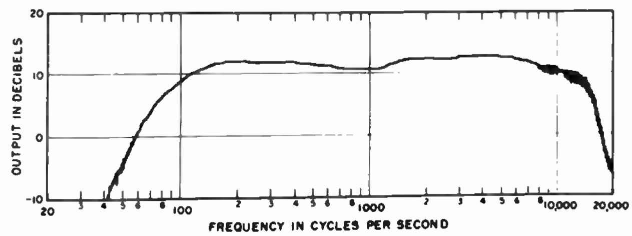

Fig. 9
Overall frequency response of the system.

A FLUX-SENSITIVE HEAD FOR MAGNETIC RECORDING PLAYBACK

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ABSTRACT

A playback head of special construction provides signals proportional to the flux from the recording medium, rather than its time derivative. Power from a high-frequency oscillator is applied to the head. The output signal appears across a separate winding and is in the form of a modulated carrier, the carrier frequency being twice that of the oscillator. Its inherently flat response extending to dc at the low-frequency end makes the head useful in many instrumentation applications, particularly in cases where wave-forms must be preserved, or when a recording is studied in detail by playing back the record at greatly reduced speed. Full signal levels are preserved when the speed of the recording medium is reduced. In fact, the recording can be examined point by point by taking readings with the medium stationary. Signal levels are unusually high. This fact, and the elimination of the usual low-frequency equalization makes the new head appear attractive in sound recording. A simple adaptor for playback of magnetic recordings through a standard broadcast receiver requires, in addition to the drive mechanism, only a small oscillator feeding the head and a small transmitting-loop antenna fed by the signal winding of the head.

UNIAXIAL MICROPHONE

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ABSTRACT

A small unidirectional microphone has been developed with the following features: maximum sensitivity along the axis of the microphone, a high ratio of electrical output to size, a sharper directivity pattern than a cardioid, a directivity pattern that is independent of the frequency and a blast-proof vibrating system. The high discrimination which this microphone exhibits to sounds which originate from the sides and rear makes it particularly suitable for long-distance-sound pick-up in radio, television, sound-motion pictures and sound-reinforcing systems.

APPLICATIONS OF HIGH INTENSITY MICROPHONES

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Last year at this meeting a miniature condenser microphone system was described, which had a range of sound pressure levels up to 220 db. These microphones are now being used in many different applications and these uses will now be discussed.

Jet Noise Levels

The manufacture, testing and use of turbo jet and ram jet engines have created many problems in connection with the intense noise produced by the operation. The present day turbo jet engine burns approximately 5,000 to 8,000 pounds of fuel per hour. The acoustic power increase is approximately proportional to the fourth power of the fuel consumption, and this corresponds to approximately 70 KW at its highest speed. The S. P. L. (sound pressure level) is approximately 160 db at a distance of 1 nozzle diameter from the engine.

The sound pressure level developed by an engine is a precise value depending upon the fuel consumption, and measurements on a number of engine cells have shown that the sound output is within a few tenths of a decibel when the fuel is correctly metered.

There are three noise level situations which cause concern with operation of jets:

1. A short full power check before taking off.
2. Adjustments in plane after installations.
3. Finally, what is probably the most potent source of inference, factory testing of jet engines.

At the present time objections come principally from adjustments in the plane and factory testing. Factory testing of jet engines represents the major source of annoyance to nearby office workers and residential areas. This testing also constitutes a hazard in that acertain partial or permanent impairment of hearing can be produced by operations' personnel being exposed to this noise.

In the research and design on engines, high ambient pressures and temperatures are involved when a microphone is used to obtain data within or near the combustion chamber. Types of burner instabilities occur and the roll of flame driven standing waves in burners is being studied. The names given to these instabilities are:

1. In rockets, "Chugging" and "Screaming."
2. In afterburners, "Rumbling and "Queaking"
3. In ram jets, "Resonance," "Rough Burning," "Pulsing" and "Whistling."

The 21 type condenser microphones can be operated at higher temperatures than conventional microphones, since the materials used are Micalex, glass and stainless steel. The Micalex becomes unstable above 1,000 degrees F. and other parts are stable up to 1600 degrees F. For short periods of time, such as an interval of less than one minute, the microphone can be directly exposed to 1,600 degrees F.

Where continued temperatures above 700 degrees are encountered in the measurements, the microphone is used with a probe tube. The probe tube usually has a bore of 1-3 mm and of a length to provide the necessary temperature gradient. The probe tube also provides more of point source pickup and reduces diffraction of sound around it and allows it to be mounted in a wall of a pipe or engine. The length of the probe tube varies from 3" up to experimental unit, 14" in length. The walls of the probe tube can be cooled by liquid, air, or covered with heat resistant insulation so that the temperature at the microphone end is within accepted limits. Usually stainless steel is used so as to resist the corrosive action of heat and the various types of liquid fuels and propellants. Figure 1.

The wall of the probe tube is sufficiently thick so that an attenuation of at least 50 db is provided.

Where the ambient barometric pressure exceeds 30 psi, it may be necessary to provide a bypass from the front of the diaphragm or the chamber, to the housing at the rear of the microphone so as to equalize the static pressure.

When the temperature at the diaphragm is elevated beyond 200 degrees, the voltage between cathode and ground drops, and it is advisable to provide means for maintaining a constant potential of 200 volts.

Noise Control in Engine Plants

Noise control of jet engine testing cells has become a compulsory part of factory testing. Factories are usually located in somewhat remote areas to residential sections, but progressively these areas are built up and complaints of the residents require adequate noise control.

Present acceptable daytime sound levels can approach a value of 72-75 db and nighttime levels of 60-65 db before complaints will be received.

An engine at 5 feet will develop approximately 160 db S. P. L. at full power. Some engine plants have as many as 50 individual testing cells in operation simultaneously and the S. P. L.

is raised to 177 db. Exhaust stack treatment, tunnels, ducts and resonators are used to provide various degrees of attenuation. The cost of providing the attenuation is between 500 and 1,000 dollars per db, and at least 50 db of attenuation at 100 cycles is required. Higher powered engines are being developed and it is anticipated that in the near future the initial noise will be increased by a factor of 5-10 db.

Noise Monitoring Facilities

The management of factories must provide means of continuously monitoring the noise interference in a neighborhood and take appropriate measures to keep it within acceptable limits so as to avoid legal action. Facilities for this monitoring are now in use experimentally and are being planned for several areas which include office and residential areas.

The procedure consists of mounting microphones in open structures, such as a tower, church or school belfry of the residential areas. The output of the microphone is amplified to a level of approximately + 10 VU and transmitted over private or leased telephone circuits to the plant receiving terminal. The telephone circuits are equalized for uniform response up to 8,000 cycles and selection of cable pairs can provide a signal-to-noise ratio of 50 db. The threshold of residential ambient noise is seldom less than 40 db, and this allows a range up to 90 db.

At the receiving terminal, line amplifiers provide sufficient gain to compensate for the loss of the telephone cable. (The equalized 1,000 cycle gain is equivalent to the loss of 4 db per circuit mile.)

In addition to monitoring the noise, equipment is available to:

1. Operate a warning light when the S. P. L. in the region of this microphone exceeds the specified interference level.

2. Record noise on tape or sound level recorders.

Equipment used at the pickup point is the 21 type condenser microphone, having a dynamic range of 30-140 db S. P. L., and a 100 db gain amplifier capable of + 10 VU output. The gain of the system is adjusted so that the maximum expected level in the area willdevelop + 10 VU and maintain the highest signal-to-noise ratio possible without producing cross talk in adjacent cable circuits.

Calibration of the microphone, amplifiers, telephone cables and line terminal equipment and recording facilities, may be provided by mounting a small stable loudspeaker near the microphone. This loudspeaker is energized by a calibrated reference tone which is transmitted over a separate outgoing telephone cable.

The monitoring at the exhaust stack or within a few diameters of the engine is accomplished with the 21-BR200 type microphone.

Experimental tests over a period of several months in a mid-western jet engine factory, indicate that the microphone system can be exposed to conditions of weather, including 100% humidity and temperature ranges from —20 degrees F. to 100 degrees F., and the overall change in sensitivity including microphone, amplifier and telephone cables was less than 2 db over a one month period of time.

When the aircraft engine noise exceeds the predetermined complaint level in the residential area, the procedure is to reduce the fuel consumption temporarily or shut down the required number of engines to keep within the specified level.

Hearing Loss in Industry

The loss of hearing to personnel operating and testing equipment in factories today is considered to be a factor which management must evaluate, and provide protection for the worker. It is estimated today that over 7 billion dollars are now involved in legal action resulting from claims on loss of hearing. Drop forges, trip hammers, riveting operation and the like, develop peak sound pressure levels in excess of 150 db. Employees working in these high noise fields without ear protectors have a permanent loss of hearing at frequencies above 1,000 cycles.

Both the 21-B and 21-BR types of microphones are used in these cases, since the S. P. L. involved is in the operating range of both types.

Other Applications

The 21-BR type microphone is used to determine the vibration of fuel lines, tanks and other parts in rockets. Safe risk distances for operating personnel adjacent to rocket launching apparatus is determined by measuring the S. P. L. at the launching platform.

Motor car engine timing-chain noise is measured by mounting a probe tube in close proximity to the individual links of the chain around the sprockets.

In the medical field, small animals are used for experimental purposes to study the effect of exposure to blast. A probe tube is inserted in the animal at the point of interest and the internal pressure can be accurately measured on the 21-BR type microphone.

In the field of vibration, the microphone may be used to trace the nodal pattern of vibrating turbine buckets, as well as recording the axial modes of a vibrating turbine wheel.

21 Type Microphone Sensitivities

21C Microphone - Open circuit sensitivity, −46 db re 1 volt; maximum sound pressure level, 140 db; frequency range, 5 cycles to 17 KC.

21BR-180 Microphone - Open circuit sensitivity, −66 db re 1 volt, ± 5 db; maximum sound pressure level, 180 db; frequency range, 5 cycles to 17 KC.

21BR-200 Microphone - Open circuit sensitivity, −86 db re 1 volt, ± 5 db; maximum sound pressure level 200 db; frequency range, 5 cycles to 17 KC.

21BR-220 Microphone - Open circuit sensitivity, −106 db re 1 volt, ± 5 db; maximum sound pressure level, 220 db; frequency range, 5 cycles to 17 KC.

Figure 2, shows as an abscissa the open circuit output voltage and the ordinate is the input pressure in dynes per square centimeter.

Figure 3, is a chart of sound pressure level (S. P. L.) - Dynes vs. db.

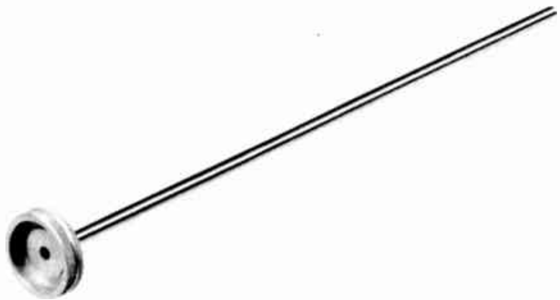

Fig. 1
159A probe tube.

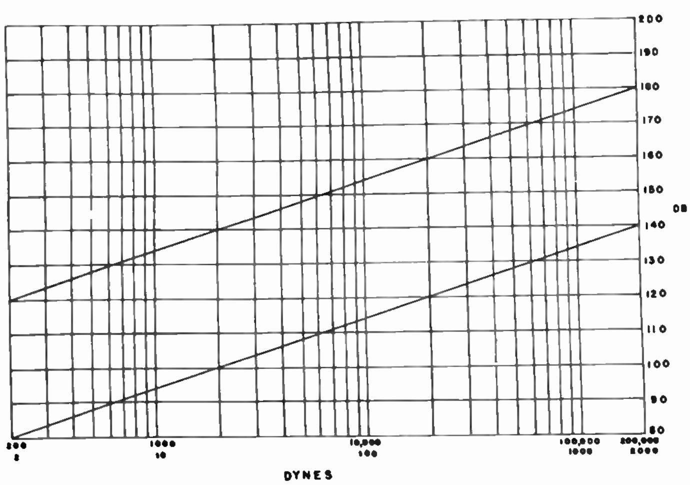

Fig. 2
Open circuit output voltage vs. input pressure in dynes per square centimeter.

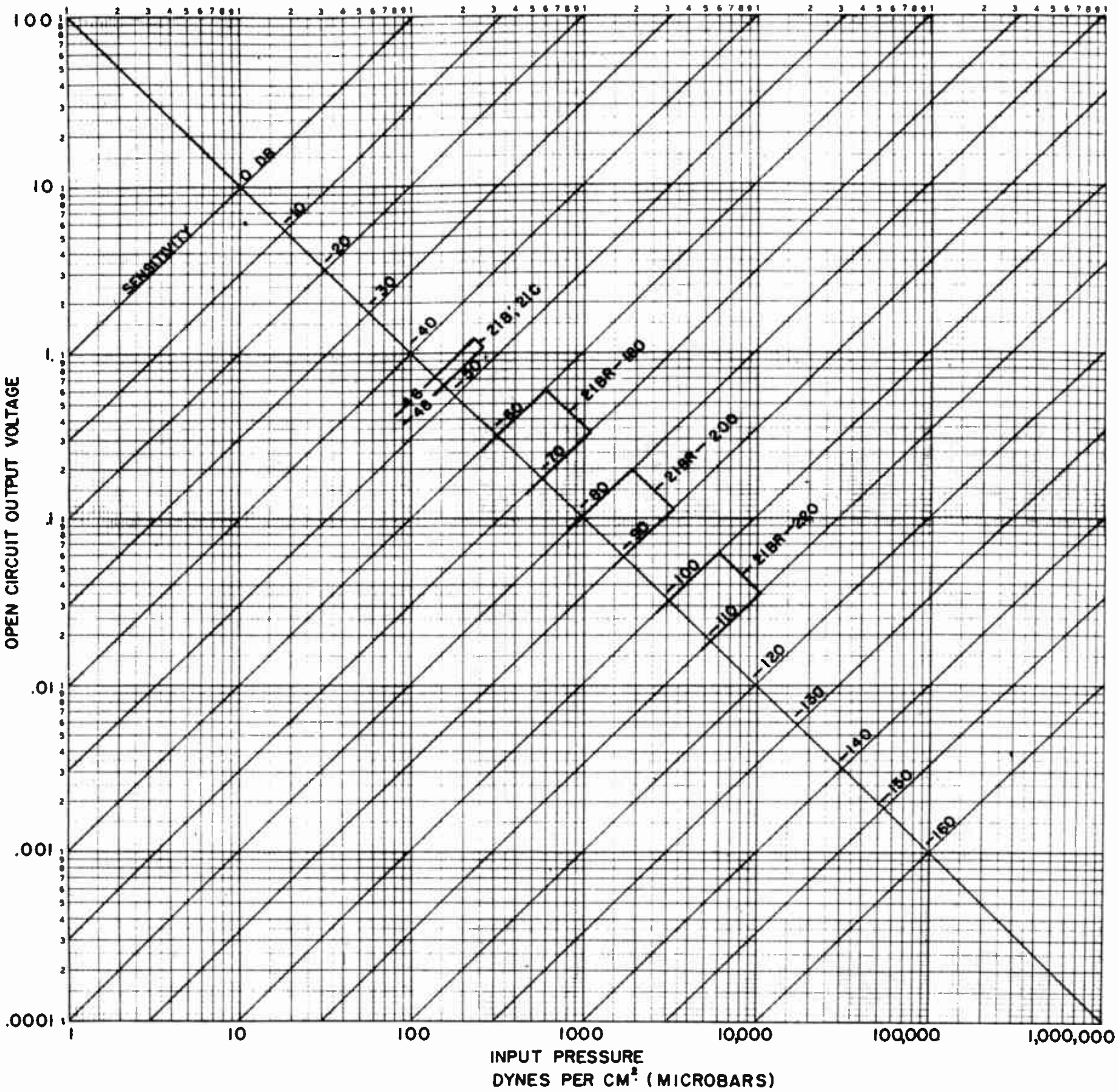

Fig. 3
Chart S. P. L. -- dynes vs. db.