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A SIMPLE HARMONIC-DISTORTION TESTER

There are many people who build amplifiers who follow published circuits and do not have full instrumentation for the testing and evaluation of the completed unit. In most cases, they are assured that the amplifier they have built will perform in a satisfactory manner, because they use a circuit published by a reputable organisation and follow carefully all the information published with the circuit. It is a fact, of course, that few private individuals will possess some of the more expensive items of equipment necessary to carry out more advanced tests, and a harmonic distortion meter falls into this category.

Even without the use of such an expensive item of equipment, it is possible to make total harmonic distortion checks, provided that very low orders of distortion do not require to be measured. If we recall the standard method of measuring total harmonic distortion, we find that it consists of setting up a meter or other indicator to read full scale with the output of the amplifier fed into it, and then inserting a filter which rejects the fundamental from the meter circuit. The small remaining meter reading is a measure of the distortion present in the signal fed into the instrument.

The object of this note is to describe a cheap and simple bridge circuit which can be used as the fundamental rejection filter in a measuring setup. A separate indicating device is also required, but here an oscilloscope or ac millivoltmeter, two likely items to have on hand, will fill the purpose well.

The Circuit

The circuit of the rejection filter is shown in Fig. 1, from which it will be seen that the heart of the unit is a Wien bridge plus a potentiometer. The shunt and series resistive elements of the bridge consist of a ganged 100K two-section carbon linear potentiometer, and form the "F" or frequency control. The capacitive elements of the bridge may be selected in two values by the "High/Low" switch; the frequency ranges over which the bridge will tune are approximately 400 cps to 25 Kc, and approximately 20 to 500 cps, for the high and low ranges respectively. The "R" or resistance control consists merely of a 10K linear carbon potentiometer. The only remaining feature is the "In/Out" switch, which controls the connection of the detector.

It will be seen that the Wien bridge with the added potentiometer may be regarded as a modified Wheatstone type bridge, in which the fundamental frequency may be cancelled out by adjustment, leaving only harmonic distortion and noise. A bridge of this type is capable of being adjusted to reject an extremely narrow band of frequencies with very high attenuation, and is therefore very suitable for the purpose in mind here. The width of the "notch," and the degree of attenuation offered to the fundamental will vary with operating conditions, as one may expect.

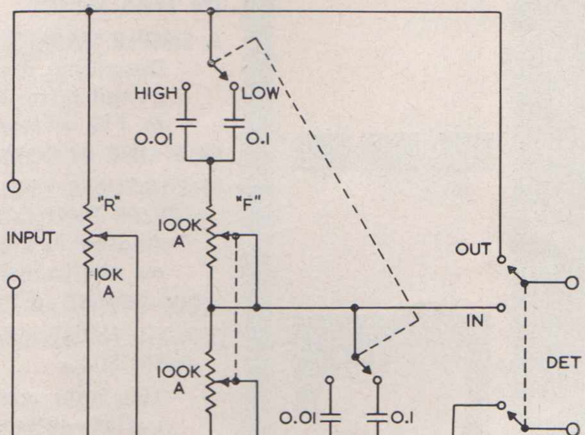


Fig. 1

Detector

The best detector to use with this device is probably an ac millivoltmeter or an oscilloscope, or both. The former will, unless the oscilloscope is carefully calibrated, afford a more precise measurement of the distortion products, but the oscilloscope will be more useful in observing the type of distortion present. The detector must possess reasonable sensitivity, remembering that if we are, for example, to measure 1% total distortion in a 6-watt amplifier feeding a 15-ohm load, a reading of 40 db below 9.9 volts will result, i.e., 0.099 volts, 99 millivolts. Although it is unlikely that a simple unit of this kind could be operated down to distortion levels of the order of 0.1%, this would call for a reading by the detector of —60 db below the 9.9 volts, 9.9 millivolts.

In the event that a detector of suitable sensitivity is unavailable, one could consider the use of a second amplifier coupled to an output meter as the detector. Care must be used here, as the second amplifier will inevitably add to the apparent measured distortion, and it would probably be unsafe to use this method unless the degree of distortion being measured was comparatively high and the second amplifier was a good one.

Construction

Little instruction on the subject of construction can be needed with such a simple unit. The circuit would be put together in a small metal case, with the case isolated. A separate grounding terminal on the case may assist in some cases in keeping noise out of the measuring circuit. The adjustment of the controls will be facilitated by using fairly large knobs on them.

The degree of attenuation offered to the fundamental frequency in a bridge is determined in part by the exactitude with which the two reactive arms of the bridge can be adjusted to have exactly the same elements of R and C at the null point. Some improvement will result, therefore, from accurate matching of the two pairs of capacitors, and from the use of matched elements in the ganged "F" control. The matching of the two sections of this control is unlikely to be better than about 10% unless high-quality units of the precision type are used. One could therefore consider experimenting with the use of two separate controls, although this may render adjustment more tedious.

Operation

The operation of this unit is very simple. The general test set-up is shown in Fig. 2. Adjust the oscillator for the frequency at which the measurement is to be made, and the output level and amplifier under test for the desired operating conditions and output level.

Turn both controls on the filter to the counterclockwise (maximum resistance) positions. Then with the detector switch in the "Out" position, note the reading on the detector; this represents the total output from the amplifier under test, or 100%. Now switch the filter "In" and adjust the "F" control until a null is found. At this point the null may be quite small. Now successively adjust the "R" and "F" controls until no further reduction can be made in the reading at the detector, adjusting the detector sensitivity as required. Note the final reading at the detector.

This final reading represents harmonics plus noise, and may be converted into a percentage reading by multiplying it by 100 and then dividing by the 100% reading noted above. Make sure that both voltage readings are expressed in the same units.

Hints and Tips

The use of an oscilloscope as the main or an auxiliary indicator is of great value, not only in determining the orders of harmonic distortion present in an amplifier, but in checking that one is in fact measuring distortion and not noise. Although it will in general be safe to assume that the noise level in an amplifier is lower than the total distortion products, a fault in the amplifier or in the setting up of the testing hook-up can result in a high noise level at the detector. This will show up on the oscilloscope as the "grassy" appearance of white or wide-band noise, or by a dominating 50 or 100 cps component, or both. The noise level in the amplifier under test or the measuring circuit must be appreciably better than —40 db and —60 db respectively for successful measurements to be made at levels of 1% and 0.1%.

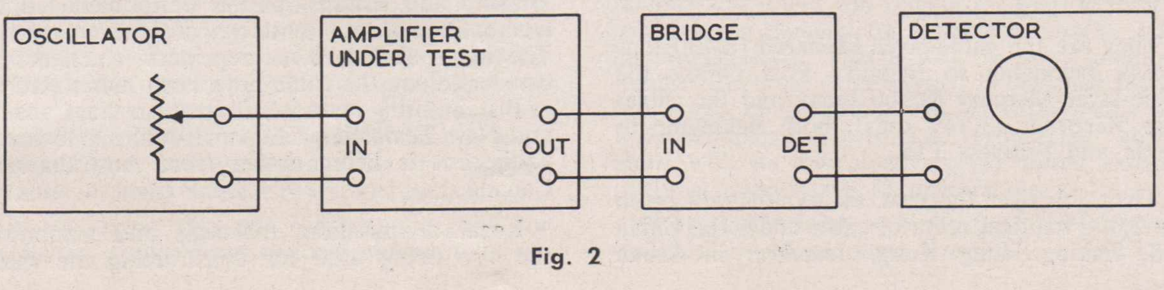


Fig. 2

One cannot expect to be able to measure low levels of distortion in an amplifier if the signal source purity is not notably better than the sort of level we are expecting. For example, many of the more common audio generators have about 0.25% distortion in the output, which means that one could certainly not measure a lower figure than this, even if the amplifier performance was in fact better. As this is an acceptably low level of distortion, trouble may not arise.

Where it is necessary to have a signal source of much greater purity (we were recently making measurements at 0.02%), the usual technique is to use a narrow-pass filter tuned to the fundamental frequency used for tests. This offers possibly 40 to 50 db of attenuation to harmonics, which, when added to the say —52 db of the second harmonic (—52 db = approximately 0.25%), gives us perhaps —102 db for the nearest harmonic, corresponding to better than 0.001% distortion.

If an attempt is made with the aid of an oscilloscope to evaluate the separate harmonic components which contribute to the total harmonic distortion reading obtained, it must be remembered that the total reading is the geometric sum of the components. This means that the levels of the individual components as seen on the oscilloscope, compared with the envelope amplitude of the complete display, will not give a true picture of their relative magnitudes.

For example, in a small push-pull amplifier, let it be assumed that the second and third harmonics are measured at 0.2% and 0.5%, other harmonics being negligible. The geometric sum of these components gives a total harmonic distortion figure of 0.54%. This is why the oscilloscope will often show two or more components each of which appears to have, and in fact does have, an amplitude almost as large as the total amplitude.

If in doubt about the purity of the signal from the audio oscillator, use this filter to check the oscillator also. In fact the filter can be used for the audio sections of radio and TV receivers, modulators and other applications, as well as for audio amplifiers.

NEW LINK IN COMMONWEALTH ROUND-THE-WORLD CABLE

by Trevor Blore

Recently the cable-laying ship Mercury left the Thames for Singapore, with a full load of deep-sea telephone cable. The Mercury will team up with two other vessels to lay the latest link in Commonwealth communications.

The three ships taking part in this operation are the same team which laid the great telephone cable link across the Pacific from Vancouver to Sydney, by way of Hawaii, Fiji and New Zealand, to bring Australia into direct cable communication through Canada and the Atlantic cable called CANTAT.

They are the cable-layer Monarch (8,400 tons gross), belonging to Britain's Post Office; the cable-layer Mercury (8,960 tons); and the cable-ship Recorder (3,349 tons), both belonging to Cable and Wireless Ltd.

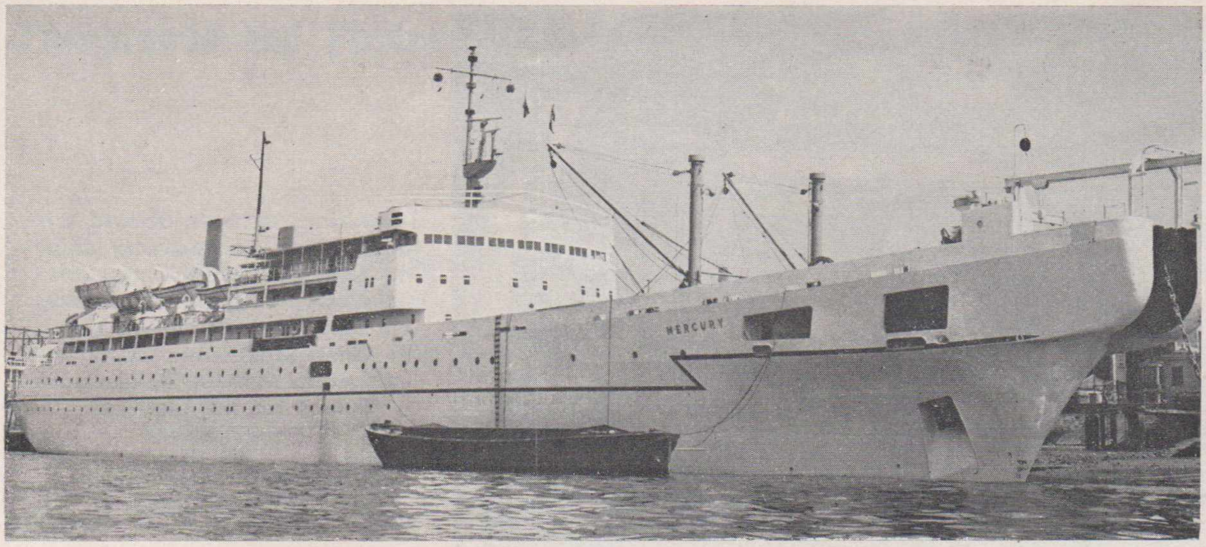
Their job over the next six months will be to lay 2,000 nautical miles of cable under the China Sea, linking Hong Kong, Jesselton in Sabah (North Borneo) and Singapore. The cable will have a capacity of 80 telephone channels, with stable circuits for all types of telecommunications.

Five Partners

This is the first stage of the new South-East Asia communications system called SEACOM which will eventually extend from Singapore to Sydney and thus link up with the trans-Pacific cable which Queen Elizabeth II opened at the end of last year.

SEACOM is the joint undertaking of five countries — Australia, Canada, Malaysia, New Zealand and Britain—and is being managed by a committee of representatives of the five partners. The cable and deep-sea repeaters which act as boosters along the cable have been manufactured in Britain, using materials from Australia, Canada, and New Zealand, while some of the land-based equipment is being drawn from Australia and Canada.

Local organisation, materials and manpower are also being used for constructing the shore



Britain's latest cable-laying ship, Mercury.

stations of this link. Highly trained engineers from the Cable and Wireless company's headquarters in Britain will train and supervise local technicians. The link will thus be of economic and technical benefit to Hong Kong, Sabah and Singapore while still under construction.

The cable-laying ships which will tackle this big task are among the rarest types afloat. The newest and largest of this type is the United States vessel Long Lines (11,200 tons) belonging to the American Telephone and Telegraph Company, which is now working in the Pacific.

Next in size comes Mercury, followed by Monarch. The British Post Office has a second cable-laying ship, the Alert. The only other ships of this type listed are two Russian vessels of which little is known, and a French ship.

Giant Pulley

A cable-ship is very distinctive in appearance. In her bow is a big sheave looking like a giant steel pulley. This enables the cable and its repeaters to be paid out or hauled in over the bow. Pin-point precision in navigation and ship-handling are required in this type of work, and it is to give the necessary flexibility that diesel-electric propelling machinery is favoured.

In general appearance, Recorder is similar to Mercury and Monarch, but much smaller. Her normal function is the maintenance and repair of existing cables, but she has already made an essential contribution towards the SEACOM lay by making an extensive survey of possible routes for the new cables. To carry out this task she steamed over 4,000 nautical miles through parts of the China Sea usually avoided by shipping because of many small islands and reefs.

In the laying stage she will act as a guide for the layers, going ahead to mark the path for the cable with buoys. Although all the cable-ships, both layers and repairers, are fitted with the latest possible shipboard navigation equipment, a buoy-laying guide is still necessary in an area where few precise navigational aids such as radio beacons are available.

Recorder, which acted in a similar capacity during the laying of the Pacific cable, will also be loading more than 400 tons of armoured cable for the shore ends of SEACOM at Hong Kong, Jesselton and Singapore.

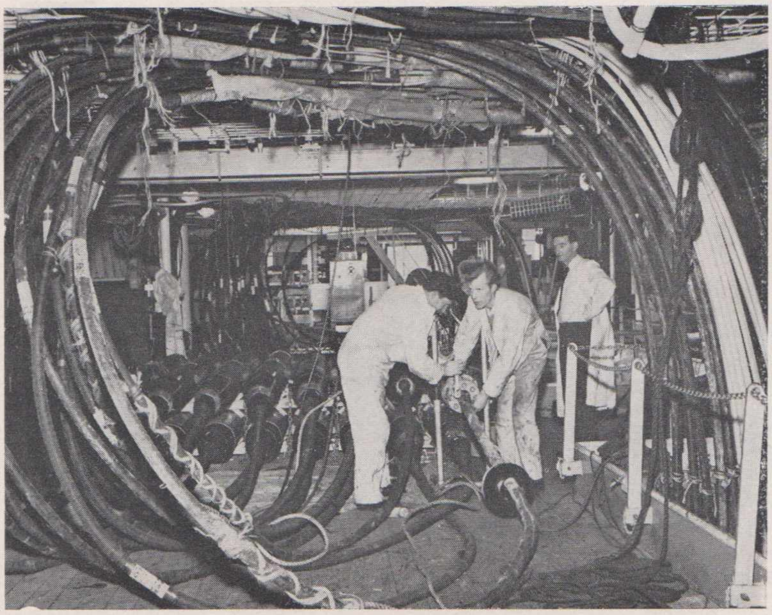
Normally she is one unit in a fleet of six ships of the Cable and Wireless fleet stationed around the world to guard and maintain the company's world-wide cable communications system. Their bases range from Port of Spain, Trinidad, and Gibraltar in the west, to Singapore and Suva, Fiji, in the east.

They are ready to race instantly to any point in the oceans where a fault in a cable may have developed, to "fish" up the faulty cable from miles down on the ocean bed, to repair it and to relay it. It is remarkable, too, how quickly the navigation officers of these ships, with the assistance of scientific officers, can locate a mid-ocean fault.

X-Ray for Cable Joints

Despite the development of earth satellite communications, there will remain for the foreseeable future a big demand for reliable submarine telecommunications. That is why the new Commonwealth telephone cable system is designed for an initial life of 20 years. All its components are fine examples of precision engineering which, along with its raw materials, are tested exhaustively at every stage of manufacture.

Every cable joint is X-rayed and, to prevent chemical growth or other deterioration, gold plat-



Technicians at work aboard Britain's latest cable-laying ship, Mercury. They are joining cable-ends to repeaters which one day will amplify cable signals under the China Sea. Picture was taken just before Mercury sailed from Britain for the Far East.

ing is used in the repeaters which are laid at intervals of about 20 nautical miles along the cable.

These repeaters are encased in ten-feet long, torpedo-shaped, steel containers with water-tight bulkheads, weighing half a ton and able to stand the terrific pressures of the ocean deeps. They amplify the cable signals hundreds of thousands of times. That is how speech channels of a clarity equal to the best internal telephone systems can be obtained across the world.

SEACOM is wholly a Commonwealth project, designed to meet the growing demand for reliable regional and world communications by governments, trade, industry and the public.

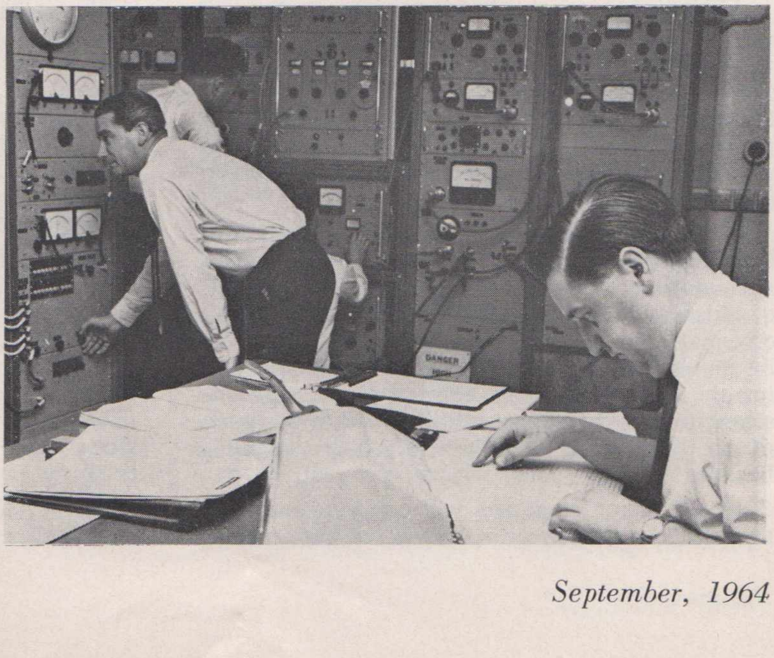
Its completion will enable many thousands of telephone and other communication users already linked by radio systems in South-East Asia to be joined with the Commonwealth and other international telephone cable networks while at the same time enjoying better connections between themselves.

World Girdle

Though primarily designed to serve the needs of the Commonwealth, SEACOM will be available on suitable terms to other countries of the region who can arrange to link with it.

This Commonwealth telephone cable system was begun by spanning the Atlantic between Britain and Canada in 1961. The links between Australia, New Zealand and Fiji were completed

Page 207 Please



Complex electronic equipment is used aboard cable-laying ships for routine testing and fault finding in the most exacting task of cable laying and repair.

4: MULTIPLIER PHOTOTUBES

PART 2

Noise

The amplification of a multiplier phototube is usually high enough so that the noise in the dark current completely dominates coupling-resistor noise except for very small resistances. Under normal operating conditions, the noise which limits detectability results from amplified thermionic emission. Thermionic emission may originate from both the photocathode and the dynode surfaces. The latter emission is usually negligible as a result of the difference in gain through the tube. If the multiplication of the secondary emission is assumed to be noise-free, the expression for the rms noise current is similar to that for a vacuum phototube, Eq. (22), as follows:

$$\overline{I^2 \varDelta f}^{\frac{1}{2}} = \mu [2\, e\, i_d\, \varDelta f]^{\frac{1}{2}} \quad \ldots \quad \ldots \quad (32)$$

where μ is the amplification factor of the multiplier phototube and the other symbols are as defined previously. As in the case of vacuum phototubes, it is possible to calculate the minimum value of coupling resistance R which may be used. If it is assumed that the tube-generated noise is just equal to the coupling Johnson noise, as in Eq. (24), the minimum value of R is given by:

$$R = \frac{2kT}{\mu^2\, e\, i_d} \quad \ldots \quad \ldots \quad (33)$$

For example, if the equivalent cathode dark current i_d is 10^{-15} ampere and the gain of the tube is 10^6, the value of R for which the two noise sources are equivalent is 50 ohms. Thus, the multiplier phototube is far superior to the vacuum phototube for the amplification of very small light signals. The possibility of very low values of coupling resistance permits the observation of high-speed phenomena not possible with vacuum phototubes having large coupling resistances.

The above discussion does not consider the increase in noise resulting from the secondary-emission amplification mechanism. If this source is included, a more refined expression may be written:[18]

$$\overline{I^2 \varDelta f}^{\frac{1}{2}} = \mu \left[2\, e\, i_d \left(1 + \frac{B}{m-1}\right) \varDelta f \right]^{\frac{1}{2}} \quad (34)$$

where m is the secondary-emission ratio per stage (usually of the order of 4) and B is a statistical factor (found by measurement on a 5819 to be 1.54.[19]).

An important consideration in the operation of multiplier phototubes is the **ratio of the signal to the noise.** The output signal current I_B may be expressed as follows:

$$I_B = \mu\, F\, R \quad \ldots \quad (35)$$

where F is the flux in lumens on the photocathode and R is the sensitivity in amperes per lumen. (F and R can also be expressed in terms of watts instead of lumens.) The following simplified expression may be written for the ratio of the dc signal current to the rms noise current in a bandwidth △f:

$$\frac{I_B}{\overline{I^2 \varDelta f}^{\frac{1}{2}}} = \frac{F\, R}{[2\, e\, i_d\, \varDelta f]^{\frac{1}{2}}} \quad \ldots \quad \ldots \quad (36)$$

In the detection of low light levels, it is often advantageous to modulate the light by means of a "chopper" and to couple the multiplier phototube to an amplifier having a narrow bandpass at the chopping frequency. In this way the dc component of the dark current is eliminated, and the inherent signal-to-noise ratio of the multiplier phototube is more readily realized.

For example, when the modulation of the light is sinusoidal, a modulation factor **M** can be defined as the peak-to-peak cathode photocurrent amplitude divided by the average cathode photocurrent. The rms output-signal current can be expressed as

$$\frac{i_k M \mu}{2\sqrt{2}}$$

where i_k is the average photocathode current. If the average cathode current is small compared with the equivalent cathode dark emission i_d, the following expression may be written for the signal-to-noise ratio S/N:

$$S/N = \frac{\text{rms modulated signal current}}{\text{rms noise current}}$$

$$= \frac{Mi_k}{4\left[e\, i_d \left(1 + \frac{B}{m-1}\right) \Delta f\right]^{\frac{1}{2}}} \quad (37)$$

It is frequently advantageous to rate a multiplier phototube by its **equivalent noise input** or **ENI.** This figure is the amount of light in lumens (or other radiation units) which produces an rms signal current just equal to the noise current in a bandwidth of one cycle. For example, if a square-wave modulation is assumed for which the peak-to-peak amplitude is just equal to the unmodulated current with on time equal to off time, a modulation factor M of $8/\pi$ can be assumed in Eq. (37). If **F** is the unmodulated flux, the average cathode current i_k, is then given by

$$i_k = FR/2 \quad (38)$$

For the case where S/N is equal to unity, ENI is equal to the unmodulated light flux F. The value of ENI is then determined as follows:

$$\frac{S}{N} = 1$$

$$= \frac{(ENI)R}{\pi\left[e\, ie \left(1 + \frac{B}{m-1}\right) 1\right]^{\frac{1}{2}}} \quad (39)$$

or

$$ENI = \frac{\pi\left[e\, i_d \left(1 + \frac{B}{m-1}\right)\right]^{\frac{1}{2}}}{R} \quad (40)$$

Note that this equation may be used to determine the equivalent photocathode dark current. For example, when B equals 1.54 and m equals 4, the value of i_d is given by

$$i_d \cong 0{\cdot}4 \times 10^{18} R^2 (ENI)^2 \quad (41)$$

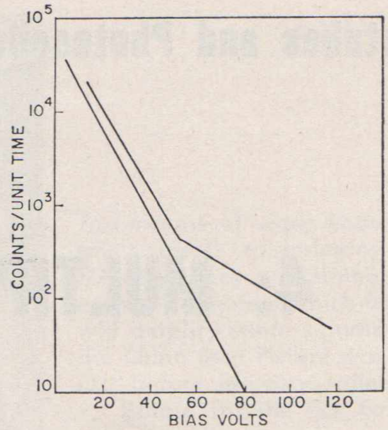


Fig. 50—Pulse-height distribution of dark-current pulses in two 7264 multiplier phototubes. The data were obtained by integral-bias counting.

When the dark current is observed on a wide-bandpass oscilloscope, it consists of unidirectional pulses of variable amplitude. It is presumed that these pulses represent thermionic electrons from the cathode amplified by secondary emission. The distribution of the heights of these pulses is quite closely exponential[20] with a trend to a double-slope characteristic.[21]

The cause of this distribution is not clearly understood. In the case of tubes such as the 931A and 6655A, which have CsSb dynodes, thermionic emission may originate from the dynodes as well as from the cathode. This explanation could well account for the many small pulses. On the other hand, it has been speculated that the distribution of secondary emission itself may be exponential. This point of view is proposed by J. A. Baicker[21] who also suggests that the two-slope characteristic shown in Fig. 50 is the result of single and multiple emission of electrons from the cathode. The multiple emission may be the result of impact by positive ions. However, the evidence for this assumption is not as yet clearly established. The statistics of secondary emission are discussed further below.

Noise in the Signal. When the photocurrent is well in excess of the thermionic emission, measurement precision is limited by the randomness of photoemission and secondary emission. This type of limitation is most prevalent in applications such as the detection of a star against the background of the sky, where the modulated signal is produced by scanning back and forth across the star and in the detection of small marks on scanned paper. The expression for the rms noise current output is identical to Eq. (32) or to Eq. (34) (when secondary-emission statistics are included), except that the average cathode photocurrent i_k is substituted for i_d. When the modulation of the light is sinusoidal and the magnitude of the modulation is small compared with the background, the expression for the **rms noise current in the signal,** N_s, may be determined by a development parallel to that of Eq. (37), as follows:

$$S/N_s = \frac{\text{rms modulated signal current}}{\text{rms noise current in signal}}$$

$$= \frac{M}{4}\left[\frac{i_k}{e\left(1+\frac{B}{m-1}\right)\Delta f}\right]^{\frac{1}{2}} \quad (42)$$

In an application of this type, which requires maximum sensitivity in the presence of a light background, the multiplier phototube used should have high cathode sensitivity. Gain is unimportant except at the first stage, where high dynode-No. 1-to-cathode voltage is required to minimize noise from the statistical variation of secondary emission (through the factor **m**).

In most practical multiplier phototubes, some of the photoelectrons fail to enter the secondary-emission section of the tube as a result of imperfect design or misalignment of tube components. The **collection efficiency** for the photoelectrons is usually near unity, but in some tubes may be of the order of 0.5 or less. If this consideration is included in Eq. (42), the cathode current must be the **collected current** rather than the **emitted current.** The collected current may be defined as follows:

$$i_k\ (\text{collected}) = i_k\ (\text{emitted}) \times \epsilon \quad (43)$$

where ϵ is the collection efficiency. Eq. (42) then becomes

$$S/N_s = \frac{M}{4}\left[\frac{i_k\epsilon}{e\left(1+\frac{B}{m-1}\right)\Delta f}\right]^{\frac{1}{2}} \quad (44)$$

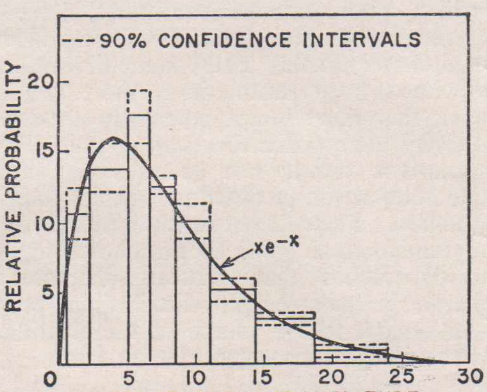


Fig. 51 — Measured amplitude distribution of anode pulses due to single photo-electron inputs for a 2-inch diameter, 14-stage multiplier phototube having Cs_3Sb dynodes. Gain per stage is approximately 3.

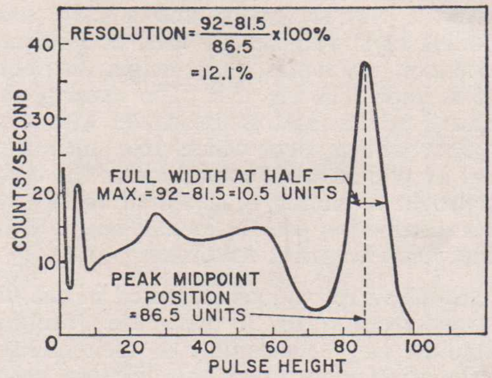


Fig. 52—Distribution of pulse heights observed in a scintillation counting experiment using gamma rays from Cs^{137} to excite a NaI (Tl) crystal.

This equation may be used to provide an approximate measure of the collection efficiency, or at least a relative comparison between tubes.[18]

The noise in the signal is similar to the dark noise in that it also consists of random pulses of variable amplitude. The random spacing of the pulses corresponds to the basic randomness of the emission of photoelectrons. In this case pulses originating from the dynodes are negligible. The distribution of anode pulse heights has been measured at the Lawrence Radiation Laboratory[22] for single-photoelectron inputs; data obtained are shown in Fig. 51. The curve passes through a maximum for small pulses instead of increasing indefinitely near zero pulse height, as the dark-current distribution apparently does. The distribution is approximately that calculated from Poisson statistics.

Scintillation Counting.[23-28] Another type of application in which the statistics of operation of the multiplier phototube are important is scintillation counting. In a typical application, nuclear disintegrations produce gamma rays which cause scintillations in a crystal such as NaI(Tl). A multiplier phototube coupled closely to the face of the crystal converts the scintillations to electrical output pulses. Because the energy of a light flash is closely proportional to the gamma-ray energy and because multiplier phototubes are linear in operation, the electrical pulse height can be used as a direct measure of the gamma-ray energy. However, the number of photoelectrons per scintillation is relatively small (of the order of several hundred). The output pulses vary in height because of the statistics of the small numbers and because the scintillations themselves vary. An important requirement in nuclear spectrometry is the ability to discriminate between pulses of various heights; hence, the importance of **Pulse-Height Resolution.**

Measurement of the pulse-height resolution of a multiplier phototube has not been standardized;

however, a NaI(Tl) crystal and a Cs^{137} source of gamma rays are generally used as a reference combination. A typical pulse-height distribution curve is shown in Fig. 52. The main peak of the curve at the right is associated with monoenergetic gamma rays which lose their entire energy by photoelectric conversion in the crystal. Pulse-height resolution is measured as the width of this distribution peak at its half height divided by the pulse height at maximum.

Pulse-height resolutions measured in this manner vary from 6 to 20 per cent. Multiplier phototubes vary considerably in their ability to resolve scintillation pulses of different heights. Good optical coupling is required to use all the light from the scintillation effectively. This requirement makes it necessary to provide the tube with a semitransparent photocathode on the window-faceplate and a scintillating crystal coupled directly to the faceplate. High and uniform photocathode sensitivity is essential, especially in the spectral region corresponding to the blue emission from the crystal. Fig. 53 compares the distribution of light from the NaI(Tl) source and the S-11 spectral response commonly used in the coupling multiplier. It is also important that electrons emitted from the cathode be efficiently used by the first dynode.

Pulse-height-resolution measurements are a reliable guide to efficient operation in scintillation counting. It should be noted, however, that pulse-height resolution is not solely determined by the characteristics of the multiplier phototube; the properties of the scintillating crystal, its housing, and the coupling to the phototube and the location of the gamma-ray source are also important.

Another characteristic used to describe the effectiveness of multiplier phototubes for scintillation counting is the so-called **Plateau Characteristic.** Although the term is widely used, there is no accepted definition for plateau; adoption of this concept may be traced to the parallel use

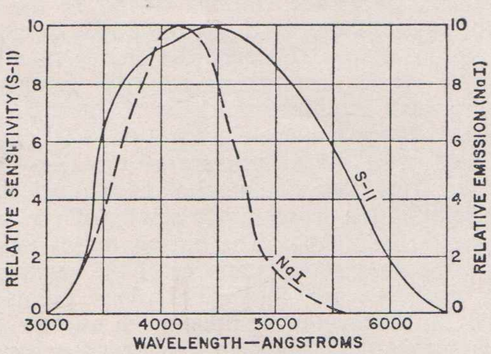


Fig. 53—Distribution of light from a scintillating NaI(Tl) crystal compared with the typical (S-11) spectral response of multiplier phototubes most commonly used in scintillation counting.

of scintillation counters and Geiger counters. Pulse-height resolution is a preferred measure of scintillation counting efficiency; however, because of the interest in plateau characteristics for certain applications, a brief description of the general implication of the term is given below.

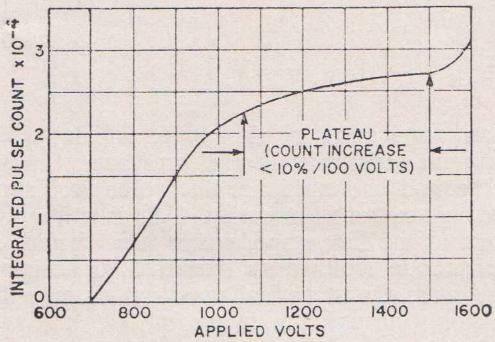


Fig. 54—Typical plateau characteristic.

The plateau characteristic is obtained in the same manner as pulse-height-resolution data, except that the pulses are recorded by integral-bias rather than differential-bias. The number of pulses larger than a particular value is plotted as a function of the voltage applied to the multiplier phototube. The plateau which develops (Fig. 54) corresponds not to the valley to the left of the photopeak in Fig. 52, as might be expected, but to the region of the curve at the extreme left in Fig. 52 just before the sharp upturn.[29] Operation on the plateau corresponds to the counting of scintillation pulses originating from Compton-scattering, as well as from photoelectric conversion.

It is generally desirable to have a relatively flat plateau which extends for several hundred volts. A good plateau characteristic is partially determined by such properties as low dark current and high photo-cathode sensitivity; it is also determined by the particular amplification-voltage characteristic. Thus, a rapid variation of gain with voltage results in a short and steep plateau; this effect is not inherently undesirable, but merely corresponds to a scale change. Plateau characteristic should not be used for indiscriminate comparison of different types of multiplier phototubes. Pulse-height-resolution data are a more fundamental guide to the choice of multiplier phototubes than plateau characteristics. Similarly, a pulse-height distribution provides greater insight to the source of the scintillations than the integral-bias-type plateau curve.

When a multiplier phototube is used to observe very short light flashes, such as those which occur in scintillation counting, **After-Pulses**[30] (i.e., minor secondary pulses following the main anode-current pulse) are sometimes observed. Two general classes of after-pulses are characterized by the time between the main pulse and the after-pulse: (1) delays of the order of nanoseconds; (2) delays of the order of microseconds. The former have been shown to be the result of feedback of light to the photocathode. The fact that light is generated in the output stages of the tube has been verified by many observers, especially in tubes in which the construction is open enough to permit observation of the dynode areas. The light output follows the current level in the tube; at reasonably high levels of current, the dynodes at the end of the tube seem to be covered by a blue-green light.

Light generated by luminescent effects associated with the high-density pulse current in the output stages of the tube is reflected and transmitted back to the photocathode. Delay time is a combination of the transit time of the secondary and primary electrons through the multiplier phototube and the transit time of the light itself. This type of feedback has been minimized by baffles designed into the structure of the tube. After-pulses in the nanosecond range are usually observed only under conditions of very-high-gain operation, of the order of 10^9.

The second type of after-pulse, of microsecond delay, has been observed in many different types of tube. No consistent explanation of their cause has been proposed, although they are clearly some type of regenerative effect. Fig. 55 shows some exaggerated after-pulses from an experimental tube. When the gain and voltage are sufficiently high, even "after-after" pulses may be observed.

Studies of the microsecond after-pulses under various conditions indicate that they are of several different origins. In one class, the amplitude of the after-pulse increases at least as rapidly as the square of the amplification factor; this relationship suggests a regeneration effect dependent on feedback from the anode end of the tube.

Feedback effects which have time delays of the order of microseconds can be circumvented in special applications by pulsing the voltage so

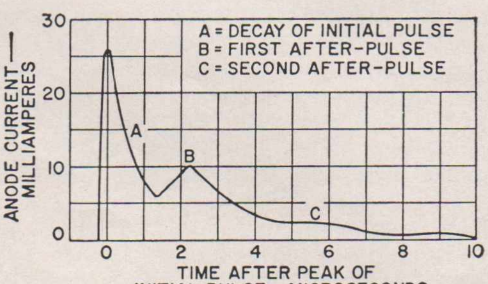


Fig. 55—Multiple after-pulses observed in an experimental multiplier phototube following a high current primary pulse. The initial pulse is generated by the light from a pulsed CRT; time constant of the phosphor and circuit combined is approximately 0.8 microsecond.

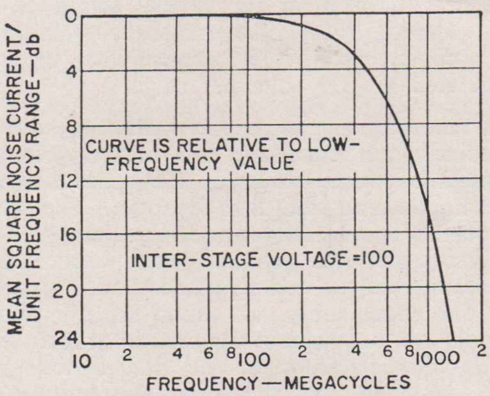


Fig. 56—Power spectrum of the noise from the 931 multiplier phototube operated at 100 volts per stage, as calculated by R. D. Sard.

that high gain is achieved before the regenerative pulse develops. Post[31] was able in this manner to operate 931A tubes at voltages of 4 to 5 kilovolts with very high gains, output-current peaks to 0.7 ampere, and pulse rise times of the order of 0.8×10^{-9} second.

Transit-Time Effects

One of the principal advantages of multiplier phototubes compared with simple photodiodes is the high amplification achieved without appreciable loss in frequency response. Calculated power spectrum of the noise for type 931 is shown in Fig. 56.[32] (The 931 was an earlier form of the present 931A multiplier phototube. The electrode structures are identical; the principal differences are in the supporting members and test specifications, particularly for dark current and sensitivity.) The figure shows the power spectrum of the noise pulses arising from the amplification of single electrons from the photocathode. The loss of frequency response above 100 megacycles results partly from the shaping of the output-current pulse by the passage of the amplified electron cloud from the next-to-the-last dynode through the anode structure to the last dynode. The electron cloud is then further amplified at the last dynode and passes again to the anode, even oscillating in the anode space before final collection. The electron cloud is also spread out by variations in transit time through the multiplier section. These transit-time variations arise from the different energies and directions of secondary electrons. This calculated frequency response has been supported by pulse measurements which show that a type 931A multiplier phototube has a rise time (10 to 90 per cent) less than 10^{-9} second.[31]

The actual delay time between the arrival of a photon and the recording of an electrical pulse in the anode circuit of the multiplier phototube may be much longer than the pulse rise time. The pulse delay time is the result of the accumulated transit times for the several stages of the tube. For a 931A, the transit-delay time is approximately 16.7×10^{-9} second when the tube is operated at 100 volts per stage.

In tubes having large photocathodes suitable for scintillation counting, one of the principal transit-time effects occurs in the space between the cathode and the first dynode. The large photocathode necessitates a fairly long path to the first dynode to provide good photoelectron collection from the entire photocathode. In addition, for some tubes, all areas on the photocathode are not equally distant in transit time of the photoelectrons to the first dynode. In tubes designed for short-time resolution, the photocathode areas are curved and the first few dynodes are oriented to minimize transit-time spread.[12]

In a new type of multiplier phototube presently under development, transit times are further reduced by the use of accelerator grids between dynodes (see Fig. 35).[11] Secondary electrons are thus subjected to a higher accelerating field near the emitting surface and to a decelerating field near the collector. The effect is almost an order-of-magnitude improvement over tubes having comparable cathode areas. In some high-speed tubes, the last-dynode and anode leads are constructed to form a twin-lead transmission line to the elements themselves.

Because of the very short time response of the multiplier phototubes, it has been difficult to find a test light source which has a sufficiently short time of flash. A spark source,[33] which produces a good delta-function light impulse having a main pulse width less than 10^{-9} second, is suitable for the measurement of the time delay in multiplier phototubes. Fig. 57 shows the transit-time delay for an 8053 as a function of supply voltages; the curve closely approximates the inverse half power of the applied voltage. This effect is to be expected, provided the effects of initial velocities and secondary-emission delay are negligible. The intercept of the line on the time axis is at 5.2×10^{-9} second. This effect has been previously observed;[34] it is probably due to the delay induced by the circuit within the tube. Fig. 58 shows the time delays for a number of multiplier phototubes over a range of operating voltages.

In most applications, the delay time of a multiplier phototube is not as important as the pulse rise time or the pulse width for a delta-function input. Fig. 59 shows the output pulse width at half maximum amplitude for an 8053 as a function of the reciprocal square root of the voltage. The light source used was the spark light source described above. The pulse width observed is spread by the width of the light pulse itself, approximately 0.7×10^{-9} second. The output pulse width also follows the inverse half power of the applied voltage, as does the transit-time

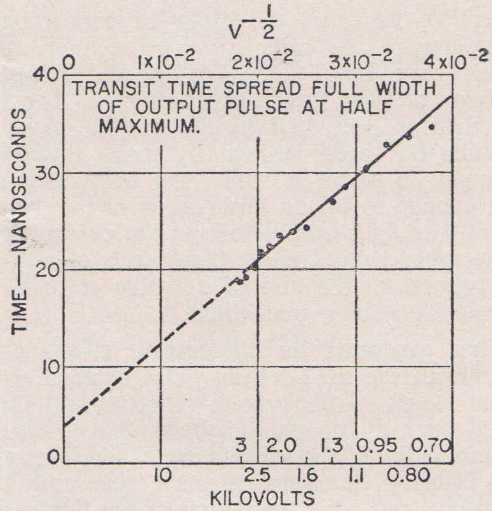


Fig. 57—Transit time as a function of the square root of reciprocal applied voltage for a type 8053 multiplier phototube.

delay. This relationship indicates that the transit-time spread is determined more by the tube structure (e.g., unequal path lengths) than by initial velocities. These data also suggest a finite intercept on the time axis of 4×10^{-9} second.

Rise Time. For the same delta-function input mentioned above, the rise time, which is closely related to the pulse width, has been measured for a number of multiplier phototubes as the time required for the pulse to rise from 10 to 90 per cent of the maximum value. These values are plotted for a range of typical operating voltages in Fig. 60. No correction has been made for the finite rise time of the light pulse itself, which is estimated to be in the order of 0.6×10^{-9} second.

If the inherently wide passband of the multiplier phototube is to be fully used, it is important

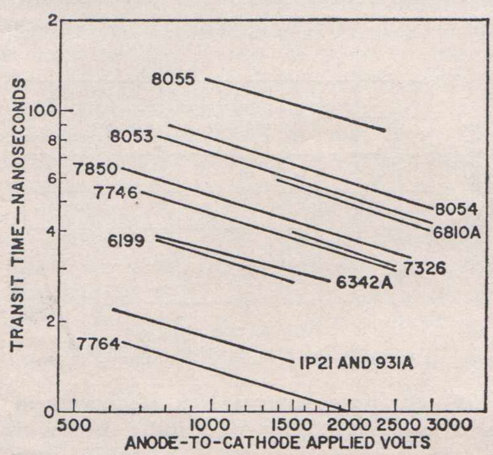


Fig. 58—Transit time as a function of supply voltage (log scale) for a number of multiplier phototubes.

not to limit the response in the anode output circuit. In a 931A tube, for example, the capacitance of the anode to all other electrodes is 6.5 picofarads. If the capacitances of the leads and the input of a first-stage amplifier tube are included, the total shunt capacitance can be 20 picofarads. If it is desirable to maintain a time constant of 10^{-8} second, the coupling resistor must be less than 500 ohms. At the very shortest times, the tube elements become part of a transmission line and "ringing" (transient oscillation) occurs if the tube and circuit are improperly designed and matched.

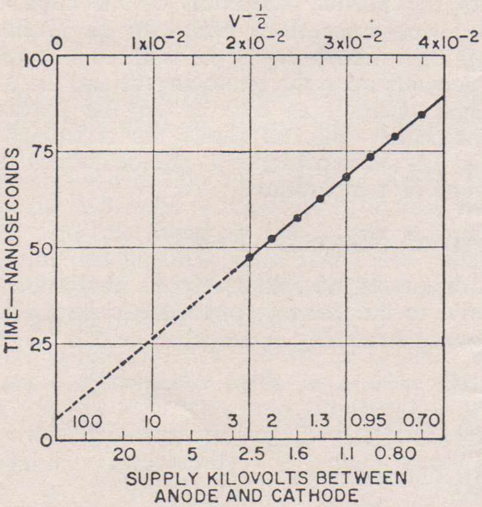


Fig. 59—Transit time spread of an 8053 as measured by the full width of the output pulse at half maximum as a function of the inverse half power of the applied voltage.

Linearity Of Output Current

The output current of a multiplier phototube has been shown to be proportional to the light input over a wide range of values.[20] The limit to linearity occurs when space charge begins to form. The first limitation of space charge is not necessarily in the space between the last dynode and anode, but more frequently in the space between the last two dynodes. The voltage gradient between anode and last dynode is usually much higher than for other dynodes, and therefore results in the limitation at the previous stage, even though the current is less. The maximum current, at the onset of space charge, is proportional to the 3/2 power of the voltage gradient in the critical dynode region. By use of an unbalanced dynode voltage distribution and increasing the interstage voltages near the end of the tube, it is possible to increase the output current in a given tube. In the case of the limiting currents, it is necessary to restrict the operation to pulsed light to avoid damage to the tube. Fig. 61 shows the range of linear current which can be obtained from the 931A, and the region in which the space charge limits the linearity. Table VIII shows the maximum current which can be drawn from various multiplier phototubes.

It should be pointed out that a linear behaviour is not always obtained from multiplier phototubes. For example, if the test light spot on a 931A is not directed close to the centre of the active area of the photocathode, disturbing effects may arise from the proximity of the ceramic end plates. Near the end plates, the fields are not uniform and are affected by charge patterns on the insulator spacers, which change with the current level. An exterior negative shield placed around the bulb wall can also improve tube linearity. Ageing effects resulting from the passage of excessive current may change the sensitivity of the tube and cause an apparent nonlinearity.

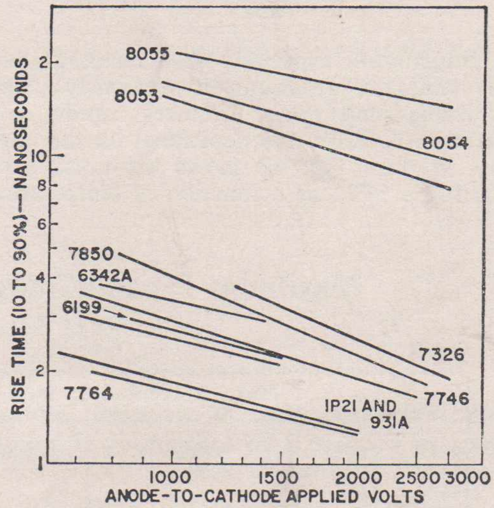


Fig. 60—Rise time (10 to 90 percent) as a function of voltage for a number of multiplier phototubes.

Temperature Effects

The gain of a multiplier phototube is fairly independent of temperature over the normal operating ranges. Careful measurement with low current (to avoid fatigue effects) usually indicates a positive variation of gain with temperature. For a 1P21 (having Cs_3Sb dynodes) Engstrom[20] has reported an increase in gain of approximately 0.3 per cent per degree centigrade rise in temperature.

Photocathodes usually show a slight increase in sensitivity with increasing temperature at the long-wavelength threshold of the spectral response. Otherwise, however, they are quite stable with temperature except for permanent changes, which probably result from redistribution of cesium at higher temperatures.

A most important characteristic of multiplier phototubes is the rapid increase of dark current

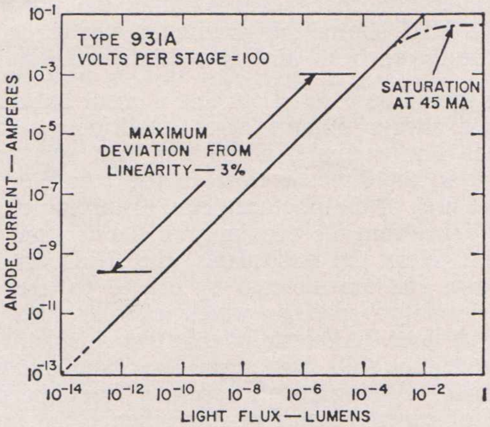


Fig. 61—Range of linearity, current as a function of light flux, for a type 931A multiplier phototube.

with temperature, especially as a result of thermionic emission, as discussed previously. Similarly, background noise increases rapidly with temperature because it is dependent on the dark-current origins. Fig. 62 shows the noise background for a 1P21 as a function of temperature.

Considerable advantage in low-light-level operation may be achieved by cooling of the tubes. However, not all multiplier phototubes can be cooled without compensating for the temperature variation of the resistivity of the photocathode layer. For tubes such as the 1P21, in which the photocathode is overlaid on a solid conductor, there is no problem. However, in the semitransparent type of photocathode, since the photocathode is a semiconductor, the conductivity at low temperatures may become so poor that the emission of photoelectrons from the centre results in a positive charge pattern which effectively blocks the normal operation of the tube. No fixed lower-temperature limit can be given for proper operation because the minimum temperature depends upon the photocurrent and the dark-emission current, as well as on the particular photocathode. Fig. 63 shows the resistivity per square for semitransparent photocathodes as a function of temperature.

Effect of Magnetic Fields

To some degree, all multiplier phototubes are sensitive to the presence of magnetic fields. Typical loss of sensitivity in the presence of a magnetic

TABLE VIII

Maximum (Space-Charge-Limited) Output Current for Various Multiplier Phototubes

Tube Type	Max. Saturated Current (Amperes)	Over-all Voltage	Voltage Distribution**
931A, 1P21, 1P22, 1P28, 6328, 6472	0.045	1000	1, 1, 1, 1, 1, 1, 1, 1, 1, 1
2059	1.75+	2648	1, 1.46, 0.83, 1, 1.2, 3.3
5819, 6217, 6342A, 6655A, 6903	0.045++ 0.37	1200 2500	2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 2, 1, 1, 1, 1, 1, 1.9, 2.7, 4, 1.5
6810A, 7264, 7265	0.23+++ 1.2†	2500 3800	2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1.25, 1.75, 2.0 2, 1, 1, 1, 1, 1, 1.3, 1.5, 1.9, 2.3 2.8, 3.8, 4.4, 5, 6
7046	0.23††	2750	4, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1.25, 1.75, 2.0
7850 4459	0.30	2500	2, 1.4, 1, 1, 1, 1, 1, 1, 1, 1.25, 1.5, 1.75, 2.0
7746	0.30	2200	2, 1.4, 1, 1, 1, 1, 1, 1.25, 1.5, 1.75, 2.0
8053	0.70 0.23	2500 1950	2, 1, 1, 1, 1, 1, 1, 4, 3.5, 4, 4.8 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1

*Note that types with identical geometry have been grouped together; it has been assumed that all would have the same space-charge characteristic, although in most cases the "satellite" types were not separately tested.

**The numbers represent the relative divider stage voltages: cathode-to-first dynode, first-dynode-to-second-dynode, etc. In most cases the stage voltages have been increased toward the output end of the tube to increase the space-charge-limited output current.

+Data from D. L. Lasher and D. L. Redhead, RSI, **34,** 115 (1963); the 2059 is essentially a five-stage 931A.

++Based on data for 931A which has identical geometry after the first stage.

+++Lawrence Radiation Laboratory Counting Handbook, UCRL-3307, December 2, 1958.

†W. Widmaier, R. W. Engstrom, R. G. Stoudenheimer, "IRE Transactions on Nuclear Science," **NS-3,** November 1956.

††Based on 6810A data because of identical dynode and anode design.

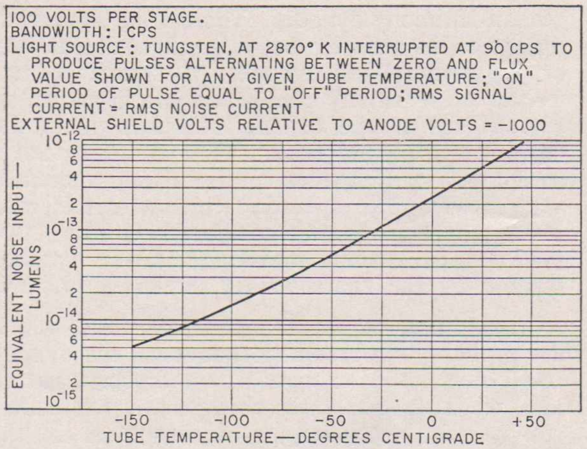


Fig. 62—Background noise variation in multiplier phototubes as a function temperature.

field is shown in Fig. 64. The loss of gain results from the deflection of electrons from their normal path between stages. Tubes for scintillation counting are generally quite sensitive to magnetic fields because of the relatively long path from the cathode to the first dynode.

If multiplier phototubes are to be used in the presence of magnetic fields, as is often the case, it is essential to provide magnetic shielding around the tube. High-mu-material shields are generally available commercially. In some experiments, even the earth's magnetic field may be critical, especially if the tube is moved about.

It is possible to take advantage of magnetic fields to modulate the output current of the multiplier phototube. Under the application of normal fields, no permanent damage results. However, it is possible to cause a slight magnetic polarization of some of the internal structure of the tube. If this condition should occur, the performance of the tube may be somewhat degraded by loss in collection efficiency; however, it is a simple matter to "degauss" (demagnetize) the tube by placing it in an alternating magnetic field and then gradually withdrawing it. A maximum field of 100 gausses at the centre of a coil operated on a 60-cycle alternating current is usually sufficient to degauss a tube.

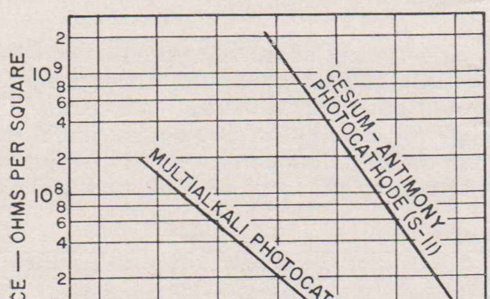


Fig. 63—Resistance per square as a function of temperature for the Cs-Sb and the multialkali semitransparent photocathodes. These data were obtained with special tubes having connections to parallel conducting lines on the photocathode.

Fatigue And Life Characteristics

It is difficult to predict the precise changes in sensitivity of a multiplier phototube which may occur during the course of operation. The fatigue characteristic is a function of output current, previous history, and type of dynode material. Because fatigue is quite variable from tube to tube, only typical patterns can be described.

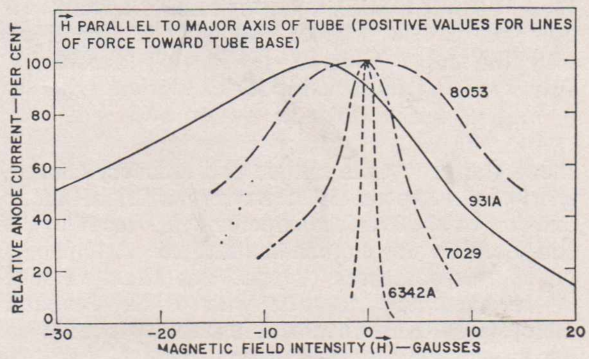


Fig. 64—Variation of output current of several multiplier phototubes as a function of magnetic field strength.

Generally, sensitivity changes become more rapid as the output current increases. In fact, for an individual tube, the sensitivity change is approximately a function of the product of time and output current, especially for rather large currents. It may be that changes in dynode characteristics result from an alteration of the surface caused by the impact of the primary electrons. One possibility is that cesium is released from the surface and then recombines elsewhere in the tube. The release of cesium may be expected to be more or less proportional to total charge impact, as indicated above.

When sensitivity of the tube is lost as a result of the passage of a heavy current, it frequently is recovered when the tube is removed from operation. This recovery is accelerated by an increase in temperature within the permitted range. (Too high a temperature may cause permanent loss in sensitivity.) Recovery is probably the result of cesium returning to the dynode surfaces.

Because recovery occurs even during operation, sensitivity loss is not determined by the product of current and time at very low currents. Fig. 65

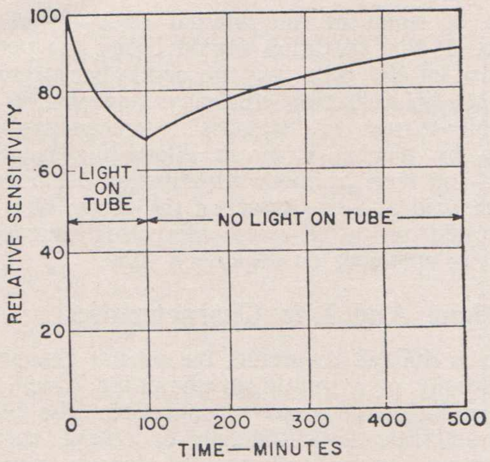


Fig. 65—Short-time fatigue and recovery characteristics of a typical 1P21 operating at 100 volts per stage and with a light source adjusted to give 100 microampere initial anode current. At the end of 100 minutes the light is turned off and the tube allowed to recover sensitivity. Tubes recover approximately as shown, whether the voltage is on or off.

shows the short-time fatigue and recovery characteristic of a typical 1P21 having an initial anode current of 100 microamperes; the recovery is considerably slower than the fatigue. At currents of 10 microamperes or less, this situation may be reversed. For a tube with Cs-Sb dynodes, therefore, little improvement in stability is achieved by use of an anode current smaller than 10 microamperes.

Over a longer period, the rate of sensitivity change decreases, as shown in Fig. 66, but the change tends to become more permanent and recovery is only partial.

Multiplier phototubes having silver-magnesium or copper-beryllium dynodes are much more stable at high operating currents than those having

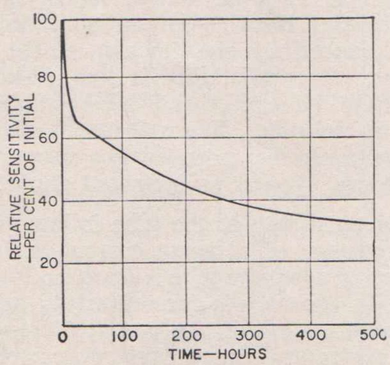


Fig. 66 — Typical sensitivity loss for a 1P21 operating at 100 volts per stage for a period of 500 hours. Initial anode current is 100 microamperes and is readjusted to this operating value at 48, 168, and 360 hours.

cesium-antimony dynodes. There is no significant difference in stability between silver-magnesium or copper-beryllium dynodes. A typical characteristic of sensitivity change on life is shown in Fig. 67 for a type 6342A multiplier phototube (silver-magnesium dynodes). The sensitivity tends to increase at first, then levels off and decreases very slowly. The operating current in this case is 2 milliamperes, as compared to the 100-microampere current used for the Cs-Sb dynodes typified by the characteristic shown in Fig. 66.

In addition to the life characteristics, which are probably the result of changes in the dynode layer itself, other changes of a temporary nature also occur. Not all these changes are well understood; some are charging of insulators in the tube.

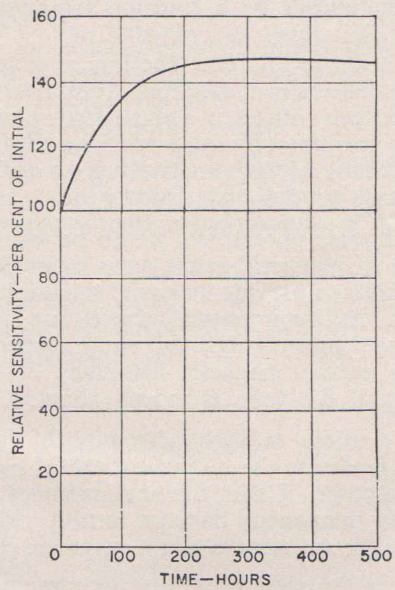


Fig. 67—Typical sensitivity variation on life for a 6342A multiplier phototube (silver magnesium dynodes) operating with 1250-volt anode supply voltage for a period of 500 hours. Initial anode current is 2 milliamperes and is readjusted to this operating value at 48, 168 and 360 hours.

Fig. 68 illustrates one of the peculiar instabilities which are sometimes observed in multiplier phototubes. When the light is first turned on, the current apparently overshoots and then decays to a steady value. This particular phenomenon, observed in a developmental type, was probably the result of the charging of the supporting insulator for the dynodes. The effect was observed to occur more rapidly at higher currents, presumably because of the greater charging current. Observation of the phenomenon at different stages in the tube showed that it originated between the first and second stages. Electrons striking the insulator probably resulted in secondary emission and a resultant positive charge.

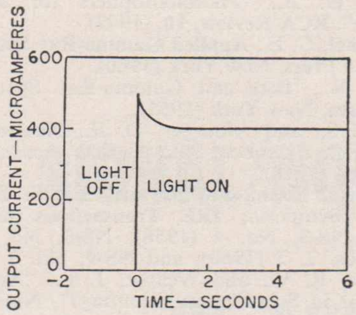


Fig. 68—Sudden shift in anode current probably as the result of insulator spacer charging. Observation was made using an experimental multiplier phototube in which the effect was unusually large.

The change in potential affected the electron optics in the space between dynodes. The effect was observed as an increase in some tubes and as a decrease in others. This particular development tube type was modified to minimize the effect by use of a metal shield to cover part of the spacer at each end of the first dynode space.

A related phenomenon is the variation of pulse height with pulse-count rate in scintillation-counting applications. Thus, when a radioactive source is brought closer to a scintillating crystal a greater rate of scintillations should be produced, all having the same magnitude. In a particular multiplier phototube a few per cent change in amplitude may result and cause problems in measurement. Fig. 69 shows the typically minor variation of pulse height with pulse-count rate for a type 6342A multiplier phototube.[35]

In order to investigate the phenomena of pulse-height variation with pulse-count rate, a purposely exaggerated experiment was devised. Instead of a scintillating crystal, a pulsed cathode-ray tube was used as a light source. Two pulse rates were studied: 100 and 10,000 pulses per second. Pulse duration was one microsecond; decay time to 0.1 maximum was 0.1 microsecond. The experiment was devised to study the rate at which the multiplier-phototube output response changed when the pulse rate was suddenly switched between the two rates. Tubes such as the 6342A, and especially the 8053 and

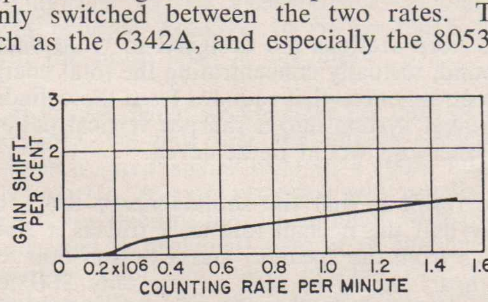


Fig. 69—Typical variation of pulse height with pulse-count rate for a 6342A. (Cs^{137} source with a NaI (Tl) source).

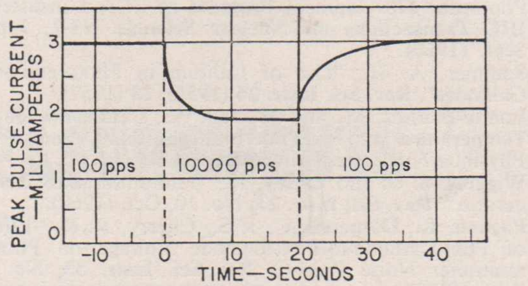


Fig. 70—Variation of output pulse height as the rate of pulsing is changed in a poorly designed experimental tube. Light pulses were provided from a cathode-ray tube. At the left of the graph, which shows the pulse-amplitude envelope with time for the output of the multiplier phototube, the pulses are at 100 per second. The pulse rate is increased suddenly to 10,000 per second and again reduced as indicated. Changes in amplitude are probably the result of insulator charging.

8054, showed practically no effect (of the order of one per cent or less). Fig. 70 shows the pulses during the switching procedure for a competitor's multiplier phototube. The adjustment decay curves are approximately exponential. The phenomena were completely reversible and were observed on many different tube types (to a lesser extent). The time-decay period of several seconds suggests the changing of an insulator spacer to a new potential as the result of the increased charge flow and the subsequent modification of interdynode potential fields.

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7000-POUND LOUDSPEAKER

The spectacular "Fountain of the Planets" at the New York World's Fair is cued by a huge RCA loudspeaker, the most powerful ever built. Each element in the Fountain's display of water patterns and fireworks is synchronized with music and the rainbow of lights colouring the water jets. The music was recorded on tape by a 60-piece philharmonic orchestra and is reproduced by RCA professional audio tape equipment. Musical notes occupy only half the tape's width; the remainder carries tone pulses that cue a computer-type network in controlling the Fountain's thousands of operations.

Heart of the automatic system is a 7000-pound loudspeaker with a maximum output equal to some 1000 console phonographs operating at full volume. The $30,000 speaker for the Fountain display was designed by RCA Laboratories, and manufactured by Commercial Radio-Sound, distributor of RCA engineered sound products in the New York area.

The speaker appears as two huge metal saucers joined bottom to bottom, by a cellular structure. This centre unit is made up of three circular tiers each containing 16 cast-aluminium horn sections. A separate speaker driver mechanism, used with each of the 48 horn sections, is capable of producing the full spectrum of sound (50 to 15,000 cycles).

The horn sections are designed to "fold back" the sound, virtually concentrating the total energy at a central source that radiates from the cylindrical speaker system into a sharper vertical pattern than otherwise would be achieved.

The result is that the sound energy drops off at only half the normal rate as it travels a given distance from the speaker, and a person 600 feet away hears nearly as well as one only 300 feet away. At the Fair, the closest approach to the huge speaker is 300 feet, the radius of the Fountain.

SIGNAL/NOISE MEASUREMENTS IN AUDIO AMPLIFIERS

The classic method of measuring signal-to-noise ratio in an audio amplifier consists of setting the amplifier up with an input signal that results in the development of the full rated output of the amplifier; the output level is then noted, the input signal is removed, and the output level again measured. The ratio between the two measurements then gives us the figure we require. In the case of preamplifiers, the amplifier is set up to develop a specified output level. Because operating levels and other conditions vary, it is often necessary to stipulate the conditions under which the measurement has been made.

The results obtained in this way will depend on two factors, in addition to the characteristics of the amplifier on which the measurement is being made. The two additional factors are (a) the signal level at the input of the amplifier, and (b) the bandwidth of the instrument used to measure the output levels.

Signal Level

When we are dealing with main amplifier units, which in general contain no operational controls, the input signal level is determined by the necessity to drive the amplifier to the rated output. In this case, the input signal level is in general unimportant to the measurement, as the signal level may be expected to be so much greater than the noise level at the input.

However, when we consider the case of a preamplifier, we find that the unit is designed to deliver a rated signal level to a main amplifier. The margin of gain provided will usually mean that if we operate the preamplifier with the gain (and level if provided) control at the maximum position, then the rated output level will be realised with a very small input level, which is in fact much smaller than the input level with which the unit is intended to be operated.

If we regard the noise developed in the first stage of a preamplifier as a constant, then with small input signal levels the measured signal-to-noise ratio will depend on the actual input signal level used. To get a realistic measurement, therefore, it is customary to set the amplifier up with the designed input signal level, and then adjust the gain control for the required output level. This more nearly approximates actual operation, and results in a better signal-to-noise ratio. In many cases where the information is not otherwise stated, it will be necessary to specify the conditions under which the measurement is made. As a typical example, a preamplifier was taken at random and tested. The designed input signal level is 5 mv, and signal-to-noise ratio measured as just described is —65 db. However, when a 10 mv signal is applied and the gain control readjusted to give the required output level, the ratio measures at better than —70 db. If we set the gain control at the maximum position and adjust the input level for the required output, the input becomes about 2 mv and the signal-to-noise ratio falls to —57 db.

Bandwidth

Although the problems of relating signal-to-noise measurements with preamplifier input levels is easily solved by stating the conditions of measurement, the problems associated with the bandwidth of the measuring device cannot be disposed of so readily. For one thing, there are often several types of noise present simultaneously, some of them having their own characteristic frequency coverage.

It will usually happen that the bandwidth over which signal-to-noise measurements are made in an audio amplifier will be determined either by the response of the amplifier itself, or the response of the analyser or other unit used to make the measurements, or both. Because most analysers

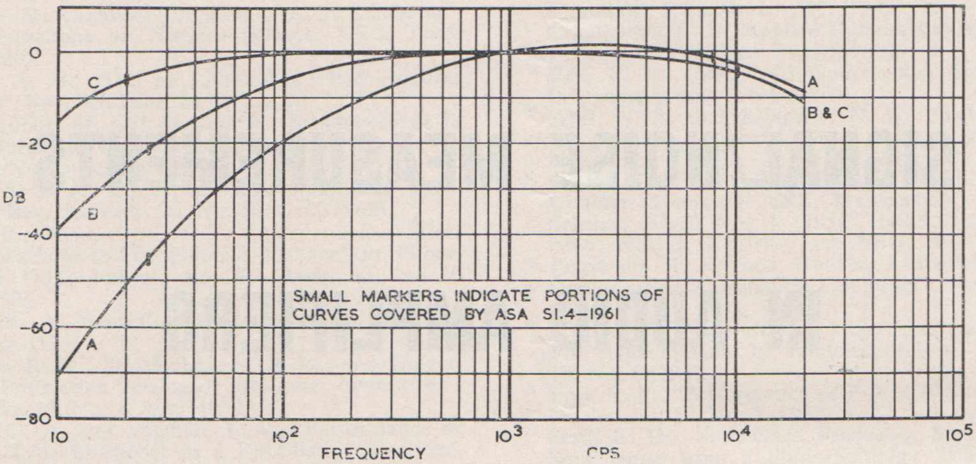


Fig. 1

used today will have a very wide bandwidth, it is often assumed, in the absence of other data, that the signal-to-noise measurements apply over the frequency range of the amplifier. This is a very reasonable assumption.

However, published specifications for the testing of audio amplifiers suggest or require the inclusion in the measuring device or immediately ahead of it a weighting network which will modify the response of the instrument, and therefore will modify the bandwidth over which the measurements are made. The "Specification for Methods of Measuring and Expressing the Performance of Audio Frequency Amplifiers," April, 1962, issued by the Audio Manufacturers' Group of the British Radio and Electrical Manufacturers' Association, suggests that measurements be taken both with and without a weighting network.

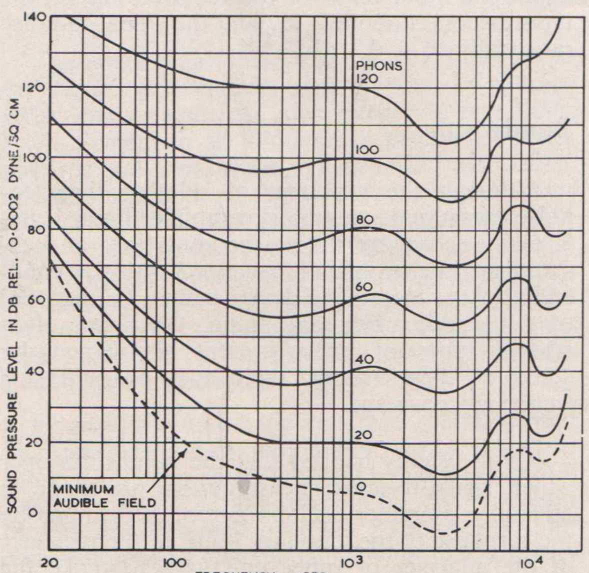


Fig. 2

Paragraph 4.8.2. of that Specification says in part: "Measurements should preferably be taken both with and without a weighting network between the amplifier output and the input to the measuring instrument; when a weighting network is used its characteristics should comply with those recommended by the International Electrotechnical Commission, as given in curve A of IEC Publication No. 123 — Recommendations for Sound Meters."

Turning to the American scene, we find that Institute of High Fidelity Manufacturers Inc. Publication IHFM-A-200, dated September, 1959, entitled "IHFM Standard Methods of Measurement for Amplifiers," requires the use of a weighting network. Paragraph 2.5.3 says in part: "In addition, the frequency response of the (measuring) instrument shall be weighted so that it follows the 40 db (A) curve of ASA Standard Z24.3-1944." This Standard has since been replaced by ASA Standard S1.4-1961.

Weighting Networks

Before going on to discuss the matter further, it will be profitable to see just what the two weighting networks, or rather, their response curves, mean in practical terms. An examination of the specifications mentioned earlier in this note shows that there are three weighting curves mentioned in each, and the curves are in fact the same in each case. The curves, with their identifying letters, are shown in Fig. 1.

These curves have been plotted in accordance with the specified curves as detailed in the IEC Publication No. 123 already mentioned, in which the shape of the curve is specified for the frequency range 10 cps to 20 Kc. However, the tolerances on all three curves laid down by the IEC is plus 5 db and minus infinity at 25 cps and below, and is plus 6 db and minus infinity at 10 Kc and above. Tolerance over the other portions of the frequency coverage varies from ±2 db to ±6 db, depending on frequency. If further details are required, reference should be made to the specifications.

Probably for the reason just explained, the curves given in the ASA Standard S1.4-1961 cover smaller frequency ranges. The A curve covers 25 cps to 8 Kc, the B curve 25 cps to 10 Kc, and the C curve 20 cps to 10 Kc. In other respects, however, the curves are essentially identical.

It will readily be seen that the use of curve A, which is the one with which we are concerned here, permits the noise level present at the lower frequencies to be much higher than that in the mid-frequency range. The use of such a weighting network will allow the specification of a much superior signal-to-noise ratio than could be done using an indicator with a flat frequency response.

Reason for Weighting Networks

It may at first, to those less familiar with the techniques described here, seem that the use of a weighting network is moving away from the presentation of a true picture of the state of affairs. It could be pointed out that the shape of the response curve of such a network is such as to reduce the effect of some of the more troublesome types of noise. Among these could be included stray 50 cps pickup, 100 cps noise resulting from the rectification process in the power supply, and the characteristic 1/f noise of a transistor.

On the face of it, these points are valid, until the matter is considered a little more closely. The reason for the inclusion of the weighting network is to give a closer relationship between the noise level present at the various frequencies, and the characteristic of the device with which the noise is going to be heard, that is, the ear.

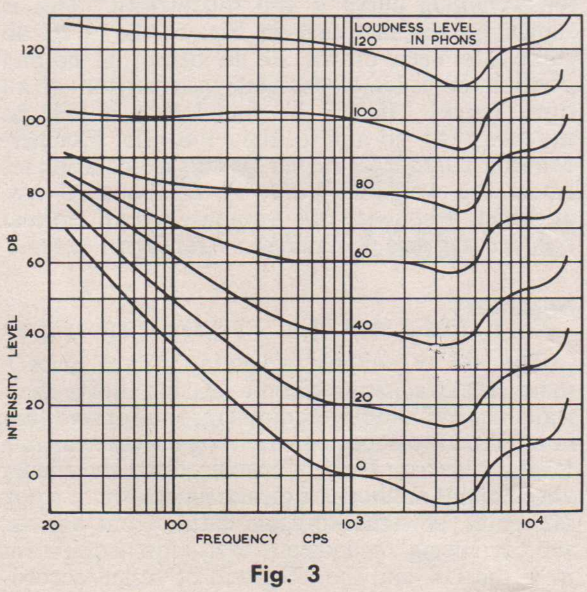


Fig. 3

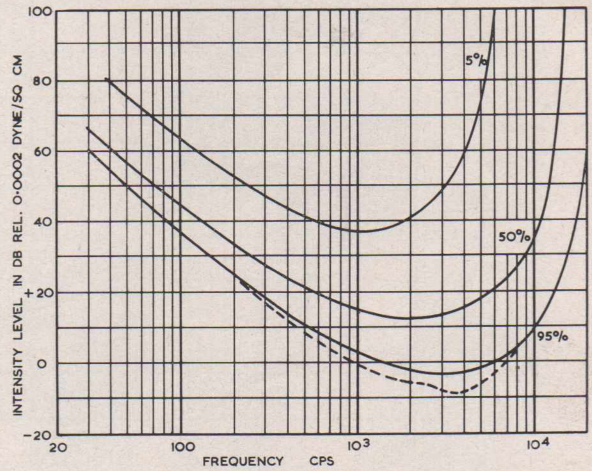


Fig. 4

It has long been known that the human ear is not only far from being a linear device, but also has a frequency response which is far from flat. Every handbook on high fidelity reproduces a set of Fletcher-Munson curves, which show the relative response of the ear with respect to the response at 1 Kc, taken at various sound levels. A set of these curves is reproduced in Fig. 2. The zero loudness level was taken at the threshold of hearing, and the other curves at relative levels as indicated. It is interesting to note that the response of the ear tends to flatten out as the loudness is increased, but it is at the lower sound levels that our attention must be directed in the case of noise, as in any case we expect the noise output from an amplifier to be at a very low level.

Further work done on this subject since the publication of the Fletcher-Munson curves is shown in Fig. 3. Here we see the result of work carried out by Robinson and Dadson of the National Physical Laboratory (UK), carried out using more advanced techniques. These latest figures show small variations when compared with the earlier figures of Fletcher-Munson, but tell the same basic story. To illustrate the story more clearly, reference should also be made to Fig. 4. This figure shows the American Standard Association reference threshold of hearing, together with three other curves which result from tests of large numbers of subjects. These three curves represent the threshold of hearing contour for percentages of the total population. For example, 5% cannot hear pure tones below the levels indicated by the curve so marked, 50% cannot hear below the next curve, and 95% cannot hear below the third curve.

It must be noted that although the actual threshold of hearing may vary from one person to

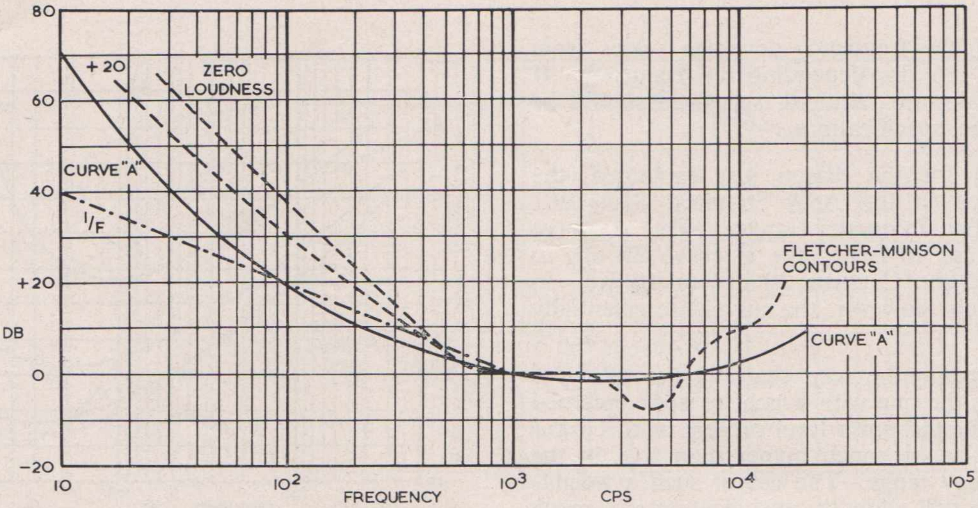


Fig. 5

another, the curves show that the threshold of hearing contours remain remarkably similar. All of this can be retold in terms with which the amplifier experimenters are more familiar. If we regard the ear as having a certain frequency response at the —3 db points, then the response will be widened, particularly in the bass region, as the mid-frequency level is increased.

It can now be seen that if we take the response of the ear into consideration, we can tolerate much more noise, say at 100 cps, than we can at 1 Kc, whilst the subjective effect, or excitation of the ear is not increased. If the curve of the weighting network matches the curve of the hearing threshold, then we can assert that a subjective test will show no more noise at the lower frequencies than is present at 1 Kc. This is in spite of the fact that the amplifier may in fact have a considerably higher noise output at the lower frequencies. After all, the main object is to make sure that we cannot HEAR any noise, not to make sure that it is not present.

A Comparison

After what has already been said, it will be interesting to compare the weighting network curves with the hearing threshold contours, as a check on the validity of the argument. To do this, Fig. 5 has been prepared in which will be seen the reciprocal of the A curve mentioned in the two specifications quoted earlier, together with two hearing contours taken from Fletcher-Munson, one of these being the threshold or zero loudness level curve and the other the +20 phon loudness contour.

If we take the zero loudness or threshold of hearing curve in Fig. 5, then we can say that all sound levels that remain below the zero loudness curve, with respect to the 1 Kc reference, will be heard at the same apparent loudness. It will immediately be seen that this will allow much higher noise levels at frequencies below 1 Kc before the apparent noise level becomes greater than that at the reference frequency.

If now we consider the reciprocal of the weighting curve A, this gives us the level contour to which the relevant specifications allow the noise at various frequencies to rise, with respect to the 1 Kc point. There is a strong similarity between the weighting curve A and the Fletcher-Munson zero loudness contour, and, of course, this is not accidental. The comparison of these curves in this way gives further weight to the reasons already mentioned for the use of weighting curves, and shows that this is a legitimate process to adopt in assessing noise performance of audio equipment.

Even if we take a case which is worse, and use the +20 db Fletcher-Munson curve, that is, the hearing contour with the level at the reference 20 db above that for the zero loudness contour, the weighting curve is still satisfactory. This is shown by the fact that in Fig. 5, the +20 db curve has been drawn 20 db below its normal position in order to facilitate comparison of all three curves. It will be found that it will be necessary to go up to the +40 db Fletcher-Munson contour or higher before the contour re-enters the weighting curve A at about 20 cps, at which frequency the response of all normal speaker systems is falling off rapidly.

Summary

The use of suitable weighting curves gives a more realistic appreciation of the noise performance of audio equipment, and there are internationally-accepted weighting curves available for the purpose. Makers' specifications are usually vague about methods of measurement, but a study of figures of signal-to-noise ratios from various sources seems to indicate that most equipment from the UK and the USA will be tested according to the specifications mentioned; this has to be borne in mind when comparing equipments, some of which may have been tested using flat response indicators, and which therefore appear to have a lower signal-to-noise ratio.

As with other methods of testing amplifier performance, it is necessary to state the conditions of measurement for the figures to carry a maximum amount of information. The necessity for more complete and meaningful specifications for audio equipment has often been mentioned in these pages, and this is yet one more aspect of that argument.

COMMONWEALTH CABLE

Continued from page 190

by December, 1962, and the remaining trans-Pacific link from Fiji to Vancouver came into public service last December. The Atlantic and Pacific cable are connected by a microwave radio system across Canada.

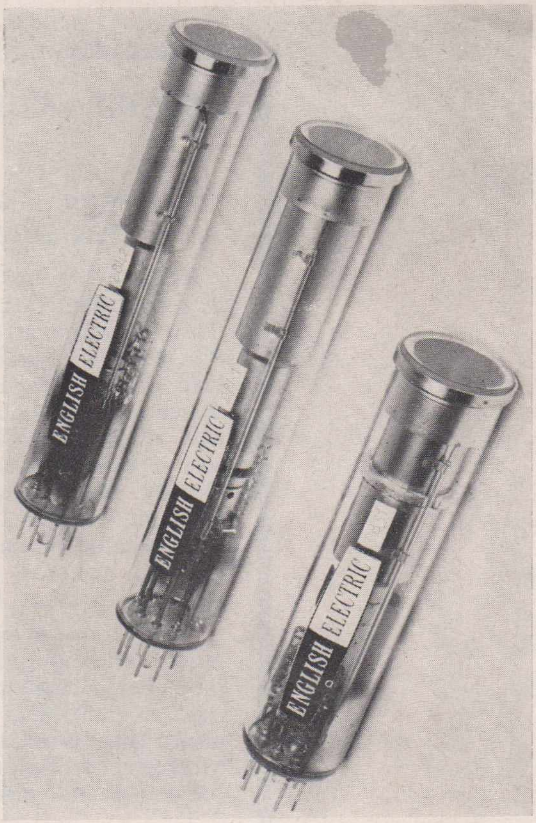
The first section of SEACOM from Hong Kong to Singapore will be opened for public service about the beginning of February, 1965, but it may be several years before the completion of the system between Singapore and Sydney.

The original grand concept behind this new Commonwealth telephone communications system was that it should girdle the world, but there must necessarily be some years of planning, organisation and construction before this can be achieved. Meanwhile, Mercury, Monarch and Recorder will get on with the latest link.

(Courtesy, U.K. Information Service.)

NEWS AND NEW RELEASES

EEV SEPARATE MESH VIDICONS



EEV has introduced into its range of television camera tubes three new high resolution 1-inch vidicons type P831, P841 (JEDEC 8507), and P842 (JEDEC 8541). In these tubes a separate mesh construction is used which, combined with an improved photo-conductive layer, provides high sensitivity coupled with low signal and low dark current shading effects. When operated at high voltages, higher and more uniform resolution and improved signal uniformity are obtained over a wider range of signal voltage than can be expected from standard vidicons. To derive full advantage of the uniformity of the photo-conductive layer a suitable focusing coil and deflecting yoke should be used which will not introduce scanning-beam-landing errors.

Limiting resolutions up to 1,000 TV lines may be obtained at the centre of the picture when these tubes are operated with high voltages on grid 3 and the mesh. Under these conditions optimum resolution is achieved when grid 3 voltage is 0.6 to 0.7 of the mesh voltage. The P831 and P842 have the additional features of low power (0.6 watt) heaters which make them eminently suitable for small battery powered cameras.

The P831 is a short ruggedised vidicon for use under arduous conditions of severe shock and vibration experienced in many industrial and military applications, whilst the P842 is suitable for broadcast, educational, and industrial applications. Selected tubes are available for colour and special broadcast purposes. The P841 differs from the P842 only in the type of heater used, which is the standard 4 watt variety. It is also suitable for general applications as the P842. Similarly selected tubes are available for special applications.

BRITISH EXHIBITION, AUSTRALIA, 1964

Moore Park, Sydney, N.S.W.
25th September - 10th October

EEV will be exhibiting at the above exhibition in association with their Australian representatives, Amalgamated Wireless Valve Company Pty. Ltd., on stand A18 in the Manufacturers' Hall. The display will comprise typical samples drawn from all the main groups of EEV products, with special emphasis upon Conventional Valves and Television Camera Tubes for which EEV already has substantial business in Australia. Vacuum Variable Capacitors will also be prominent because of their obvious advantages in that climate, and the wide opportunities for their adoption in many radio equipments.

Another main feature will be made of Microwave valves for Radar and Communications, these being considered as having great potential sales in Australia. The marketing effort will be under the personal direction of the EEV Sales Manager, Mr. Bob Coulson, who will be available for consultation throughout the Exhibition.

Editor .... **Bernard J. Simpson**

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