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A Fundamental Analysis of Loud Speakers

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By John F. Nielsen

Engineering Dept., F. A. D. Andrea, Inc.

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A Fundamental Analysis of Loud Speakers

A Radio Club of America Paper Discussing the Signals a Loud Speaker Is Required to Reproduce—Factors Determining the Quality of Output from a Loud Speaker—Some Causes of Distortion in Reproducers

By JOHN F. NIELSEN

Engineering Dept., F. A. D. Andrea, Inc.

CENTURIES before we dreamed of modern loud speaking equipment, the natives of Africa had crude systems of communication in the form of cocoanut shells connected by a taut string, which acted as a medium for transmitting sound vibrations. Outgrowths of these crude systems of communication are our present telephone network and radio systems.

The primary function of any communication system is to transmit intelligence and entertainment. In considering the operation of any such system, the reproduced sounds may be referred to as having two properties, i.e., intelligibility and naturalness. In radio broadcasting, the communication system is supplemented by entertainment, and the property of naturalness, therefore, increases in importance in the reproduced speech. Moreover, the transmission of music imposes even more severe requirements upon a communication system because of the wide range of frequencies and intensities required for proper appreciation. It is the purpose of this paper to present in a popular fashion a few of the fundamentals of operation of one link of such a system, namely, the acoustic reproducer.

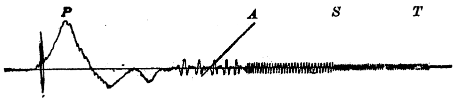


FIG. 1

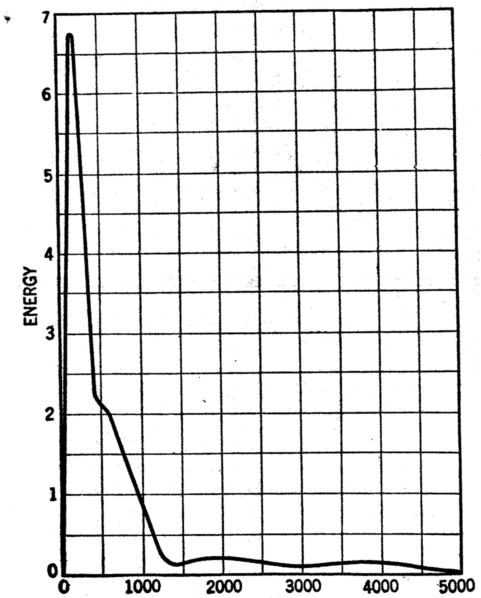


FIG. 2

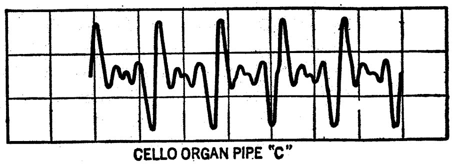
The fact that there is ample opportunity for distortion in those parts of a radio system preceding the loud speaker is apparent from a consideration of the change the speech wave must undergo between studio and loud speaker. Although there is equal opportunity for distortion in the transmitter and receiver, transmitter distortion is generally negligible. The fact that a broadcasting station serves a large volume of receiving sets would point to this state of affairs, since the receiver must be far cheaper than the transmitter. Quality in the receiving set itself is affected by the sharpness of tuning of the radio-frequency stages, by the time constant of the grid leak-condenser combination of the detector circuit, by the characteristic and power capacity of the audio amplifier, and finally, by the loud speaker itself.

Before considering in detail the characteristics of loud speakers, let us digress for the moment and consider the nature of the signal it must reproduce. In general, the loud speaker should reproduce faithfully both speech and music, each of which presents its own peculiar problems.

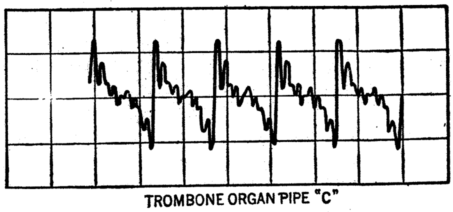
Speech consists in general of two fundamental types of sound, namely, continuents and stops, and their combinations[1] (see bibliography on page 590). The former are those produced by a continuous flow of air, such as the letters F, S, etc., while the latter consists of those sounds produced by a sudden stoppage of air, such as letters, P, B, and M.

For instance, analyzing the word "Past," we notice, in Fig. 1, that "P" appears as a transient indicated by a high broad peak; "A," a nearly continuous frequency of approximately 800 cycles varying in amplitude; "S" and "T" are of a high frequency character, of low amplitude, and continuous.

It is readily seen from the nature of the word that, in order to obtain perfect reproduction, the loud speaker must reproduce frequencies of an extreme nature with proper relative amplitude and without time lag. If a loud speaker is inefficient at the upper extreme of its frequency spectrum, it is generally noticed that "S," "T," and other high-frequency combinations, are either missing entirely or are of low relative intensity. In addition, a loud speaker may have resonant peaks at certain frequencies which may so exaggerate some sounds as to completely mask others. Speech energy is distributed over a frequency band of about 50 to 10,000 cycles per second and, in general, has a maximum between 150 and 250 cycles. The frequency distribution of speech energy is shown graphically in Fig. 2.



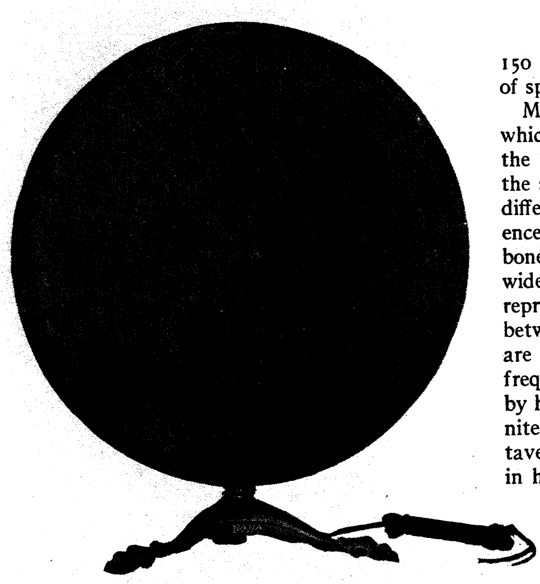
CELLO ORGAN PIPE "C"



TROMBONE ORGAN PIPE "C"

FIG. 3

Music is characterized by various harmonics which may be of larger or smaller amplitude than the fundamental. These harmonics distinguish the same note in the same octave as played on different instruments. Fig. 3 shows the difference between a cello organ pipe "C" and a trombone organ pipe "C". It is readily seen that a wide frequency spectrum must be faithfully reproduced to enable the listener to distinguish between different instruments. Musical sounds are characterized by being sustained at definite frequencies for comparatively long periods and by having the change in pitch take place in definite musical intervals called, thirds, fifths, octaves, etc. Musical notes are usually very rich in harmonics; in some instances, as in the case of the cello, the harmonics may even exceed the fundamental frequency in intensity. Musical energy is distributed over a frequency band of from about 16 cycles to something over 10,000 cyles



A TYPICAL MODERN CONE LOUD SPEAKER

per second, and usually has its maximum below 1000 cycles. However, it has been found that a frequency range of about 50 to 5000 cycles is tolerable for natural reproduction of both speech and music.[2] (see bibliography on page 590).

Having considered the nature of speech and music, it is evident that the perfect reproducer should give constant response when actuated by constant audio signal impulses, and be free from resonant effects or hangovers of any sort. It is at once apparent that the action of the loud speaker may depend to some extent on the circuit elements used to couple it to the last amplifier tube, since the coupling devices may resonate the loud speaker at some audio frequency.

It has been variously suggested that the quality of reproduced speech and music depends both upon the average response of the sound reproducing element to steady tones, and to the irregularity of the response frequency characteristics. The former serves as a basis for a rough estimate of quality and relative loudness of fundamental notes, while the latter is an index from which it is possible to predetermine the clarity of the reproduced speech and music. That is to say, a response-frequency characteristic obtained by applying steady single frequencies to the loud speaker gives only a general indication of the action of the loud speaker when it is actuated by transient notes, sudden stops, etc. To predict the effect of hangovers which tend to confuse the listener by changing the relative phase displacement of independent notes, it is necessary to know something about the resonant peaks in the response characteristic. Obviously, quality also depends on the nature of the load characteristic of the motor element. Since, as previously pointed out, the energy of both speech and music is more or less concentrated below 1000 cycles per second, the loud speaker, in actual service, must necessarily operate with a wide variation in amplitude. For this reason it is desirable that the efficiency of the loud speaker be approximately constant for all armature excursions commonly met in practice, otherwise, the large amplitude frequency notes, or the smaller amplitude high-frequency notes, will be over-emphasized.

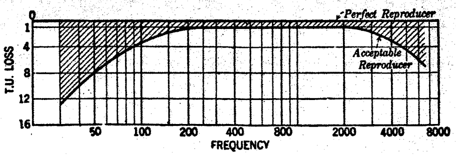


FIG. 4

It has been shown elsewhere that musical tones between 200 and 2000 cycles have in general the same average intensity and that the human ear at the intensities generally used in reproduced music or speech has about the same sensitivity over this range.[3] (see bibliography on page 590). Further, it has been shown that departures from faithful reproduction above and below this range are far less noticeable than departures within this range. For example, changes in response at 70 or 6000 cycles are about one tenth as serious as the same changes between 200 and 2000 cycles. As the range of maximum sensitivity is approached, given departures from true reproduction become more serious; thus, at 90 or 4000 cycles, a given departure from the true signal is about half as serious as at 1000 cycles. Consequently, if it is taken for granted that equal departures from the original signal do equal damage at points of equal auditory sensitivity, it is possible to arrive at a basis for determining the maximum departure of response from perfect reproduction allowable for tolerable reproduction. Using this as a basis, a response-frequency characteristic can be drawn which represents approximately the limit beyond which it is unnecessary to go for acceptable reproduction. Such a curve is shown in Fig. 4. From the standpoint of relative loudness, the response-frequency characteristic of any loud speaker which falls within the shaded area is substantially as acceptable as a perfect unit. This, of course, holds only for relatively smooth characteristics, since resonance peaks of relatively large amplitude and sufficient sharpness always introduce sustained vibrations or hangovers, and these constitute an entirely different type of distortion. Representative response characteristics of two commercial cone loud speakers, are shown in Fig. 5.

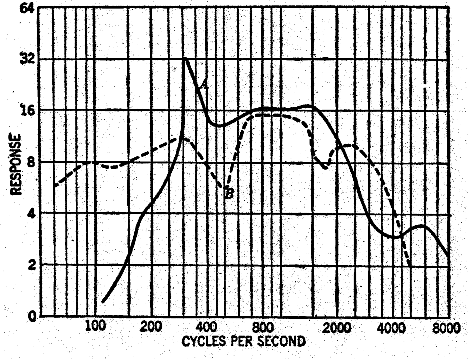


FIG. 5

A comprehensive method of measuring or rating a loud speaker in terms of its resonance peaks is probably as unnecessary as it is difficult. There are, however, a few conclusions that may readily be drawn from a first inspection of the response curve. A broad peak indicates high damping action, and a sharp peak, low damping. Therefore, if the broadness of any resonance peak is rated in terms of multiples or sub-multiples of the geometric mean frequency, the relative length of the hangover can be approximately determined. Thus, a resonance peak of unit breadth at, say, seven tenths of its maximum height, will allow vibrations to persist roughly half as long as will one of the same amplitude and half its breadth, and in the former, these vibrations, for a given frequency, are about half as serious. It therefore appears worth while to examine closely the height and breadth of each resonance peak if its amplitude exceeds the average characteristic by 40 to 50 per cent. The absolute height of peaks that may be neglected is more or less a matter of opinion, and therefore, limits can only be fixed by measurement of the undesirable effects produced. Certainly, greatest harm will be produced by peaks falling within the frequency spectrum, most important from the standpoint of auditory sensitivity. Whence it would appear that the harmful effects of peaks can be weighted in accordance with the response curve of Fig. 4.

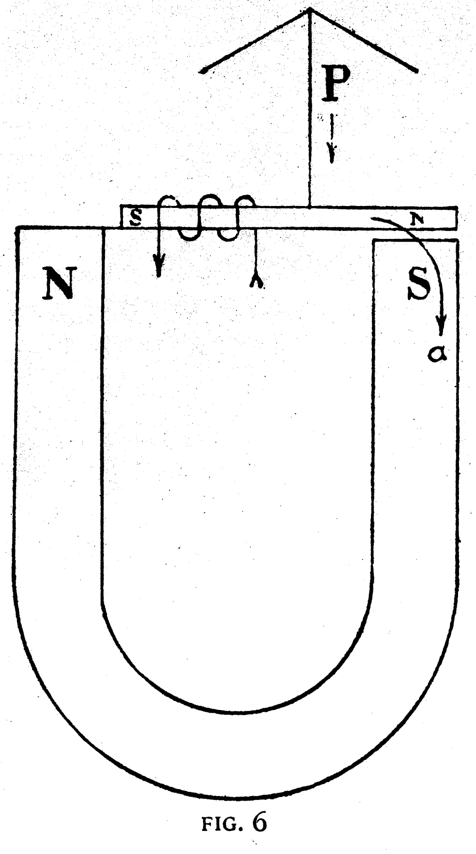


FIG. 6

THE LOUD SPEAKER'S MECHANISM

HAVING considered, in general, the desirable characteristics of loud speakers, let us investigate the mechanism that is to produce these characteristics.

A loud speaker may be considered as made up of three systems:

1. The motor element, which converts the electrical impulses into corresponding mechanical vibrations.
2. The coupling system, which transmits the mechanical vibrations from motor to diaphragm.
3. The diaphragm or loading device, which radiates the mechanical vibrations into the air as waves of sound.

The simplest type of motor element in common use is the vibrating reed type. It consists, in general, of an armature pivoted or hinged at one end and actuated at the other, a magnet to supply a steady uni-directional magnetic flux, and a winding coupled to the magnetic circuit which is capable of superimposing an alternating or pulsating signal flux on the steady flux already present. A schematic diagram of such a unit is shown in Fig. 6. The free end of the armature is normally at rest in a steady uni-directional magnetic field supplied by the permanent magnet. When an alternating or pulsating current is passed through the coil coupled to the armature, the free end of the armature is alternately attracted and repulsed by the remaining pole. Thus, the electrical impulses in the coil are converted into mechanical vibrations which are, in turn, transmitted to a diaphragm through the medium of the driving rod.

A brief inspection of the figure will show that this type of motor is not free from distortion. Let Φ represent the steady flux across the air gap; $\alpha \sin \omega t$, the flux due to a signal current through the windings, and P the force acting on the armature.

Then:

$$
\begin{aligned}
P &= K(\phi + \alpha \sin \omega t)^2 \\
&= 2K\phi\alpha \sin \omega t + K\alpha^2 \sin^2 \omega t + K\phi^2 \\
&= 2K\phi\alpha \sin \omega t - \frac{K\alpha^2}{2}\cos 2\omega t + K\frac{(2\phi^2 + \alpha^2)}{2}
\end{aligned}
$$

Obviously, the first term represents a reproduction of the signal impulse, while the second term represents a second harmonic of the signal[4] (see bibliography on page 590). The remainder of the force adds a steady component to the steady pull exerted by the permanent magnet. It would seem, since that part of the coefficient of the second harmonic which is proportional to the signal, appears as a squared term, that the second harmonic could be made neg-

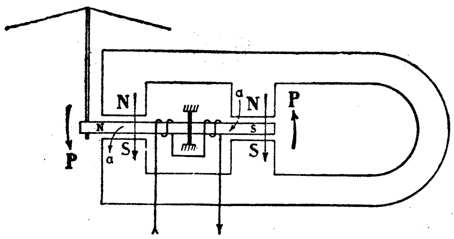


FIG. 7

ligibly small by the simple expedient of keeping the ratio $\frac{\Phi}{\alpha}$, large. Space will hardly permit a discussion of this point. Suffice it to say that good design dictates a limit to this ratio which must necessarily be determined by efficiency, and saturation of armature and pole pieces. Moreover, if a large permanent magnet is used, a stiff armature suspension will be required. Since the reed itself has a resonant period, great care must be exercised to properly fix this period in the frequency spectrum and to provide proper damping. Greatest apparent efficiency will, of course, be obtained by allowing the resonant period of the reed to fall between, say, 800 cycles and 2500 cycles. Best quality can generally be obtained if the resonant period falls near 100 cycles, and is highly damped. It is at once apparent that there are a number of factors which limit both the efficiency and the quality of this type of instrument.

Another type of motor of more recent design, which is very much in favor at present, is the balanced armature type shown in Fig. 7. Among other advantages, this type of structure will take larger loads without producing second harmonics of the signal. Using the same nomenclature as above, we have:

Force due to one set of poles

$= K(\phi + \alpha \sin \omega t)^2$

Force due to the remaining set of poles

$= K(\phi - \alpha \sin \omega t)^2$

The total force acting on the armature is obviously the difference of these two, or:

$$P = K(\phi + \alpha \sin \omega t)^2 - K(\phi - \alpha \sin \omega t)^2 = 4 K \phi \alpha \sin \omega t$$

In this case, the overtone and the additional steady pull, due to the signal, which were present in the output of the reed type motor, vanish. This results, then, in an armature vibration, which is proportional to the signal and which contains no distorting components. It is also a fact that the balanced type of unit will in general reproduce much stronger signals without undue distortion than is the case with the reed type unit. Moreover, if the load contains sufficient damping, the response-frequency characteristic will obviously be more uniform than that of the reed type motor. This type of unit is, of course, not entirely free from resonance, although its fundamental resonant peak is generally not as serious as that of the reed type unit.

Fig. 8 shows the moving coil type of motor. Its operation is, in general, similar to that of the units described above, and lack of space forbids further comment here. This type of instrument may be made very free of mechanical resonant effects, since the mass and stiffness of the armature and its suspension system may be reduced.

CAUSES OF DISTORTION

THERE are numerous causes of distortion in loud speaker motors in addition to those already mentioned. Probably the worst offenders are:

1. Saturation of armature and pole faces.
2. Iron losses, including hysteresis and eddy currents.

A detailed discussion of the effects of saturation is beyond the scope of this paper. A simple analysis will, however, serve to point out the general effects to be expected. Saturation occurs in practically all commercial loud speaker motors, at relatively large armature excursions. This particularly applies to reed type motors and balanced armature type motors. It seems reasonable to suspect that the saturation of armature and pole faces in these instruments may be due, not to the alternating current in the windings directly, but rather to the permanent magneto-motive force producing large momentary fluxes through the pole faces and armature at large armature excursions. As is often the case, a direct current bias in the windings of a loud speaker, used directly in the plate circuit of an amplifier, may cause armature saturation at very small armature excursions. Be the cause what it may, the effects are the same in that they add odd harmonics of the signal output. Consider a sinusoidal signal as shown in Fig. 9, and for simplicity, consider the magnetization curve of the iron involved to be shown in Fig. 10. This, of course, neglects hysteresis and the curvature of the B-H curve, but it is sufficient to illustrate the point. A sine wave signal of sufficient amplitude will produce an armature flux as shown. That is, the peaks of the sine wave will be flattened. Let the signal magneto-motive force be:

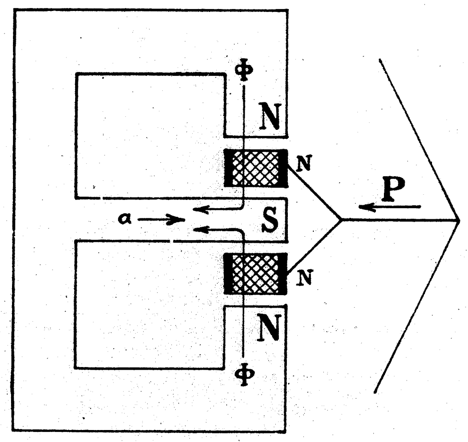


FIG. 8

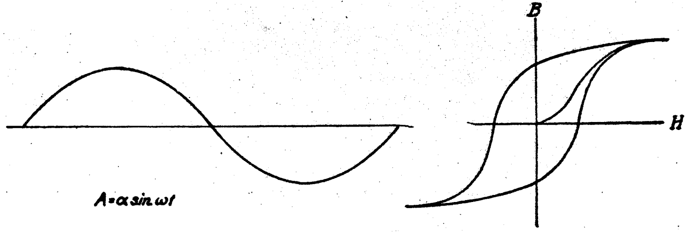


FIG. 9

$$A = \alpha \sin \omega t.$$

The resulting flux may then be represented as[5] (see bibliography on page 590):

$B = \beta_1 \sin \omega t + \beta_3 \sin 3 \omega t + \beta_5 \sin 5 \omega t$ for the case in hand. In addition, there will also be a series of even harmonics for any practical case. Using the previous nomenclature, we have for the reed type instrument, operating at low flux density*:

$$P = K(\phi + \beta_1 \sin \omega t + \beta_3 \sin 3 \omega t + \beta_5 \sin 5 \omega t \ldots)^2$$
$$= K\phi^2 + K\beta_1^2 \sin^2 \omega t + K\beta_3^2 \sin^2 3 \omega t + K\beta_5^2 \sin^2 5 \omega t + \ldots$$
$$+ 2K\phi\beta_1 \sin \omega t + 2K\phi\beta_3 \sin 3 \omega t + 2K\phi\beta_5 \sin 5 \omega t$$
$$+ 2K\beta_1\beta_3 \sin \omega t \sin 3 \omega t + 2K\beta_1\beta_5 \sin \omega t \sin 5 \omega t$$
$$+ 2K\beta_3\beta_5 \sin 3 \omega t \sin 5 \omega t + \ldots$$
$$= \frac{K}{2}(2\phi^2 + \beta_1^2 + \beta_3^2 + \beta_5^2 + \ldots)$$
$$+ 2K\phi(\beta_1 \sin \omega t + \beta_3 \sin 3 \omega t + \beta_5 \sin 5 \omega t + \ldots)$$
$$- \frac{K}{2}(\beta_1^2 \cos 2 \omega t + \beta_3^2 \cos 6 \omega t + \beta_5^2 \cos 10 \omega t + \ldots)$$
$$+ K\beta_1\beta_3 \cos(\omega t - 3 \omega t) - K\beta_1\beta_3 \cos(\omega t + 3 \omega t)$$
$$+ K\beta_1\beta_5 \cos(\omega t - 5 \omega t) - K\beta_1\beta_5 \cos(\omega t + 5 \omega t)$$
$$+ K\beta_3\beta_5 \cos(3 \omega t - 5 \omega t) - K\beta_3\beta_5 \cos(3 \omega t + 5 \omega t) + \ldots$$
$$= 2K\phi\beta_1 \sin \omega t + 2K\phi\beta_3 \sin 3 \omega t + 2K\phi\beta_5 \sin 5 \omega t +$$
$$+ K\left(\beta_1\beta_3 + \beta_3\beta_5 - \frac{\beta_1^2}{2}\right) \cos 2 \omega t$$
$$+ K(\beta_1\beta_5 - \beta_1\beta_3) \cos 4 \omega t - K\left(\beta_1\beta_5 + \frac{\beta_3^2}{2}\right) \cos 6 \omega t$$
$$- K\beta_3\beta_5 \cos 8 \omega t - \frac{K\beta_5^2}{2} \cos 10 \omega t + \ldots$$
$$+ \frac{K}{2}(2\phi^2 + \beta_1^2 + \beta_3^2 + \beta_5^2 + \ldots)$$

Interpreted, this amounts to a force acting on the armature equivalent to the signal and a number of even and odd harmonics as shown above. It is apparent that the amplitude of the harmonics increases with the degree of saturation.

Similarly, for the balanced armature motor we have:

$$P = K(\phi + \beta_1 \sin \omega t + \beta_3 \sin 3 \omega t + \beta_5 \sin 5 \omega t + \ldots)^2$$
$$- K(\phi - \beta_1 \sin \omega t - \beta_3 \sin 3 \omega t - \beta_5 \sin 5 \omega t + \ldots)^2$$
$$= 4K\phi\beta_1 \sin \omega t + 4K\phi\beta_3 \sin 3 \omega t + 4K\phi\beta_5 \sin 5 \omega t + \ldots$$

Obviously, the odd harmonics are still present in their original relative amplitudes in the mechanical force acting on the armature. It will be noticed, however, that the conglomeration of added even harmonics present in the vibrating reed type motor, balances out in this case.

In addition to the introduction of harmonics due to saturation, there are present numerous other forms of distortion, even for very minute armature vibrations. Copper losses in general are negligible, but iron losses are responsible for a great deal of distortion at high frequencies.

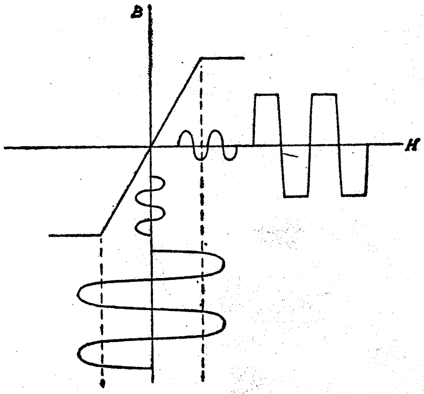


FIG. 10

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*A rigorous treatment, would of course, involve even harmonics as well as odd ones since there is always a permanent uni-directional magnetic flux in the armature of the reed type instrument. For simplicity, the shift in axis due to the permanent flux has been neglected.

Iron losses are due to hysteresis and to eddy currents. Hysteretic effect may in general be sufficiently minimized by the use of a good grade of iron, and lamination of that part of the magnetic circuit traversed by the alternating flux appreciably reduces eddy current losses. Eddy currents are due to induction and are induced in the metallic portions of the motor structure by virtue of the changing magnetic flux. Eddy current losses increase as the square of the frequency, and hence tend to reduce the high-frequency response of the motor. Eddy current losses are also dependent on the excursions of the armature and thus may cause amplitude distortion due to their variation over the signal cycle. The frequency distortion due to eddy currents is, however, generally far more serious than the amplitude distortion, and their effect is generally quite apparent in response characteristics.

In order that the armature vibrations be imparted to the air as sound waves, it is necessary to couple a loading device to the motor element. The loading device may consist of a horn together with a small diaphragm and air chamber, or of a large diaphragm which imparts the vibrations directly to the air. The function of either type of loading element is much the same although their action differs somewhat. Properly designed horns apply an almost constant load to a motor element and may thus be made to produce a much smoother response-frequency characteristic than the cone type (large diaphragm) device[6] (see bibliography on this page). The essential difference in the two lies mainly in the fact that the load presented by the horn is almost pure radiation resistance over the operating range, while that supplied by the cone is far from constant, resulting generally in an irregular response characteristic, and is very similar in its action toward the mechanical system to a complex impedance load in an electrical circuit.† Aside from the difference in relative smoothness of their response characteristics the frequency band covered in the two cases is quite different. See Fig. 11. The lowest frequency radiated by a horn is a function of its length. Many horns function in a manner similar to an open organ pipe, in that the lowest frequency transmitted is

$$F = \frac{\text{Vel. of Sound in Air}}{2\,(\text{Length of Horn})}$$

to a first approximation. This obviously depends on the shape of the horn and the shape of the opening. The lowest frequency efficiently radiated by the cone is, among other factors, determined by the size of the structure and the amplitude of motion. In addition, the highest transmitted frequency efficiently radiated by this type of loading device is partly determined by the effective high-frequency mass of the diaphragm. In some diaphragms, at high frequencies, only a small portion of the diaphragm near the driven point is effective as a radiator, the remainder of the device acting in general as a power absorbing network. That is to say, the high-frequency vibrations may travel from apex to edge of the cone as well as being directly radiated from the driven point. The effect of these impulses traveling across the face of the diaphragm is twofold: First, power lost in deformation of the diaphragm face, and, second, out-of-phase radiation. These may frequently occur to such an extent that the radiated sound is much reduced. In addition, the usual diaphragm has many resonant points of its own and thus may present a variable load to the motor.

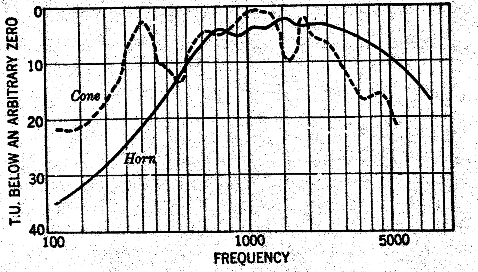

FIG. 11

The efficiency and response-frequency characteristics of a loud speaker depend to a large extent upon the device used to couple the motor to the loading element. In the case of the horn radiator, this device usually consists of a short light driving rod and is, in general, quite efficient and relatively free of distorting effects. In the case of the large diaphragm (cone) loading device, the coupling device must in general include a mechanical transformer, which amounts to a lever or system of levers for increasing the force. In the ideal case the mechanical transformer consists of a frictionless lever of zero mass. In practical cases it may consist of members having appreciable mass and considerable stiffness of suspension, amounting to a complex network, which further complicate the action of the loud speaker as a unit. This particular phase of the subject, however, has been treated in detail elsewhere[7] (see bibliography on this page).

The human ear which in the end is the final judge of quality, is far from a perfect instrument. Its response characteristic is far from linear either with frequency or amplitude[8] (see bibliography on this page). Moreover, the ear is in itself a modulator, due to the nonlinearity of its characteristics[9] (see bibliography on this page). Such being the case, it is often possible for an observer to apparently hear a fundamental note, when only harmonics of the note actually impinge on the ear drum[10] (see bibliography on this page). Therefore, it may often be permissible to allow a certain amount of distortion to actually take place, and still maintain tolerable quality. Thus, harmonics produced by a loud speaker may often cause a slight apparent increase in efficiency without materially affecting quality. The naturalness of reproduced speech and music depends to a large extent on the energy level at which it is reproduced. That is to say, the psychological reaction of the observer depends on whether or not the signal is delivered at normal intensity. Again, harmonics of the original signal are frequently not detected by the ear until the energy level is such that the harmonic output of the reproducer approaches that of the original signal. Moreover, relatively large irregularities in the response characteristic of an acoustic reproducer are frequently allowable at either end of the frequency spectrum, as previously pointed out. Consequently, a perfect reproducer, having a linear response characteristic, might not appear to have an appreciable advantage over a less perfect device with a reasonably acceptable characteristic.

BIBLIOGRAPHY

1—"Nature of Language," R. L. Jones. *Electrical Communication*—Vol. 2, No. 1. July, 1923.
2—"High Quality Reproduction of Speech and Music." W. H. Martin and H. Fletcher. *Journal A. I. E. E.* Vol. XLII, No. 3. March, 1924.
3—"The Relation between the Loudness of a Sound and Its Physical Stimulus," J. C. Steinberg. *Physical Review*. October, 1925.
4—"Design of Telephone Receivers for Loud Speaking Purposes," C. R. Hanna. *Proc. I. R. E.* August, 1925.
"Theory of Magneto-Mechanical Systems," R. L. Wegel. *Journal A. I. E. E.* October, 1921.
"The Electromagnetic Theory of the Telephone Receiver," A. E. Kennelly and H. Nukiyama. *Proc. A. I. E. E.* April, 1919.
5—"Fouriers Series and Spherical Harmonics," Byerly.
6—"Function and Design of Horns for Loud Speakers," C. R. Hanna and J. Slepian. *Journal A. I. E. E.* February, 1924.
"Acoustical Impedance and Theory of Horns and of the Phonograph," A. G. Webster. *Proc. National Academy of Sciences*. 1919. Vol. 5.
"Experiments on the Vibration of Air in Conical Horns," A. G. Webster. *Proc. National Academy of Sciences*. 1920. Vol. 6.
"Theory of Sound," Lord Rayleigh. Vol. 2.
"Performance and Theory of Loud Speaker Horns," Goldsmith and Minton. *Proc. I. R. E.* August, 1924.
7—"Methods of High-Quality Recording and Reproducing of Music and Speech Based on Telephone Research," J. P. Maxfield and H. C. Harrison. *Bell System Technical Journal*. July, 1926.
8—"Physical Measurements of Audition and Their Bearing on the Theory of Hearing," Harvey Fletcher. *Journal of Franklin Institute*. Vol. 196, No. 3. September, 1923.
9—"Auditory Masking and Dynamics of the Inner Ear," R. L. Wegel and C. E Lane. *Physical Review*. February, 1924.
10—"Physical Criteria for Determining the Pitch of a Musical Tone," H Fletcher. *Physical Review*. September, 1923.

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†This applies to large flexible diaphragms such as paper cones. With a very stiff diaphragm of small size, plunger action and more uniform response may result.