H W Houck.

PROCEEDINGS

of the

RADIO CLUB *of* AMERICA

Vol. 2 No. 12 October, 1923

The Fundamentals of Loud Speaker Construction

A Technical Discussion of the Factors Which Must Be Considered in Converting Electric Current into Sound Waves

By A. NYMAN

Recent years have seen a very rapid development in loud speakers for use with radio receiving sets In this paper, which was read at a meeting of the Radio Club of America on September 28, 1923, the writer outlines the essential features of a successful loud speaker and also some of the experimental results obtained during an investigation leading to the development of one commercially successful type of instrument.

IT HAS been found that music reproduction requires the presence of notes ranging in frequency from 25 cycles per second to 5,000 cycles per second. The quality of reproduction is affected to a large extent by the loudness of individual frequencies; hence, the necessity of bringing in each frequency at a value proportional to the original volume. It can readily be seen that the quality of the pick-up instrument or microphone, as well as the design of the transmitting and receiving systems, is of the utmost importance.

Apart from the pick-up and transmission, the following qualities are required in the loud speaker itself:

(1) Uniform intensity of sound at all frequencies from 25 cycles to 5,000 cycles.

(2) Absence of resonance points capable of responding at a frequency different from that applied or giving an excessive volume of sound when their own fundamental frequency is applied.

(3) The ability to reproduce a combination of frequencies with a volume of each frequency proportional to the input.

(4) Absence of distorting harmonics at any individual frequency applied.

(1), Uniform intensity of sound at all frequencies is particularly important in reproducing every kind of sound. For example: A weak or missing range of frequency is noticeable even to an untrained ear. However, if it is near either end of the total range, i. e., below 400 or above 3,000 cycles, an untrained ear may sometimes fail to detect this defect. Similarly, an individual missing frequency can be occasionally overlooked. A loud range distorts the quality to a considerable extent, and a loud individual note has a very unpleasant blasting effect.

(2), if overlooked, is particularly liable to give blasting or an unnatural ring to certain notes. The fundamental may be suppressed and a harmonic of an altogether different pitch come through, possibly considerably louder than the applied note.

(3), dealing with combinations of frequencies, is particularly noticeable in speech reproduction. Normal vowel sounds consist of a fundamental of rather small volume and harmonics often much larger than the fundamental. Unless the proportionality is maintained, the sound of the voice will change, giving the impression of a changed pitch; a tenor voice may sound like a bass; a soprano like a contralto, or vice versa. The higher harmonics again determine the individual characteristics of the voice. Thus, in order to recognize a person's voice, the higher harmonics up to the 20th or 30th must be included and kept at their proportional value. What is true of the voice is true of most musical instruments.

Regarding (4)—the absence of distorting harmonics at any individual frequency—certain materials have qualities which give them

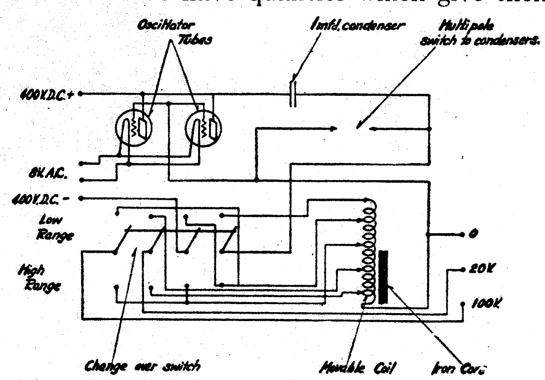

FIG. 1

Oscillator designed to cover a range from 150 to 10,000 cycles peculiar forms of vibration. Thus, the vibrations of brass are usually different from those of aluminum, wood, or micarta. This is generally due to a number of harmonics, each modifying the original note. In a loud speaker the pleasing quality and the naturalness of reproduction are dependent to a very great extent on the choice of materials, particularly of the material carrying a large amount of energy of sound.

METHODS OF TESTING LOUD SPEAKERS

THE four essential features of the loud speaker have been investigated by different test methods, partly dynamical and partly physiological; i. e., depending on aural observation.

Fig. 1 shows a diagram of an oscillator designed to cover a range from 150 to 10,000 cycles. A number of steps of condenser capacity raise the frequency about 50 to 100 per cent., while for each step the movement of an inductive coil on and off an iron core gives gradual variations of frequency. Each step of condenser is calibrated for frequency at different coil settings which are indicated on a graduated scale. The coil acts as an inductance and also as a transformer. Operating the set at 20 watts, the amount of power drawn to the loud speaker is small, giving good voltage and frequency regulation on load. In order to make the loud speaker circuit equivalent to a tube circuit, a resistance equal to the tube impedance is included in series with the loud speaker. Although the voltage on the oscillator remains fairly constant throughout the whole range, for quantitative measurements the voltage can be checked at each reading.

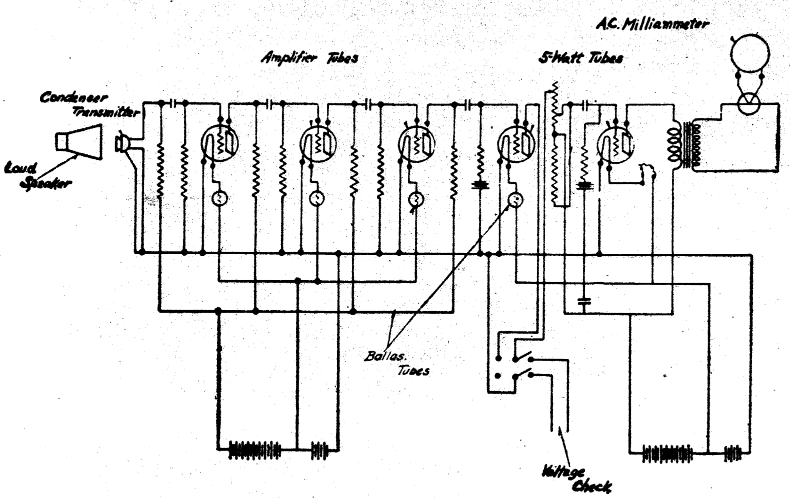

FIG. 2
Apparatus for measuring the sound from a loud speaker

Fig. 2 shows the pick-up arrangement for measuring the sound from a loud speaker. A condenser transmitter pick-up is considered very close to the ideal sound-receiving instrument and has been used by many investigators as a sound standard. The pick-up of this transmitter is amplified through a resistance amplifier, precluding distortion, and the resultant current measured on a milliammeter. The last stage, containing a step-down transformer, is also used for checking the voltage at each frequency. Hence, any possibility of reduction of received current at low frequencies is balanced by a corresponding reduction of the measured value of voltage.

Sound volume tests were conducted as follows:

The oscillator was operated through the complete range at fairly constant voltage, while measurements of sound by condenser transmitter were recorded and corrected by the value of voltage measured at each frequency. This arrangement gives a complete cycle from current to current and is evidently equivalent to the cycle from sound to sound. In addition, a point is obtained at 60 cycles to determine the loudness of very low notes.

The above test gives valuable data for investigation of the uniformity of sound and of the absence of resonance points. Listening to the sound, while performing this test, makes it possible to detect any foreign noise, rattle, or sound at a different frequency from that applied.

The ability to reproduce accurately any kind of musical sound or speech can be tested best by actual music and speech reproduction. Again a condenser transmitter has been used for the pick-up of sound. A number of stages of amplification (resistance coupled) bring the current to the loud speaker, while an audibility meter is so arranged that the volume can be cut down to any suitable loudness. Repeating each note on the piano several times is one of the best means of detecting any disturbing harmonics. Each note should come through clearly and should correspond exactly to the original piano note. Low notes in particular should be checked for the presence of the fundamental tone. Some designs of loud speakers, while giving a loud note at these pitches, are found to be completely devoid of the fundamental—the note is just the sum of all overtones.

Speech transmission over the same circuit gives a splendid test for quality and recognizability of reproduction. For proper speech reproduction the volume should be adjusted to equal, approximately, the loudness of the original speech. Of course, in a loud speaker designed for a large audience, with a special view to great volume, the speech must sound normal at the volume desired. The same loud speaker would not necessarily give natural reproduction at a lower volume.

An additional test for actual music reproduction is essential. Thus, a piano selection, a baritone solo, and a soprano solo are particularly good for detecting any faults in quality. In addition, a violin or a flute solo can be used to advantage to determine the ability of the loud speaker to reproduce the high notes naturally. The table below shows the list of tests and results that can be learned from each:

TESTS OF LOUD SPEAKERS

1. Measurement of volume (60 to 5,000 cycles) . . .	Uniformity of volume, absence of resonance points and foreign sounds
2. Musical scales on piano	Accurate reproduction of quality on each note, particularly the low notes
3. Speech . . .	Clearness of articulation. Individuality of voice
4. Piano selection .	Clearness and naturalness on abrupt tones
5. Baritone and soprano singing .	Clearness and naturalness of sustained notes
6. Flute or violin .	Reproduction of high notes
7. Speech and music	Naturalness of superimposed sounds

The last test, the combination of music and speech, is very desirable. Each possesses individual characteristics, and the ideal loud speaker would maintain them. Very often, however, the presence of music will distort the speech, and vice versa. Of course, in this latter case we could not expect the loud speaker to reproduce correctly a number of musical instruments simultaneously, although the distorting effect might not be as noticeable as in the case of speech and music.

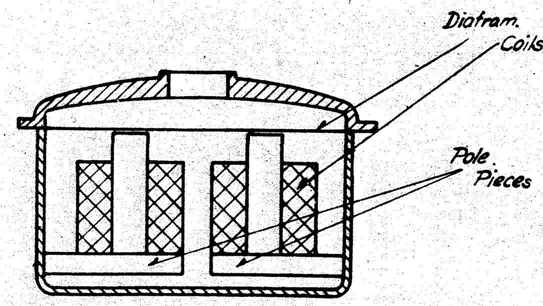

FIG. 3
Loud speaker unit operated on the same principle as the ordinary telephone receiver

THE STRUCTURE OF LOUD SPEAKERS

IN A COMPLETE loud speaker the following mechanical parts can be segregated and investigated separately:

(1) The electromagnetic structure
(2) The sound-producing element
(3) The sound-amplifying and distributing element

Figs. 3, 4, 5, and 7 show four distinct types of electromagnetic structures.

Fig. 3 shows a loud speaker operating on the same principle as an ordinary telephone receiver. It has a thin iron diaphragm held at a small distance from two magnetic pole pieces which are energized by a permanent magnet and also by two coils, one on each pole piece. The volume that can be obtained from this type of loud speaker is somewhat limited on account of the close spacing between the diaphragm and the pole pieces. Moreover, certain notes are accentuated, due to the resonance of the diaphragm. This, however, is not necessarily a defect. It is possible to overcome the resonance feature by means of a proper sound-amplifying device. The magnet in this type is often made adjustable. This permits a very close magnetic balancing of the diaphragm and a consequent improvement in quality.

Fig. 4 shows a moving-coil type of loud speaker. A circular coil is located in a round air-gap, with an iron core in the center. This air-gap is traversed by a strong magnetic field, excited by an inner coil which carries direct current, while the circular coil mentioned above carries sound-producing alternating current and is attached to the center of a dia-

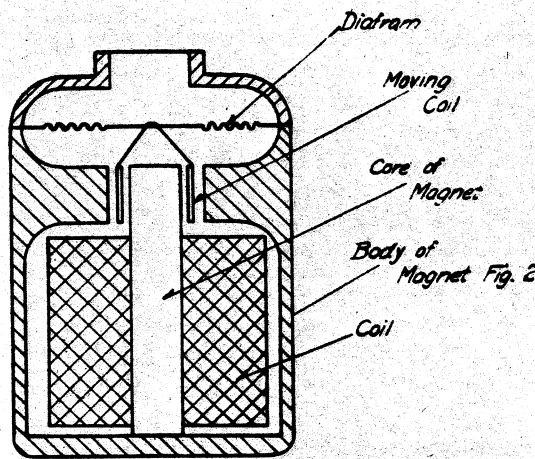

FIG. 4
The moving coil type of loud speaker

phragm. Very satisfactory results can be obtained with this type of loud speaker.

Fig. 5 shows what may be termed the enclosed-armature type. A small iron armature is located in the center of a coil and suspended by two thin piano wires. The coil is surrounded by two U-shaped pole pieces, forming two air-gaps. A permanent magnet produces magnetic flux in these air-gaps. The current in the coil causes diametrically opposite pole pieces to be energized simultaneously, which causes the armature to rock. This rocking is communicated through a thin connecting rod to the center of the diaphragm.

Fig. 6 shows the sound distribution for a loud speaker constructed on this principle. The loudness is fairly uniform over the range. The graph shows the frequency from 100 cycles to 10,000 cycles on the horizontal axis, and loudness along the vertical axis.

Fig. 7 shows the "relay type" loud speaker recently developed. Its construction is similar to that of a polarized telegraph relay. A thin iron armature is located between four pole pieces, each carrying a coil. These pole pieces are magnetized by an L-shaped magnet and the coils are connected in such a manner that diametrically opposite pole pieces exert simultaneous attraction. The armature operates through a rod on a diaphragm.

Fig. 8 gives a representative curve of this loud speaker. The range is fairly wide, while no part of it is exaggerated in volume.

In all the above structures the sound-producing element is a diaphragm. Considerable variation is possible in the design of this diaphragm. Of course, the first type requires an iron or steel diaphragm, or at least an iron center. The other types have a free choice of material. Aluminum and micarta have both been used successfully. It has been found that the quality of the loud speaker is considerably improved by proper corrugation of the diaphragm.

Figs. 9, 10, and 11 show, respectively, the variation of sound intensity with frequency for three different types of diaphragm.

Fig. 9 shows the resonance points with a very stiff small diaphragm. The lowest resonant point is at 1,500 cycles. The harmonics are at 2,900, 5,000, and 6,000 cycles, i. e., approximately in proportional 1:2:3:4. These resonance points may have been modified by the presence of the horn. The resonance points below 1,500 cycles are due to the horn.

Fig. 10 is the same relation for a fairly thin flat aluminum diaphragm. The resonance points are still very pronounced.

Fig. 11 shows the relation for a corrugated aluminum diaphragm of the same dimensions as the one used in the case of Fig. 6. Up to 3,000 cycles, the resonance points are not prominent.

Fig. 12 shows some of the types of diaphragm that have been tried. (b) and (c) have been found to give the most satisfactory results. The one marked (c) is the diaphragm whose performance is represented by the curve in Fig. 11. It has the corrugations spaced at radii bearing a ratio to each other corresponding to prime numbers. This diaphragm is based on mathematical considerations worked out by Dr. Philip Thomas.

Diaphragms (g) and (h) have the property

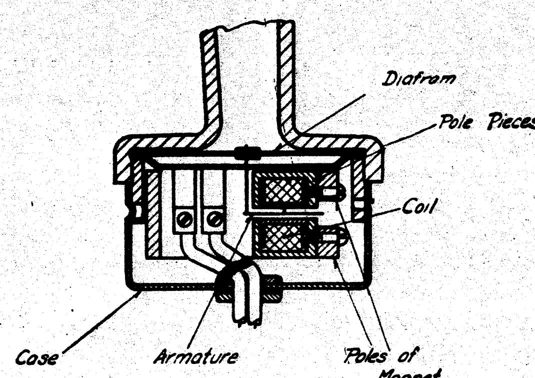

FIG. 5
The enclosed-armature type

of having the same depression from either side. Diaphragm (i) has, in addition, an identical pattern from either side, and, consequently, is less liable to buckle either one way or the other. This quality is important, as demonstrated in a succeeding paragraph.

So far only two types of sound amplifier and distributor have come into practice; namely, a horn and a large conical diaphragm. Considerable controversy ranges about the type of horn which would give the most satisfactory results. It is difficult to record the effect of horns with the method outlined above.

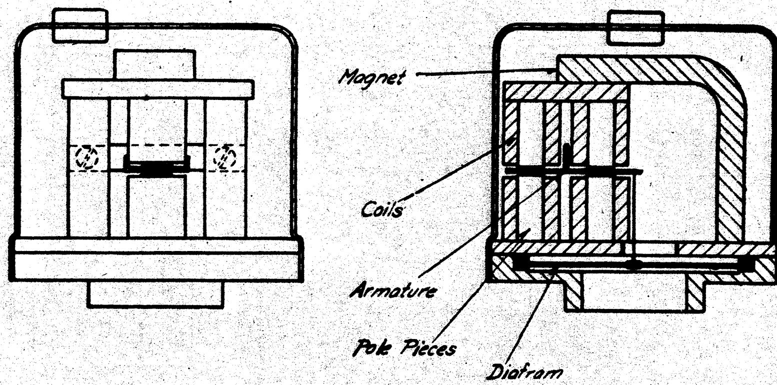

FIG. 7
Diagram of a recently developed loud speaker constructed after the fashion of the polarized telegraph relay

Speech and music are both modified considerably, depending upon the length and shape of the horn, and on the volume of the sound. A horn longer than one quarter the wavelength of the lowest pitch available gives the best reproduction. However, in practice, the length of the horn seldom exceeds three feet, approximately one fourth of the wavelength of 90 cycles, the fundamental of the horn. If the horn is shorter than one foot (270 cycles fundamental), the bass and baritone voices are likely to be distorted, since their fundamental, which is below 270 cycles, would be reduced. It has been found that a loud speaker with a magnetic balance and a horn about two feet long is capable of very good reproduction of even very low frequencies.

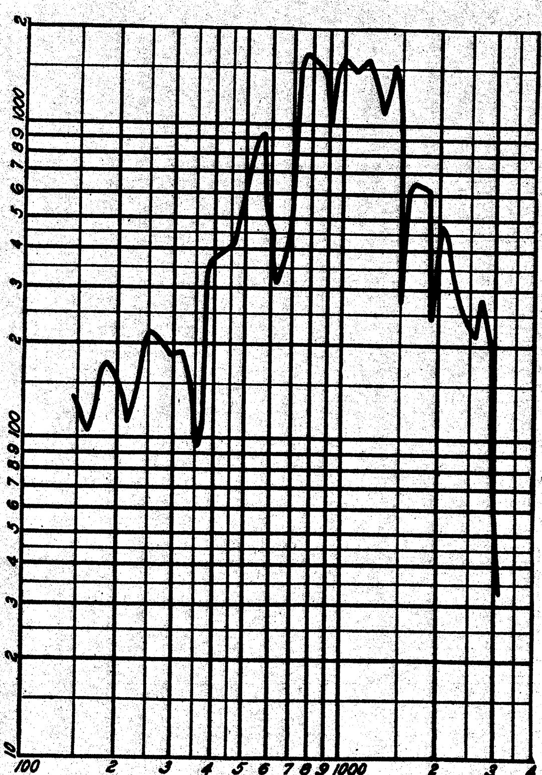

FIG. 6
Showing the sound distribution for a loud speaker of the enclosed-armature type. The horizontal axis represents the frequency, from 100 to 10,000 cycles, and the vertical axis represents loudness

Careful study has been made of materials to be used in the horn, in so far as they affect the quality of reproduction. A wood horn, or horn made of some "dead" material like hard rubber, is least likely to introduce a strange quality.

Horns of large volume carry considerable energy at resonance, which is dissipated only gradually unless the design is correct. Slow dissipation of energy would mean that some notes would be dragged out after this note had been silenced at the sending end. Aural observations give the most accurate information on horns. Experience points to the use of horns as large as possible, but designed with sufficient divergence and wide enough mouth to dissipate the energy.

Large conical diaphragms made of parchment or stiff paper have been used successfully. As a rule, it is difficult to reproduce the low range and the high range on this type of diaphragm. However, this type of sound amplifier is inherently free from resonance characteristics and therefore carries the greatest promise of future utility.

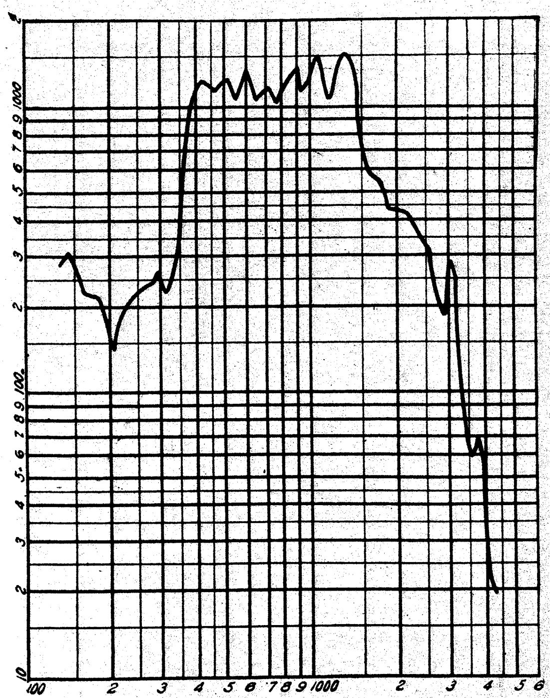

FIG. 8
The representative curve of the "relay type" loud speaker. Loudness is plotted against cycles (see Fig. 6)

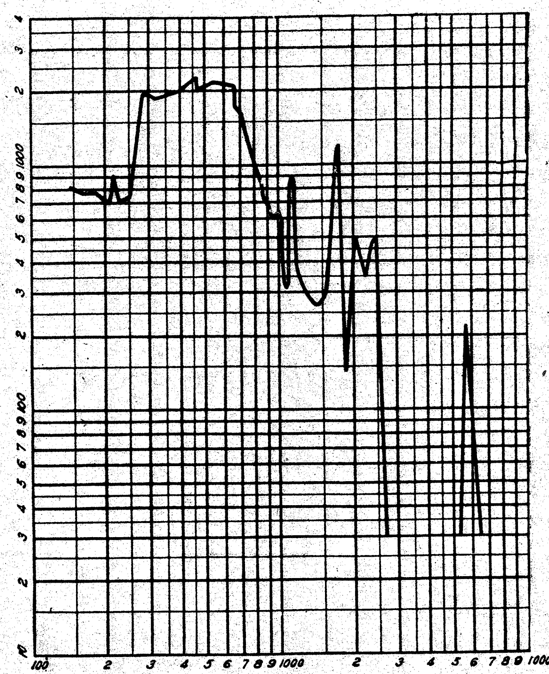

FIG. 9
Showing the variation of sound intensity (vertical axis) with frequency (horizontal axis) when a small stiff diaphragm is used

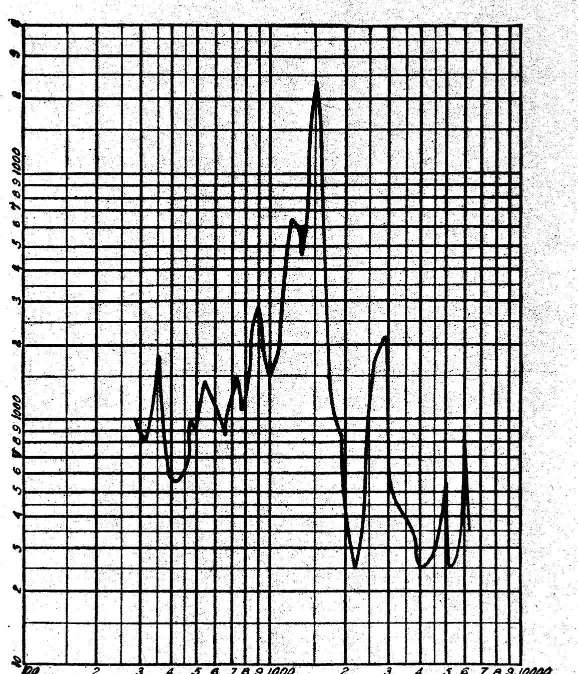

FIG. 10
Showing the same relation as in Fig. 9, but with a fairly thin, flat diaphragm

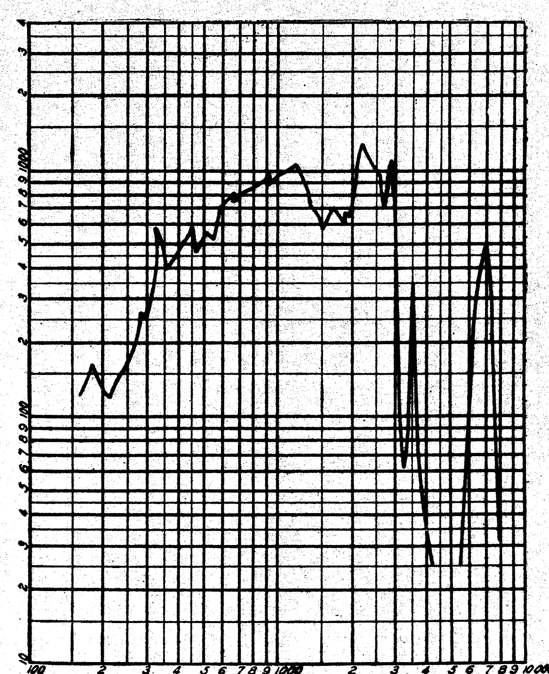

FIG. 11
Same as Fig. 9, but with corrugated aluminum diaphragm

RESONATING SYSTEMS

CONSIDERED from a mechanical standpoint, a loud speaker is invariably a complicated resonance system. Certain subdivisions of resonance, however, are possible.

1. The Mechanism as a Whole

The force of a magnetic field is in all types, except the moving coil type, counteracted by a strain in the diaphragm. In a loud speaker of the type shown in Fig. 3, that is, the telephone receiver type, this action is automatic. The diaphragm pulls down until its tension is equal to the pull of magnetic field. In the type shown in Figs. 4, 5, and 7, the normal position of the armature is such that the magnetic pull is zero. Actually, however, it is very difficult to keep the armature in this position. Generally there is a little pull one way or another, balanced by the strain in the diaphragm.

For a movement of the diaphragm, the magnetic field begins to exert a force helping this movement. If the magnetism is increased by using a stronger magnet, the force of the magnet may be made so large that it pulls the diaphragm over. Normally, a balanced condition may be obtained where very little force is required to produce a certain movement. Fig. 13 illustrates this fact. The two curves show the variation of force on the diaphragm with movement of the diaphragm, and show that, with the magnet, the diaphragm requires distinctly smaller force for the same movement.

In this way the strength of the magnet and the tension of the diaphragm determine the force for certain movements and, consequently, the resonant frequency of the whole mechanism. By adjusting the magnetism in a way to get a very close balance, this resonant frequency may be placed very low. As a rule, the damping at these low frequencies is high enough to conceal the resonance; however, the whole of the low range will be found raised. This is demonstrated in Fig. 14, showing two curves for one loud speaker, one with a .015-inch gap, and the other with a .010-inch gap. The latter had a close magnetic balance; hence, all notes and the low notes in particular are increased. These curves were taken on the relay type loud speaker. It is evident that similar adjustment is possible on all types except the moving-coil type, in which the resonance point is determined entirely by mechanical strain and the mass of moving parts.

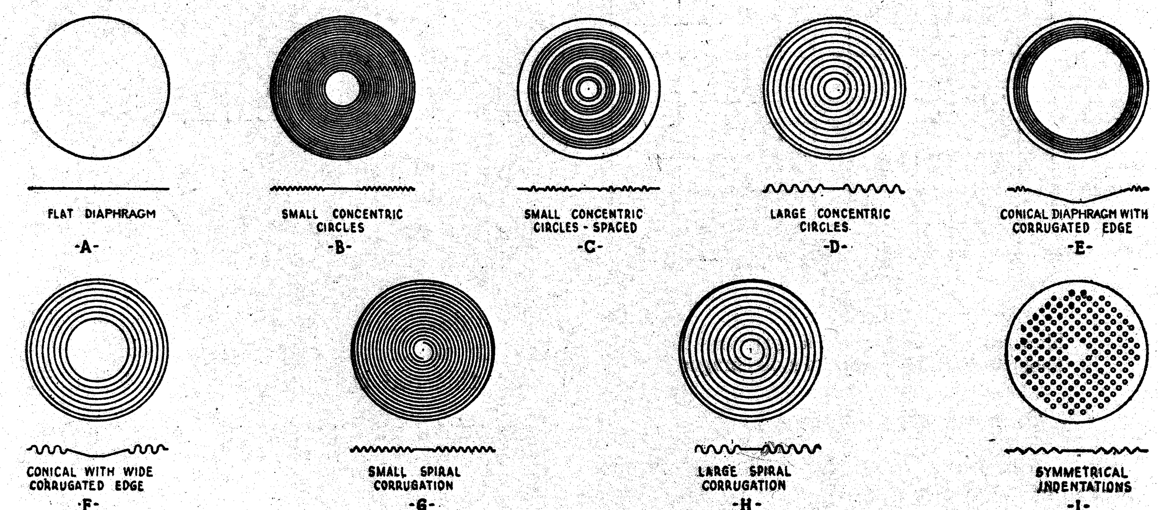

FIG. 12
Various types of loud speaker diaphragms

Fig. 13 shows a bend in the curve when the magnet is in place, i. e., there is an equality in pull for the two directions of movement. This is caused by a lack of symmetry in the diaphragm equivalent to a slight dish in one direction. A diaphragm free from this dish would give a straight line characteristic. Hence the importance of the development of a diaphragm of some such type as (g), (h), or (i) of Fig. 12.

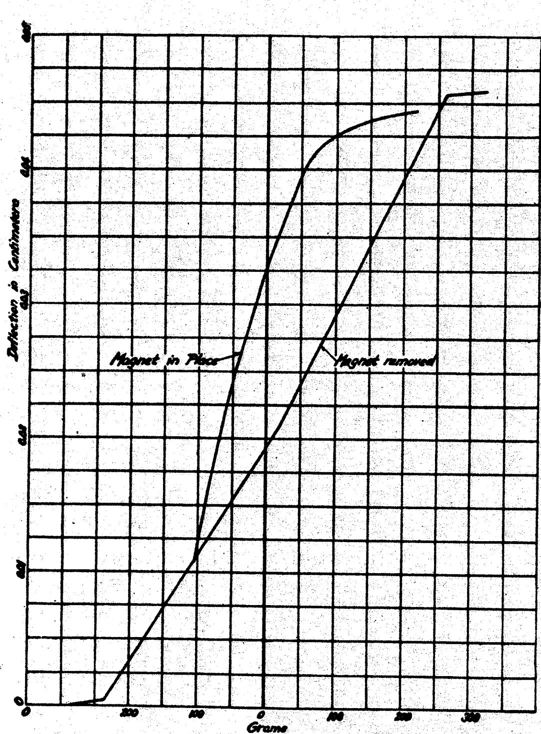

FIG. 13
Showing the effect of a permanent magnet on the movement of a diaphragm

2. *The Diaphragm and Horn*

In a foregoing paragraph the resonance points of diaphragm and horn were discussed. It must be remembered that the horn constitutes a load on the loud speaker. If it is possible to construct a load that remains constant at all frequencies, and large for a small movement of diaphragm, then the resonance of the diaphragm will be unimportant. This is one of the chief reasons of the success of large horns.

If the load due to the horn is small between its resonance points, and a resonance point of the diaphragm should occur at one of these points, the vibration may be excessive, with a resulting rattle and noise. The longer horn favors a more uniform load at different frequencies.

3. *The Armature*

The armature of a loud speaker of enclosed-armature or relay type is a strip of steel very short and stiff, but nevertheless possessing a resonance point within the audible range. It has been found that frequencies above this resonance point are difficult to reproduce. Thus, Fig. 15, made using a loud speaker with a very small stiff armature, shows a range on higher notes extending to 5,000 cycles.

Another effect of resonance of armature is the introduction of foreign notes. An example is seen in Fig. 16, showing a reduction in volume at 800 cycles. At this frequency it was observed that the note had a strange high-pitched harmonic; however, damping the armature by a piece of rubber cleared this note and brought up the volume of its fundamental. The trouble was eventually overcome by using a much stiffer armature.

4. *The Strip*

The strip supporting the armature has a resonance note, but the forces acting in it are generally very small compared with the forces in the rest of the system. Hence the effect of the strip is negligible. The only exception is in attaching the strip to supports. It seems that any looseness at this point will result in a rattle.

5. *The Connecting Rod*

The connecting rod is subject to a complicated torsional and longitudinal strain. Unless this rod is sufficiently stiff, vibrations

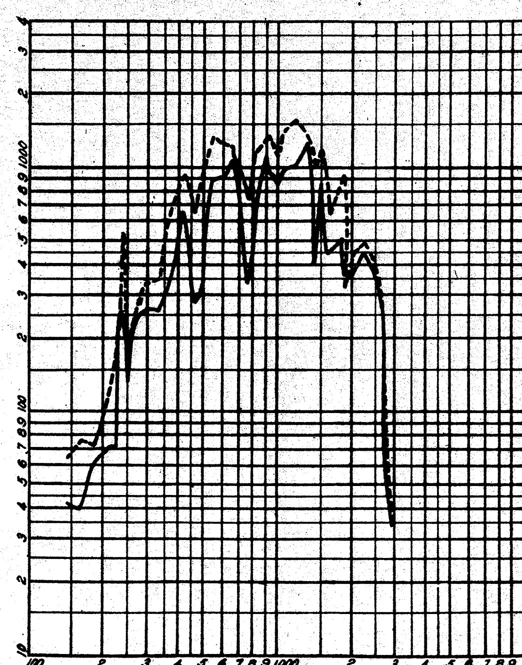

FIG. 14
Two curves taken with the same relay-type loud speaker; in one case, the gap was .015 in. (solid line), and in the other, the gap was .010 in. (dotted line)

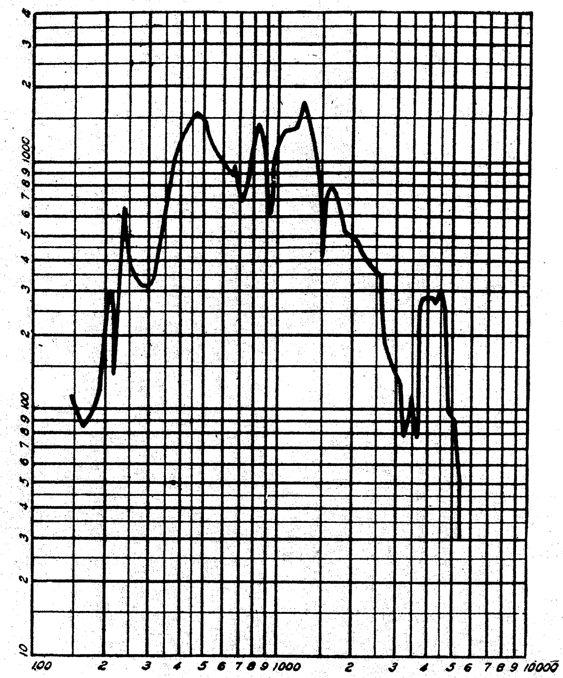

FIG. 15
Characteristic curve made with a loud speaker having a very small stiff armature. Vertical axis indicates loudness, horizontal axis indicates frequency in cycles

may be set up which introduce a foreign note at the lower frequencies and limit the sound at the higher frequencies.

CONCLUSION

IN CONCLUSION, a brief summary will be given, covering the outstanding points. The function of loud speakers is considered as that of a device for converting electric current, of frequencies ranging from 25 cycles to 5,000 cycles, into sound waves.

The essentials of this conversion are as follows:

(1) Uniform volume at all frequencies.
(2) Absence of strange sounds.
(3) The ability to reproduce a combination of frequencies correctly.

Four fundamental types of loud speakers are discussed:

(1) Receiver type.
(2) Moving-coil type.
(3) Enclosed-armature type.
(4) Relay type.

Test methods are outlined for:

(1) Measuring the volume of sound.
(2) Testing the quality of reproduction.

The effect of various parts of a loud speaker on its operation are considered, namely:

(1) The magnetic structure.
(2) The diaphragm.
(3) The horn.
(4) The details.

The art of designing a loud speaker is extremely new. The empirical work for ascertaining the effect of various factors is only in its embryo stage.

Eventually, we may expect to design a horn or a vibrating structure with the same facility as an electric motor, because a loud speaker is really an electric motor though its load is less tangible than the load of most motors.

The design of a loud speaker must be based on a scientific analysis of this load and of its reaction on the motor. This involves considerable acoustic research work, mechanical research on vibrating structures, and electrical work on the effects of vibrating parts in an electromagnetic structure.

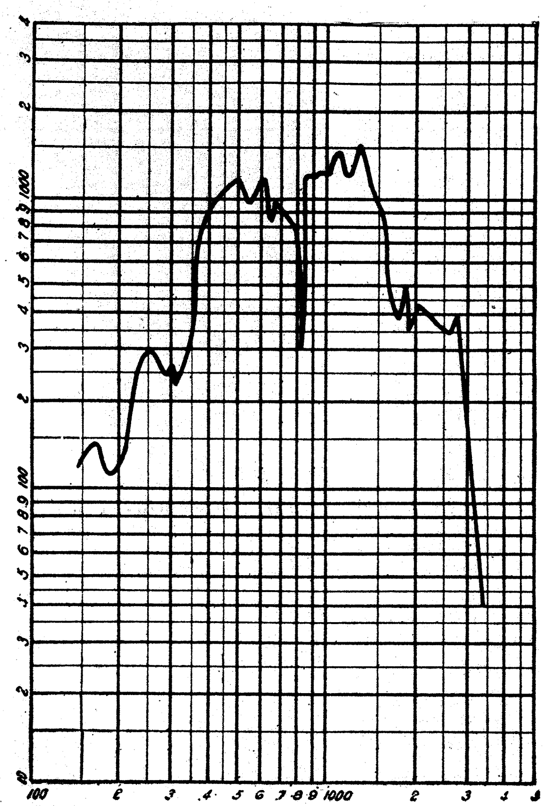

FIG. 16
In this case the armature was not stiff enough and the sound showed a reduction in volume at 800 cycles