Amplitude and Phase Measurements on Loudspeaker Cones[*]

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Summary—**Amplitude and phase measurements have been made of the mechanical motion of different points on the cone diaphragm for various critical frequencies. From these the cause of various peaks and dips in the sound-pressure curve can be determined. Such information is helpful when making changes to improve the cone design.**

INTRODUCTION

LOUDSPEAKER cones are usually designed by means of experimental processes. When a new speaker is to be developed for producing a particular frequency response, it is customary to start with a cone of approximately the desired properties and to modify the shape and paper stock systematically until the response is as close as possible to the desired curve. After this is done, it often happens that there is still something undesirable about the frequency response which is very difficult to correct. We have found that if careful measurements are made of the amplitude and phase of the various parts of the vibrating cone, it becomes possible to visualize the actual mode of vibration leading to the undesired peak or dip in the sound pressure output. This paper will describe some laboratory equipment that can be used to make these measurements, and will show how the results can be used to improve the design of the cone.

A FAIRLY COMMON ERROR

Many acoustical engineers believe that if a small microphone probe is placed close to a vibrating membrane, the sound-pressure variations which are picked up at the tip of the probe will correspond to the actual vibration of the membrane at the point. The theory is as shown by Fig. 1. Let the small area dS on the inner surface of the cone vibrate sinusoidally with a normal velocity u_0. Then the radiation pressure at a point P separated from dS by a distance h is as shown by (1) in the caption to Fig. 1. It should be noted that the quantity h occurs in the denominator. It has been argued in the literature that if h is very small the contribution to the total pressure due to dS will be much greater than that due to the rest of the cone; and therefore, the output of the microphone should be a measure of the motion of dS.

In actual practice, when working inside a loudspeaker cone, this relation does not hold. Even though the distance h for dS is very small, the area of the rest of the cone is large in comparison to dS that even though h becomes much greater the contribution to the resultant sound pressure due to the larger area, is much greater than that from the element of area dS.

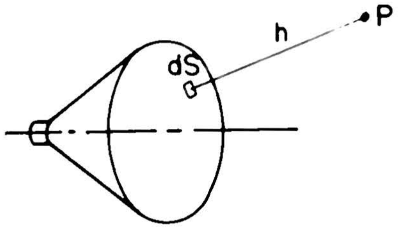

Fig. 1—Radiation pressure at point P due to element of area dS

$$dp = -i(\rho\nu u_0 dS/h)e^{ik(h-ct)} \qquad (1)$$

ρ = density of air
ν = frequency
u_0 = velocity of dS
c = velocity of sound
$k = 2\pi\nu/c$.

The curves of Fig. 2 show the phase shift between the current in the voice coil and the sound pressure near the apex of the cone, as measured with a small microphone probe. The cone was 4 inches in diameter with an included angle of 118 degrees. At low frequencies, around 100 cps, the sound pressure causes the force on the voice coil to lag by approximately 180 degrees, as shown. At 500 cps the lag is one complete cycle. At 1,900 cps the sound pressure at the apex is 2 cycles behind, at 3,800 cps it is 3 cycles behind, and at 7,400 cps it is

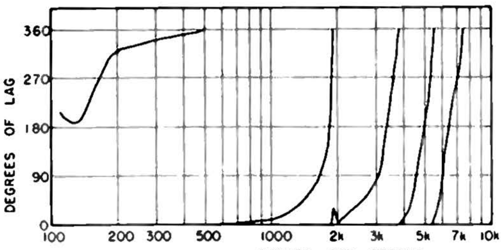

Fig. 2—Phase shift between current in voice coil and sound pressure at center of cone.

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5 cycles behind. Since the voice coil form is only about $\frac{3}{8}$ inch long and since the speaker response drops off rapidly when the voice coil form becomes a quarter-wave transmission line, it is obvious that this curve of degrees of lag has no relation whatever to the actual motion of the cone near the apex. For this reason, the study with the microphone probe was abandoned in favor of the system shown by Fig. 3.

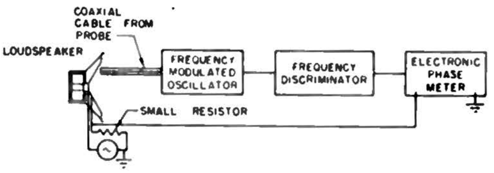

Fig. 3—Capacitor probe circuit.

MEASUREMENT OF AMPLITUDE AND PHASE OF THE CONE

The inner surface of the loudspeaker cone is coated with a thin layer of flexible conducting paint. The paint film is made so thin that there is no noticeable change in the sound-pressure response. A capacitor probe is placed near the cone surface so that the cone motion causes capacitance variations across the probe. A coaxial cable connects the probe to an oscillator tank circuit. As the capacitance varies, the oscillator is frequency modulated in step with the cone motion. The oscillator output is fed into a frequency discriminator to produce a demodulated wave, which represents the cone motion at the probe. This wave is fed into one terminal of the electronic phase meter.

In order to provide a constant and reliable reference for the phase measurements, the voice-coil current is used for comparison. A small resistor is placed in series with the coil, and thus the voltage drop corresponds to the current through the coil and, likewise, to the force on the coil due to the magnetic field. To find the relative phase between two parts of the cone, it is merely necessary to measure the motion of each one with respect to the voice coil and to subtract the two results. This method also corrects for phase shifts in the discriminator and amplifiers.

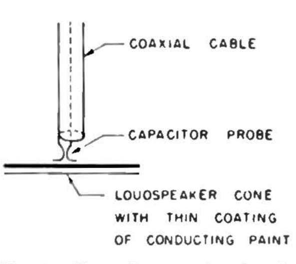

Fig. 4—Capacitor probe details.

The details of the probe are shown by Fig. 4. The diameter of the cable is $\frac{1}{4}$ inch, and the two plates cover an area about 3/16 inch square. The motion of the coating on the cone surface causes capacitance variations in proportion to the motion.

The amplitude measurements are calibrated by operating the loudspeaker at a low frequency so that the cone is moving as a piston at a fixed level. The probe is adjusted to be near the paper, and the gain of the following amplifier is adjusted to give the required output voltage. The actual motion at another frequency is thus referred to the calibration point. It is not necessary to set the levels for the phase measurements since the limiters in the phase meter eliminate variations due to changing amplitudes.

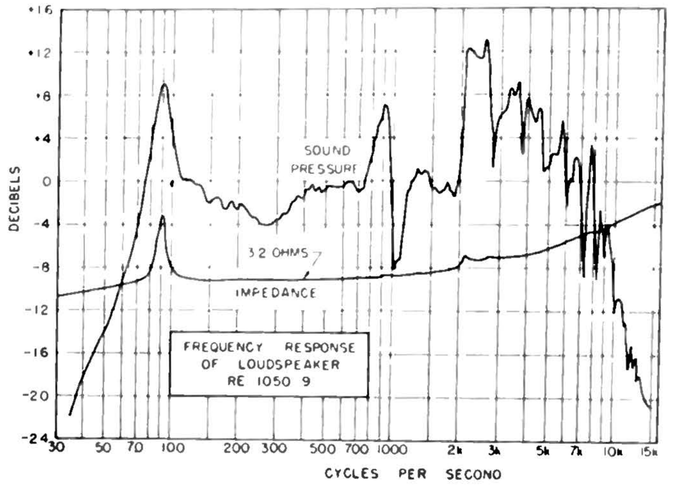

Fig. 5—Frequency response of loud speaker RE1050-9

APPLICATION TO AN 8-INCH LOUDSPEAKER

One of our speakers that had been developed experimentally had the frequency response shown by Fig. 5. It was desired to eliminate the peak near 920 cycles and the hole just past 1,000 cycles. The probe was used to measure the amplitude and phase of the apex of the cone when constant voltage was applied to the voice coil. The results are shown by Fig. 6. Because the voice-coil voltage is proportional to the velocity of motion of the coil in the magnetic field, it is evident that constant voltage tends to give a constant velocity to the cone, and the amplitude will, therefore, fall off at 6 decibels per octave with increasing frequency. Although there is a hole in the response on either side of 950 cps,

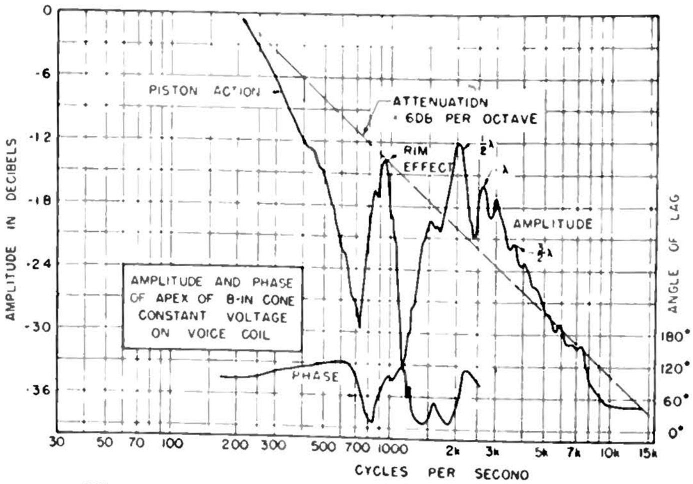

Fig. 6—Amplitude and phase of apex of 8-inch cone.

it is evident that the apex amplitude is not above normal. The phase variations are just what might be expected; as the system falls off at 6 decibels per octave, the phase angle lags approximately 90 degrees throughout the range. Each peak of amplitude corresponds to a rapid increase in phase, as is expected from the well-known relations between the amplitude and phase of such a system.

Since the cause of the trouble was not near the apex, the cone rim was examined next. The amplitude and phase curves for the cone rim are as shown by Fig. 7. This corrugation is oscillating violently at 950 cps, with an amplitude at least 14 decibels higher than for frequencies slightly higher or lower. Since the cone rim has a fairly large area and a large amplitude, it causes considerable sound-pressure output near 950 cycles.

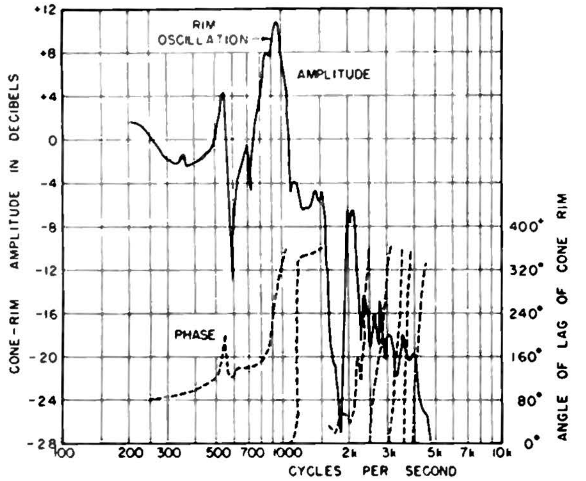

Fig. 7—Cone-rim amplitude and phase, 8-inch cone.

The motion of the entire cone was examined at 950 cps to see whether the violent rim resonance produced the peak in response. As shown by the curves of Fig. 8, the amplitude and phase of the cone motion change considerably along a radius. The apex amplitude was fairly small, but the central portion of the cone had a large amplitude. There was a node near the cone diameter, and the rim amplitude was large and 180 degrees out of phase, with respect to the central part of the cone. The sound output from the rim canceled part of the sound output from the rest of the cone; however, because the area of the cone was so large, the net result was a peak in output.

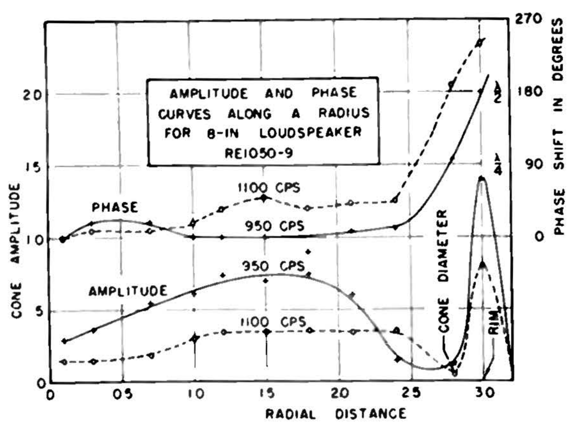

Fig. 8—Amplitude and phase curves along a radius

When the frequency was increased to 1,100 cycles per second, the rim and cone body were somewhat off resonance, as proved by Figs. 6 and 7. As a result, both amplitudes were reduced, as shown by Fig. 8. The two oscillations were still approximately 180 degrees out of phase over most of the cone, and there was some evidence of two radial nodes at this frequency. Consequently, the sound pressure developed by the rim canceled a considerable part of that developed by the cone, resulting in a hole, about 8 decibels deep, in the sound-pressure curve, as seen in Fig. 5.

These relations are not so simple as they may appear at first glance. The sound pressure at a point in front of the cone is proportional to the integral of the sound pressure generated by each element of the cone, corrected for the phase shift along the cone and for the time required for the sound to be transmitted from the elemental area to the point, in accord with (1).

Since a felted paper cone is not homogeneous and may not be completely symmetrical, the curves of Fig. 8 will be somewhat different along other radii. At certain frequencies, radial modes will also modify the amplitudes considerably. Additional information can be obtained by using lycopodium powder on the cone to produce dust patterns.

DESIGN OF THE RIM

Examination of the cone rim, shown by Fig. 9, shows that the edge of the cone has a large radius (0.156 inch). As the cone moves along its axis, the paper tends to roll around this curve, and this excites the following 0.094-inch corrugation into violent oscillation at its resonant frequency. It is evident that the cone rim and corrugation should be much narrower to reduce the radiating area, and the radius of the cone rim should be much less.

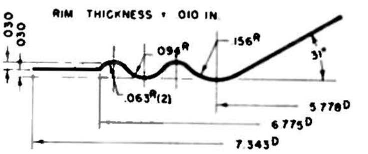

Fig. 9—Rim of 8-inch speaker.

It is sometimes difficult to decide which part of the irregularity in the sound-pressure curve is due to this rim and cone resonance. In most speakers used in commercial radio and television equipment, the effect occurs between 900 and 1,500 cps and usually consists of a peak followed by a hole. In heavy 15-inch woofers the effect may occur as low as 500 cps. If a sine wave is applied to the speaker at this frequency, the violent oscillation can be observed by touching the rim of the cone with the tip of a lead pencil. A sharp buzz will be heard at the resonant frequency.

If the space between the cone rim and the cone housing is packed full of cotton, this oscillation will be damped greatly, as shown by Fig. 10. The peak and hole are much reduced. Because the rim is stiffer than before, the low-frequency resonance occurs at a slightly higher frequency, as shown. It should be noted that rim resonance always causes a small peak in the impedance curve, and this will help identify the effect as it is the first irregularity after the low-frequency resonance. The addition of cotton is not intended to cure the trouble, but it is merely a test to show what the improvement will be if the rim is properly designed.

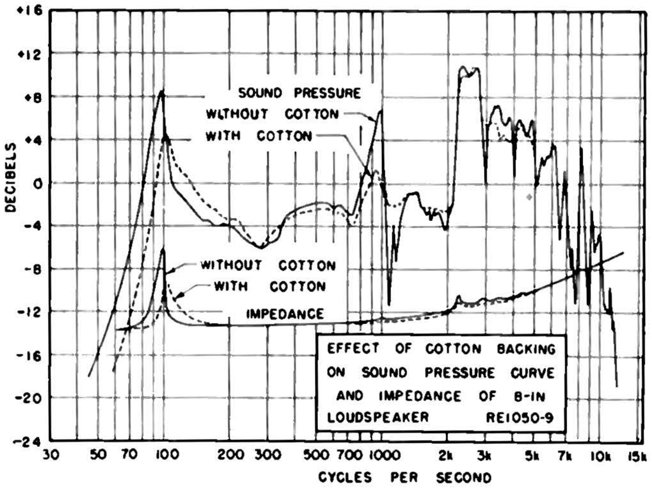

Fig. 10—Effect of cotton backing on sound pressure and impedance.

When the cone rim is narrow and has small radii, the radiating area is reduced and the amplitude of oscillation does not build up to large values. The disadvantage is that the rim may become nonlinear at low frequencies, and the rim may crack at the corrugations when used at high levels. These difficulties can be overcome by felting the rim with a soft paper stock and by adding certain compounds to produce a tough paper having internal friction between the paper fibers. This friction will help to damp out the resonances.

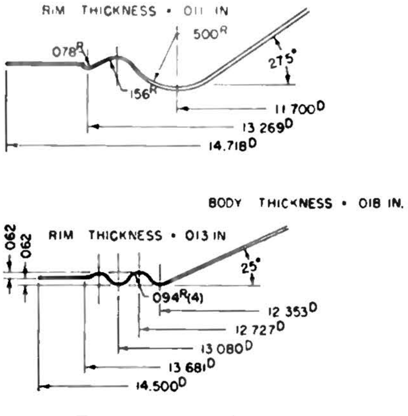

Fig. 11—Cone-rim details.

One of our early models of a 15-inch loudspeaker had a rim and roll, as shown by the upper part of Fig. 11. The rim had an unusually large radius (0.500 inch), and the rim effect caused a peak in response followed by a wide hole. When the rim was redesigned in accord with the lower part of Fig. 11, the response was considerably improved, as shown by Fig. 12. There is still a small cancellation at 720 cycles, but the curve is much smoother than before.

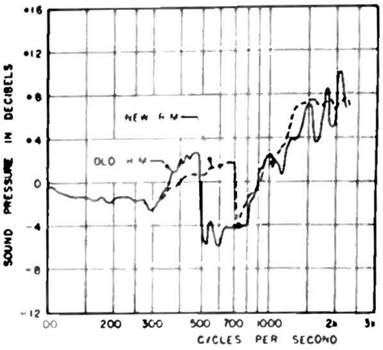

Fig. 12—Variation of sound-pressure response with rim design.

If a rim is made of a very soft, nonresonant material, such as goat-skin, the rim resonance is nearly eliminated. Fig. 13 shows the frequency response of a 10-inch loudspeaker with a leather edge. The curve is quite smooth throughout the range which is usually irregular, due to rim effects.

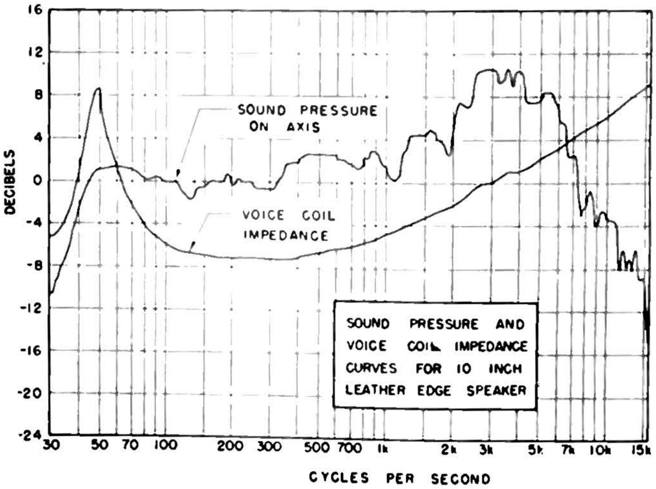

Fig. 13—Sound-pressure and impedance curves for 10-inch leather-edge speaker.

HIGHER-ORDER RESONANCES

Examination of Fig. 5 shows that the next peak occurs at 2,150 cps and is followed by a hole at 2,800 cps. A small peak in the impedance curve occurs at each of these frequencies, indicating that the sound-pressure variations are caused by resonances in the cone. Fig. 14 shows the radial amplitude and phase curves at 2,150 cps. The phase shift from the apex to the cone diameter is 180 degrees, and a circular node occurs at a radial distance of 1.4 as well as at the cone diameter. The portion of the cone near the apex is in phase with the cone rim, but the part of the cone from 1.4 to 2.7 is out of phase with the rest. Because of the large amplitude of the cone motion, the result is a peak in the sound-pressure curve.

The next resonance occurs at 2,800 cps, and the amplitude and phase curves are shown by Fig. 15. There are circular nodes at radial distances of 1.0, 2.0, and 2.8. The phase shift along the radius is somewhat irregular near the apex, but alternate sections of the cone come in and out of phase. The radiation from the alternate regions tends to cancel out in the resulting sound pressure, and the result is a hole in the response. Each higher peak and hole in the sound-pressure curve corresponds to a similar type of resonance, but, however, with more circular nodes.

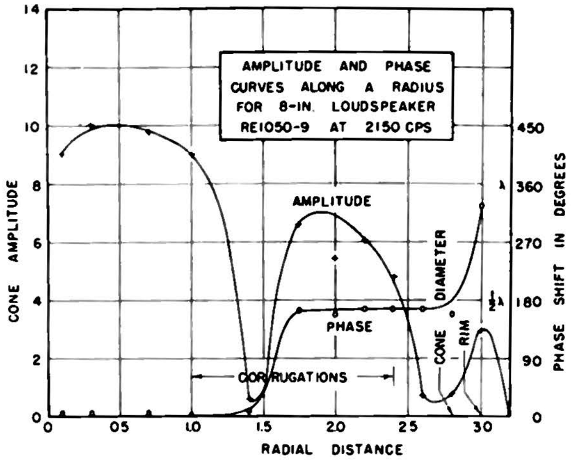

Fig. 14—Amplitude and phase curves along a radius.

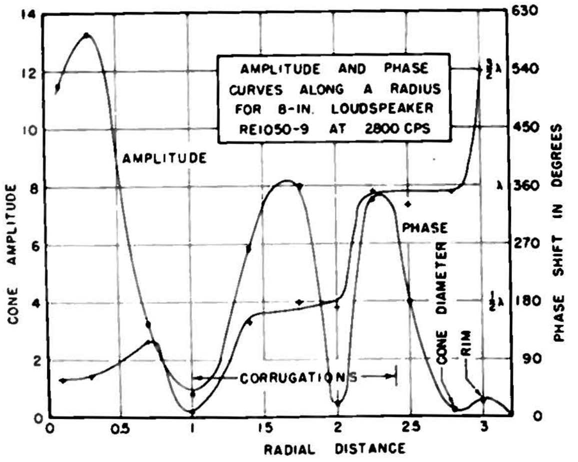

Fig. 15—Amplitude and phase curves along a radius.

AVERAGE VELOCITY IN THE CONE

If the average radial velocity of transverse wave propagation in a cone is defined as the distance between the apex and the cone diameter divided by the number of wavelengths in that distance, multiplied by the frequency in cycles per second, the measured results are as shown by Fig. 16. For low frequencies the cone behaves as a piston with all parts in phase so that the average transverse velocity can be considered infinite. At higher frequencies the average velocity varies, as shown. It decreases uniformly beyond 1,800 cps and approaches a limiting velocity, which is the same as for a flat sheet of the same material. The phase shift across the cone increases uniformly with frequency.

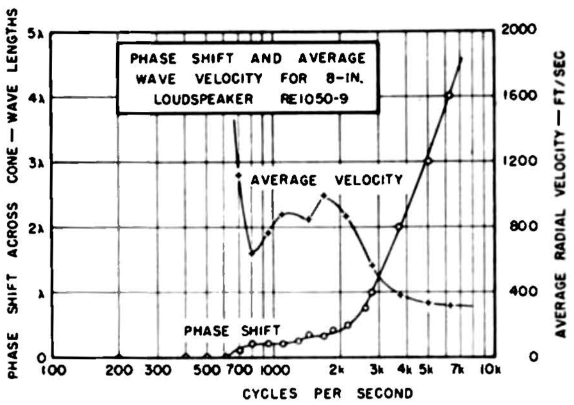

Fig. 16—Phase shift and average wave velocity.

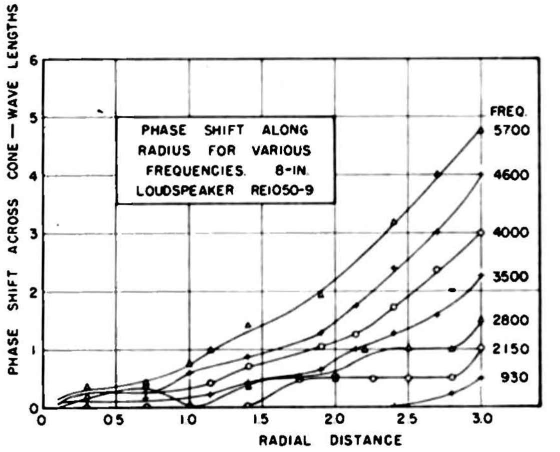

Fig. 17—Phase shift along radius.

The total phase shift along the cone increases fairly uniformly with the distance from the apex, as shown by Fig. 17. There are a few irregularities at certain frequencies, but in general the phase shift increases uniformly with frequency.

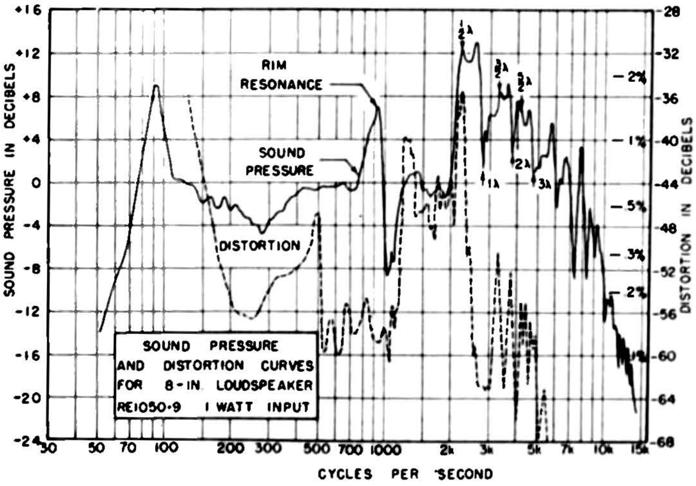

Fig. 18—Sound-pressure and distortion curves.

If the methods described are carried further by analyzing other higher modes, the major peaks and dips in the curve can be interpreted, as shown by Fig. 18.

This drawing also shows the variation of distortion with frequency for the same cone. At an applied frequency of one-half the rim resonance, the rim is excited and produces a peak in the distortion curve. Likewise, when the frequency is one-half of the next resonance (2,150 cps), a second peak occurs. There is a peak in distortion corresponding to each resonance in the cone, except that the one for the resonance at 1λ is apparently missing. The large amplitudes of motion of the cone, at a resonant frequency, lead to nonlinear effects and resulting increases in distortion.

APPLICATIONS TO OTHER LOUDSPEAKERS

The curves of Fig. 19 show that the performance of this 4-inch loud-speaker is very similar to that of the 8-inch cone already described. The irregularities in the two curves occur at higher frequencies than for an 8-inch cone but are similar otherwise. Each peak in sound pressure coincides with a small peak in the voice-coil impedance.

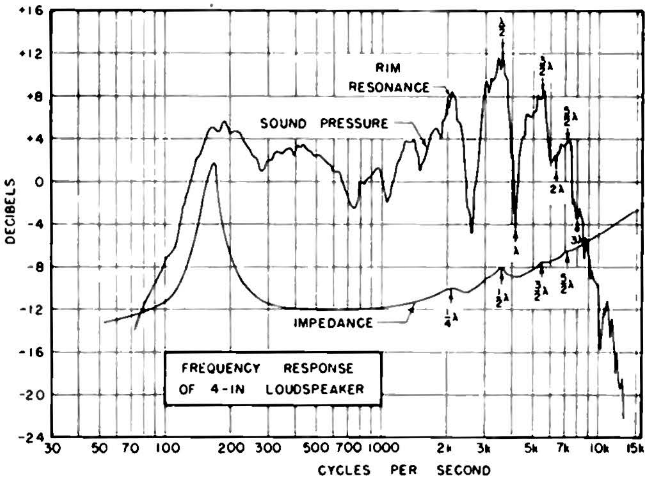

Fig. 19—Frequency response of 4-inch loudspeaker.

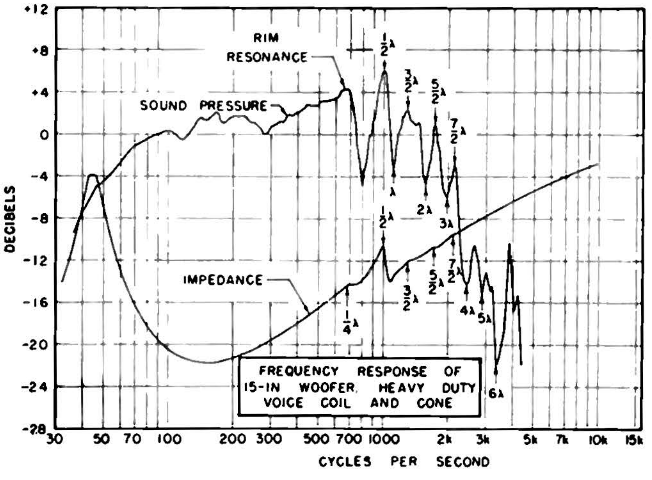

Fig. 20—Frequency response of 15-inch woofer.

When a heavy 15-inch woofer was analyzed, the results were as shown by Fig. 20. The peaks and dips in sound pressure follow the same pattern as before. It is thus evident that the irregularities in the impedance curve are very useful tools for identifying the various resonant modes. These variations in impedance can be made much larger by using a Wheatstone bridge circuit and a duplicate voice coil to balance out the rising electrical impedance. The unbalance then is a measure of the electrical equivalent of the motional impedance.

CONCLUSIONS

The illustrations shown are merely a few examples of how this equipment can be used to improve the design of loudspeakers. It has also been used to locate causes of distortion at certain frequencies. Sometimes it is possible to isolate small areas of the cone that put out almost pure second harmonic because of "oilcan" action. In other cases it has been found that the cone rocks back and forth because of an eccentric pole piece or because of dissymmetries in the cone itself. The equipment is a very useful tool for testing the various parts of the cone. Once the physical picture of the motion is obtained, it is usually possible to correct the difficulty.

ACKNOWLEDGMENT

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