The Acoustical Labyrinth

Ingeniously, the labyrinth improves the low frequency response of loud speakers and cabinets. It eliminates "boom" by eliminating cabinet resonance. It does more than this, however, and provides better over-all response than an infinite baffle

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EVER since the first cone loudspeaker was used in a box baffle, engineers have wrestled with the problem of troublesome resonances in the cabinet enclosure behind the loudspeaker diaphragm. With the development of loudspeakers and associated equipment having an extended frequency range, it became evident that something must be done about this cavity resonance as it had now become a major cause of frequency distortion in the system.

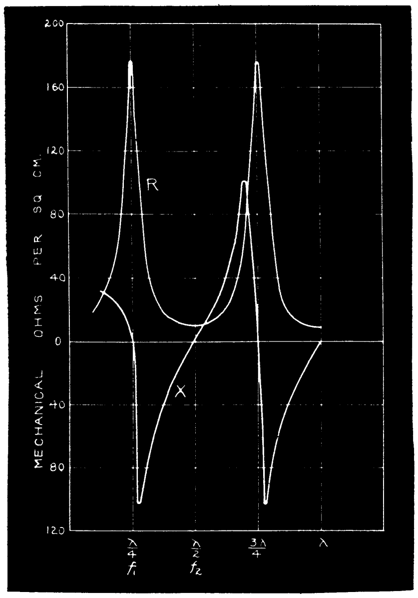

Fig. 1—Driving point impedance of a tube terminated in 10 ohms resistance

There also were other difficulties in reproduction in the low-frequency range with conventional cabinet type loudspeakers, among which were (a) poor response due to the inadequate baffle afforded by the cabinet and (b) insufficient resistance control of the diaphragm which resulted in overshooting of the moving system with consequent distortion. Another result of the inadequate damping just mentioned was a large variation in the electrical impedance of the loudspeaker at its primary resonance frequency which caused additional distortion in associated output tubes of certain types.

The acoustical labyrinth is a simple device which entirely eliminates cavity resonance by abolishing the cavity itself and which, in addition, overcomes to a substantial degree the other difficulties mentioned. It consists essentially of an absorbent walled conduit having one end coupled tightly to the back of the loudspeaker cone and the other end open. This conduit is in effect folded within the interior of the cabinet. In the photograph, the terminal opening is in the floor of the cabinet at the extreme left. The back of the cone is connected to the labyrinth through the felt lined housings shown, this construction leaving the field magnet in the open and permitting it to be operated at full efficiency without overheating.

The operation of the labyrinth may perhaps best be understood by considering first the impedance and transmission characteristics of a tube with non-absorbent walls and then passing to the practical case of the absorbent walled structure. We shall assume the tube to be driven by a rigid piston at one end and to be open at the other. The impedance per unit area on the piston is

$$Z_{00} = \rho c \, \frac{Z_l \cos kl + j\rho c \sin kl}{\rho c \cos kl + jZ_l \sin kl} \quad \cdots\cdots\cdots\cdots (1)$$

where Z_l is the impedance per unit area of the open end, ρ and c are, respectively, the density and the wave velocity pertaining to air, l

Acoustical labyrinth with back removed

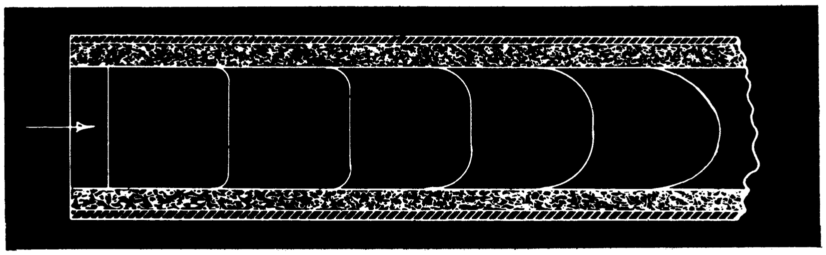

Fig. 2—Probable deformation of wave front in an absorbent conduit

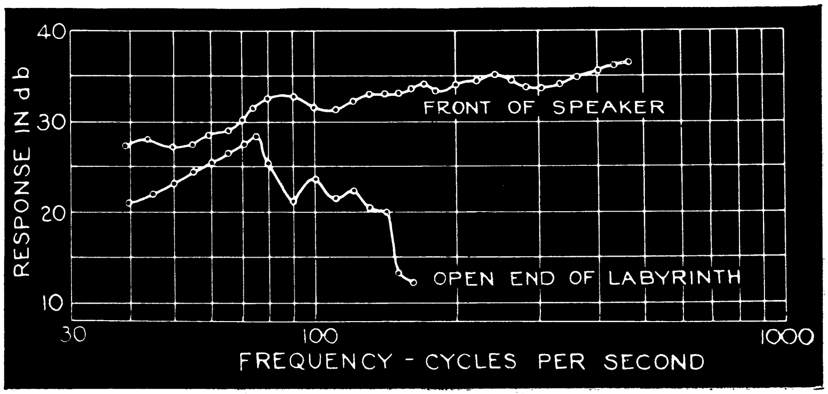

Fig. 3—Close-up response from front of speaker and from terminal opening of labyrinth

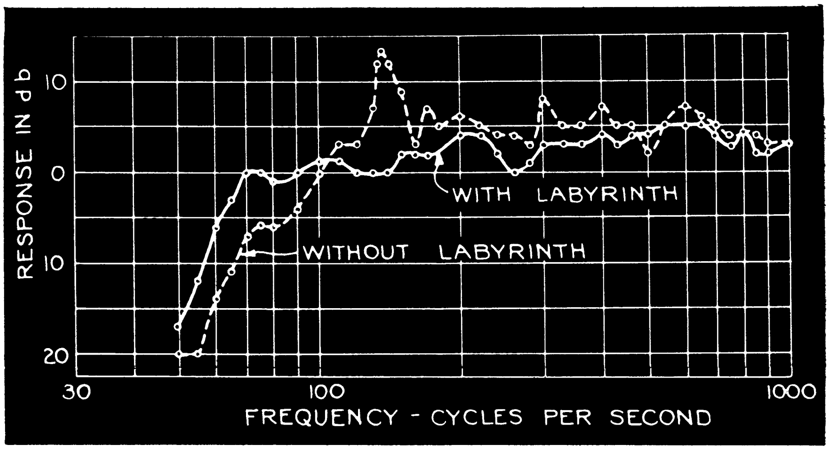

Fig. 4—Response of 8 in. cone loudspeaker in cabinet 2 ft. x 2 ft. x 1 ft. inside dimensions. Back of cabinet 2 in. from wall

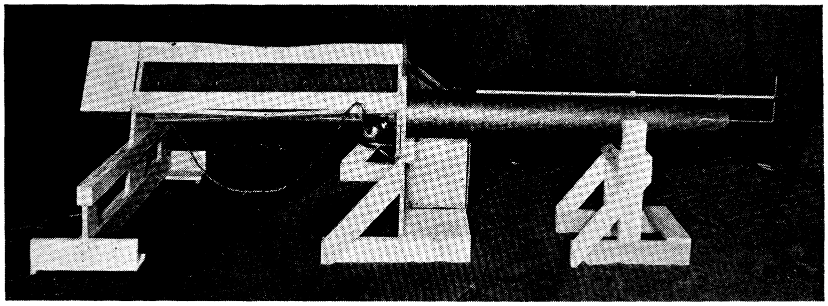

Fig. 5—Apparatus for the measurement of acoustic impedance

is the length of the tube and $k = 2\pi/\lambda$, where λ is the wave length in the same units as l.[1]

If the tube has a circular cross-section of radius r and is terminated in an infinite baffle, the impedance per unit area of the open end at low frequencies is[2]

$$Z_l = \rho c(k^2r^2/2 + j8kr/3\pi) \ldots\ldots\ldots\ldots\ldots (2)$$

It will be found that Z_l is, in general, small at low frequencies for tube areas comparable with usual loudspeaker cone areas.

In Fig. 1 is shown a plot of Eq. (1), assuming Z_l to be a pure resistance of 10 mechanical ohms per sq. cm. The abscissa is the length of the tube in terms of wave length of sound. When the frequency is such (f_1) that a given tube is one-quarter wave length long ($l = \lambda/4$), it will be noted that the impedance on the piston is a comparatively high pure resistance. When the frequency is increased to a value (f_2) corresponding to $l = \lambda/2$, the impedance becomes that of the open end, that is, the terminal impedance is transferred as if bodily to the driving point and the tube itself contributes no reactance. Furthermore, when the tube is an odd number of half wave lengths long, the phase of the air particle velocity at the open end becomes opposite to that at the driven end. At even numbers of half wave lengths no phase reversal occurs.[3] These critical impedance conditions occur repeatedly as the frequency is raised.

Now let us consider how some of the properties of the tube just discussed may be applied to a loudspeaker system. It has been mentioned, and later will be experimentally demonstrated, that the acoustic resistance load on a loudspeaker diaphragm of ordinary size is very small at low frequencies. This is true even though the diaphragm be mounted in an infinitely large baffle. However, by coupling our tube to the back of the diaphragm, we have available a very high resistance at the first quarter wave length frequency. By suitable proportioning the constants of the system, this region of high resistance and the primary mechanical resonance of the loudspeaker may both be made to occur at the same frequency f_1 located preferably below acoustic cutoff. In the practical case, this troublesome loudspeaker resonance is thus so highly damped as to be negligible in effect and the power handling capacity at low frequencies is determined by the heating of the driving coil and not, as is usual, by the striking of the moving system against its stops.

Probably everyone who has worked with open radiator loudspeakers has, at some time or other, ardently wished for a means for reversing the phase of the back radiation from the

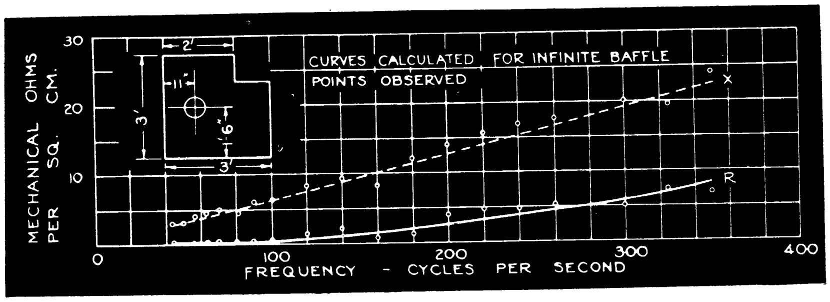

Fig. 6—Acoustic radiation impedance of 7-5/8 in. hole in plane baffle

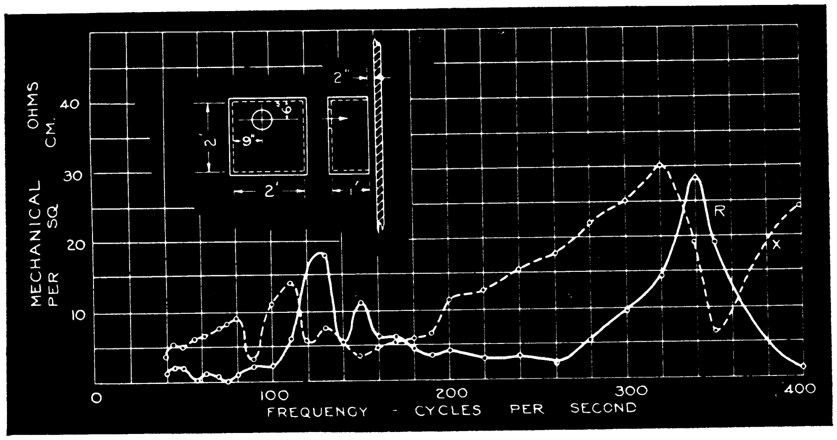

Fig. 7—Acoustic impedance of loudspeaker cabinet through 7-5/8 in. opening in front

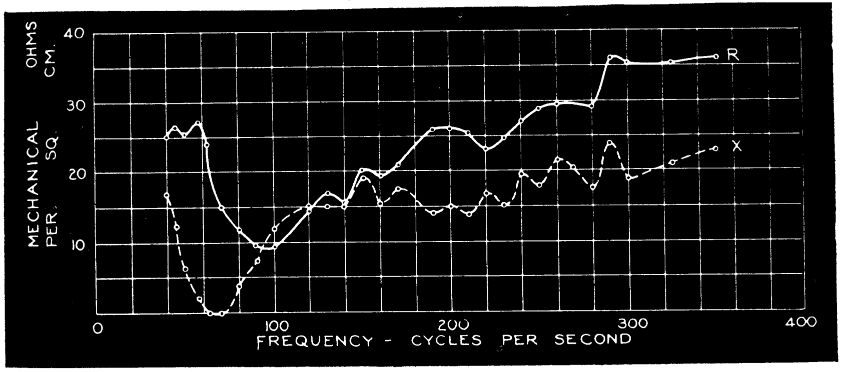

Fig. 8—Acoustic impedance of absorbent labyrinth measured at loudspeaker opening

diaphragm. We, therefore, enthusiastically take advantage of the condition occurring at the first half wavelength frequency f_2. By so proportioning the tube that this frequency lies near the lower end of the range to be transmitted, we have provided an auxiliary sound source (the open end of the tube) whose phase is the same as that at the front of the loudspeaker diaphragm and which cooperates with the latter to extend substantially the low frequency range. The fact that the tube impedance is low in this region also aids here by encouraging a greater amplitude of diaphragm motion.

Having employed to advantage the characteristics of the tube at its first two critical frequencies, we proceed upward in the frequency range and find to our embarrassment that the hitherto useful variations in its impedance and transmission now operate to produce undesirable dips and peaks in the response. However, by lining the tube with a material whose sound absorption rises suitably with frequency, we can suppress entirely these higher resonances besides accomplishing a desirable broadening out of the resistance peak at f_1. Also, the attenuation through the tube becomes very great above a moderately low frequency and the loudspeaker then behaves as a single sound source.

In the final development of the labyrinth, it was found necessary, in the absence of any adequate quantitative theory of the absorbent walled tube, to proceed experimentally and judge the results by means of measurements and listening tests. The analogous theory of the leaky electrical line would at first seem to be applicable to the case, as the absorbent lining of the tube may be shown by the following reasoning to constitute a shunt resistance element. Assume the tube (of length small compared with the wave length) to be rigidly closed at the distant end, this being equivalent to open-circuiting the receiving end of the analogous electrical line. Now, if the absorbent material acted as a series resistance there obviously could be no resistance component in the impedance measured at the driven end of the tube. We know, however, that the entire pressure generated by the driving piston must be exerted against the absorbent walls of the closed tube with consequent energy loss in the pores of the material. This loss, of course, must result in the appearance of a resistance component in the impedance on the piston. Hence, the absorbent material is equivalent to a shunt resistance.

When we attempt to apply the above theory to the practical labyrinth, however, we immediately run into the difficulty of assigning the correct value at a given frequency to the equivalent shunt resistance. In the first place, the published absorption coefficients of commercial materials are obtained under experimental conditions differing so widely from those existing in the present application that we do not feel justified in using them. They usually are obtained either for random or for normal incidence of sound upon the absorbing material, whereas grazing incidence prevails in the tube. Furthermore, no coefficients appear to be given at as low frequencies as we require.

Some speculations as to the mechanism of transmission through the tube result in further possible difficulty in the application of usual theory to this problem. Consider a plane wave generated by a piston at one end of an absorbent walled tube. It seems reasonable to assume that the abstraction of acoustic energy from the wave front will be more rapid near its absorbent boundary than at its center. Consequently the velocity is retarded at the periphery and the wave front becomes more and more convex as it progresses along the tube. It is probable too that the *rate* of absorption likewise changes progressively due to the shifting angle of incidence to the walls. Now, the classical theory of sound transmission in tubes is based upon the assumption of a plane progressive wave and, if the action outlined above takes place, must give way in that case to a much more complex one which the present author is in no position to invent.

The results of some measurements upon a typical labyrinth speaker system are given. Fig. 3 (page 23) shows the results of response measurements over the low frequency range of such a system mounted in a small cabinet, together with the effect of removing the labyrinth. The extension of the low frequency response below 100 cycles and the elimination of the cavity resonance peaks by application of the labyrinth are here definitely indicated. The two measurements were made by the rotating microphone method in a heavily damped room and under identical conditions.

In the set-up for comparing the response from the terminal opening of the labyrinth with that from the front of the loudspeaker, the microphone was placed inside the measuring room and close to a hole in the wall. The speaker system was located outside the room with its radiator to be measured sealed to the hole in the wall. The results show the response maximum at the open end occurring at the frequency f_2 and the rapidly increasing attenuation above this frequency due to absorption in the tube. At the higher indicated tube attenuations the measurements undoubtedly were vitiated by transmission through the walls of the measuring room and it is probable that the actual tube attenuation is even higher than that shown.

Measurements of acoustic impedance at various points in the loudspeaker system were felt to be essential to the progress of this development. A survey of published methods indicated that of Flanders[4] to have possible application. Flanders' apparatus, however, was intended for measurements over surfaces of the order of 0.7 inch in diameter whereas we were concerned with diaphragms and openings of about 8 inches in diameter. In changing the scale of the apparatus to this extent it was found desirable to employ a different mechanical arrangement, and the final set-up is in Fig. 5. Flanders' paper should be consulted for details of the method, which may only briefly be outlined here. In principle, the unknown impedance is measured in terms of that of a closed tube operated at one eighth wave length, at which the impedance of the reference tube is a pure acoustic capacitance having a value of 42 mechanical ohms per unit area. The sound source is a back-enclosed cone loudspeaker, seen at the left of the figure, which is coupled to a connecting tube together with which it is mounted on a carriage that may be swung into any of three positions. In one position (shown in the photograph) the end of the tube is joined to the impedance to be measured, which in this case is the labyrinth mounted on the baffle in the center. In the second position the end of the tube is closed tightly against the baffle providing an acoustic open circuit while, in the third position, the movable tube is connected to the reference tube shown at the right. This reference tube is of seamless steel construction having a $\frac{5}{16}$ inch wall and is provided with a tightly fitting piston by which the active length of the tube may be adjusted. The diameter of each tube is $7\frac{5}{8}$ inches. The unknown impedance is determined by measuring the relative phase and magnitude of the pressures at the output end of the movable tube for each of the three positions. This is done by means of the condenser microphone shown, which is connected to the center of the end cross-section of the tube by another tube of small bore. The microphone output is measured by an a-c potentiometer. In practice it was found essential to take precautions against the generation of spurious voltages due to other than air-borne sound in the tube, and to employ a heterodyne wave analyzer as a null indicator for the potentiometer at the low frequencies. All measurements were made in a heavily damped room.

The acoustic radiation impedance, measured by the above method, confronting one side of a typical loudspeaker diaphragm mounted in a plane baffle of moderate size is shown (Fig. 6). The peculiar shape of the baffle was made necessary by the arrangement of the measuring apparatus. The experimental values are indicated by the plotted points, while the curves were calculated from Eq. (2) which Rayleigh derived about 40 years ago. It appears from the present measurements that, although it was based on the assumption of an infinite baffle and radiation into free space, this equation may justifiably be applied to the usual practical conditions of operation.

Figure 7 shows the acoustic impedance on the back of a diaphragm

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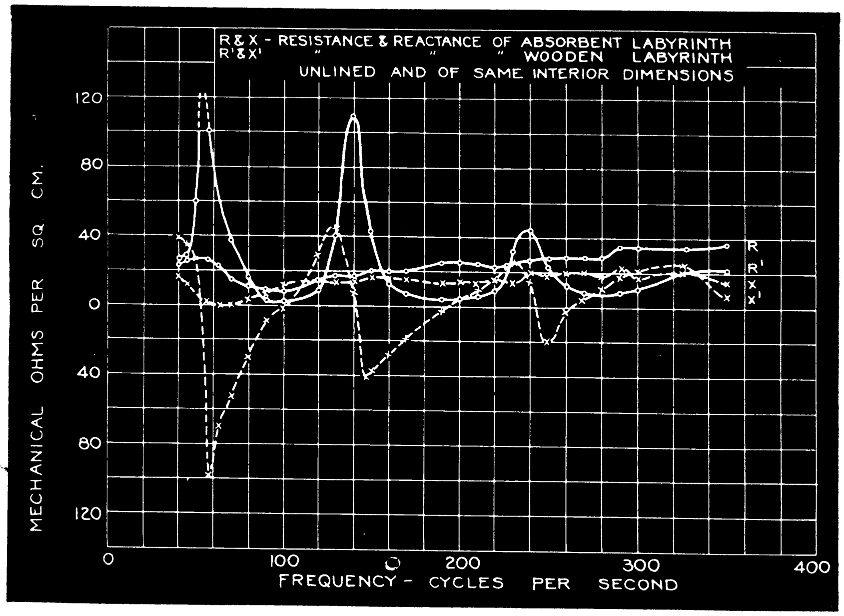

Fig. 9—Acoustic impedance of absorbent and nonabsorbent labyrinths, measured at loudspeaker opening

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(*Continued from page 27*)

mounted in a cabinet intended to represent the conditions of loudspeaker enclosure in a typical radio console placed with its back close to a wall. The impedance minimum at 140 cycles corresponds with the response peak at the same frequency in Fig. 3. It will be noted that the resistance below 100 cycles is very small. The total resistance on the diaphragm of a typical cabinet type loudspeaker is the sum of the resistances shown in Figs. 6 and 7 and is still small. As the sound power is directly proportional to the radiation resistance for a given diaphragm velocity it follows that effective sound radiation under the above conditions may be attained only with high velocities which, at the low frequencies under consideration, result in excessive displacement amplitudes.

The impedance on the back of the diaphragm of a loudspeaker mounted in a labyrinth of the type illustrated in the photograph is shown in Fig. 8. In contrast with Figs. 6 and 7, it will be observed that the resistance component predominates over most of the range and becomes very large at low frequencies. As an indication of the amount of damping afforded the loudspeaker, whose natural resonance frequency is located near 40 cycles, it may be stated that the resistance in this region is approximately 200 times that afforded by an infinite plane baffle. This resistance peak corresponds to the one occurring at $\lambda/4$ in Fig. 1. The effect of the absorbent lining of the labyrinth in modifying this peak and in reducing the reactance variations at such a low frequency is noteworthy. At higher frequencies the rise in absorption accounts for the virtual elimination of the higher order resonances of the tube.

A further experiment was performed to compare the impedance characteristics of an absorbent labyrinth with one having the same internal dimensions but made of solid wood. The results are shown in Fig. 9, where for comparison the curves of Fig. 8 have been replotted on the same scale as those for the wooden labyrinth. This gives further and striking evidence of the effectiveness of the absorbent lining. The measured curves for the wooden labyrinth are seen to have the same general characteristics as the theoretical ones for an unlined tube shown in Fig. 1. The marked falling off with ascending frequency of the amplitude of the peaks in the curve for the wooden labyrinth was caused by the inadvertent use of felt lined housings to connect the loudspeaker to the labyrinth. Even without the lined housings there would, of course, have been some falling off in the amplitude of the impedance variations due principally to the increase with frequency of the radiation resistance of the open end.

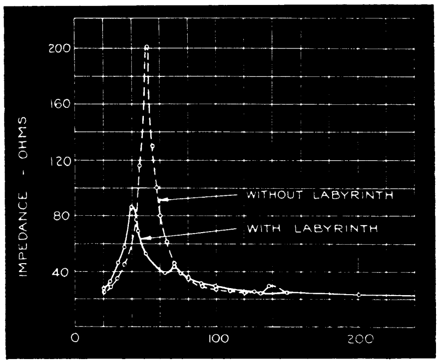

Fig. 10—Electrical impedance of loudspeaker in cabinet illustrating damping action of labyrinth

In Fig. 10 we have the results of electrical impedance measurements made on the same loudspeaker with and without a labyrinth. This again strikingly illustrates the effect of the labyrinth in damping the fundamental mechanical resonance of the loudspeaker moving system, as evidenced by the reduction to about one-third its former amplitude of the impedance peak resulting from the reflected velocity rise of the driving coil. The natural frequency is shifted from 50 down to 40 cycles by the additional air mass reactance of the labyrinth. The reduction in impedance variation is, as before mentioned, advantageous when working from certain types of vacuum tubes.

Listening tests on labyrinth loudspeaker systems compared with those of the conventional cabinet type indicate a much greater naturalness of reproduction for the former, particularly when the original sound sources are quickly available for direct listening. The absence of the usual cavity resonance "boom" is at once noticeable on speech. In the rendition of impulsive sounds of low pitch there may be recognized a striking improvement due to the elimination by the labyrinth of the usual spurious transients and "hangovers". In what may be called "loudness efficiency" the labyrinth speaker system will be found somewhat lower than one of the conventional cabinet type employing a similar driving unit. This is the expected result of the elimination of resonance peaks and non-linear distortion. The difference is difficult to evaluate because it varies with the type of program, but is not considered to be of great consequence in view of the important improvement in fidelity obtainable in the labyrinth system.

Some incidental advantages of the labyrinth system also are worth mentioning. First, unlike the usual open-backed cabinet, its internal characteristics are not adversely affected when it is placed with its back close to a wall. In fact, such a position is most favorable because the loudspeaker then operates with enhanced efficiency as a consequence of the smaller solid angle of radiation. Second, the shape of the cabinet is immaterial so long as it will contain the labyrinth. This assumes considerable importance in the case of automatic phonograph combinations where the shape of the record changing mechanism frequently calls for a cabinet so deep that cavity resonances are more than usually troublesome. Finally, as the loudspeaker, labyrinth and sub-baffle comprise in themselves the complete acoustic system independently of the cabinet, the panel resonance characteristics of the latter have an insignificant effect on the performance.

This article is based on data which originally appeared in a paper by the same author published in the October 1936 issue of the *Journal of the Acoustical Society of America.*

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[1] Crandall, "Theory of Vibrating Systems and Sound," p. 100 Eq. (288)

[2] Rayleigh, "Theory of Sound," Vol. II, p. 165.

[3] Reference 1, p. 101

[4] Flanders, A Method of Measuring Acoustic Impedance, *Jour. Acous. Soc. Am.* 4,402, 1932