Vented Loudspeaker Enclosures

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Design and performance data on aperture-type enclosures.

THE principle of the vented loudspeaker enclosure or reflex type cabinet, first described by Thuras[1], is now well known, and enclosures of this type are to-day widely used in high quality sound reproducing systems. Briefly, a vented enclosure sound system consists of a cone loudspeaker mounted in a felt-lined enclosure, which communicates with the atmosphere via an aperture or duct in the front panel. The capacitive reactance of the air volume in the enclosure and the inductive reactance of the aperture or duct are arranged to resonate at the bass resonance frequency of the loudspeaker.

Advantages

One of the main advantages of systems of this type is the improved efficiency at low frequencies, due to the re-radiation of the sound energy from the rear of the loudspeaker diaphragm via the aperture or duct after phase reversal. Other advantages are the improved transient response and reduced voice coil travel due to the additional loading of the diaphragm by the impedance of the acoustic system, as well as the relative independence of the performance from local acoustic conditions, such as the position of the enclosure in the room.

The design principles for vented enclosures, using apertures[2], as well as ducts[3] as the inductive reactances, have already been treated in some detail in the literature. These notes will be concerned mainly with the discussion of the necessary volume of such enclosures.

The main drawback of the vented enclosure, as compared with alternative methods, such as the infinite baffle or the labyrinth type of enclosure, is the relatively large size required for the reproduction of the lowest audible frequencies. In the course of the design of a new domestic sound system intended to give exceptionally high quality reproduction, the question of cabinet size became of some importance, and an investigation of the relation between size and resonance frequency was made. As a result of this a number of expressions were developed which may be of general interest.

Fig. 1 shows schematically an enclosure comprising an effective air volume V_L and a duct having length l and cross-sectional area A. The two design principles for vented enclosures which have in the past been found to give satisfactory results, state that the resonance frequency of the enclosure itself should be similar to the bass resonance frequency of the loudspeaker, and the aperture or duct area A should be similar to that of the effective radiating surface of the speaker.

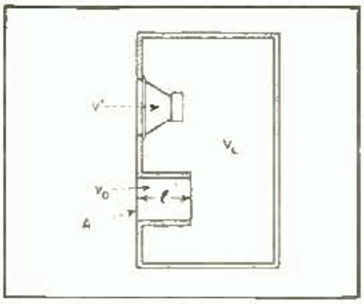

Fig. 1. Cross section through vented loudspeaker enclosure.

The inductive reactance in the case of an enclosure employing a duct may then, with close approximation, be written

$$X_L = \omega\rho / \left(1/\sqrt{A} + l/A \right) \quad \text{mech. ohms} \qquad (1)$$

where ω is the (angular) resonance frequency $= 2\pi f$ and ρ the density of air.

The capacitive reactance of the air volume is given by

$$X_C = \rho c^2 / \omega V_L \quad \text{mech. ohms} \qquad (2)$$

where c is the velocity of propagation of sound in air.

Resonance occurs when

$$X_L = X_C \qquad (3)$$

Equating (1) and (2), and solving for ω the resonance frequency is found to be

$$\omega = c / \sqrt{V_L \left(1/\sqrt{A} + l/A \right)} \qquad (4)$$

Effect of Duct Length

From this it is apparent that if the length l of the duct increases, the enclosure volume V_L may be decreased, other conditions remaining unaltered. At the same time, however, the total volume V_T which is made up of the effective air volume V_L, the volume displaced by the loudspeaker V' and that of the duct V_D, will not alter at the same rate, owing to the increase in the volume displaced by the duct.

Since
$$V_T = V_L + V_D + V' \qquad (5)$$

and $V_D = Al$, the total volume may be written

$$V_T = A \left(c^2/\omega^2 \left(\sqrt{A} + l \right) + l \right) + V' \qquad (6)$$

Now, in order to determine the length of duct corresponding to the minimum total volume, the differential of (6) with respect to l is equated to zero

$$dV_T / dl = 1 - c^2/\omega^2 \left(\sqrt{A} + l \right)^2 = 0 \qquad (7)$$

and hence

$$l_{\text{min.}} = c/\omega - \sqrt{A} \qquad (8)$$

where l min. is the duct length required to make the total volume V_T a minimum.

The volume for this condition is found by substituting (8) in (6)

$$V_{T\,\text{min.}} = A \left(2c/\omega - \sqrt{A} \right) + V' \qquad (9)$$

The corresponding air and duct volumes are given by

$$V_{L\,\text{min.}} = A\,c/\omega, \quad \text{and} \qquad (10)$$
$$V_{D\,\text{min.}} = A \left(c/\omega - \sqrt{A} \right) \qquad (11)$$

From these results is may be seen that it is generally possible by the correct choice of duct length, to effect an appreciable reduction in the overall size of the enclosure as compared to that required when an aperture only is used.

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[1] A. L. Thuras, Sound Translating Device, U. S. Patent 1869178, July, 1932.

[2] C. E. Hockstra, Vented Speaker Enclosure. *Electronics*, March, 1940, p. 34.

[3] F. W. Smith, Resonant Loudspeaker Enclosure Design, *Communications*, August, 1945, p. 35.

Example

To illustrate the effect of the duct length on total volume, let us consider a typical sound system using a 12" loudspeaker with a bass resonance frequency of 65 c.p.s. and an effective radiating surface of $A = 75$ sq. in. Then, substituting these values in the expression (8) the optimum duct length will be found to be 24½ inches, assuming the velocity of propagation of sound in air to be $C = 13{,}500$ in/sec. If the volume displaced by the loudspeaker is taken as 500 cu. in., then the total volume from (9) becomes V_T min. = 4,800 cu. in. In comparison, the volume for an enclosure possessing an aperture only, i.e., for the case $l = 0$, is found from (6) to be 10,000 cu. ins.

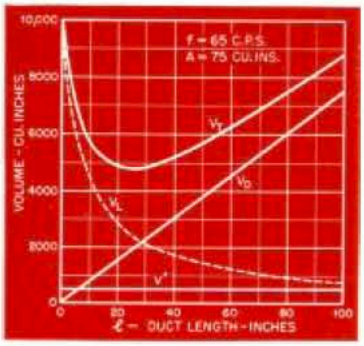

Fig. 2. Relation between duct volume, resonating air volume, total enclosure volume, and duct length for a typical vented loudspeaker enclosure.

The relationship between l and V_T for the above example have been plotted in *Fig. 2*, together with the values of V_D and V_L. It will be seen from this that as the duct length is increased there is a rapid fall in total volume, with a minimum at 24½ in.; thereafter the total volume begins to rise at a more gradual rate. It will be noticed also that the slope of the curve for V_T is relatively small in the neighborhood of the minimum. The length of the duct may therefore, be made somewhat shorter than the optimum length indicated by expression (8) without an appreciable increase in the dimensions of the enclosure. In actual practice, it is an advantage to reduce the duct length in this manner, as it will then generally be possible to accommodate the duct without folding, thereby rendering the construction simpler and reducing the amount of wood required. Another point in favor of the shortened duct is the smaller volume taken up by the duct walls, a factor which has been neglected in the above calculations. Thus, in the present example the duct length may be reduced to 13 inches with only a 10% increase in total volume above the theoretical minimum.

Apart from its effect on the over-all size of the enclosure, the extension of the aperture into a duct is desirable also for other reasons. Since the vent may be regarded as effectively constituting a second source of sound, it is advantageous to locate the latter as closely as possible to the loudspeaker from the point of view of the combined radiation impedance, as well as for the purpose of concentrating physically the source of sound. While these considerations apply to frequencies in the neighborhood of the resonance frequency of the enclosure, at higher frequencies the vent will tend to reduce the effectiveness of the baffle owing to the air leak created around the diaphragm of the loudspeaker. By the introduction of a duct it becomes possible to maintain the efficiency of the baffle at the higher frequencies due to the increased path length between front and rear of the diaphragm, while at the same time retaining the feature of close proximity between the two sources of sound at the lower frequencies.

In order to investigate the effect on the characteristics of the system when the ratio of duct length and air volume are varied, it is instructive to consider the equivalent electrical circuit of the mechanical system comprising the loudspeaker diaphragm and the acoustic resonator. *Fig. 3* is a simplified equivalent network in which the dissipative elements due to radiation and frictional losses have been omitted.

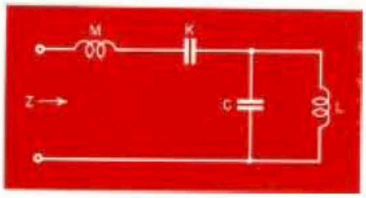

Fig. 3. Equivalent electrical circuit of mechanical system.

The vibratory system of the diaphragm comprising the stiffness of the suspension and the mass of the moving parts including the effect of air loading is represented by the series tuned circuit having capacitance K and inductance M. The acoustic system of the vented enclosure is represented by a parallel tuned circuit having inductance L and capacitance C, dependent on the stiffness of the air volume in the enclosure, and the duct and radiation mass, respectively. The impedance Z, as measured at the terminals of the network is made up of the impedances of the diaphragm Z_L and that of the enclosure Z_E in series.

Now, $$Z_L = (1-\omega^2 MK)/j\omega K \quad\text{......(12)}$$

and $$Z_E = j\omega L/(1-\omega^2 LC) \quad\text{......(13)}$$

The total mechanical impedance, therefore, is

$$Z = (1-\omega^2 MK)/j\omega K + j\omega L/(1-\omega^2 LC) \quad\text{..(14)}$$

Impedance Characteristics

In the absence of dissipative elements, the impedance characteristic of the two coupled circuits, as represented by the expression (14), will possess two points at which the impedance becomes zero, and the admittance infinite. The characteristic of the mechanical system is reflected in the electrical impedance characteristic of the voice coil of the loudspeaker, modified slightly by the electrical constants of the voice coil itself. This electrical impedance will be a maximum when the admittance of the mechanical system is infinite, and the electrical method of measurement, therefore, constitutes a convenient means of analyzing the behavior of the mechanical system.

In order to determine the two frequencies at which the electrical impedance will be a maximum, we substitute

$$MK = LC \quad\text{..............(15)}$$

in (14), since the resonant frequency of the enclosure is made equal to that of the loudspeaker, and re-arranging terms (14) becomes

$$\omega^4 - \omega^2(2K+C)/MK^2 + 1/M^2K^2 = 0 \quad\text{...(16)}$$

Solving for ω, the two frequencies are found to be

$$\omega_{1,2} = \omega_0\sqrt{1 + C\left(1 \pm \sqrt{4K/C+1}\right)/2K} \quad\text{..(17)}$$

where ω denotes the resonance frequency of the two tuned systems individually.

The relation (17) is shown in *Fig. 4*, plotted in terms of the ratio M/L against frequency. From this it will be seen that as the duct length is increased and the enclosure volume reduced, i. e. with increasing M/L ratio, the separation between the maxima in the impedance characteristic increases. It will readily be seen that too great a separation is as undesirable as very closely spaced impedance peaks.

A number of loudspeaker enclosures were designed in accordance with the

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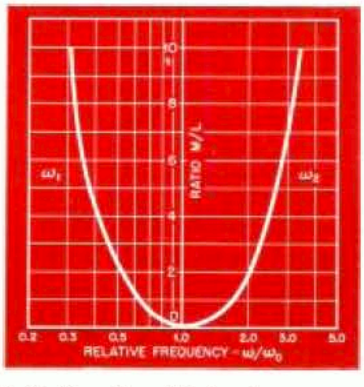

Fig. 4. Separation of the impedance maxima as a function of the ratio M/L.

Vented Enclosures

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foregoing considerations, and a complete sound system employing these principles was constructed. The loudspeaker enclosure is the central unit and incorporates an 18" exponential cone loudspeaker having a bass resonance frequency of 40 c.p.s., a medium frequency driver unit with multicellular horn, and a special wide-angle distribution electrostatic high-frequency unit together with suitable dividing networks. Allowance has been made in the calculations for the additional volume taken up.

The associated apparatus is housed in the two separate side cabinets. These apparatus units have been designed so that when they are used together with the loudspeaker enclosure as illustrated, the acoustic performance will be enhanced by the horn loading effect of the exponentially shaped surfaces of the side cabinets.

[*to page 44*]

[from page 45]

Tests

A number of acoustic and electrical measurements have been carried out on enclosures of this type in order to study their characteristics. In the first instance it was necessary to verify that the resonance frequency of the acoustic system coincided with that of the loudspeaker. For this purpose, the voice coil current was measured at various frequencies with the loudspeaker removed from the enclosure and in free air.

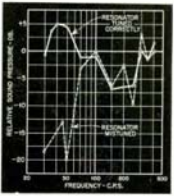

Fig. 5. Relative sound pressure at mouth of duct with the acoustic resonator tuned correctly, and mistuned, respectively.

The baffle opening for the speaker was then blocked, and a corresponding volume introduced to replace that of the speaker. The acoustic system was subsequently excited by means of a separate driver unit coupled to the air volume in the enclosure by means of a tube 3 feet in length and $\frac{5}{16}$ths in. in diameter. This precaution was necessary in order to avoid interaction between the vibratory system of the driver unit and the acoustic resonator.

The tube was introduced via the duct, and the driver unit fed from a beat frequency oscillator. A microphone was placed immediately at the mouth of the duct, and together with its associated detector amplifier, served to indicate the resonance frequency of the enclosure. It was found in each case, that the actual resonance frequency of the enclosure was lower by varying amounts, than the calculated value, and an adjustment in the duct length was necessary in order to make the resonance frequencies of loudspeaker and enclosure coincide.

Next the loudspeaker was restored, and measurements were made of the sound output from the duct by means of the microphone and detector amplifier. *Fig. 5* shows two typical characteristics obtained for the sound pressure at the mouth of the duct, with the latter tuned correctly, and with the acoustic system mistuned, respectively. (40 cycle enclosure).

Among other measurements the electrical impedance characteristic of the voice coil was determined over the useful frequency range under operating conditions. For this purpose the voice coil was connected in series with a decade resistance box, and the combination fed with signals at various frequencies from a beat frequency oscillator. By adjusting the decade resistance until the voltage drops across it and the voice coil were equal, the value of the impedance at the particular frequency could be read from the setting of the resistance box. By these means it was in each case verified that instead of the original single peak, the impedance characteristic now possessed two damped resonance peaks, the frequencies of the two maxima being approximately 31 and 55 c.p.s. in the case of the 40-cycle enclosure referred to in *Fig. 5*. This separation is regarded as quite satisfactory and has been considered to be one of the reasons for the exceptionally smooth response of the system.