Ported Loudspeaker Cabinets

JAMES MOIR*

A thorough understanding of the author's presentation will enable anyone to design and construct a bass-reflex cabinet which will provide improved performance over conventional "boxes with holes in them."

PORTED OR REFLEX CABINETS are deservedly popular as loudspeaker mountings at the present time, their special merits being the extension of the low-frequency range that may be obtained in a relatively small volume, coupled with an appreciable reduction in the amplitude distortion generated by the loudspeaker. The theory, construction, and operation is an interesting study and it is proposed to comment on some of the aspects in which present theory and practice appear to be at variance.

The first major advantage is the increase in the low-frequency output that is obtainable from a reflex cabinet when compared to the output obtainable from the same speaker unit mounted in a flat baffle, or in many of the alternative enclosures. The increase in output is the result of several contributory factors.

(a) Utilization of the acoustic power output from both sides of the cone.
(b) The close association of two radiating surfaces vibrating in the same phase.
(c) The addition of an Helmholtz resonator to the acoustic system.

Some of the many possible forms are illustrated in *Fig.* 1 from which it will be appreciated that the characteristic feature of all ported cabinets is the addition of an Helmholtz resonator coupled to the rear of the cone, the resonating elements being the acoustic capacitance of the box volume and the acoustic inductance of the mass of air contained in the port and tunnel. At, and in the vicinity of resonance, there is a considerable movement of air through the port and the energy radiated as sound from the port may exceed that radiated from the front of the diaphragm by a factor of several times. If the phase of the radiation from the port is the same (within ± 90 deg.) as that from the front of the diaphragm the total sound output will be increased. It may be shown that the combination of acoustic elements is such that the backward wave from the speaker diaphragm is reversed in phase and thus appears at the port opening *in phase* with the radiation from the front of the cone. The exact mechanism of the phase reversal will not be pursued at this point for the agreement between calculated and measured values of some of the elements in the acoustic phase changing path is poor. Actual measurements of the relative phase of the sound pressure at the port and diaphragm confirm the qualitative theory however.

Though the radiation from the port is in phase with that from the diaphragm in the vicinity of resonance it deviates considerably both above and below the resonant frequency. As the resonant frequency is usually chosen to be near the bottom end of the audio range, the deviation from phase identity below the resonant frequency is not of great consequence. Above the resonant frequency the phase difference can also reach 180 deg. and as this would reduce the total sound output it is necessary to attenuate the high-frequency radiation from the port by adding absorbent material to the interior of the enclosure. A qualitative comparison between the sound output with and without a ported cabinet is given by *Fig.* 2 from which it will be seen that some worthwhile gain is obtained over about one octave above and below the resonant frequency but the effective sound output at very low frequencies is actually reduced by the addition of the acoustic resonator.

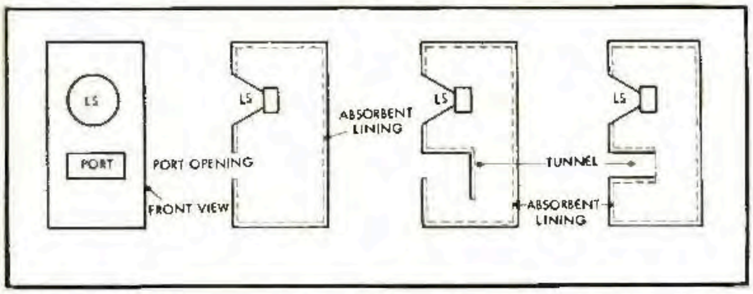

Fig. 1. Typical arrangements of ported cabinets showing two possible positions of the tunnel or duct.

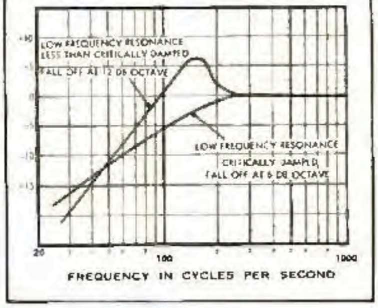

Fig. 2. Effect of damping of low-frequency resonance on acoustic output of a cone loudspeaker.

Design Procedure

The first problem to be met when ap-

---

* *73 Bawnmore, Bilton, Rugby, England.*

proaching the design of a ported cabinet is that of choosing the resonant frequency for which the enclosure is to be designed. A full discussion of the reasons governing the choice would require more space than is available and it will be shortened to the point of saying that the resonant frequency of the enclosure is usually chosen to be the same as the resonant frequency of the speaker cone. The acoustic coupling between the resonant enclosure and the resonant mechanical system of the cone and surround is assumed to be such that the electrical impedance/frequency curve of the speaker voice coil will have "maximum flatness." A typical sort of result is illustrated by *Fig.* 3 from which it will be seen that the over-all impedance/frequency curve exhibits the double humped form characteristic of coupled electrical circuits, certainly a major advantage, for as previously pointed out,[1] a flat impedance/frequency curve results in minimum amplitude distortion from the amplifier output stage.

The acoustic resonant frequency of the enclosure is controlled by the physical dimensions of the enclosure volume, the port area, and the tunnel length interpreted as in *Fig.* 4. The relation may be approached either by calculating the equivalent electrical circuit elements or by a more direct approach involving the physical dimensions only. The former gives a clearer insight into the basic process and is invaluable in any investigation but the latter method is shorter and is quite adequate for the enclosure designer. Several analyses have been made but the one most closely in agreement with measurements is that due to Planer and Boswell.[2] Their work leads to an expression for the resonant frequency,

$$f_r = \frac{2150}{\sqrt{V(1\sqrt{A} + L/A)}}\ cps \qquad (1)$$

where

V = box volume

A = port area

L = effective tunnel length

with all dimensions in inch units.

A critical comparison of the calculated and measured resonant frequencies of a dozen or more enclosures indicated that while none of the published design equations were in perfect agreement with practice, the expression quoted consistently gave the best agreement.

To the enquiring mind, marginal disagreements between theory and practice are often of greater interest than complete agreement so the subject will be pursued in an endeavor to account for the discrepancies. The factors entering into the design equations are enclosure volume V, port area A, and tunnel length L, and as the effective values of these may differ somewhat from their physical values they will be considered in turn. In the simple case where no tunnel is employed there would not appear to be any great margin for error in determining box volume V, though the literature is a bit inconsistent in deciding whether the volume of any absorbent lining should be deducted from the chamber volume to obtain the effective volume. Qualitative considerations suggest and experiment confirms that the volume of permeable linings such as fibreglass or hair felt should not be deducted from the casing volume but that allowance should be made for the volume of the more impermeable materials, such as insulation board, cane fibre or asbestos fibre tiles.

As far as can be ascertained prior literature is completely in error in dealing with the effective volume of an enclosure that includes a tunnel, the unanimous and apparently reasonable decision being that the tunnel volume should be subtracted from the internal volume in order to obtain the effective volume. This outlook would seem to be based on the simplifying assumption that the air in the tunnel takes no part in the compression and expansion cycle which characterises the acoustic regime in the volume V but merely undergoes translation along the tunnel. A little thought will suggest that this assumption is probably untenable but any doubts were resolved in a relatively simple manner.

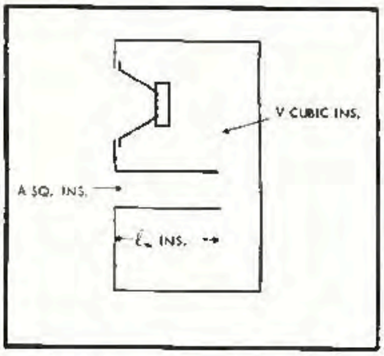

Fig. 4. Parameters important in the design of a ported cabinet.

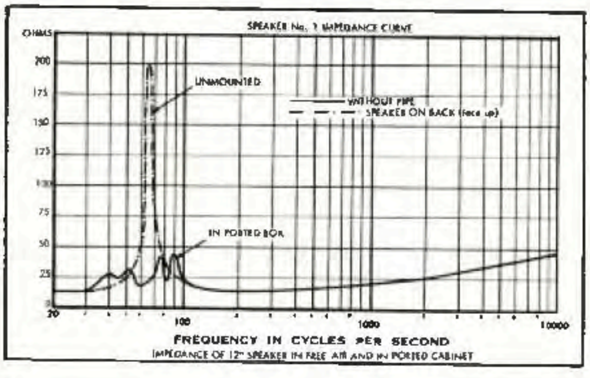

Fig. 3. Impedance of a typical 12-inch speaker in free air and in a ported cabinet.

Experimental Determination

A ported enclosure was constructed in which the tunnel volume represented some 30 per cent of the enclosure volume and of such a shape that the tunnel could be added either on the inside or outside of the box as indicated in *Fig.* 5. This artifice maintains the tunnel length substantially constant but allows the tunnel volume to be removed from the cabinet volume. The resonant frequency of the enclosure was then measured (using a precision low-frequency oscillator) with the tunnel in both positions. In neither example tested was there any indication that the position of the tunnel had any significant effect upon the resonant frequency although the test method employed was capable of detecting a frequency shift of less than one tenth of that expected from calculations based on the normal assumption.

The actual experimental verifications were carried out by two competent engineers well versed in the conventional theory and quite skeptical about the writer's preliminary suggestion that the accepted theories were in error. We may say with some confidence that the tunnel volume should *not* be subtracted from the enclosure volume to obtain the effective volume of the enclosure.

Speaker's Volume

Prior literature is also quite unanimous and apparently in error about the correction to be made for the volume occupied by the speaker unit, specifying that the effective volume of the speaker unit is that shown in solid at (A) in *Fig.* 6. Once again some preliminary theorizing suggested that the effective volume of a

---

[1] J. Moir, "transients and loudspeaker damping." Wireless World, May, 1950.

[2] Planer and Boswell, "Vented loudspeaker enclosures." Audio Engineering, May, 1948.

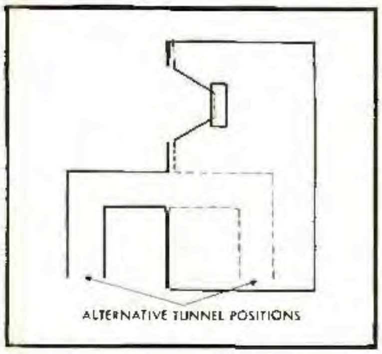

Fig. 5. Cabinet arrangement for experimental determination of effective volume of tunnel.

speaker unit is in fact only that of the iron parts and does *not* include the volume enclosed by the conical diaphragm. An enclosure divided into two half sections by a partition in the form of a thin infinitely flexible and massless diaphragm behaves as a single volume, for the diaphragm offers no obstruction—either resistive or reactive—to the movement of vibrating air particles in the vicinity of the partition. The air volume enclosed by the conical diaphragm is similarly tightly coupled to the volume of the enclosure.

Once again any doubts were resolved by a simple experimental attack. Measurements of resonant frequency of an enclosure of normal volume are insufficient to determine any change due to the insertion of a speaker unit but the use of an enclosure having an internal volume of little more than one cubic foot permits the change in resonant frequency to be accurately determined. The resonant frequency of the small enclosure was determined with and without the speaker unit, the effective volume of the speaker unit being determined by calculation from the two experimentally determined frequencies. It was confirmed by inserting wood blocks of known volume into the empty enclosure to bring the resonant frequency up to that of the enclosure with the loudspeaker.

The effective volume of the speaker determined by these two methods differed from an estimate of the volume of the iron parts, as shown at (B) in *Fig.* 6, by less than 3 per cent and bore no relation to the volume enclosed by the speaker outline.

The foregoing discussion enables the effective volume of an enclosure to be determined leaving the port area A and the effective length of the port or tunnel L to be determined. Unless a port of slit shape is adopted the effective area is the same as the physical area and it thus presents no difficulty in its determination.

The effective length of the tunnel may, and generally does, differ appreciably from its physical (i.e. measured) length. Helmholtz resonator theory presupposes that the air in the tunnel undergoes a translatory motion along the tunnel but that the air particles immediately outside the tunnel ends are stationary. This is clearly an oversimplification but an accurate mathematical determination of the effect of the air movement outside the tunnel is a difficult process that has exercised many investigators because of its importance in determining the effective length of an organ pipe.

Movement of the air outside the ends of the tunnel will clearly increase the mass of air in resonant motion and result in the effective length of tunnel being greater than the physical length. Rayleigh has proposed to allow for these "end effects" by adding an end correction $l_e = 0.4D$ to the measured length of tunnel and his proposal is confirmed at least for measurements of engineering accuracy. D is the diameter of the port if circular or the diameter of the circle having the same area as the port where the port is non-circular. The effective length of tunnel L to be used in equation (*1*) is therefore the measured length l_m plus the correction l_e. Where the port is the chamber wall thickness only the effective tunnel length will differ from the measured tunnel length by an appreciable amount for the correction length l_e, being a function of port area only, becomes greater than the physical length. With the modifications discussed, the equation presented by Boswell and Planer appears to predict the value of enclosure resonant frequency with an error of less than 2 per cent when any simple form of construction is employed.

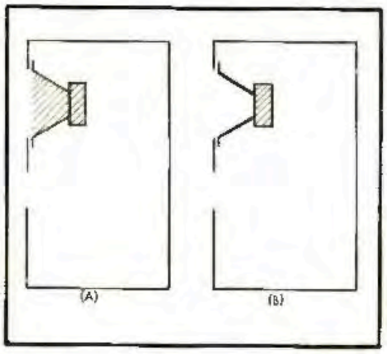

Fig. 6. Effective volume of loudspeaker unit.

The design procedure based on the Planer and Boswell equation is presented in the form of a single set of curves in *Fig.* 7, which covers the design of any size of speaker unit in any size of enclosure and with any value of enclosure resonant frequency.

Other Variables

The resonant frequency is, however, a function of (among other things) the enclosure shape. Thus when a spherical resonator with a circular opening is employed, the resonant frequency is determined almost entirely by the volume V and port area A and may be accurately calculated. At the other extreme a chamber in the form of a long narrow pipe has a resonant frequency which is deter-

(*Continued on page 83*)

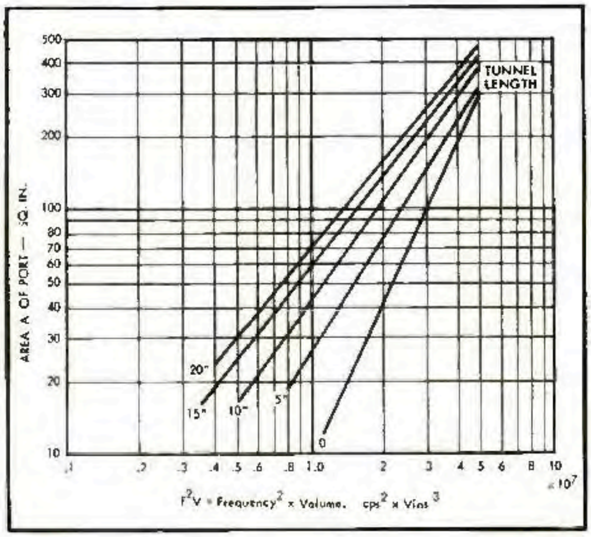

Fig. 7. Design relations of ported enclosures.

fact that top quality tape recording is both a technique and a craft. It is advisable to have a technical grasp which enables one to adjust a tape recorder, if feasible, so as to make the most of its capabilities with respect to distortion, frequency range, and signal-to-noise ratio. At the same time, one must have the craftsman's touch, which is based on experience, qualitative judgment, and—the best instrument of all in audio work—an acute ear.

PORTED LOUDSPEAKER CABINETS

(from page 25)

mined almost entirely by the pipe length, the volume V and the port area A having second order effects only. In practice cabinets do not stray too far from a cubical shape for which Planer and Boswell equation for f_r is quite adequate when the inevitable drift in the speaker resonant frequency is taken into account.

Experience suggests that almost any addition to the cabinet interior affects the measured resonant frequency, such apparently minor factors as the relative position of port and speaker or the provision of an isolating shelf between port and speaker shifting the resonant frequency by a few cps. If it is desired to build a cabinet having an accurately determined resonant frequency some final adjustment to enclosure volume or port area must be made after the unit is completed.

The gain in power output at the lower end of the frequency range is determined by, amongst other things, the Q of the enclosure, a factor that it is impossible to calculate with any pretensions to accuracy (Q for a cabinet has the same meaning as the Q for an electrical circuit, being the ratio of stored energy to dissipated energy per cycle). Energy is stored in the enclosed air volume and dissipated as sound or in frictional or viscosity losses in the cabinet and lining structure. The fraction dissipated as sound power is small, structural dissipation accounting for the majority of the losses. Structural losses in an airtight enclosure are largely due to flexion of the chamber walls and are therefore affected by the material used in the construction, but over a fair range of woods experience seems to indicate that the Q falls between 3 and 6. A high value of Q leads to "cabinet hangover" any low-frequency transient having a low-frequency tail oscillation added to the original, giving a soft and rather flabby character to the reproduction. The enclosure Q cannot be reduced to unity or there would be no advantage in using an enclosure, and so the final value must be a compromise to suit personal tastes of the user.

Acoustic Damping

Damping may be added in many ways, the most popular being the use of hair felt, fibreglass or some similar absorbent attached to the walls, though more recently it has been realized that the absorbent material is largely ineffective if mounted on the walls where the air particle velocity normal to the surface is substantially zero. Some consideration of the reason for including the damping will indicate the best position for mounting it in the enclosure.

The added damping really has two duties to perform, it decreases the Q at the resonant frequency to the desired value and it provides sufficient absorption at frequencies above twice the resonant frequency to attenuate the sound output from the port. This is essential if severe interference between sound from the front of the cone and the sound from the port is not to occur. Maximum attenuation to sound energy in the maximum number of modes of enclosure oscillation is provided by a single sheet of absorbent material suspended from the front left and rear right top corners and fastened down to the rear left and front right bottom corners. Maximum attenuation at the basic resonant frequency is given by a sheet of absorbent material across the port for at this point the velocity of the air particles is a maximum.

The thickness and character of the absorbent used across the port is considerably more critical than when it is suspended inside the cabinet. Absorbent material suspended inside the cabinet is effective as a high resistance shunted across the parallel resonant system formed by the box volume and port volume whereas an absorbent diaphragm across the port is effective as a low resistance in series with the effective inductance of the port. Thus an enclosure requiring 15 sq. ft. of half-inch felt attached to the walls will be damped to the same degree as the basic resonant frequency will be by a single thickness of calico across the port.

Both methods of damping may be employed usefully, a length of felt or fibreglass sheet being suspended in the cabinet to deal with the higher frequency modes of resonance, while the basic resonance is dealt with by absorbent material inserted in the port. Provision of a shelf having a depth of one-half that of the cabinet immediately adjacent to the port between port and loudspeaker considerably attenuates the high-frequency output from the rear of the cone, and is generally to be recommended.

A primary requirement for any loudspeaker enclosure is that it should not add too much coloration of its own creation to the outgoing signal. Some idealists might even suggest that it should add no coloration to the signal but this may be misdirected effort. Every room surface, including the floor, door panels, furniture, each hollow vase, and even the brick walls contribute their own quota of coloration to every sound reproduced in the room. Thus it would appear more reasonable to consider the amount of coloration added by the speaker cabinet against the background of coloration added by the room and its contents. If this is done it will usually be unnecessary to worry about a speaker enclosure of normal construction until the piano is removed from the room.

Adequate freedom from cabinet vibration can usually be secured by the use of half-inch plywood or one of the reconstructed wood boards for the body, stiffened either by a triangular corner block of 4-inch side, or half a dozen one-inch square struts across from wall to wall. As a third alternative half a dozen 3 × ¾ stiffening strips screwed "edge on" across the walls in a random pattern can be recommended. Cross bracing strips or 3-inch deep stiffeners both serve as an excellent support for absorbent material, spacing it well away from the walls.

If the ultimate in vibration-free housings is required, a double walled construction of ⅜-inch plywood spaced ½ inch apart and having the space packed with dry sand is excellent. An enclosure built from ½-inch plywood with half-inch insulation board glued to the plywood under pressure is less troublesome to construct in some ways, but gives excellent results.

Shape of Cabinet

Enclosure shape is important, though that importance is not revealed by any design equation. Shapes in which one dimension exceeds the others by a large factor are generally to be avoided. Thus, pipes with or without adequate internal damping have always proved disappointing. Irregular-shaped interiors appear to have some acoustical advantage that is not revealed by current practice in measurement, an advantage that is possessed by the triangular corner cabinet. Corner mounting is generally to be preferred both from the acoustical and domestic points of view, for no other shape permits such a large number of cubic feet to be so inconspicuously concealed.

While internal irregularity has its advantages the opposite is true of the exterior. Each external edge and corner produces irregularities in the primary high-frequency response due to diffraction at the surface discontinuity, and though these irregularities are masked to some extent by the generally reverberant sound they should be borne in mind when considering alternative enclosure designs.

The position of the port with respect to the speaker is not highly critical but there is some slight theoretical advantage in placing the port near to the speaker opening. Klapman has shown that the effective radiation resistance presented to a diaphragm is directly proportional to the number of diaphragms if they are all closely associated in space. Close spacing has the disadvantage of increasing the high-frequency radiation from the port unless precautions are taken to prevent it, but if such precautions are taken the balance of advantage is marginally in favor of close spacing of port and speaker openings.

The subject of loudspeaker housings is one of considerable complexity, but it is of such importance as to justify extended consideration. The present contribution is taken from the chapter on Loudspeakers in a book "High Quality Sound Reproduction" shortly to be published by Chapman & Hall of London, in which the subject of ported cabinets and other forms of speaker mounting are considered in greater detail. All of the illustrations in this article are from the same book.

INTERACTION IN FEEDBACK DESIGN

(from page 42)

the same for all amounts of feedback. This is shown by the dot and dash construction line in *Fig.* 6.

Figure 7 shows the same family of curves normalized to the same level. This gives a better idea how the addition of feedback over a two stage amplifier will vary the response. The curves in *Fig.* 6 and *Fig.* 7 are for the special case where *n* is unity, or the rolloff point of the two networks identical.

In cases where they are divergent to begin with, some feedback is necessary to bring the 6-db-slope point up to a level of 6 db attenuation. This follows the same general pattern shown in *Fig.* 6