The Influence of Room Boundaries on Loudspeaker Power Output*

ROY F. ALLISON

Allison Acoustics Inc.,
Natick, Mass. 01760

Although it is well known that nearby boundaries affect the radiation angle (and thereby the power output) of small acoustic sources, loudspeaker systems generally have not been designed with due regard for these effects. Conventional loudspeakers oriented in typical use positions in living rooms exhibit variations of the order of 5 to 12 dB in low-frequency power output. The problem is examined quantitatively and some practical measures for improvement are suggested.

INTRODUCTION: A source of acoustic energy is "small" when its physical dimensions are small in comparison with the wavelengths being radiated. Therefore, the diaphragms of direct-radiator loudspeaker systems are small acoustic sources at low frequencies.

The acoustic power output of such a source is a function not only of its volume velocity but also of the resistive component of its radiation load. Because the radiation resistance is so small in magnitude in relationship with the other impedances in the circuit, any change in its magnitude produces a proportional change in the magnitude of radiated power.

The resistive component of the radiation load, in turn, is inversely proportional to the solid angle of space into which the acoustic power radiation occurs. If radiation is into half-space, or 2π steradians, the power radiated is twice that which the same source would radiate into full space, or 4π steradians. If radiation is confined to π steradians by two intersecting boundaries, the power output of the source is again doubled. And if the radiation is further confined to $\pi/2$ steradians, by placing the source in a corner formed by three mutually perpendicular boundaries, its power output is doubled once more. Olson [1] depicts this graphically and these relationships are familiar ones. In the same reference, however, Olson warns that such results hold true only when the dimensions of the source and the distance to the boundaries are small compared with the wavelength. That qualification's import has not been generally appreciated.

Direct-radiator loudspeaker systems have been designed for, and tested in, environments of either 4π or 2π steradian radiation angle. The 2π option has been gaining acceptance in recent years; Small [2] used 2π in his definitive work on direct-radiator systems because it approximated reality in living rooms more closely than 4π. Allison and Berkovitz [3], however, found a substantial low-frequency notch (Fig. 1) in the average of 22

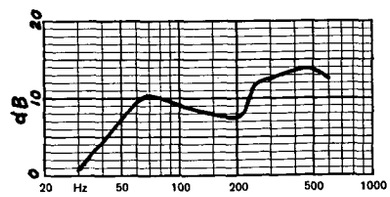

Fig. 1. Average spectral balance at 22 listening positions in 8 living rooms, produced by 16 closed-box speaker systems of moderate size fed one-third octave pink noise.

spectral balance curves obtained at actual listening positions in eight living rooms. The investigation that is the subject of this paper was prompted by that finding. More recently Long [4] showed reverberant response curves of loudspeakers placed at various locations in a room but

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did not explain the pronounced dips at middle-bass frequencies in terms of power output. Rosenberg [5], in a 1973 paper on the problems of making meaningful measurements on a loudspeaker, pointed out the necessity of placing it in a typical use orientation with respect to room boundaries because its power output is dependent on such placement. He suggested a test room containing at least three reflecting boundaries.

The objects of this paper are to define quantitatively how a low-frequency loudspeaker's power output is related to its position in a room, to test the theory with actual measurements, to develop general rules for optimal placement, and to show how loudspeaker system cabinet design can facilitate such optimal placement.

TEST CONDITIONS AND EQUIPMENT

A single loudspeaker system, typical of the great majority now in use by serious listeners, was used for all tests. It is a three-way closed-box acoustic suspension system, with a nominal crossover from woofer to mid-range speaker at 575 Hz. The grille cloth molding was removed for the tests, and the mid-range and tweeter speakers were disconnected. Without molding the overall dimensions of the cabinet are 25 by 14 by 10¼ inches (63.5 by 35.5 by 26 cm). The woofer is nominally 12 inches (30.5 cm) in diameter. It is centered in the 14-inch (35.5 cm) dimension of the front panel and its center is located 7½ inches (19 cm) from one end of the 25-inch (63.5-cm) front-panel dimension.

Measurements were made outdoors, using sine wave signals. The boundaries were clay soil and poured concrete. Because the aim was to measure total power radiated, measurements of output were made so as to sample adequately the entire space into which the speaker radiated. Pressure levels obtained were converted to intensity, weighted according to the solid angle represented, summed for the entire radiation angle, and the sum converted to PWL (power level re 130 dB = 1 acoustic watt). As a check on accuracy of measurement equipment, the test system was checked for absolute output level versus frequency in a 4π environment by an independent acoustics laboratory. Agreement was within 1 dB.

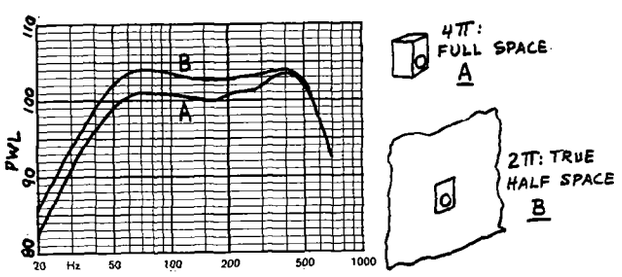

Fig. 2. Power level (PWL) versus frequency of test woofer with radiation angle loads of 4π steradians (curve A) and 2π steradians (curve B). At upper end of frequency range, cabinet front panel reduces radiation angle toward 2π or half-space, with increase in power radiated (A). Power input to system is 1 watt at 3.5 ohms.

Where distances to boundaries are not shown in illustrations, the closest cabinet panel is 1 inch (2.5 cm) distant from a wall at ground level (to allow for baseboards in real rooms) or ½ inch (1.27 cm) from a wall if above ground level.

Test equipment consisted of the following Bruel & Kjaer units: type 1024 sine-random generator, type 4133 microphone and type 2619 preamplifier, type 4230 sound level calibrator, type 2113 spectrometer, and type 2305 level recorder. An AR power amplifier was used to drive the loudspeaker.

Fig. 2 shows PWL versus frequency for the test loudspeaker under two standard measurement conditions, 4π and 2π space. Note that the 4π curve rises to and meets the 2π curve at the upper end of the woofer's frequency range. This is explained by the fact that the minimum dimension of the cabinet front panel, 14 inches (35.5 cm), is ½ wavelength at 485 Hz. At this frequency and above, the panel is an effective 2π baffle for the woofer.

SINGLE BOUNDARY CASE

There are several possible methods for calculating the effect of a nearby boundary on the power output of a small source. A very simple way is shown in Fig. 3, considering the source and its image beyond the boundary to be a pair of small sources vibrating in phase and equal in strength. The pressure directivity pattern for such a pair of sources is given by Beranek [6]. For each assumed value of x/λ, the relative pressure is found at arbitrary distance for consecutive small increments of θ. Squaring these pressure values, multiplying by $\cos\theta$, and summing the values thus obtained yields the total relative power radiated for the assumed value of x/λ. Repeating this process for the range of values of x/λ of interest produces the curve shown in Fig. 4. A computer is most helpful in this task.

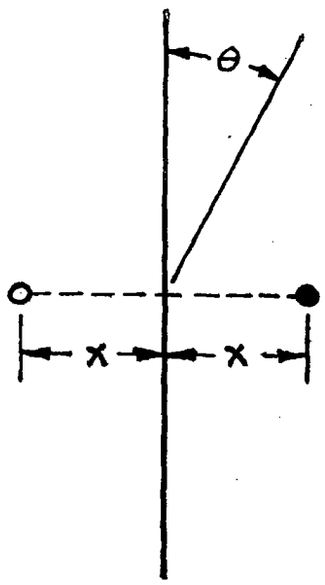

Fig. 3. Model of sound source close to a reflecting boundary. Directional pattern and power output in real half-space are the same as they would be if boundary were removed and the image source were present instead.

Pressure directivity pattern:

$$p = \frac{\sin[(4\pi\, x/\lambda)\sin\theta]}{2\sin[(2\pi\, x/\lambda)\sin\theta]}$$

Relative power radiated for a particular value of x/λ:

$$P = \sum_{\theta=0}^{\pi} p^2 \cos\theta$$

The predicted 3-dB augmentation of power output is obtained only when the source is a very small fraction of

a wavelength from the boundary. At 0.1 wavelength the gain is about 2.5 dB. It falls to zero dB (the full-space power output magnitude) at $\lambda/4$. An interesting phenomenon is apparent in the region between $\lambda/4$ and $\lambda/2$: the radiated power is actually less than the 4π space value, reaching a minimum of about -1 dB. Above $\lambda/2$, the boundary has virtually no effect on radiated power. If the distance between source and boundary is 24 inches (61 cm), $\lambda/4$ occurs at 140 Hz.

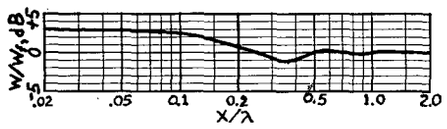

Fig. 4. Augmentation of power output versus free-field value for a single reflecting boundary. When distance x to the boundary is a small fraction of wavelength, the effective radiation angle is reduced to 2π steradians.

The test loudspeaker system (in common with others similar in size and configuration) is nearly always used with its back placed close to a wall, as in Fig. 5. When so placed the average path length from the center of the woofer to the wall is 21 inches (53.3 cm). Using this value for x in Fig. 4, and applying the boundary augmentation versus frequency magnitudes so obtained to the full-space power curve in Fig. 2 (curve A), the calculated power response, curve A, in Fig. 5 is predicted. This is in close agreement with the measured power versus frequency curve, curve B in Fig. 5.

It is clear that the saddle-shaped power curve is the result of changes in the radiation angle over the woofer's operating range. At low frequencies the boundary is effective in restricting the radiation angle to 2π steradians.

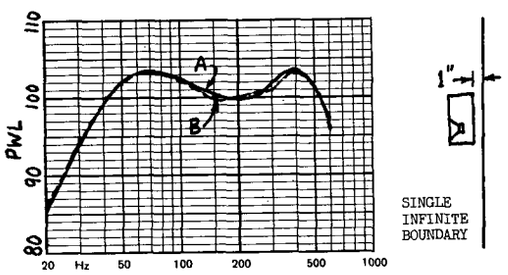

Fig. 5. Calculated (A) and measured (B) PWL versus frequency for test system with back of cabinet parallel with and 1 inch (2.5 cm) from single boundary. Saddle-shaped output indicates that distance from woofer to wall is too great for maintenance of boundary augmentation up to frequency at which front panel becomes effective 2π baffle.

In the middle frequency range the boundary is too far away to serve this purpose, and the cabinet front panel is not large enough to have any effect. Consequently in this frequency region the radiation angle is 4π steradians. At higher frequencies the cabinet front panel reduces the effective angle again to 2π.

Merely increasing the front panel dimensions would not eliminate this effect, because the path length from woofer to boundary would be correspondingly increased. In order to keep the radiation angle at or close to 2π over the full range of the woofer, it is necessary to place the woofer close enough to the boundary so that it remains effective in solid angle reduction up to the frequency at which the cabinet front panel becomes effective. In other words, x must not exceed one half the minimum dimension of the woofer mounting panel.

The most immediately obvious way in which to accomplish this is to mount the woofer in a panel facing the boundary, as shown in Fig. 6. But simple things are rarely

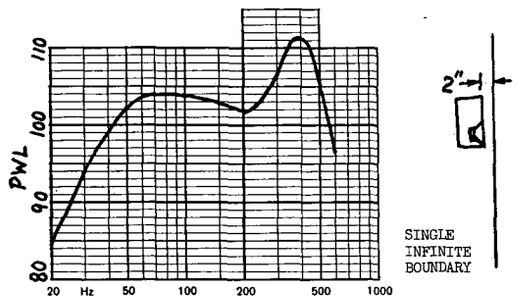

Fig. 6. Facing woofer panel of cabinet toward wall creates conical horn in space between, with new problem worse than old one.

simple, and a conical horn formed by the space between the boundary and the cabinet panel loads the woofer to produce a large peak in power output.

When the test cabinet is turned so that its side is close to the boundary (Fig. 7), a power versus frequency curve is obtained that is virtually identical with the true 2π response (Fig. 2, curve B). The only significant difference is an increase in cutoff slope above 450 Hz, where x/λ is in the 0.25 to 0.5 region.

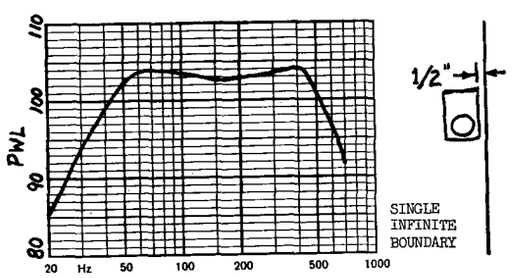

Fig. 7. Simply putting the side of the cabinet next to the wall, so that distance from center of woofer to wall is not more than half the minimum dimension of cabinet's woofer mounting panel, maintains 2π radiation angle throughout frequency range, avoids horn loading. But rooms have more than one wall.

TWO- AND THREE-BOUNDARY CASES

Real rooms have more than one wall which must be considered. Waterhouse [7, 8] and Waterhouse and Cook [9] have investigated extensively the matter of boundary influence on small sound sources. The formulas given by Waterhouse are:

for a single boundary,

$$W/W_f = 1 + j_0(4\pi x/\lambda);$$

for two boundaries intersecting at a right angle,

$$W/W_f = 1 + j_0(4\pi y/\lambda) + j_0(4\pi z/\lambda) + j_0[4\pi(y^2 + z^2)^{1/2}/\lambda]$$

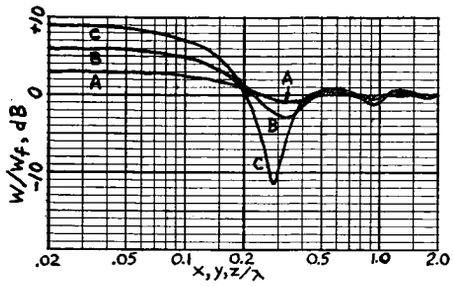

Fig. 8. Power output of a source relative to its free-field power output, when close to a single wall (A), two walls intersecting at a right angle (B), and three mutually perpendicular walls (C). Abscissa shows source location in terms of fractional wavelengths (x/λ, y/λ, and z/λ). For two- and three-boundary cases, curves apply only on lines of symmetry ($y=z$ or $x=y=z$).

and for three intersecting boundaries mutually perpendicular,

$$\begin{aligned} W/W_f = \; & 1 + j_0(4\pi x/\lambda) + j_0(4\pi y/\lambda) + j_0(4\pi z/\lambda) + \\ & j_0[4\pi(x^2 + y^2)^{1/2}/\lambda] \\ & + j_0[4\pi(x^2 + z^2)^{1/2}/\lambda] + j_0[4\pi(y^2 + z^2)^{1/2}/\lambda] \\ & + j_0[4\pi(x^2 + y^2 + z^2)^{1/2}/\lambda] \end{aligned}$$

where W is the power radiated by a source located at x/λ, y/λ, and z/λ with respect to reflecting boundaries. W_f is the power that would be radiated by the source in 4π steradian space, and $j_0(a) = \sin a/a$, the spherical Bessel function.

These expressions are plotted as curves A, B, and C, respectively, in Fig. 8 for a source located symmetrically

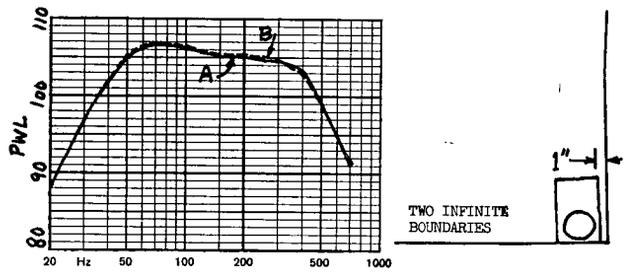

Fig. 9. Calculated (A) and measured (B) PWL versus frequency for test system with cabinet side and bottom adjoining two intersecting boundaries. 1-inch (2.5-cm) spacing from wall is for baseboard; actual distances to center of woofer from boundaries are 7½ and 8 inches (19 and 20 cm). Effective radiation angle of π steradians is well maintained. However, third boundary must be considered in practical rooms.

with respect to the boundaries. Curve A is identical with that in Fig. 4. A remarkable feature of both curves B and C is the very significant reduction in power output below the full-space magnitude which occurs for distances in the region of 0.3λ. For the two-boundary case, the radiated power reaches a minimum of -3 dB; for the three-boundary case, about -11.5 dB. Thus a source located on the line of symmetry from a corner intersection will experience, within the range of frequencies for which the spacing is less than 0.5λ, a variation in radiation resistance of 20 dB. For locations off the line of symmetry the variation is less than 20 dB but is likely to be of appreciable magnitude.

As the source is placed closer to the boundaries, the frequency at which the notch appears becomes higher. In the two-boundary case (Fig. 9) it is possible to get the test

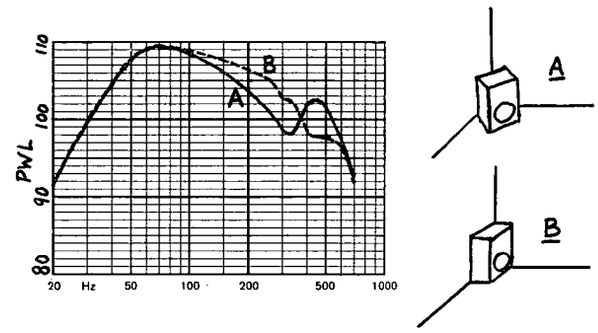

Fig. 10. A. PWL versus frequency for two orientations of test system in a room corner. Results of the unconventional placement (B) are clearly superior, but this cabinet design prevents getting the woofer close enough to corner apex to maintain $\pi/2$ radiation angle over full range.

system close enough to the intersection to yield a useful result. The only price paid for a smooth power output curve approximately 5 dB above the full-space value is a reduction in the upper cut-off frequency to about 400 Hz. Of course that is of no consolation if the crossover frequency of the system cannot be made that low, or in the case of a full-range speaker.

When this practice is attempted in a three-boundary corner, however, it is less successful. Fig. 10B shows a rather steeply sloped power output curve. The test system in this position would be usable only with a crossover frequency of 300 Hz or so, and a decrease in the system Q would also be desirable in order to decrease the slope. On the other hand, conventional orientation of the cabinet in this corner (Fig. 10A) probably would be needed for

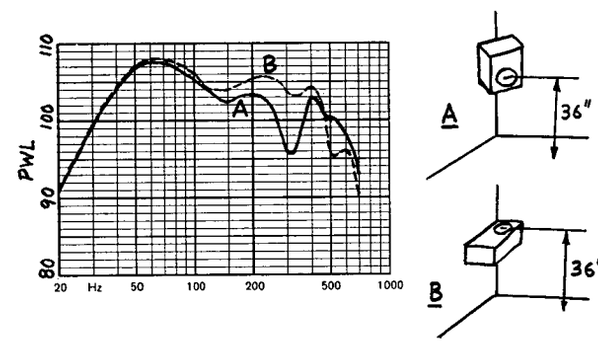

Fig. 11. How power output is affected by moving the cabinet up 3 feet (0.9 m) from the corner along the wall intersection. Here orientation B is very much better than A.

adequate room coverage from the middle- and high-frequency speakers. The low-frequency power response would be considerably worse with the cabinet in this attitude.

Moving the cabinet up off the floor along the wall intersection (Fig. 11) provides no improvement with conventional cabinet orientation. It is obvious that the notch just above 300 Hz in curves A of both Figs. 10 and 11 is produced primarily by reflections from the walls, not the floor. When these reflections are moved up in frequency

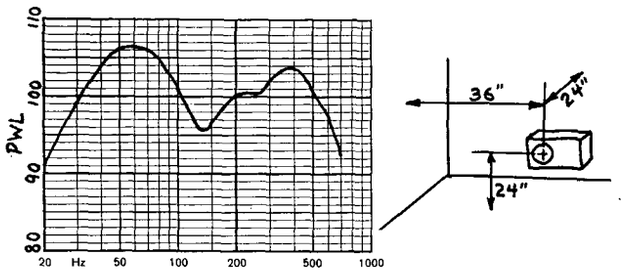

Fig. 12. Simulation of low-frequency results to be expected from an "omni" system placed well away from a corner into the room. Getting clear from all the boundaries is not the way to avoid the effect of the corner; it merely moves the hole down in frequency.

by means of the unconventional orientation (Fig. 11*B*), power output in the woofer range becomes considerably more uniform.

Some loudspeaker systems are meant to be used at locations a few feet from any boundary. Fig. 12 shows the power output of the test system when the woofer is

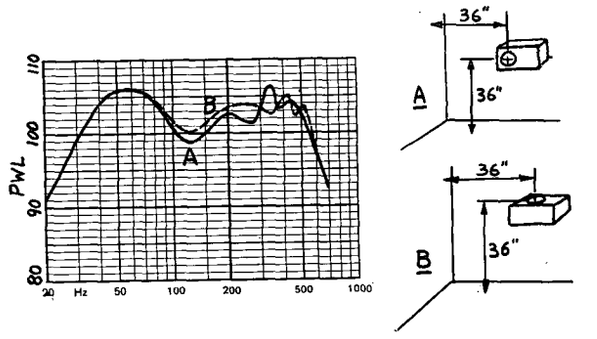

Fig. 13. Fairly typical location for a "bookshelf" speaker system, on a table or shelf close to one wall and 3 feet (0.9 m) from the intersection of another wall. Power output not as irregular as in Fig. 12, but not very much better. Getting woofer as close as possible to the nearest boundary (curve *B*) is, again, better than conventional orientation.

24 inches (61 cm) above the floor, 24 inches (61 cm) from one wall, and 36 inches (91.4 cm) from the other wall. It is apparent that the strong effects of the corner cannot be avoided by moving the source away from all the boundaries by any reasonable distance.

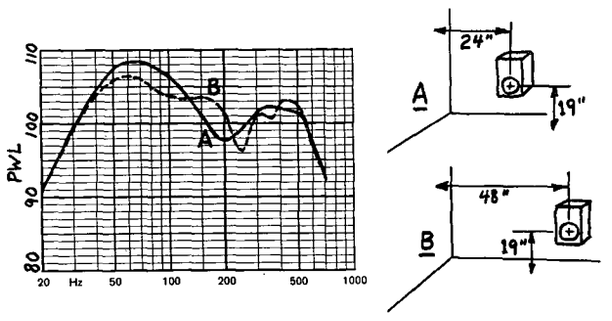

Fig. 14. PWL versus frequency for test system standing on base 11 inches (28 cm) high, with back of cabinet close to one wall and at two distances from other closest wall. 4-foot (1.2-m) curve *B* would be preferred to that for 2-foot (0.6-m) distance from third boundary *A*, but at neither distance does this widely used system on its base provide uniform power output, despite its potential capability to do so.

A more typical placement of a loudspeaker system such as the test unit is that shown in Fig. 13. With conventional orientation the variation in power output is about 7½ dB in the woofer's frequency range. Some improvement is secured by turning the side of the cabinet to the wall.

Probably the most common placement for systems of this kind is on a low base, stand, or table as in Fig. 14, with the woofer end of the cabinet down and the back close to one wall. Power level versus frequency curves are shown for two distances from the other wall.

The sequence in Fig. 15 reveals what may be the most practical way to obtain reasonably flat power output from the test system in an actual room. The woofer is kept as close as possible to two boundaries; as the system is moved gradually away from the third boundary, the power output versus frequency curve becomes progres-

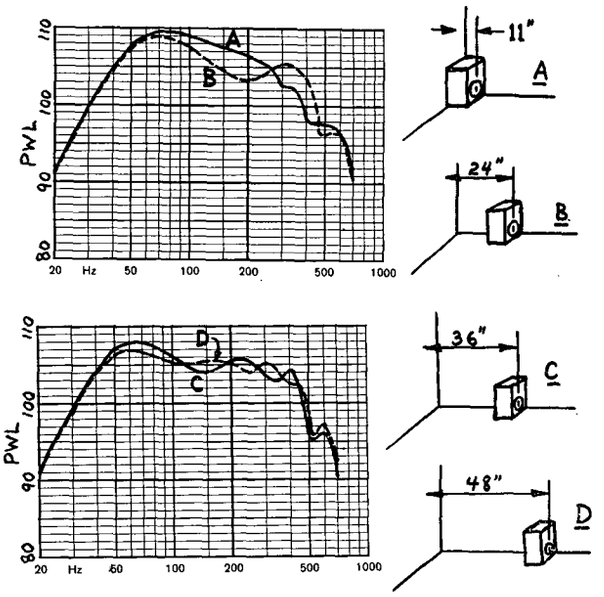

Fig. 15. Sequence showing the effect of positioning the bottom and side of the test system next to the floor and one wall, and moving the system away from the other wall in increments of 1 foot (0.3 m). For curve *A* the woofer center is at the minimum possible distance from the third boundary, 11 inches (28 cm); for *B*, 2 feet (0.6 m); for *C*, 3 feet (0.9 m); and for *D*, 4 feet (1.2 m).

sively more smooth and less tilted. At the 4-foot (1.2-m) distance (curve *D*), the power output variation is ±1½ dB up to 450 Hz.

OTHER CONSIDERATIONS

Calculations were made with the assumption that the boundaries were 100% reflecting, which implies infinite stiffness. The close agreement of the measurements with calculated values demonstrates that the actual boundaries used (packed clay soil and poured concrete) approached the ideal. Walls in real rooms are usually not so stiff; consequently, neither the reinforcement nor the destructive interference should be as fully effective as shown. On the other hand, even frame walls and floors are relatively stiff at their intersections, and it is the reflections from areas close to intersections that are of primary importance. Not much amelioration of the effects should be expected in practical room situations.

Other room boundaries in addition to the three nearest the source will of course generate standing waves at the room resonance modes, but will have little effect on power output. In most cases the nearest "other" boundary, for a system placed as in Fig. 15, will be the ceiling. A boundary has little effect beyond 0.75λ. If the ceiling is 7½ feet (2.3 m) above the woofer, it will be 0.75λ away at 113 Hz. Therefore the three nearest boundaries alone control the effective radiation angle above 113 Hz. Between 113 and 75 Hz, this hypothetical ceiling reflection would increase power output very slightly, reaching a maximum of less than 1 dB at about 92 Hz. Radiated power would be decreased between 75 and 37.5 Hz, with a minimum of about −1 dB at 53 Hz. Power output would be increased gradually below 37.5 Hz, reaching +2 dB at 20 Hz and increasing asymptotically toward +3 dB at still lower frequencies.

The woofer in the test system was designed originally for a relatively low crossover frequency, and only the woofer range is dealt with here. But the same boundary effects apply to mid-range units as to woofers. In order to minimize the effect of a boundary intersection on the mid-range unit, the distance between them must be at least 0.75λ at the crossover frequency. Therefore, while a very low crossover frequency may be helpful in keeping the woofer out of trouble, it will exacerbate the mid-range problem.

The shortcomings of presently used test facilities for loudspeaker systems now become insistently clear. Neither a 4π nor a 2π anechoic chamber can yield much information on how the system will behave at low frequencies in an actual use situation. Rosenberg's suggestion for a test room consisting of three mutually perpendicular hard boundaries, with the other three boundaries completely absorptive, deserves serious consideration. This is the only kind of test facility of reasonable size and cost that can be used to assess power output at low frequencies in a realistic manner. It is far better than a reverberant room of comparable size, because there are no nondiffuse standing waves present to interfere with accurate measurements. The measurements must be made at a sufficient number of points as to provide an accurate sampling of the total power output, of course.

CONCLUSIONS

It has been shown that the low-frequency power output of contemporary loudspeaker systems, when they are used in real rooms, is affected adversely and significantly by reflected impedance from the boundaries. These effects are unavoidable with loudspeaker systems designed in accordance with current practice.

The most severe effects are those which occur when the system is placed at a distance from all room boundaries; the worst case is that in which it is remote and equidistant from them. Some improvement within the normal woofer frequency range is obtained when the woofer is placed very close to one boundary only. Significant improvement is attainable if the woofer is placed very close to two intersecting boundaries and several feet from the other. With woofers of the usual size and enclosures of conventional design it is not possible to place the woofer close enough to three boundaries simultaneously so that a $\pi/2$ radiation angle can be maintained up to a convenient crossover frequency. Finally, care must be taken to place the mid-range unit beyond the adverse influence of boundary intersections at and above the crossover frequency; that is to say, at least 0.75λ from the intersection. One system designed in accordance with these findings is shown in Fig. 16.

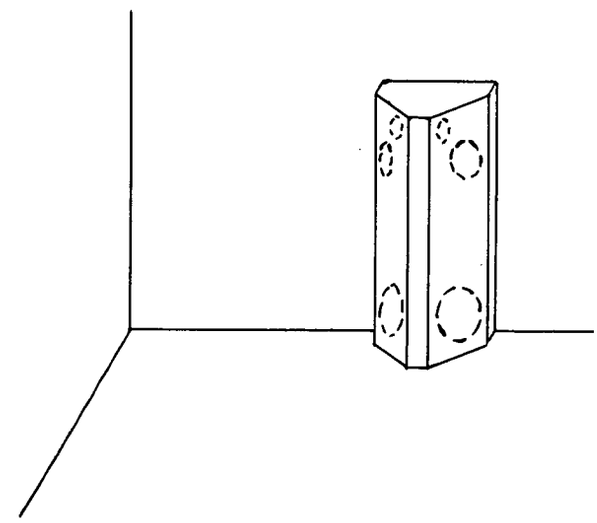

Fig. 16. A new loudspeaker system, designed to optimize boundary augmentation so that the radiation angle is controlled and the acoustic power input to the room is constant with frequency.

It remains true that the ultimate determinant of fidelity to an original source is the sound field at the listener's ears. Even if a loudspeaker system is made capable of delivering uniform power to a room, the energy is redistributed by the room's nondiffuse resonance modes, and the listener's location with respect to these standing waves is not knowable.

Nevertheless, if loudspeaker systems are designed with due regard for these boundary effects, another hitherto unpredictable variable, the loudspeaker's actual radiation load, can be brought under control. This will certainly reduce the average deviation from the ideal of the sound field in the room. The improvement that is possible is easily audible and appears to be worth the effort.

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THE AUTHOR

Roy Allison went from a background as an editor of radio engineering and consumer audio magazines to Acoustic Research, Inc. in 1959. He became chief engineer in 1960, Plant Manager in 1964, and Vice President/Engineering and Manufacturing in 1967. He left Acoustic Research at the end of 1972 and is now President of Allison Acoustics Inc.

Mr. Allison is a Fellow of Audio Engineering Society and a Member of Institute of Electrical and Electronics Engineers.