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The Influence of Room Boundaries on Loudspeaker Power Output*

ROY F. ALLISON

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

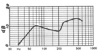

Fig. 1. Average spectral balance at 22 listening positions in 8 living rooms, produced by 16 closed-box speaker systems of moderate size fed one-third octave pink noise.

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 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.

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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 midrange 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.

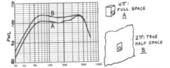

Fig. 2. Power level (PWL) versus frequency of test woofer with radiation angle loads of 4π steradians (curve A) and 2π steradians (curve B). At upper end of frequency range, cabinet front panel reduces radiation angle toward 2π or half-space, with increase in power radiated (A). Power input to system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

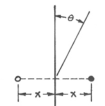

Fig. 3. Model of sound source close to a reflecting boundary. Directional pattern and power output in real half-space are the same as they would be if boundary were removed and the image source were present instead.

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:

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

sidering 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 θ, 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.

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.

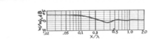

Fig. 4. Augmentation of power output versus free-field value for a single reflecting boundary. When distance x to the boundary is a small fraction of wavelength, the effective radiation angle is reduced to 2π steradians.

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.

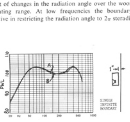

Fig. 5. Calculated (A) and measured (B) PWL versus frequency for test system with back of cabinet parallel with and 1 inch (2.5 cm) from single boundary. Saddle-shaped output indicates that distance from woofer to wall is too great for maintenance of boundary augmentation up to frequency at which front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

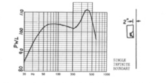

Fig. 6. Facing woofer panel of cabinet toward wall creates conical horn in space between, with new problem worse than old one.

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.

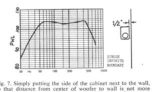

Fig. 7. Simply putting the side of the cabinet next to the wall, so that distance from center of woofer to wall is not more than half the minimum dimension of cabinet's woofer mounting panel, maintains 2π radiation angle throughout frequency range, avoids horn loading. But rooms have more than one wall.

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,

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

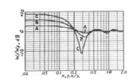

Fig. 8. Power output of a source relative to its free-field power output, when close to a single wall (A), two walls intersecting at a right angle (B), and three mutually perpendicular walls (C). Abscissa shows source location in terms of fractional wavelengths (x/λ, y/λ, and z/λ). For two- and three-boundary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

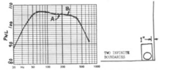

Fig. 9. Calculated (A) and measured (B) PWL versus frequency for test system with cabinet side and bottom adjoining two intersecting boundaries. 1-inch (2.5-cm) spacing from wall is for baseboard; actual distances to center of woofer from boundaries are 7½ and 8 inches (19 and 20 cm). Effective radiation 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

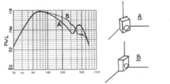

Fig. 10. A, PWL versus frequency for two orientations of test system in a room corner. Results of the unconventional placement (B) are clearly superior, but this cabinet design prevents getting the woofer close enough to corner apex to maintain $\pi/2$ radiation angle over full range.

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

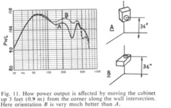

Fig. 11. How power output is affected by moving the cabinet up 3 feet (0.9 m) from the corner along the wall intersection. Here orientation B is very much better than A.

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

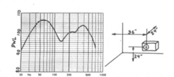

Fig. 12. Simulation of low-frequency results to be expected from an "omni" system placed well away from a corner into the room. Getting clear from all the boundaries is not the way to avoid the effect of the corner; it merely moves the hole down in frequency.

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

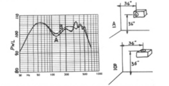

Fig. 13. Fairly typical location for a "bookshelf" speaker system, on a table or shelf close to one wall and 3 feet (0.9 m) from the intersection of another wall. Power output not as irregular as in Fig. 12, but not very much better. Getting woofer as close as possible to the nearest boundary (curve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

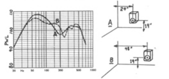

Fig. 14. PWL versus frequency for test system standing on base 11 inches (28 cm) high, with back of cabinet close to one wall and at two distances from other closest wall. 4-foot (1.2-m) curve *B* would be preferred to that for 2-foot (0.6-m) distance from third boundary *A*, but at neither distance 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-

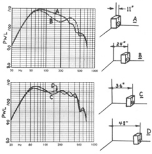

Fig. 15. Sequence showing the effect of positioning the bottom and side of the test system next to the floor and one wall, and moving the system away from the other wall in increments of 1 foot (0.3 m). For curve *A* the woofer center is at the minimum possible distance from the third boundary, 11 inches (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.

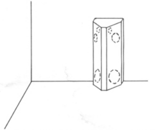

Fig. 16. A new loudspeaker system, designed to optimize boundary augmentation so that the radiation angle is controlled and the acoustic power input to the room is constant with frequency.

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 Sound Field in Home Listening Rooms, II*

ROY F. ALLISON

The average of sound pressure level versus frequency curves at listener locations in home listening rooms has been shown to have a substantial trough in the middle of the bass range. Reflected impedance from the room boundaries causes a reduction in woofer loading (and thereby a loss of acoustic power output to the room) in the same frequency region for conventional loudspeaker systems in normal positions in a room. Uniform power output versus frequency can be obtained by appropriate design of the loudspeaker system and its proper placement with respect to the room boundaries. The effect of these measures on the sound field as measured at typical listener locations in several listening rooms is reported.

INTRODUCTION: In 1972 Allison and Berkovitz [1] measured sound pressure versus frequency at listener locations in several living rooms, produced by the loudspeaker systems being used in those rooms. When 22 response curves were averaged, the composite curve was rather smooth except for a surprising low-frequency notch (Fig. 1). It was known that the loudspeaker systems did not show any such anomaly when tested in anechoic environments. In every room where these tests were made, however, the owner had placed the loudspeaker cabinets conventionally, that is, with the back close to a room wall. Therefore it was assumed that the strong reflection from this wall reduced the woofer's power output at the frequency for which the distance to the center of the woofer was a quarter wavelength.

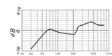

Fig. 1. Average sound pressure level versus frequency at 22 listening locations in eight living rooms. Pink noise input to loudspeaker systems, one-third octave analysis.

Allison investigated in detail in a 1974 paper [2] the effects of room boundaries on loudspeaker power output, confirming experimentally the results predicted by Waterhouse [3], [4] and Waterhouse and Cook [5] in a series of papers published from 1955 through 1965. Allison tested the acoustic power output of the woofer of a closed-box system with outside dimensions of 25 by 14 by 10¼ inches (635 by 355 by 260 mm), a design typical of contemporary high-quality loudspeaker systems, under a wide range of environmental conditions. This "test standard system" is capable of extraordinarily flat acoustic power output when operating into ideal 2π steradian space, but when oriented conventionally in real rooms its power output variation is typically 5–12 dB. The variation can be as much as 20 dB. Fig. 2 shows PWL (power level re 130 dB = 1 acoustic

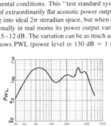

Fig. 2. Power level versus frequency for test standard loudspeaker system. Cabinet back close to wall, center of woofer 3 ft (0.9 m) from adjacent wall and same distance above floor.

watt) versus frequency for this loudspeaker system when placed with respect to the three nearest room boundaries, as it might be on a bookshelf. Fig. 3 shows PWL versus frequency for the same loudspeaker system in another common orientation—on a low base or a small table.

It was found that a quite unconventional orientation of the test loudspeaker system was required in order to load it uniformly so that it could generate relatively flat power input to the room. The woofer must be brought as close as possible to two intersecting room boundaries and kept away from any other. As Fig. 4 shows, when the woofer end of the box is put against one room boundary (the floor, in this case), the side of the box is brought close to one wall, and the nearest other wall is at least a few feet distant, then the power output of the woofer is smooth and not excessively tilted. But a lower than normal crossover frequency

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is necessary for a woofer used in this way, and the midrange loudspeaker must be kept far away from a boundary intersection or the power notch is simply transferred from the bass to the middle range. A sketch of a system designed to meet these requirements was shown in [2]. A production system modeled after it is shown in Fig. 5.

The room boundary paper concluded with a caveat: "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.[1]

"Nevertheless, if loudspeaker systems are designed with due regard for these boundary effects . . . (it) will certainly reduce the average deviation from the ideal of the sound field in the room . . ."

It is the purpose of this present paper to show quantitatively how the sound fields at a significant number of listener locations are affected by loudspeaker orientation with respect to the room boundaries, so that the practical improvement to be expected from a flat bass power input to the room can be determined.

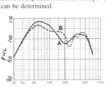

Fig. 3. Power level versus frequency for test standard system with cabinet back close to wall. Center of woofer 19 inches (480 mm) above floor, distance to adjacent wall 2 ft (0.6 m) for curve *A* and 4 ft (1.2 m) for curve *B*.

TEST PROCEDURE AND EQUIPMENT

The aim was to measure how much, if any, improvement in uniformity of the sound field can be expected by real listeners in real rooms if the bass power input to the rooms is made flat. Put another way, is the difference worth while, or do the field aberrations introduced by standing waves in normal rooms completely swamp any power output variations of the source?

To answer these questions, the sound fields at actual listener locations in five rooms were measured. Stereo music systems had been installed in each of these five rooms for some time. Locations for the two loudspeaker systems, and seating arrangements for listeners, had been chosen without benefit of sound measurements. The residents had set up each room making the usual compromises between what seemed to be a reasonable loudspeaker placement on the one hand, and furnishings comfort and appearance on the other.

No changes were made in any of the rooms for these tests. A series of measurements was made for every listener location in each room, a "listener location" being defined as a chair or sofa where people normally sat while listening to reproduced music seriously. Obviously not every seating location in every room met the requirement. In one room there were four listener locations; in three rooms, three listener locations each; and in the fifth room, only one. Thus there were 14 listener locations altogether. In each case the measuring microphone was placed as close as could be estimated to the center of the space where the listener's head would normally be, but the vertical position of the microphone diaphragm was always maintained at 1 meter (39⅜ inches) above the floor. This is an arbitrary dimension, but it certainly approximates the average distance of a seated listener's ears from the floor.

The location of both the left- and the right-channel loudspeaker systems as found in each room was marked on the

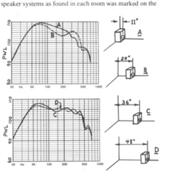

Fig. 4. Power level versus frequency for test standard loudspeaker system oriented as shown with respect to three nearest room boundaries.

floor with masking tape. Subsequently measurements were made at each listener location for loudspeaker systems placed at both marked locations; the height of the test system above the floor was varied in accordance with the test program, but the loudspeaker system location was maintained vertically over the original mark.

Four measurements were made at each listener location for each of the loudspeaker locations. The first three measurements in each group were made with the same test

[1] After these words were written, Groh [6] described a method of "placement equalization." This involves determination of the standing waves in a listening room that are related to peaks and dips in the measured sound pressure versus frequency curves at a listener location, and moving the loudspeaker systems and/or listener position so as to smooth the room transmission curves. It is a useful technique but rather disruptiveof conventional furniture arrangements.

standard loudspeaker system as was used in Allison's 1974 room boundary paper [2], with only the woofer operative. The power output of this system in a wide variety of environments has been documented. The three orientations used for measurement were as follows.

1) Back of cabinet parallel with and close to the rear wall, center of woofer 48 inches (1.2 m) above the floor. The exact power output versus frequency curve will vary in accordance with the distance to the nearest side wall in each case, but it will always be similar to that shown in Fig. 2.

2) Back of cabinet parallel with and close to the rear wall, center of woofer 19 inches (483 mm) above the floor. The power output curve should be similar to those shown in Fig. 3.

3) Woofer end of cabinet on the floor, side of cabinet parallel with and close to the wall. In this orientation the power output versus frequency curve of the test system will be considerably smoother, and (depending on the distance in each case to the nearest adjacent wall) similar to one of the curves shown in Fig. 4.

The fourth measurement in each group was made with the loudspeaker system shown in Fig. 5. This is a direct-radiator loudspeaker system specifically designed for uniform power loading by the room. In each case it was located at the floor mark with its base on the floor and its back close to the rear wall. This system will be identified henceforth as system *D*.

In each room, therefore, eight response curves were taken at each listener position: a group of the four measurements described above for the left marked loudspeaker location, and another group of four for the right loudspeaker location. With a total of 14 listener positions among the five rooms, there are 28 loudspeaker-to-listener transmission curves for each of the four loudspeaker–room coupling combinations.

The test signal was pink noise from a General Radio type

Fig. 5. Loudspeaker system *D* designed for uniform power output into a room. A woofer is mounted at the bottom of each of the two forward-facing panels in the prism-shaped cabinet. A mid-range unit and tweeter are mounted at the top of each of the same two panels.

1382 random-noise generator driving a Dyna power amplifier. Voltage at the amplifier output terminals was 3.5 volts rms.[2] The noise bandwidth of the GR 1382 is 20 Hz to 50 kHz. Consequently the power available to the loudspeaker within each one-third octave band was (12/Z)—15.3 dB, where Z is the nominal impedance. Z is 3.5 ohms for the test standard system and 8 ohms for system *D*.

The measuring microphone was a ¼-inch (6.4-mm) diameter B & K type 4135, used with B & K type 2619 preamplifier, type 4230 sound level calibrator, type 2113 spectrometer, and type 2305 level recorder. For the one-third octave bands centered at 200 Hz and lower, recorder chart paper speed was 0.1 mm/s, giving an averaging time of 50 s for each band. Pen writing speed was 4 mm/s. Above 200 Hz the paper speed was switched to 0.3 mm/s, and writing speed to 16 mm/s. One of the 28 groups of room transmission curves is shown in Fig. 6.

In the five rooms a broad spectrum of characteristics was

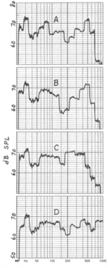

Fig. 6. Group of four sound pressure level versus frequency curves for room 1, listening location 3, left loudspeaker location. Pink noise signal, one-third octave analysis. Curves *A*–*D* are for loudspeaker systems and orientations as described in text.

found. The floor area varied from 175 ft² (16.3 m²) to 406 ft² (37.7 m²). One room was very nearly square; another room was almost twice as long as it was wide. The other rooms had intermediate proportions. Left and right loud-

[2] 3.1 volts as read on a Data Precision model 245 which, like most ac voltmeters, responds to an average rectified value but is calibrated to read rms values of a sine wave. The true rms value of Gaussian noise is 11.3% higher than the indicated reading on such a voltmeter.

speaker systems were on a long wall in two rooms, a short wall in two rooms, and on intersecting walls in the other room. There did not seem to be any abnormality common to all the rooms that would bias the test results in any way.

ANALYSIS OF DATA

After reading one-third octave band sound pressure level values from the level recorder charts and tabulating them, the first step was to investigate the amplitude of band-to-band variations in sound pressure level for each individual curve.

Inspection of the data reveals that, within each group of four curves, the three curves for the test standard loudspeaker system in orientations *A*, *B*, and *C* are always very much alike in the one-third octave bands centered below 80 Hz. Moreover, the curve for loudspeaker system *D* always has the same relationship to the other three curves of the group in this frequency range. Consequently there is no reason to extend the analysis below the 80-Hz band.

At the upper end a functional limit is set by the useful range of the test standard system which, in orientation *C*, does not extend much above 400 Hz. For that reason the analysis is limited to the eight one-third octave bands with center frequencies at 80, 100, 125, 160, 200, 250, 315, and 400 Hz.

Three numbers were derived to characterize each of the 112 individual curves.

1) $\overline{X}$, the mean value of the eight one-third octave sound pressure level values. Calculation of $\overline{X}$ is necessary in order to derive σ, but it is of some importance in its own right also, because it is a rough indication of the system's efficiency in this frequency range.

2) σ, the standard deviation. This is obtained by subtracting each of the eight one-third octave sound pressure level values from the mean value, squaring each deviation, averaging the squared values, and extracting the square root of the average. In other words, it is the rms value of deviations from the mean; it is the best indication of response "roughness."

3) The magnitude of the difference between maximum and minimum values of sound pressure level within this frequency range, abbreviated max–min. This measure of the extreme deviations is also useful in evaluating response roughness.

Table I is a summary of the average values of $\overline{X}$, σ, and max–min in decibels for the curves taken at listener positions in each room, and also shows the average values for all rooms (with each room given equal weight). The average values for all rooms taken together are displayed graphically in Fig. 7.

It is clear that, on the average, flatness of the sound field at listener locations is well correlated with flatness of power

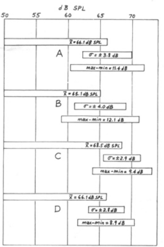

Fig. 7. Comparison of $\overline{X}$, σ, and max–min averages for five listening rooms, with loudspeaker systems oriented as described in text. See also Table I.

Table I. Average values of $\overline{X}$ (dB SPL), σ(dB), and max–min (dB) derived for each individual sound pressure level versus frequency curve at listener positions in each room, and the average values for all rooms with equal weight per room. Analysis is for 1/3-octave bands from 80 to 400 Hz inclusive.

	Standard, *A*			Standard, *B*			Standard, *C*			System *D*		
	$\overline{X}$	σ	max–min	$\overline{X}$	σ	max–min	$\overline{X}$	σ	max–min	$\overline{X}$	σ	max–min
Room 1	66.34	2.92	9.13	65.10	3.64	11.38	68.26	2.53	8.06	66.24	2.53	7.94
Room 2	64.13	3.14	8.83	64.01	4.27	12.08	67.95	2.79	8.83	64.21	2.90	9.17
Room 3	63.78	5.76	18.25	62.21	4.79	13.75	65.07	3.01	11.0	62.85	3.50	11.0
Room 4	67.57	3.64	11.33	67.01	3.64	12.25	70.22	3.05	9.33	69.07	2.57	8.0
Room 5	68.69	3.30	9.58	67.29	3.67	11.08	71.16	3.23	9.92	68.01	2.51	8.33
Average of rooms	66.1	3.8	11.4	65.1	4.0	12.1	68.5	2.9	9.4	66.1	2.8	8.9

input to the room from loudspeaker systems. How significant this amount of improvement is must be judged by the reader, but there is no doubt that it is distinctly audible.

There is another noteworthy aspect of these data. At frequencies below 80 Hz the sound pressure level values recorded for the test standard system are virtually constant regardless of the orientation. Between 80 and 400 Hz, however, the mean value of sound pressure level at listener locations is 2.4 dB higher for orientation *C* than for orientation *A*, and 3.4 dB higher than for orientation *B*. This is indicative of a real and useful increase in efficiency of the system in this 2⅔ octave frequency range.

At any listener location the sound pressure level versus frequency curve is determined by two variables that are virtually independent: the power output versus frequency of the loudspeaker system, and the distribution of standing wave patterns versus frequency in the room. It is to be expected that, among a large number of samples, there will be a few cases in which the two variables will tend to complement each other; that is to say, occasionally a nonflat loudspeaker power curve will result in a smoother sound pressure level curve at a listener location than would be obtained with a loudspeaker system having a flat power output. Here there are 28 samples for each orientation of the test standard system and for system *D*. Using σ as the criterion for smoothness, and ranking the curves within each group in order of increasing values of σ (1 would be the smoothest curve, 4 would be the roughest), the results are as shown in Table II.

In 22 cases of a possible 28, one of the systems generating relatively flat acoustic power (*C* or *D*) produced the smoothest sound pressure level versus frequency curve at the listener location. The roughest curve was produced by one of the nonflat systems in 25 cases.

It is instructive to examine the data in another way. If we average the sound pressure level values by frequency for all curves representing the same loudspeaker orientation one room at a time, and then average the room values giving equal weight to each room, the average response curves shown in Fig. 8 are obtained. Standing wave patterns have only a second-order effect; these curves are a fair approximation of the average sound energy flow in a plane 1 meter (39⅜ inches) above the floor.

The total power emitted by the test standard system in orientation *C* does not really have the mild dip shown at 125 Hz in Fig. 8, curve *C*. This dip is attributable to the fixed distance of the microphone to the floor plane and the nearly constant distance to the ceiling. It can be assumed that the other curves in Fig. 8 include a depression by a similar amount at that frequency.

Table III gives values of $\overline{X}$, σ, and max−min for the weighted average response curves of Fig. 8.

Table II. Number of times each loudspeaker orientation ranked first, second, third, and fourth in smoothness of sound pressure level versus frequency curve at listener locations. There are 28 groups of four curves each.

Rank	Curve *A*	Curve *B*	Curve *C*	Curve *D*
1	5	1	10	12
2	5	3	10	10
3	9	8	5	6
4	9	16	3	0

CONCLUSION

Loudspeaker systems which are designed and/or located with respect to room boundaries so as to produce uniform power output nearly always provide more uniform sound fields at listener locations than do conventionally designed and oriented systems. This is true despite the presence of nondiffuse normal resonance modes in home listening rooms.

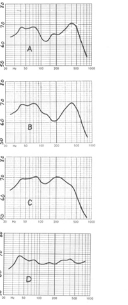

Fig. 8. Average sound pressure level versus frequency, with equal weight per room, of 28 curves at listener positions for each of the loudspeaker system orientations.

Table III. $\overline{X}$, σ, and max – min derived from the average values of 28 sound pressure level versus frequency curves, with equal weight per room, for the one-third octave bands from 80 through 400 Hz.

	A	B	C	D
$\overline{X}$, SPL	66.1	65.1	68.5	66.1
σ, dB	2.65	3.06	1.44	1.02
max – min, dB	8.7	8.4	4.2	2.7

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THE AUTHOR

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NOTES