The Loudspeaker/Living Room System

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"What do people actually hear when they put on a record and sit in their favorite chairs, and why do they hear what they do?"

As part of a research project on loudspeaker measurement techniques, Acoustic Research recently measured the "frequency response" of the sound fields produced by loudspeakers in normal listening rooms. We wanted objective field data on real-life listening situations: what do people who buy high-fidelity loudspeakers, and put them where they will fit best in their living rooms, actually hear when they put on a record and sit in their favorite chairs? And (just as important for our purpose) *why* do they hear what they do? Which aspects of a loudspeaker system's performance are significant in determining the perceived frequency response, and which (if any) are not?

These questions arise, of course, because of the very significant differences in results obtained when loudspeaker systems are tested in different ways. The "frequency response" depends on the environment into which the speakers of the system radiate, the angle from the system at which the measurement is made, the distance of the microphone from the system, and even the time (relative to the input signal) of the measurement. It is not surprising that there is misunderstanding and controversy whenever loudspeaker measurements are discussed. Some of these differences may be clarified by the illustrations that follow. They show the results of tests on one particular model of speaker system under various conditions, with comments on each type of test. (To answer the obvious question in advance, it is an AR-3a system).

Tests made in an anechoic environment—either outdoors or in a chamber with completely sound-absorbing treatment on the walls—provide information on the direct radiation from the system but only at one angle from it at a time. Figure 1 shows the anechoic response of the individual speakers in the system, taken through the crossover network, at three angles: 0° (directly in front), 30° off the axis and 60° off the axis. The low-frequency part of the woofer curve was taken outdoors, since anechoic chambers are not perfectly sound-absorbent at very low frequencies. The mid-range and tweeter curves were taken in an anechoic chamber but with the speakers on large flat baffles to eliminate diffraction effects.

Figure 1 is only a starting point. This kind of response is never heard as direct radiation from a speaker system, because at and near the crossover frequencies there are two speakers, physically separated in the cabinet, radiating simultaneously. Their phase relationship for rays of direct radiation changes with the angle of the ray, reinforcing or cancelling in the region of overlap. This interference effect is shown in Fig. 2. These are anechoic chamber curves of all three speakers of the system, remounted in the cabinet and operating together. The cabinet's molding has been removed and the speaker mounting plate extended by a flat baffle. Response is shown at the same three angles as for Fig. 1. It should be realized, however, that while the curves in Figure 1 are typical of those that would be obtained for rays at the same angles in all planes, this is not true for the system curves in Fig. 2. The interference effects would be different for similar angles in different planes around the cabinet.

The first sound that reaches a listener's ears, regardless of the listening environment, is represented accurately by a response curve taken under the conditions that apply for Fig. 2. The exact curve that would apply depends on the angle of the listener with respect to the cabinet, of course. But this relatively simple situation does not last very long.

After a period of somewhat less than one millisecond, diffraction effects—reflections from the grille cloth molding and the cabinet edges—cause further perturbations in the response at any particular angle. This can still be considered "direct radiation" because, even though it is the result of reflections, it is caused by the cabinet and it is independent of the listening environment. Diffraction effects are visible in Figure

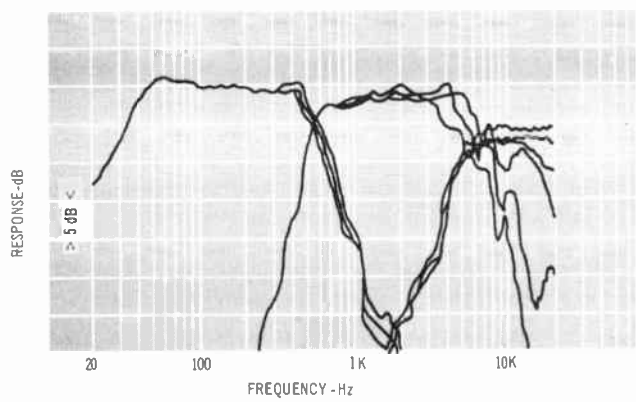

Fig. 1—Flat-baffle anechoic response of each of three speakers in the system, taken at angles of 0, 30, and 60 degrees.

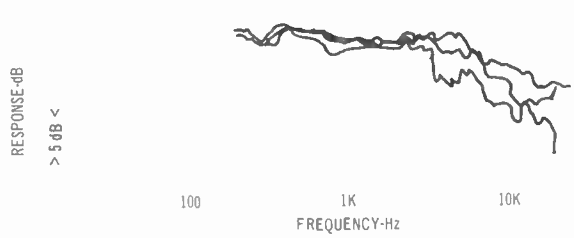

Fig. 2—Anechoic response of complete system in cabinet, but with grille cloth molding removed to minimize diffraction, at angles of 0, 30, and 60 degrees.

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3. These curves correspond to the ones in Fig. 2 except that the grille cloth molding has been reinstalled. Such curves represent accurately the sound field at listeners' ears during the time interval between the onset of diffraction (less than one millisecond) and the arrival of the first room reflections (3 milliseconds or so).

The room reflections build up in density (that is, the time intervals between individual reflections become shorter) and increase in total intensity, then fade away as the sound energy is absorbed by successive bounces from the walls and room furnishings. This reverberant field energy exists in significant amplitude for a period of ¼ to one second, depending on the reverberation time of the room and upon the original intensity. During this interval hundreds of reflections will occur, each of which affects the "response" of the instantaneous sound field at the listeners' ears. The sound pressure level of the reverberant field is quite uniform throughout the room. If the listener is more than four or five feet away from the speaker system, the reverberant field is significantly greater in amplitude than the direct field for most frequencies, regardless of the direction in which the speaker is "aimed."

The reverberant field is composed of sound energy that originates as radiation from the speaker system in *all* directions —not just the rays sent directly toward listeners. Therefore its "frequency response" is really the sum of the output at all angles (the acoustic power response of the speaker system), as modified by the frequency characteristics of the room itself.

How does the room modify the reverberant field response? Figure 4 shows the unmodified acoustic power response of this speaker system, with mid-range and tweeter level controls at maximum settings. This curve was obtained in a reverberant chamber—a small room deliberately made as reflective as possible, with minimum sound absorption. Its frequency characteristic is known and compensated in the measurement system, so that Fig. 4 is an accurate representation of the system's true power output vs. frequency. The room is not reliable below about 700 Hz, but the system is known to be omnidirectional below that frequency; thus its anechoic output at low frequencies can be considered to be representative of its acoustic power output. By comparing Fig. 4 with the results of the same kind of measurements made in actual rooms, therefore, the effects of the room can be seen.

We made such measurements at several locations in each of eight real-life rooms. They were the music listening rooms— the living rooms or recreation rooms—of eight AR-3a owners in the Greater Boston area. Neither the speaker systems nor the furniture was moved for these tests; the only thing we changed was the level control settings for the mid-range and tweeter units. They were turned to maximum for the tests, so that the results could be compared directly. The rooms varied substantially in size, shape, and "liveness."

Figure 5 is one set of curves for one of these rooms. The microphone for this test was placed eight feet from the left-channel speaker system and directly in front of it. Figure 5A is the curve obtained with the speaker cabinet in its normal position, facing the mike; 5B is the curve obtained by rotating the speaker cabinet 30°; 5C is the curve obtained with the speaker cabinet rotated 60°. Turning the cabinet, rather than moving the microphone, minimized the effect of room mode differences that would occur at different room locations. In this way we could change the frequency response of direct radiation reaching the microphone (as demonstrated in Figs. 2 and 3) and evaluate the effect on the total sound field in the room at the microphone location. The great similarity of the three curves of Figure 5 show clearly that the field at the location of the microphone is primarily reverberant—that the amplitude of direct radiation from the speaker system is far below the amplitude of the reverberant field. This was true for all normal listener locations in all the rooms.

Figure 6 is a curve obtained at another listening location in the same room, with both speaker systems operating and in normal physical orientation. This is a typical curve, about average in over-all shape and with a little more roughness than average. In general, we found that there were no sharp peaks or dips caused by room modes above 1 kHz. Whatever correction in general slope might be desirable could be done

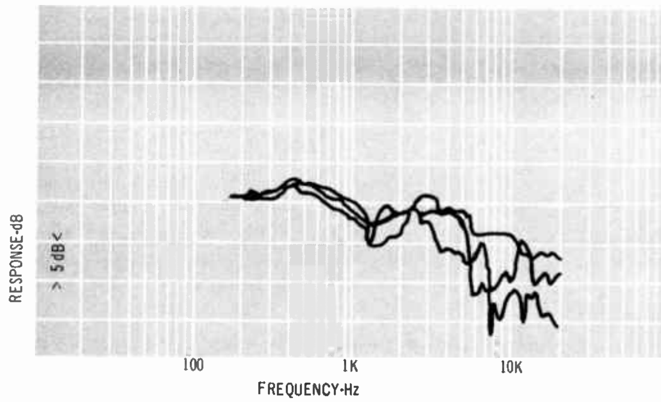

Fig. 3—Anechoic response of complete system in cabinet, with grille cloth molding, at angles of 0, 30, and 60 degrees. Diffraction would produce elevated output in 1.5-kHz region at some other angles.

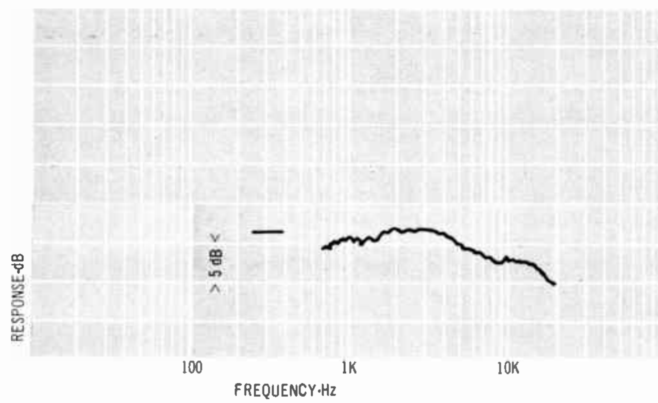

Fig. 4—Acoustic power response of the speaker system, measured in a reverberant chamber. Straight line at left shows relative woofer level.

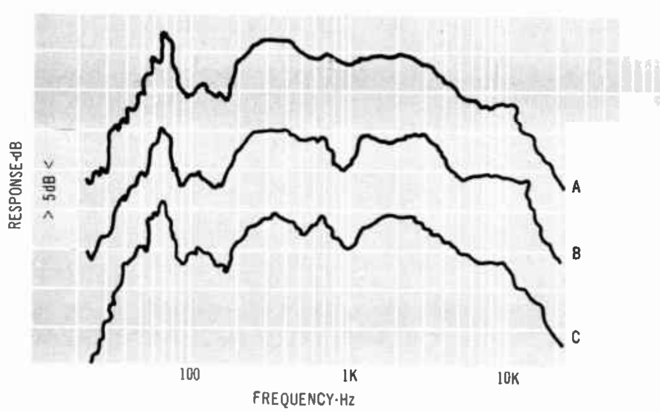

Fig. 5—A, Frequency response of loudspeaker and room at location eight feet from speaker system, with speaker aimed directly at microphone; **B,** same with speaker cabinet rotated 30 degrees, and **C,** same with speaker cabinet rotated 60 degrees.

quite accurately with a treble tone control or the level controls on the speakers. As for the room modes at low frequencies, notice the differences below 1 kHz between Figs. 5 and 6: correction for one room location would make response worse at the other location. It is difficult to see any justification for resonant narrow-band "room equalizers" if the speaker systems are good to start with.

One might argue that the relative amplitudes of the direct and reverberant fields are of no consequence. The direct wave reaches the listener first. Since directional perception is undeniably carried on by detection of very small time differences between the direct waves from two speaker systems, isn't it probable that listeners base their judgments of spectral balance also on the first-arrival sound wave, and ignore the reverberant field's spectral balance?

The first argument in response to that proposition is a negative one. Frequency response of the first-arrival wave is not affected by the room. *If* the direct wave's spectral balance were the perceived spectral balance, therefore, a speaker system would sound the same in any room; an orchestra would sound the same in any hall. Experience tells us that this is not so. As a positive test, however, we made binaural recordings (using a dummy head, with microphones built into the ears) of music played through speakers in several of the rooms. We rotated the speaker cabinet several times during each recording, as we did for the response curves in Fig. 5, thereby changing the direct sound's frequency response substantially.

Listening to these recordings with stereo headphones we were unable to hear any differences in spectral balance between the 0°, 30°, and 60° cabinet angles for any normal listener location of the dummy head. Slight differences could be heard if the dummy head was brought to within three feet of the speaker cabinet. Conclusion: listeners base judgments of spectral balance on the sum of the direct and reverberant sound fields, and for all normal listener locations the reverberant field predominates in amplitude. Therefore, the acoustic power frequency response of a speaker system is of primary importance. The direct radiation at any particular angle is important only insofar as it affects the ratio of direct to reverberant sound at a particular listener location in the room. By the same token, wide, uniform dispersion of output at all frequencies is necessary to achieve maximum uniformity in the reverberant field and assure its predominance at locations close to the speaker systems.

Another important question is this: what is the proper spectral balance of the reverberant field—what should be its frequency response? The first impulsive answer would be, "Flat, of course." If the goal is maximum accuracy in reproducing the concert-listening experience, that is the wrong answer, at least for recordings as they are now made and for live broadcasts using present microphone techniques.

The main microphones for recording sessions and live broadcast are always set up quite close to the instruments. Often they are very close indeed, particularly for soloists on the stage. As a result these microphones are in the "near field"—the direct sound predominates, and the microphones receive a spectrum of energy that is either flat or with accentuated high frequencies.

A concert hall audience, on the other hand, is well within the area of reverberant field predominance. That is true even for small intimate halls. The reverberant field of the average concert hall has a spectral balance that slopes down at the high-frequency end much more severely than that of the average living room. To duplicate at home the spectral balance of the sound perceived at a live concert, therefore, the energy put into the room by the playback system must also slope down at high frequencies. That slope should be tailored to make up the difference between high-frequency absorption in the hall and the home listening room.

Figure 7 contains two frequency response curves. One is a plot of the average spectral balance of four typical concert halls, measured (without audience) at orchestra-floor seats between ⅓ and ½ way back in the hall from the stage. The solid part of this curve is the actual empty-seat measurement; the dashed part shows the average result that would be expected with the audiences in place. The other curve is the average spectral balance we measured for 22 normal listener locations in eight living rooms with AR-3a speaker systems. It is clear that the best match would be obtained with both the mid-range and tweeter levels turned down well below maximum, and with a small amount of bass tone control boost or placement of the speakers in positions more favorable for bass output. These are average curves, however, and should be interpreted only as a place from which to start. In view of the actual variations found in both concert halls and home listening rooms, maximum realism for each record can be obtained only if one is willing to recognize that these slope variations do exist and to make liberal use of tone controls to correct for them. Æ

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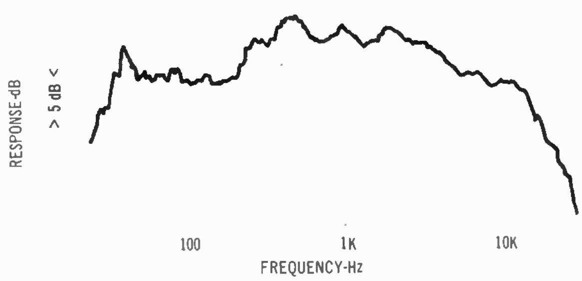

Fig. 6—Frequency response at another listening location, same room as Fig. 5, both speaker systems operating.

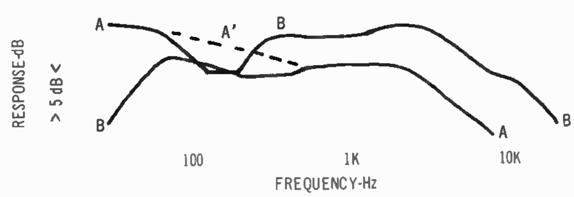

Fig. 7—A, Average spectral characteristic of concert halls, as actually measured without audience; **A'**, predicted result with audience, and **B**, average spectral characteristic produced by AR-3a systems at 22 listening locations in eight living rooms.