Loudspeaker Systems with Optimized Wide-Listening-Area Imaging*

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Efforts to improve loudspeaker performance in two areas are discussed: (1) the range of listener positions over which accurate, stable stereo imaging is available, and (2) the uniformity of radiation pattern with frequency. These problems are interdependent: solution of the former appears to require solution of the latter. Described is the design of a loudspeaker system[1] that yields stabilized imaging over a wide range of listener positions, a consistent radiation pattern across the audio band, flat frequency and power response from 20 Hz to 20 kHz, high power-handling capability and acoustical output, reasonable efficiency, comparatively resistive input impedance, and low distortion. In part the design is based on a listening experiment, also described, to determine the radiation pattern of optimal image stability: an oval. Also described is a computer optimization routine employed to design a phased array of 14 dynamic drivers per cabinet to implement this radiation pattern from 200 Hz to 20 kHz, with a compatible omnidirectional pattern from 20 Hz to 200 Hz. There are associated low- and high-level equalization and processing. Following commercial realization, a second design, closely similar to the first but with 8 drivers per cabinet, has been realized, and the first design has undergone revision as well. More recently, designs with 4, 5, and 6 drivers per cabinet, respectively, have been realized to produce most of the forward half of the oval radiation pattern only. Measurements, listening tests, and independent reviews indicate that the design goals have been substantially met.

0 INTRODUCTION

The requirements of a high-quality loudspeaker system are usually considered to be flat frequency response, low distortion, linear phase, and adequate acoustic output, all with respect to the limits of human audition. Systems seriously deficient in one or more of these areas are unlikely to be considered accurate transducers.

Within the class of loudspeakers that meet these criteria, however, there still is notable variation in sound quality, indicating that these stated criteria do not adequately characterize a loudspeaker's sonic performance.

The hypothesis of this design is that the sound quality of a loudspeaker system substantially meeting these criteria is determined primarily by its radiation pattern: the detailed specification of its acoustical output, that is, magnitude and phase response as a function of frequency and angle for all audible frequencies and all angles. In a normal room, sound projected from the loudspeaker at oblique angles is reflected toward the listener by walls, floor, and other surfaces. The timing, amplitude, spectrum, and angle of arrival of each sound all contribute to the perception. In essence, what we hear when we listen to a loudspeaker system in an enclosed space is its radiation pattern. This principle holds for any sound producer: to sound like a Stradivarius, a violin must have the radiation pattern of a Stradivarius.

It is therefore desirable in considerations of loudspeaker design or analysis to include these detailed three-dimensional spatial-output acoustic characteristics. Simplified measurements such as on-axis or reverberant responses will convey insufficient information fully to predict sound quality. In practice, a computer is a virtual necessity for acquiring and processing the large volume of data involved.

In the first phase of the project, the effects of the radiation pattern on acoustic imaging were studied to derive an optimized target pattern. Hardware realization followed, pending the outcome of this investigation.

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[1] U.S. Patents 4,503,553 and 4,503,554 (1985 March 5).

1 CHOICE OF RADIATION PATTERN

As described in Sec. 2.3, existing loudspeaker systems commonly exhibit radiation patterns that vary significantly with frequency, imparting a characteristic signature to the sound (re)produced. It was felt that a radiation pattern more consistent with frequency would provide a more lifelike, less "loudspeakery" presentation.

As it happens, a particular choice of frequency-consistent radiation pattern also will preserve the position, amplitude, spectral balance, depth, and ambience of sonic images simultaneously over a broad range of positions in the room.

1.1 Front Horizontal Radiation

Sound projected forward, directly at the listener's ears, plays the major role in perceived image position and fusion. The intent here was to determine which characteristics of the front horizontal-radiation pattern, if any, would render well-fused images whose apparent position did not change with listener location. The approach was based on the psychoacoustics of horizontal localization.

By comparing the signals at the ears, the brain is thought to derive two primary psychoacoustic cues that determine the perceived horizontal position of a sound source: the interaural-amplitude difference and the interaural-time difference.

When the listener is off to either side of the centerline with conventional stereo loudspeakers, the direct sound arrives both sooner and louder from the near loudspeaker, which tends to overshadow sound from the other loudspeaker in both time and amplitude (at both ears) and causes the image to collapse progressively into the near loudspeaker. To hear properly balanced sound, the listener must remain on or near the centerline.

From theory we set out to remove this restriction by employing the phenomenon of time/intensity trading, the ability to compensate for a left or right bias in the time of arrival by introducing a counterbias in amplitude. As the listener gets closer to one loudspeaker and sound arrives sooner, sound from the far loudspeaker must get louder by a prescribed amount to compensate. This means the loudspeakers have to be directional—radiating more loudly in some directions than in others. In theory, if the pattern of loudness as a function of angle is chosen properly, the imaging will be rendered stable for listening positions throughout the room.

1.2 Listening Test

A listening feasibility test was performed to determine whether well-fused off-axis imaging is possible and, if so, what radiation pattern or patterns would optimize the image stability throughout a range of listener locations.

Each of four subjects was asked to stand at a series of positions around a pair of loudspeakers fed monophonic pink noise pulsed at a 3-Hz rate, and to adjust a remote balance control to center the image. There were multiple trials. For all, the degree of fusion and balance settings were noted, and the balance settings subsequently averaged by position, to yield a radiation pattern resulting in the best overall stability by position.

Two conventional 2-way loudspeakers were placed 10 ft (3 m) apart facing the listener. The spacing was chosen as typical of a domestic listening room. The basic imaging properties of the loudspeakers were checked by playing monophonic music, speech, and noise signals to both while listening in the test room on the centerline, with the loudspeakers and listener forming an equilateral triangle. Under these conditions a compact, well-fused, central image was heard.

The experimental listening environment was a large [approximately 24 by 32.5 by 12.5 ft (7.3 by 9.9 by 3.8 m)] empty room having uneven walls and sloping ceiling. The loudspeakers were placed on the floor, at least 7 ft (2.1 m) from the nearest wall, to delay the earliest horizontal echoes by at least 14 ms and the earliest ceiling echoes by 22 ms or more, and to attenuate these echoes enough to ensure that the direct sound from the loudspeakers was dominant at the listeners' ears. Floor placement was chosen to minimize disparity between direct arrival and floor bounce. A 5-ft (1.5-m) rug was placed under each loudspeaker to attenuate high-frequency reflections from the wooden floor. Since this was primarily a test of horizontal localization and the floor reflection comes from the same horizontal angle as the direct sound, the floor-reflected signal can be considered part of the direct arrival and is believed not to exert a confounding influence on the results.

The choice of wide-band signal was based on the desire to render audible anomalous behavior in any part of the spectrum, while the pulsing emphasized time-of-arrival-related effects, which were expected to be troublesome at listening positions far off centerline.

Listener positions were on a 2-ft (0.6-m) grid in broad arcs around the loudspeakers, extending all the way around the sides of the system. Subjects stood in turn at each of the indicated positions and faced the midpoint of the span between the loudspeakers. At each position the loudspeakers were individually rotated to face the listener, who then adjusted the hand-held balance control to center the sound. The degree of electrical left/right compensation was noted as a function of position. The subjects reported verbally on the degree of fusion.

The balance readings were averaged as a function of angle, resulting in a nearly elliptical polar pattern (Fig. 1), with the greatest compensation being about 14 dB, at a listening position to the sides of the loudspeakers and in line with them. This was later reduced to 9–10 dB in the final design (Fig. 2), after the 10-ft (3-m) experimental spacing was deemed to be on the high side of distances used in typical living rooms.

While the most compact imaging was generally obtained on centerline, well-fused images were consistently obtained at a range of positions stretching well off center. While there sometimes seemed to be a point of ambiguity at about 1 ft (0.3 m) left or right of centerline, image compactness generally improved beyond this point and extended usefully virtually to the sides of the loudspeakers. At extreme positions, subjects reported fused images on some trials and not on others. Once perceived as fused, an image tended to remain so until the sound was interrupted and/or the listener changed position.

The time/intensity-trading studies consulted [1], [2] used headphones to present the stimulus and reported that image fusion tended to be unobtainable for time disparities much in excess of 1 ms. Since in our test this corresponded to listener positions 1–2 ft (0.3–0.6 m) off centerline, we were surprised to find that image fusion was maintained to positions well outside this range.

The total amplitude correction for an off-centerline listening position should consist of the difference in arrival amplitudes resulting from the square of the pathlength differences, plus additional amplitude compensation for the arrival-time differences via time/intensity trading.

The former component, calculable from the geometry of the situation and plotted with the experimentally derived polar responses in Figs. 1 and 2, is seen to comprise the bulk of the compensation observed in the experiment. The arrival-time compensation only, which is the difference between the two curves, amounts to only about 4–5 dB at extreme positions. The headphone-based studies indicate a time/intensity tradeoff of at least 6 dB/ms of disparity, which for the range of time differences encountered in our test (about 10 ms) implies the need for maximal arrival-time compensation on the order of at least 60 dB. It is therefore questionable that time/intensity trading is significantly operative in off-centerline imaging. For the conditions described it may be that the human auditory system largely ignores timing information and bases its judgments of horizontal localization primarily on amplitude information.

Since sound attenuation with distance and time/intensity trading are both, to first order, independent of frequency, it should follow that the radiation pattern of a constant-imaging loudspeaker must be similarly independent of frequency. We verified this by holding trials with the test loudspeakers pointing straight forward, not being turned toward the listener. At off-centerline positions, with balance levels adjusted as well as possible, there was evident absence of image fusion, with highs localized to the near loudspeaker, lows toward the far loudspeaker, and the midrange somewhere between the two. This effect is consistent with the above analysis and with the fact that the test system has a radiation pattern typical of front-firing loudspeakers: narrowing with increasing frequency within each driver's range. Subjects at off-centerline positions received different left/right-magnitude spectral responses, preventing image fusion. Pointing the loudspeakers toward the subject at each position preserved left/right balance with frequency and enabled fusion as described.

We thus were led to the specification of a loudspeaker with a frequency-constant radiation pattern, both for general acoustical quality and for maintenance of off-centerline imaging.

Figs. 1 and 2 are computer-generated plots of the two contours, showing both channels as viewed from above, to indicate proper orientation in normal stereo operation. Several points are worth making.

1) The patterns for each loudspeaker are directional as described, with differences of approximately 14 and 9–10 dB between the loudest and softest axes. (The polar axes are on a scale of 10 dB per division, a total range of 30 dB.)

2) The loudest axis points not out into the room but at the other loudspeaker because the position of maximum disparity is, of course, all the way over on the side, outside the range of the loudspeakers and in line with them. It is at this angle that the sound from the near loudspeaker should be quietest and that from the far loudspeaker loudest.

3) In order to maintain image fusion, the radiation pattern of the loudspeaker system must adhere to this contour across substantially the entire audio band, or else different spectral components of a single image will appear to arrive from different directions, rendering image position vague and imprecise. In other words, the frequency response or total balance of the system cannot change markedly as one walks around it—only the level.

1.3 Complete Horizontal Radiation

The listening test directly established the contour for the front half of the pattern, the half that radiates out into the room toward the listener.

Our intent in selecting the back half of the radiation pattern was to use the wall bounce as a controlled acoustic delay, in a fashion similar to the operation of a delay-line-based multichannel ambience-recovery system. In this case the delay is acoustic rather than electronic, frontally oriented, and shorter in time, and

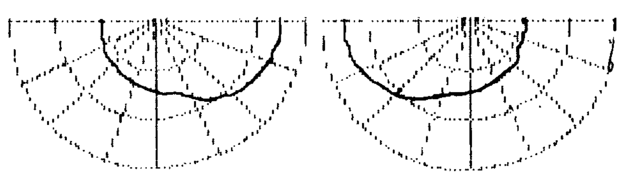

Fig. 1. Radiation pattern for well-fused off-centerline imaging. Maximum amplitude difference 14 dB, experimentally derived using two conventional two-way loudspeakers 10 ft (3 m) apart (10 dB/div).

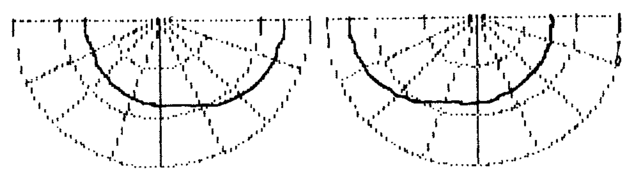

Fig. 2. Radiation pattern for well-fused off-centerline imaging. Maximum amplitude difference 9–10 dB for two conventional two-way loudspeakers less than 10 ft (3 m) apart (10 dB/div).

therefore is interpreted by the brain as a source of depth information. The result is to delineate more clearly the direct and reflected components to the ear and render more palpable the perception of depth and ambience.

To preserve good image fusion via the Haas or precedence effect (that the ear is captured by the initial arrival of a sound), it was desired to have the level of any echo be at least a little lower than the level of the direct sound, to minimize ambiguous localization cues that might blur the imaging. This suggested a nominally bidirectional pattern. Forward and backward radiation start out from the loudspeaker at the same time, equal in amplitude, but the backward sound has to travel farther, bouncing off at least one wall before arriving at the listener's ears, so it reliably arrives both later in time and lower in level than the direct sound, preserving image fusion. Note that many performing ensembles radiate sound bidirectionally, as do many planar-type loudspeakers. Unlike the case with some of them, front and rearward radiation in these designs are in phase, avoiding low-frequency cancellation.

The final rearward contour chosen is in fact just the front half flipped over, mirror image, as illustrated in Fig. 3 (after Fig. 2). Since the wall behind the loudspeakers acts more or less as an acoustic mirror, flipping the pattern back again, the early ambient sound is subject to the same distance/intensity trade as the direct sound, and the two are thereby kept in balance across different listener positions, as is the resulting perception of depth.

This choice of rear horizontal contour had the practical advantage in the first three product realizations of making the two loudspeakers identical, avoiding the need for mirror-image pairs. It also allows the listener to walk behind the loudspeakers and still get proper imaging (with the channels reversed).

Obviously, the user exerts influence over the entire imaging result by acoustic treatment of the front and side walls and floor—whether curtains and rugs are used, how far away from the walls the loudspeakers are placed, etc.—and also by his or her proximity to the loudspeakers. Further control of the ratio of direct and reverberant energy may be had by toeing the loudspeakers slightly in toward the listener, with some narrowing of the optimal-imaging area.

1.4 Vertical Radiation

Choosing the vertical-radiation pattern was considerably simpler than choosing the horizontal pattern.

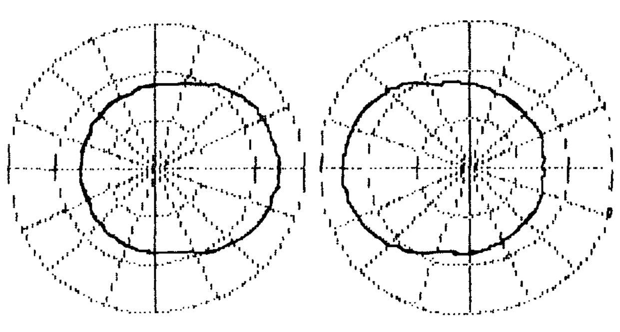

Fig. 3. Desired complete horizontal radiation pattern, after Fig. 2.

The primary requirement was the maintenance of fairly broad dispersion across the frequency range, in part so that the sound quality does not change dramatically as the listener stands and sits.

We also desired in the 360° realizations to limit the dispersion directly up above the loudspeaker, because such radiation can create tall images or instruments overhead after it bounces off a low, hard ceiling.

Combining vertical and horizontal requirements results in a composite (three-dimensional) desired radiation pattern that looks like an elongated torus.

2 HARDWARE DESIGN: REALIZING THE RADIATION PATTERN

The first practical design goal was a loudspeaker system with the desired radiation pattern, flat power response from 20 Hz to 20 kHz in typical home listening rooms, and peak-acoustic-output capability of 110 dB SPL in such rooms at inaudible distortion levels when used with commercially available power amplifiers.

The starting point was the inherent spatial acoustic behavior of actual loudspeaker drivers and baffles.

2.1 Choice of Drivers

The directionality of a driver as a function of frequency depends primarily on the linear size of the effective radiating surface and is independent of the method of transduction. A 10-in (254-mm) vibrating piston will begin to get directional around 800 Hz, a 1-inch (25-mm) piston around 8 kHz, irrespective of motor mechanism. "Directional" here means theoretically -3 dB at 45° off axis.

Because driver directionality does not depend on transduction, the common dynamic driver is on equal terms in this regard with more exotic transduction technologies, such as electrostatic, ribbon, or ionic. Previous work of our own [3] indicates that a properly designed dynamic driver introduces no audible distortion or other artifacts in normal use, nor does it otherwise suffer from inherent sonic limitations. This conclusion is supported by similar work of Villchur and Allison [4] and Bose [5], among others. Overall the dynamic driver is the most cost-effective, rugged, and widely available technology capable of realizing the desired acoustic goals—with no compromise in sound.

2.2 Vertical-Pattern Realization

Realizing the vertical component of the radiation pattern was a straightforward matter of using drivers within frequency ranges for which their output is largely omnidirectional or at least half-omni and employing only one driver per vertical array in each frequency range. The woofer/midrange crossover frequency was chosen to be 450 Hz, the midrange/tweeter crossover 3.15 kHz. The tweeter diaphragms are ½-in (12-mm) domes to extend vertical dispersion through the top octave.

The vertical baffle formed by the floor-standing cabinet aids in preventing sound above the deep bass from being radiated directly vertically. The tweeters are less influenced by this effect because they are at the top of the cabinet, so a tweeter grille cap with a sonically opaque top and transparent sides is placed over them to limit high-frequency vertical dispersion and avoid a strong ceiling bounce.

2.3 Horizontal-Pattern Realization

In order to preserve image position and fusion around the listening room, the horizontal-radiation pattern had to adhere to the specified directivity contour over substantially the entire frequency range. The design process required detailed characterization of the spatial properties of individual drivers.

Typical loudspeaker behavior is illustrated in Figs. 4 and 5, which show the horizontal radiation of a well-regarded conventional (front-firing) commercial four-way loudspeaker system, using one driver per frequency range, plotted in one-third-octave increments and bundled by octave, 20 Hz to 20 kHz. At low frequencies the pattern is broad and omnidirectional; at higher frequencies it becomes more and more narrow, indicating a rolloff in the power response of the system. Along the loudest axis, the curves go through a fairly narrow amplitude range, that is, the on-axis direct response is approximately flat. As is well known, this inconsistent behavior—flat on-axis response and a progressively narrower (and then suddenly broader after each crossover point) beam pattern accompanied by diminishing power response at higher frequencies—is typical of virtually all direct-firing loudspeakers and imparts a characteristic signature to their reproduced sound [6].[2] Compared with the desired curve (Fig. 3), this pattern is too broad at lower frequencies and too narrow at high frequencies.

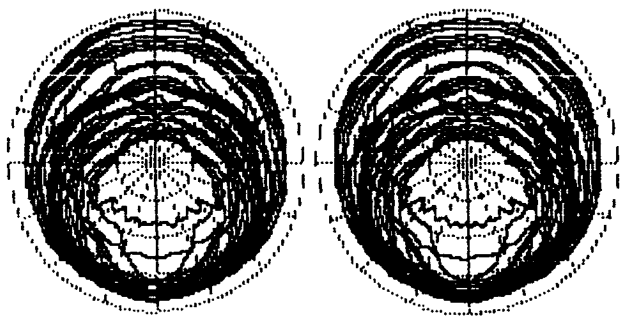

Fig. 4. Measured horizontal radiation pattern for conventional (forward-facing) multiway loudspeaker pair. One-third octaves, 20 Hz to 20 kHz.

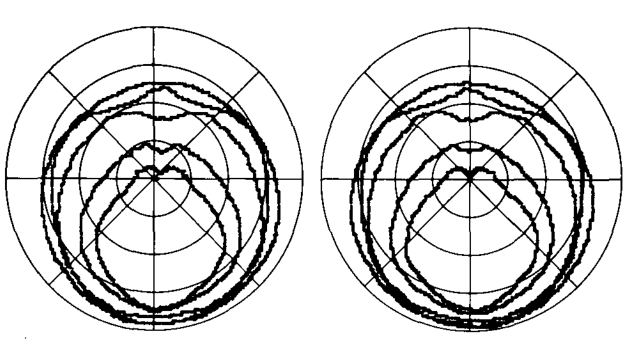

Fig. 5. Measured horizontal radiation pattern for conventional (forward-facing) multiway loudspeaker pair. Octaves, 20 Hz to 20 kHz.

Fig. 6 is a comparable picture of a quite different radiation pattern, for an equalized multidriver loudspeaker with eight of nine identical drivers facing rearward, producing predominantly reflected sound. This system has a sound signature audibly different from forward-firing loudspeakers.

The design task for our systems then was to make the natural single-driver patterns narrower at low frequencies, broader at high frequencies, and otherwise adhere to the desired contour at all frequencies.

Our proposed solution was to adopt a technique from radar and sonar technology, that is, a phased array of drivers, wherein the signal to each driver is contoured in both magnitude and phase such that the acoustical outputs of the drivers sum in space to produce the desired beam pattern across the audio band.

The complement chosen for the first realization of this system is four nominally 10-in (254-mm) woofers, four 4-in (102-mm) midranges [one each on four sides of a 14.5-in (368-mm) square cabinet], and six 0.5-in (12.5-mm) tweeters in a regular hexagonal array. The second realization has two woofers and midranges and four tweeters. [The third, fourth, and fifth (half-oval) realizations have one woofer, one or two midranges, and two or three tweeters, with the radiation pattern also shaped by irregular baffles.]

Interdriver equalization is carried out at high level by the crossover network, enabling the loudspeakers to be used with conventional stereo amplifiers, while overall system equalization for the first two realizations is provided by external line-level active equalizers connected in series in the existing amplifier system. In the larger system, four pairs of drivers (two pairs of tweeters and one pair each of midranges and woofers) are in mirror-image positions on the cabinet and connected in parallel, leaving 10 sets of signals to be electrically contoured by the crossover network. In the smaller systems, one pair of tweeters receives the same

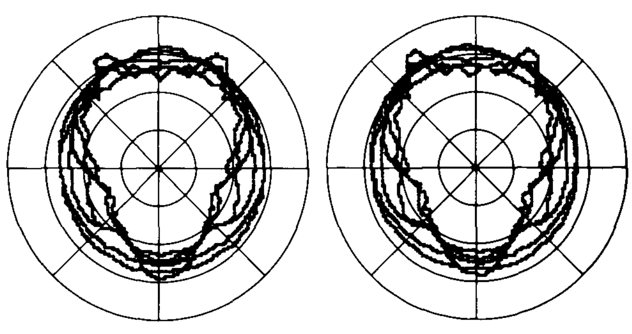

Fig. 6. Measured horizontal radiation pattern for predominantly reflective (8 of 9 identical drivers facing rearward) equalized loudspeaker pair. Octaves, 20 Hz to 20 kHz.

[2] In [6] Moran analyzes the relationship between frequency-inconsistent radiation patterns and "loudspeakery" sonic equality.

signal; the other drivers all receive individually tailored signals. (In the most recent three systems, which have no external equalizers, the drivers all receive individually tailored signals.)

The first step in the crossover design was to measure the impulse response of each driver as mounted in the cabinet with all grilles in place, at 5° intervals from 0° to 180° (37 responses total per driver). Note that the effects of all cabinet reflections, grille refractions, and the like are included in the raw data and accounted for in the subsequent design.

At each angle, 128 responses were averaged to improve the signal-to-noise ratio. Responses were taken in a large room and time-gated to avoid the effects of echoes. The raw impulse signal was first passed through a −3-dB/octave pinking filter to provide equal energy per octave. The response of this filter alone was measured and subsequently subtracted from the raw data, leaving the response of the driver or system under test.

The impulse-response data were converted via a fast-Fourier-transform program to frequency magnitude and phase responses at each angle and bundled into one-third octaves to reflect the quasi-logarithmic frequency sensitivity of the ear. The raw data were software-downsampled to improve low-frequency resolution. Above 160 Hz the gating time was 44 ms, below it was 880 ms.

The result for each driver was a radiation-pattern file consisting of its magnitude and phase responses at each of the 37 angles from 0° to 180° and the 31 frequencies from 20 Hz to 20 kHz. The radiation-pattern files of all the drivers in the system were collected in a single spatial/frequency data base for ready software access.

A network-analysis editor program was written to allow the entry of the crossover topology and initial part values. Driver-terminal electrical impedances were measured at one-third-octave frequency increments and stored in computer files.

The actual crossover design was handled by a program that consisted principally of an electrical-network-analysis routine and a spatial-response calculator, operating under a supervisory optimization routine.

From the electrical data, the program computed the magnitude and phase of the voltage at each of the drivers' terminals at one-third octaves across the audio band. From this information and the spatial data base, the program calculated the radiation pattern of the composite system from 20 Hz to 20 kHz at 5° increments.

By comparing this computed output frequency by frequency with the desired-radiation-pattern template (the same template for all frequencies), the program was able to derive a single overall figure of merit for a design, representing its rms deviation (in decibels) from the desired template. The supervisory routine then iteratively adjusted the values of the crossover elements and computed each corresponding figure of merit, retaining changes that reduced the rms error (nonlinear, least-squares minimization).

In essence, the program was able to design, measure, and evaluate the spatial frequency response of a complete loudspeaker system—including all acoustical and electrical driver, cabinet, and crossover effects—and to decide whether it had made an improvement. The program was run until an optimal fit to the desired radiation pattern was obtained.

The final calculated horizontal radiation pattern is illustrated in Fig. 7 and the actual measured radiation pattern of the corresponding design is plotted in Fig. 8. The two show fairly close agreement. The measured response is smoother and less jagged because it represents the average response in each one-third-octave band bundled for clarity into octaves; the calculated response employs discrete frequencies.

The measured pattern adheres closely to the desired template from 200 Hz on up, broadening out to omnidirectional below that region since low frequencies impart no directional information. Compared with the radiation of the conventional loudspeaker, the increase in uniformity across the audio band is evident.

The magnitude- and phase-transfer functions from the first system's terminals to each of the drivers are shown in Figs. 9 and 10, plotted 20 Hz to 20 kHz on vertical scales of 10 dB per division and 180° per division, respectively.

2.4 Efficiency

There was concern that the crossover network would seriously degrade system efficiency by having significant insertion loss. Apart from using drivers that were not inefficient, measures were taken to:

1) Minimize the number of crossover elements in series with the woofer, midrange, and tweeter on the loudest ("prime") axis;

2) Employ wherever possible good-quality "lossless" elements (inductors and capacitors rather than resistors) in realizing the crossover. In some cases in which the final design called for a finite resistor in series with an ideal inductor, the two were combined into a single lossy inductor.

The efficiency of the woofers had to be balanced against their ultimate undistorted acoustic-power output at low frequencies: woofers with sizable overhang—l outside the gap—were chosen for superior large-signal performance (high maximum output capability at low frequency), but large magnets were required—high B—to overcome inherent inefficiency.

The final system sensitivity is approximately 90 dB/2.83 V/meter through the midrange, which is comparable with that of existing loudspeaker systems and well-matched to the existing range of commercial power amplifiers.

2.5 Input Impedance

The impedance of the system was another concern. If the already uneven impedance functions of the drivers were corrupted by the crossover network, the result might have been a load that few amplifiers could drive without instability. We therefore had the crossover-design program also compute the electric input impedance of the composite system across the audio band. This information provided a basis for choosing certain topologies over others and in some cases for restraining the program from altering certain part values.

The resulting equalized loudspeaker systems have a 20-Hz to 20-kHz impedance curve centered closely on 4 Ω (the range is 2.5–8 Ω) and work stably with existing amplifiers. Their phase angles are not extreme, ranging approximately from +20° to −40°.

2.6 The Processor

As described, the first systems are augmented by outboard line-level analog signal processors, which connect into the tape-monitor, external-processor, or preamplifier-output jacks of the existing stereo system. The primary purpose of the processor is overall system equalization. The default equalization curve of each processor, which results in flat power response in the average home listening room, is to first order the inverse of the spectral power demands made by typical musical material, so that the increased power demands made by the equalization are generally modest. In the final analysis, of course, it is system sensitivity that largely determines actual power requirements. The lower level equalization network was designed using another circuit-analysis/optimization routine to implement the inverse power response.

The use of outboard equalization allowed the loudspeaker radiation pattern, efficiency, and input impedance to be optimized without regard to overall response, that is, there was no need to compromise any of these in order to provide de-facto high-level equalization, as must sometimes be done in purely passive systems.

In addition to the equalization stages, there are a number of controls and circuits in the processors to compensate for anomalies in listening rooms, boundary reinforcement, and/or source material, and (in the first processor) to protect drivers.

3 ASSESSMENT

Although the ultimate judgment of reproduced sound remains an aesthetic matter, it is evident that the design choices have had an audible effect. Compared with conventional and many unconventional loudspeakers, for example, the top octaves are clearly better dispersed. Imaging is indeed maintained over a very wide range of listening positions; an A/B comparison against conventional loudspeaker systems with the listener well off centerline is almost tantamount to a comparison of stereo with mono.

Spectrally, the systems exhibit little position sensitivity even down to the upper bass/lower midrange, presumably because of the spatial consistency of the output. Crossover regions are relatively seamless, there being no audible evidence of "phasiness" despite the multiplicity of drivers.

We also have auditioned the first system with the prime axes pointing out at the listener. Under these conditions there is no wide-area imaging. The loudspeakers act in this regard more like conventional, di-

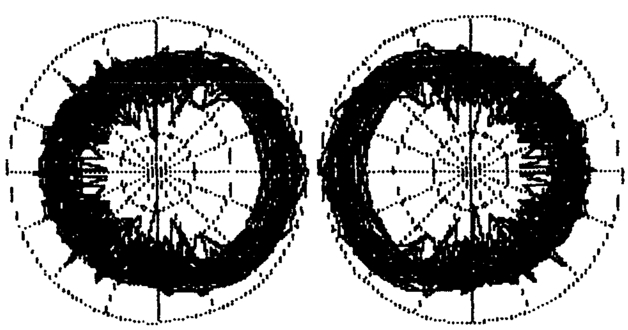

Fig. 7. Calculated horizontal radiation pattern for constant-imaging loudspeaker pair. Discrete frequencies, no averaging.

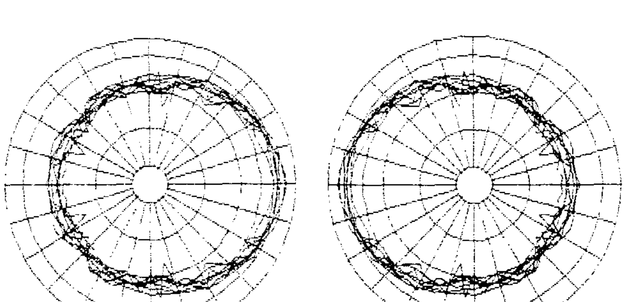

Fig. 8. Measured horizontal radiation pattern for constant-imaging loudspeaker pair. One-third octaves, bundled into octaves 20 Hz to 20 kHz.

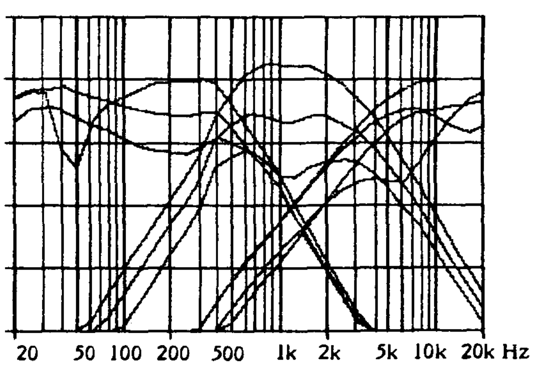

Fig. 9. Magnitude transfer function from input terminals to each of the drivers. 10 dB/div, 20 Hz to 20 kHz.

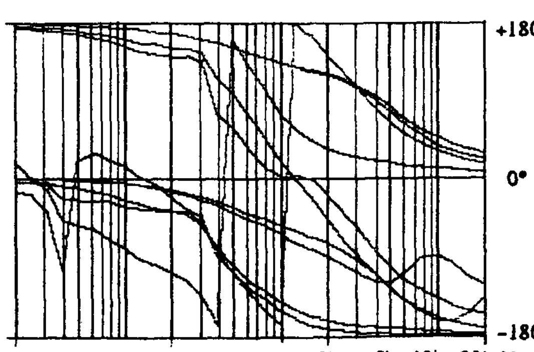

Fig. 10. Phase transfer function from input terminals to each of the drivers. 180°/div, 20 Hz to 20 kHz.

rectional loudspeakers, except that the directionality is maintained constant across the audio band. The most audible effect is that the treble is better integrated and better dispersed with the rest of the image instead of being localized to the tweeters, so there is again less of a loudspeakery signature.

Overall, there appears to be good agreement between sound quality and the radiation pattern of the system.

Further applications of these techniques should permit the realization of loudspeaker systems whose radiation patterns have been matched to any number of requirements. In general, wider spacing should require narrower beams, and vice versa. For a given loudspeaker arrangement and a specified listening area, there should be an optimal radiation pattern for each loudspeaker, to optimize in turn the performance of the ensemble. For example, in a three-channel presentation the ideal center loudspeaker should perhaps have a bowtie pattern. There may be further benefits to extending the idea of controlled radiation patterns to systems where each cabinet radiates multiple beams, fed from independently derived signals.

4 ACKNOWLEDGMENT

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APPENDIX

Figs. 11–15 show measured horizontal radiation patterns of five commercial loudspeaker systems developed from the work described in this paper.

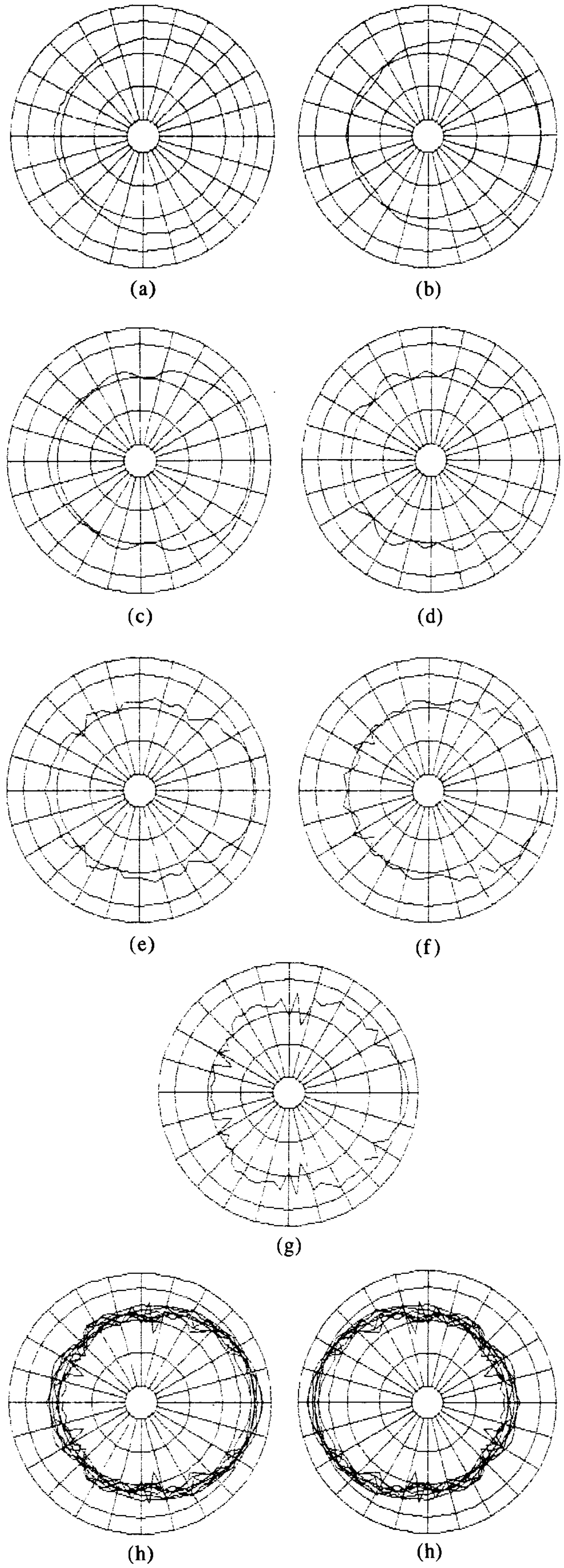

Fig. 11. Horizontal radiation for 14-driver equalized loudspeaker system, bundled by octave. 10 dB/div, left loudspeaker only shown. (a) 175–350 Hz. (b) 350–700 Hz. (c) 700 Hz–1.4 kHz. (d) 1.4–2.8 kHz. (e) 2.8–5.6 kHz. (f) 5.6–11.2 kHz. (g) 11.2–22.4 kHz. (h) Composite radiation pattern (stereo pair).

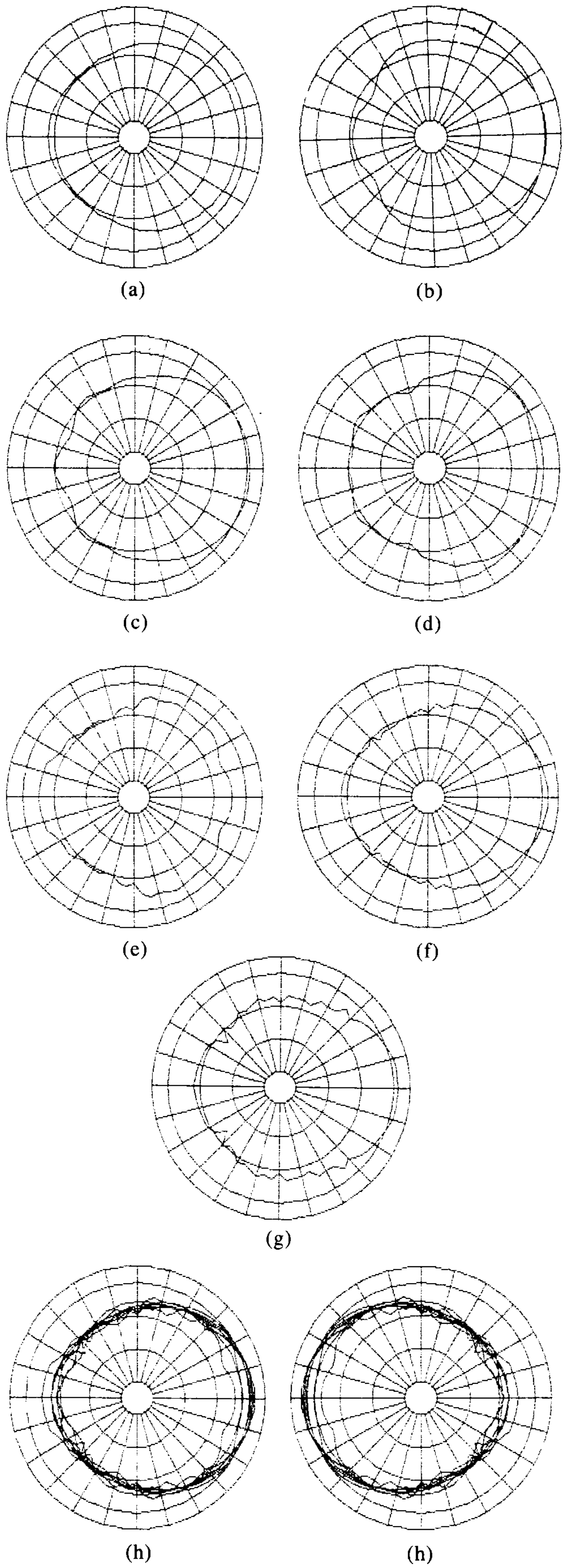

Fig. 12. Horizontal radiation for 8-driver equalized loudspeaker system, bundled by octave. 10 dB/div, left loudspeaker only shown. (a) 175–350 Hz. (b) 350–700 Hz. (c) 700 Hz –1.4 kHz. (d) 1.4–2.8 kHz. (e) 2.8–5.6 kHz. (f) 5.6–11.2 kHz. (g) 11.2–22.4 kHz. (h) Composite radiation pattern (stereo pair).

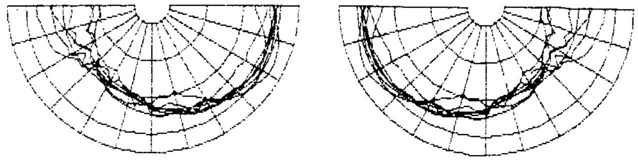

Fig. 13. Composite horizontal-radiation pattern for 6-driver loudspeaker system (stereo pair), bundled by octave. 10 dB/div, 175 Hz to 22 kHz. Front wall, 1 ft (0.3 m) behind loudspeakers, is included.

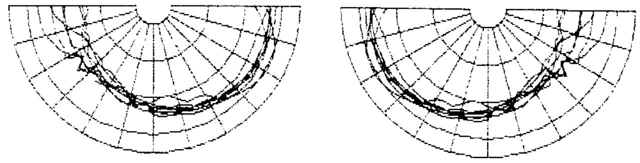

Fig. 14. Composite horizontal-radiation pattern for 5-driver loudspeaker system (stereo pair), bundled by octave. 10 dB/div, 175 Hz to 22 kHz. Front wall, 1 ft (0.3 m) behind loudspeakers, is included.

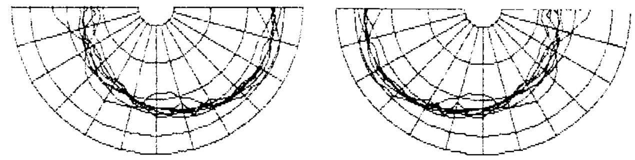

Fig. 15. Composite horizontal-radiation pattern for 4-driver loudspeaker system (stereo pair), bundled by octave. 10 dB/div, 175 Hz to 22 kHz. Front wall, 1 ft (0.3 m) behind loudspeakers, is included.

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