The Loudspeaker As A Spherical Sound Source

***Winslow N. Burhoe**

It has long been known to physicists and audiophiles that the ideal loudspeaker would radiate sound equally in all directions, at all frequencies without any distortion. The usual visual image which is called to mind is that of a small pulsating sphere, perhaps the size of a tennis ball. As this imaginary ball expands and contracts, it transmits a pressure wave to the air which then expands as a spherical wave of sound. Unlike wave motion in strings or on the surface of water, sound waves are three dimensional.

The term "omnidirectional" applies to the three dimensional spherical wave pattern this ideal sound source would generate. This term has been abused in recent years by being applied to speakers that do not technically qualify as omnidirectional. Some have been omnidirectional only over a very narrow frequency bandwidth and most are not omnidirectional at any frequency. As a consequence, there has been little industry or consumer excitement over speakers which have been introduced and labelled "omnidirectional".

It is essential for true and valid omnidirectionality that two conditions be met: (1) Omnidirectionality at all frequencies, and (2) equal energy radiation in *all* directions—up, down, left, right, forward and backward. Omnidirectionality is NOT a substitute for other high fidelity specifications; it cannot compensate for poor frequency response or high distortion. It is of no advantage unless applied to wide frequency bandwidth. However, when the traditional high fidelity values of flat frequency response, low distortion, and wide bandwidth are embodied in a truly omnidirectional speaker, a major improvement in sound reproduction is achieved; the close approximation of the mythical ideal speaker, a Spherical Sound Source.

Like all other historical advances in the art of high fidelity, true omnidirectionality provides a greater degree of musical realism and increases the aural perception of the listener. The psycho-acoustic effects of a stereo pair of true Spherical Sound Sources requires many hours of acclimatization, but once the listener's ear has accepted the more complicated aural impulses, the result is the most realistic perception of sound reproduction possible.

It has become a well known fact in recent years, even among audio consumers, that a speaker providing the listener with a combination of direct and reverberant sound imparts a greater sense of spaciousness and realism to the listening room. A truly omnidirectional speaker carries this concept many steps further by providing the maximum possible reverberant field effect, ie., the ratio of reflected energy from an omnidirectional speaker arriving at the ear from all directions, milli-seconds after the direct input, imparts an ambience and realism to the reproduced signal unequalled by any direct or partially reflective speaker.

The amount of reverberant field effect of any speaker is determined by the amount of dispersion, especially of mid and high frequency energy, the amount of reflective versus absorbant surfaces in a listening room, and the speaker's position in relation to those reflective surfaces. In order to effectively utilize the maximum effect of reverberant field in an acceptable listening environment, a speaker must be able to accurately supply the listener's ear with two distinctly different and separately perceived aural inputs: the transient information and the tonal information.

The transient wave form provides the brain with bits of purely digital information. The time of first arrival of the transient at each ear is compared and the difference between these two arrival times provides a directional analysis and the greater part of the stereo image. Without proper transient information the stereo image becomes distorted, possibly through exaggeration of the size of the image, possibly through a minimization of the difference between channels.

The tonal information provides the brain with the actual musical overtones. The ear has the ability to act as a Fourier Analyzer and to separate all the complex tonal input into its actual frequency content. Even the most complicated harmonic structures and overtones are individually analyzed and then transmitted separately to the proper information processing sections of the brain, where the listener enjoyment of the reproduced musical signal occurs.

As long as a speaker provides transient information that can be accurately identified by the ear, the presence of a reverberant field effect serves to multiply and enhance the tonal input from the original musical signal allowing the brain a longer period to identify and enjoy the complexities of the musical overtones. Therefore, the greater the reverberant field, the greater the psycho-acoustic pleasure becomes.

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The lack of accurate transient response from the speaker, or an unusual listening environment that would provide an extreme saturation of reflected sounds (the opposite of an anechoic chamber) could result in a muddy or blurred sound. The problem of transient information can be overcome with proper speaker design and an unduly high percentage of reflected sound would never be a problem in a normal listening room.

In a closed acoustical environment such as a normal listening room, an additional benefit of a spherical sound source is its ability to produce a field of sound, in much the same way that the earth produces a gravitational field. Because of the reverberant or reflective characteristics of a room and the psycho-acoustic effects of reverberation, the acoustic field produced is equivalent to a uniform field. In other words, there is no apparent source and no apparent change of loudness in different room positions. Because the stereo effect or image is created by the sound of first arrival, or the transient input, there is no degradation of stereo imaging in these uniform sound fields created by the Spherical Sound Source (transients are radiated equally in all directions). An accurate stereo effect is achieved over the entire listening area, provided only that there is a direct line-of-sight path between each spherical sound source and the listener. The psycho-acoustic effects of reverberation described above enable any normal room to closely approximate the effect of a large concert hall more effectively than any other type of transducer. The uniformity of the acoustic fields enables comfortable listening anywhere in the room, even next to one of the Spherical Sound Sources. Listener fatigue is virtually non-existent.

In order to optimize the acoustic field effects, the room should be divided mentally into equal areas with symmetrical reflective characteristics. The Spherical Sound Sources should be located as close to the center of each such area as possible, in order to maximize the amount of reflection and therefore increase the reverberant field effect occurring in the listening environment. The effects on placement are relatively subtle, however, and truly omnidirectional speakers provide an acceptable level of placement flexibility in most listening rooms.

Achieving a Spherical Sound Source

Conventional bookshelf speakers, whether two-way or three-way, which have the speakers mounted on the same surface in the front of a rectangular box, all have similar directional characteristics. Over some portion of the frequency range of a woofer or tweeter, the drivers operate in a linear fashion whose sound radiation characteristic pattern is hemispherical; that is, the sound radiated off axis as far as 90 degrees in any direction, is equal to the sound radiated straight ahead. (It is a common misconception that speaker's radiate sound mostly in the direction they are facing.)

At very low frequencies, the dispersion pattern is even wider; sound is actually radiated backwards from the speaker—this is why speaker placement affects bass response, there being conspicuously more reflected bass when the speaker is in a corner than when it is in the middle of the room or up in the air. At high frequencies, however, all tweeters become directional, that is, the hemispherical radiation pattern narrows to a straight beam whose diameter is the same as that of the tweeter. In a two inch tweeter this transition occurs between 6 kHz and 8 kHz; in a one inch tweeter it occurs above 13 kHz. In general, good dispersion is achieved only if the diameter of the cone is smaller that the wave length of sound concerned.

By taking four conventional bookshelf speakers with acceptable frequency response, linearity, distortion specifications, and hemispherical dispersion over the entire audio bandwidth, and mounting them with a small enough horizontal separation in a four sided cabinet, it is possible to create a speaker that would closely approximate a Spherical Sound Source.

The cost of building a speaker that meets these criteria is high, due to the complexity of the drivers that must be used. I firmly believe however, that the most devoted audiophiles and music lovers would find the enjoyment received from the complex aural and psycho-acoustic effects described above well worth the expense. Until a physicist or acoustic engineer manages to actually build a working model of the mythical "Pulsating Sphere" the hi fi industry and the consumer must settle for the "Spherical Sound Source" available. Anyone who makes the effort to find and listen to a "Spherical Sound Source" long enough to appreciate its benefits will not be disappointed. Æ

Omnidirectional Radiation

G Sioles

Science and technology as well as the arts have been characterized by controversy, and audio is no exception with such arguments as "pentodes vs. triodes" in amplifiers, the relative importance of measurements vs. listening tests in evaluating loudspeakers being typical. Sometimes the controversy is more imagined than real and derives its substance from insufficient knowledge, or over-simplification. It is the purpose of this article to discuss a recent "controversy" over the relative merits of omni-directional and "conventional" speakers.

Ideally, the performance specification sheet for a loudspeaker should look the same as one for an amplifier, with the exception of a few physical descriptors of one that do not have an easily definable counterpart in the other (e.g. output impedance). A loudspeaker, however, propagates sound in a three-dimensional continuum, whereas the signals processed by the amplifier are propagated in one, a pair of wires. Because of this, an additional important set of data is needed to show how the acoustic power is radiated in the various directions. It is a statement which is not generally discussed in any great detail because representation of the data is cumbersome (imagine looking at sixteen frequency response curves depicting the performance as it varies with direction from the source). But, we would like to discuss this difference between the loudspeaker and other elements in the audio reproduction chain because it is basic.

It is possible to argue, because of the variety of available room placements, that a loudspeaker should radiate uniformly over a solid angle of between π and 4π steradians. Further, the *power* output in free space (not simply axial pressure vs. frequency response) may have a special form to account for the increase in output at low frequencies resulting from wall reflections. It is not acceptable to have a uniform radiation pattern over 4π steradians at low frequencies, becoming directional at middle and high frequencies in such a manner that the net result is a non-uniform pressure vs. frequency characteristic in the reverberant field of the listening room. And yet, this is not uncommon.

Since non-directional behavior or controlled broad directivity is nominally desirable, from where derives the prejudice in some quarters against omnidirectional speakers? First, some speakers considered to be omnidirectional are not, but instead are directed-reflected type radiators. Second, those who feel that omni's are deficient in certain areas may be making generalizations from a very few poor examples. We are not aware, prior to now, of the existence of true omnidirectional speakers as serious contenders in the high performance speaker race. It would seem that omni's are put down in absentia—despite the fact that designers of conventional speakers generally strive to make speakers non-directional over as much of the frequency range as they can manage.

The question more properly may be, are there any true omni speakers? The answer is no. It is exceedingly difficult to produce a speaker that has uniform radiation over a spherical surface in the near field. What happens in the reverberant field (where people normally listen) is another matter. It is possible to produce a speaker which is essentially a true omnidirectional source, as heard in the reverberant field. It does not suffice, however, to place a number of driver units of individually indifferent frequency responses on the surface of a sphere and hope to get good results. True, omni behavior will result but at some cost in frequency response. Suppose we assume a good design—are there problems uniquely associated with omni's, and are they inherent? I do not think so, but a discussion of potential difficulties is worthwhile.

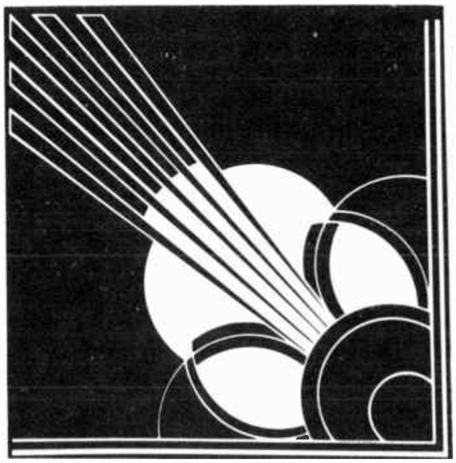
A true omnidirectional source must be either a point source (not possible) or a finite pulsating sphere (not practicable). In practice, an omnidirectional speaker comprises sources so small as to be non-directional as a consequence of their smallness, or sources of known directivity occupying a fraction of a "spherical" surface and equalized so that they radiate constant power vs. frequency, or some combination of the two. If there is any faulting of this approach it may be in the requirement for a multiplicity of sources. What happens is this:

In the frequency range where a number of sources are radiating, the pressure vs. frequency response characteristic will be a function of the microphone position and, in general, will not be "flat". But this is not what we hear. We hear the integrated power output as modified by the listening room characteristics. This poses no problem, if the integrated power output is constant with frequency. There is a possible unlooked-for effect, however, with regard to stereophonic localization. If two multiple driver speakers are so placed with respect to the listener that he does not receive the same "free field" response from both, the stereo images will be imprecise. This may appear to be a significant flaw until one thinks more about the whole process of localization.

Obviously, the problem is potentially most severe if the entire range is covered by a number of drivers, since then the non-uniform response with direction will extend to relatively low frequencies and have more of an effect on the stereo information received by the listener, *if* the speakers are not symmetrically positioned. (If only part of the spectrum is covered by multiple units, it is only the stereo information in this range that may be affected). But, this can be prevented by symmetrical speaker placement. Indeed, symmetry of the listener himself with respect to the two sources is essential to preserve the accuracy of the stereo images, since the process of stereo localization depends on the perception of time and intensity differences between the two channels. These intensity differences are in large measure vitiated by the movement off the axis of symmetry by the listener of approximately one foot. This is because a time of arrival difference of approximately 1 msec. makes necessary an increase of almost 10 db for the later source to be perceived as existing—lacking in this, the sound will appear to come entirely from the near source. Such constraint on the listener is more restrictive than the requirement of symmetrical orientation of speakers. In fact, with omni-directional speakers the tendency to lose the stereo effect is less when the listener moves away from the axis of symmetry—a significant advantage.

Finally, the acoustic characteristics of the listening room are far more important than most people realize. Because the ratio of reverberant to direct sound from omnidirectional speakers is higher than that from more directional types, the effect of the room is correspondingly greater. Since many listening environments (e.g. some audio dealers' showrooms) are less than good acoustically, an omni speaker may come off second best in an A-B listening test with a more directional type. However, for one who does not wish to be fixed in space for his listening enjoyment, and can provide a reasonably good acoustic environment, an omni-directional speaker system is definitely advantageous. Æ

Quadraphony Needs Directional Loud-speakers



***Benjamin B. Bauer**

When stereo began its spectacular rise in popularity more than a dozen years ago I presented a paper before the Audio Engineering Society demonstrating that Stereophonic Perspective could be improved significantly, regardless of listener position by proper design of the directional characteristics of loudspeakers and their placement with respect to the listening area. The improvement is explainable in terms of semi-directional polar patterns of conventional (e.g. "bookshelf-type") loudspeakers; it can further be enhanced with more strongly directional (e.g. "dipole" or "gradient") radiators[2]. A similar analytical and experimental process leads us to conclude that quadraphony also benefits from properly positioned semi-directional and directional sound sources.

What about the role of "omnidirectional" loudspeakers we hear so much about? It turns out that true omnidirectional radiation at all frequencies is difficult to achieve in practice; "semi-omnidirectional" performance, however, can be attained with relative ease. Omnidirectional loudspeakers obviously do not require directional orientation to cover a quadraphonic listening area reasonably well and, therefore, often are able to provide quadraphonic performance superior to that obtained with improperly oriented semi-directional loudspeakers; this is a very commendable attribute of systems intended for use by the lay public. On the other hand, omnidirectional loudspeakers can result in nasty wall reflection problems, and furthermore, any knowledgeable Hi-Fi enthusiast, or one who takes a bit of trouble to optimize loudspeaker placement, is apt to gain more satisfaction and improved quadraphonic performance with well designed semi-directional loudspeakers; or, if he is fortunate enough to obtain them or skillful enough to devise them—with properly designed dipole units.

To provide a better understanding of the principles involved in applying directionality to quadraphonic loudspeaker arrays we discuss first the physics of omnidirectional or semi-omnidirectional, semi-directional, and directional loudspeakers.

Omnidirectional Loudspeakers

At first blush, it would appear easy to design an omnidirectional loudspeaker; actually the task is rather formidable. A truly omni-directional radiator is defined by a spherical surface which expands and contracts radially equally and inphase. There are not many practical ways in which such a transducer can be fabricated. One approach is to use a hollow sphere (or two abutting hemispheres) of suitably polarized piezoelectric material (e.g. polycristalline lead zirconium titanate ceramic), including suitable internal and external electrodes to receive the electrical signals. Such a ball vibrates uniformly radiating equal amounts of sound intensity in all directions. Unfortunately such a transducer does not perform efficiently in air, (albeit it works fine underwater).

To improve efficiency we can place a large number of small moving-coil loudspeakers on the surface of a sphere; but since the radiation characteristics of all the units must properly overlap, this approach turns out to be quite complex and expensive. Another possibility is to install a ring of small loudspeakers around a cylindrical drum, or even to place a single transducer on the end of the drum and to confront it with a reflector adapted to direct the medium and high-frequency sounds equally all around into the horizontal plane. Thus, from the truly omni-directional ceramic ball loudspeaker we progress in steps to various practical "semi-omnidirectional" designs which radiate sound relatively uniformly only in the horizontal plane.

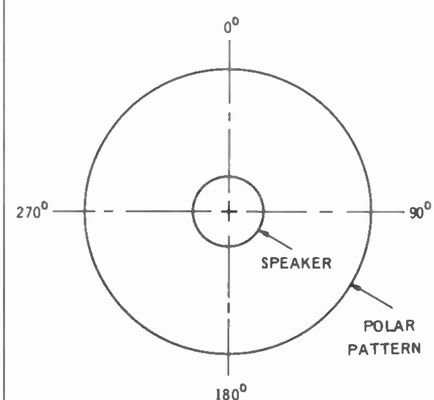


Fig. 1—Polar pattern of an omni-directional speaker in free space.

Graphically we show this uniform radiation in Fig. 1 by a circular "polar pattern," which signifies that the sound pressure radiated at a given distance in a 360° compass is constant.

Next, we consider briefly what happens when an omnidirectional loudspeaker is placed near a reflecting wall or corner. In this circumstance its performance can best be analyzed by the method of virtual images. For example, in Fig. 2(a) the loudspeaker center is placed at 1 ft. from a reflecting wall. Because sound travels at a speed of 34,400 cm/sec, the wavelength at a low frequency, say 50 Hz, is 34,400/50 = 688 cm (22.6 ft.)—much greater than

1. "Broadening the Area of Stereophonic Perception" *Tenth Annual Convention of the A.E.S.*, N.Y., Sept. 29, 1958.
2. B.B.Bauer, *Jour. A.E.S.*, 8, 2, 91-94 (April 1960).

*CBS Laboratories, Stamford, Conn.

the distance between the loudspeaker and its image (2 ft.). Both the real and the virtual source may be assumed to radiate inphase resulting in the doubling of sound pressure, with the polar radiation characteristic remaining nearly circular, as shown by the pattern

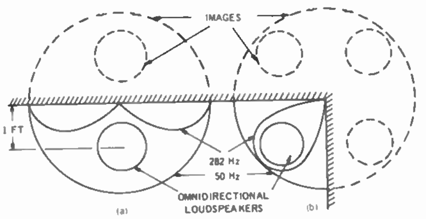


Fig. 2—Polar pattern of omnidirectional loudspeakers placed (a) near a wall (b) near a corner.

labeled "50 Hz" in Fig. 2(a). In reality, real radiation is only outside the wall P shown in solid line. The virtual source and radiation being shown in dash-line. (The presence of this virtual source accounts for increased bass when a loudspeaker is placed near the wall). At higher frequencies, the wavelength λ becomes comparable with the distance between the loudspeaker and its image, resulting in interference patterns. For example, at 282 Hz the distance is precisely ½ λ resulting in total cancellation of radiation in a direction perpendicular to the wall, as shown by the polar pattern labeled "282 Hz." At other frequencies, different patterns will be generated. Placed in a corner, again at 1 ft. from both walls, as shown in Fig. 2(b), three virtual images are formed. Again, at 50 Hz the pattern is nearly circular, and the radiated sound pressure is increased four-fold. At 282 Hz, the radiation near the walls drops to zero, but the radiation along the diagonal is a maximum, resulting in a rather narrow polar radiation pattern. Again, at other frequencies different patterns will be formed.

Therefore, the response from an omnidirectional loudspeaker is rather unpredictable near reflecting walls or corners, suggesting that the presence of acoustical absorption on or near the walls may be desired to avoid the higher-frequency reflection modes.

Semi-Directional Loudspeakers

The majority of "bookshelf-type" and similar loudspeakers are semidirectional. This is to say, they are omnidirectional at low frequencies becoming relatively directional at high frequencies. This is illustrated by the way of example in Fig. 3 where at (a) is portrayed a loudspeaker consisting of a sealed box (popularly known as "infinite baffle") say 12 × 20 in. in cross-section, enclosing a driver with a piston width W = 8" or approximately 20 cm. In actual practice the piston is circular or elliptical; but to make our example as simple as possible we assume it to be rectangular with the long dimension perpendicular to the paper.

At a low frequency, say 50 Hz, where the wavelength is much greater than the dimensions of the box, the particles of air displaced by motions of the piston move to-and-fro together in imaginary channels—much like water flowing from an opening, as illustrated by the streamlines in Fig. 3(a). At a distance from the box, it becomes possible to strike a circular surface along which all the streamlines are distributed with a near equal density of flow, corresponding to equal sound pressure which expands in concentric circles away from the loudspeaker. Under this circumstance the loudspeaker behaves like an omnidirectional radiator.

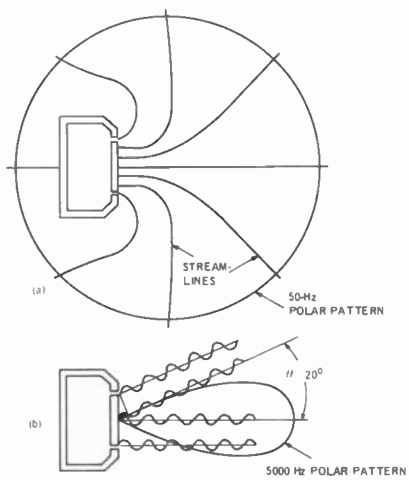


Fig. 3—Polar patterns for a piston in closed box, for (a) low frequency (50 Hz) and (b) moderately high frequency (5000 Hz)

As the frequency increases the wavelength becomes progressively shorter with the consequence that sounds from various portions of the piston are no longer inphase causing the radiation off the principal axis to be diminished or even to become completely cancelled. For example, consider the situation at 5000 Hz where λ is but 34,400/5000 = 6.88 cm (2.7 in.). As may be seen in Fig. 3 (b), the wavelets from the center and edge of the piston in the direction parallel with the axis are in additive phase resulting in intense sound radiation forward of the piston; but at some angle, θ, the wavelets are found to be in phase-opposition causing complete cancellation. In the example given, θ is readily found as follows:

$$\sin \theta = (\lambda/2)/(W/2) = \lambda/W \qquad (1)$$

or, since λ = 6.88 cm, and W = 20 cm, $\sin \theta = 6.88/20 = 0.344$; or $\theta = 20°$. From its on-axis maximum, the radiated sound pressure progressively diminishes to zero as shown by the polar-pattern in heavy line in 2(b). It is obvious that, in this last example, we are dealing with a narrow directional pattern which is unsuitable for high-quality sound reproduction at widely spaced positions in the room. To "broaden" the directional pattern sufficiently to obtain reasonably good coverage, we must restrict the upper frequency at which a piston is allowed to radiate. A workable rule of thumb for *circular* pistons is that the wavelength should not be less than the diameter of the piston. For an 8-inch piston this corresponds to 1720 Hz. To provide a satisfactory radiation pattern to 20,000 Hz the diameter of the piston should no exceed approximately 34,400/20,000 = 1.7 cm (0.68 in.).

At this point the reader might wonder why not use the small piston for all frequencies simply by making it work that much harder at low frequencies. This approach is counter-productive because the sound pressure generated at any given frequency at any point in space is related to the volume of air displaced by the motion of the piston, i.e. by its area multiplied by its linear vibration amplitude. Thus, an 8-inch diameter circular piston vibrating with a ¼-inch motion is apt to provide adequate bass sound; a 1.7-cm diameter piston which has 1/22 the area of an 8-inch piston would have to have a 22-times longer stroke for the same sound output. —or 5½ in. which obviously is impractical.

Thus, the designer is caught between the limitations of maximum allowable piston amplitude, at one end of the frequency scale, with the directional radiation problems at the other, and he has to allocate the range covered by each piston to a relatively limited band of frequencies. This explains why a superior loudspeaker system usually will employ several drivers of different diameters interconnected electrically with dividing networks to convey to each its proper portion of the spectrum. Typically, the response pattern of a good semi-directional loudspeaker is omnidirectional (circular) at low frequency narrowing down to a 90°-60° included angle at about 1000 Hz and remaining within this range up to the highest frequency of interest, as various radiators of progressively smaller size

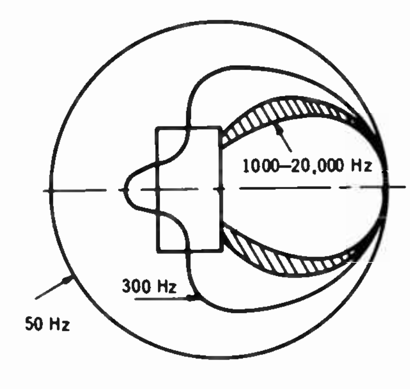


Fig. 4—Typical polar patterns for a conventional semi-directional (e.g. bookshelf-type) loudspeaker at various frequencies.

come into play, as shown in Fig. 4. Because the baffle box diminishes the radiation toward the back at mid-frequencies, such a semidirectional loudspeaker is less bothered by reflections from the walls or corners, than an omnidirectional unit. Without pretense of offering a treatise on loudspeaker design, it should be noted that the polar pattern of a loudspeaker cone can be modified by shaping, adjusting compliance, adding acoustical lenses etc.

Dipole Loudspeakers

A dipole loudspeaker is simply a piston (e.g. loudspeaker mechanism) vibrating in open air without an enclosure to confine the back radiation. The efficiency of such a device is a function of frequency because the radiations emerging from each side of the piston tend progressively to cancel each other as the wavelength increases. Efficiency may be improved by adding to the piston a baffle, as shown in Fig. 5, which increases the distance between the front and the back of the piston. It is easy from Fig. 5 to visualize that, in the perpendicular front, or zero degree direction, the back sound radiation has to travel an added distance D before it can proceed to the front; the added distance giving rise to a phase differential between the two waves producing a net sound pressure at a given point in space designated as P_0. As we move in a circle to the 90° direction, the radiations from both sides become equal and in antiphase; thus there is a zone of silence at all points on a surface S perpendicular to the axis. As one travels to the back, or 180° direction, the distance D comes again into play (except that this time, from front-to-back) resulting in a maximum sound pressure at P_{180}. It is not difficult to prove mathematically that as one moves around the circle, the pressure function follows a cosine law, the polar pattern taking on the form of two circles at both sides of the piston. To avoid an excessive loss of efficiency the dimension of the baffle should be no less than approximately $\frac{1}{6}$th the wavelength of the lowest frequency of interest. At high frequency the radiation from the piston narrows down in a manner similar to that described in Fig. 3. Therefore, the highest operating frequency for any one piston should be that corresponding to a wavelength equal to its dimensions. An 8-inch diameter loudspeaker installed in a 13-14-inch baffle, has a satisfactory operating range between 250 and 1700 Hz. A second, correspondingly smaller gradient loudspeaker would be needed to cover a range between 1700 Hz and 10,000 Hz, etc. The polar pattern obtained with a composite gradient loudspeaker would then be approximated by the broadened circular outlines in Fig. 5.

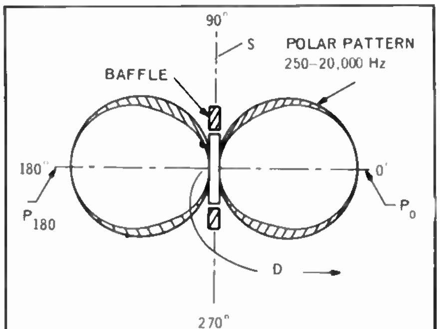


Fig. 5—Theoretical polar pattern of a dipole loudspeaker composed of progressively smaller dipole elements to cover the full frequency range between 250-20,000 Hz. (Below 250 Hz, an omni-directional loudspeaker is used).

Experience has shown that response below 250 Hz can readily be provided with a conventional (omnidirectional) loudspeaker in an infinite baffle, without greatly influencing the aurally perceived directional characteristic of the gradient array.

Thus, a practical dipole loudspeaker generally is omnidirectional below about 250 Hz, and exhibits a figure-eight pattern above 250 Hz, as shown by the heavy outline in Fig. 5. The frequency response of the combination must be carefully tailored to be "flat" overall. The biggest advantage offered by the dipole loudspeaker array is that it retains its cosine-law directional pattern over that portion of frequency which conveys the major part of directional information i.e. between 250-20,000 Hz.

A few dipole loudspeakers are available commercially. Usually they employ electrostatic high frequency sections and a moving coil bass section. For the present, however, the majority of high fidelity enthusiasts will have to be content with semi-directional loudspeakers to obtain the improved area coverage described below.

Application of Directional Loudspeaker to Stereophonic Arrays

The wrong and the right way of placing conventional semi-directional loudspeakers (e.g. bookshelf loudspeakers) for stereophonic listening is shown in Figs. 6 and 7, reproduced here from the paper referred to previously[2] with the kind permission of the Audio Engineering Society. In the first case, the loudspeakers are placed parallel to the front wall of the room. A listener at position P is at a greater distance from loudspeaker A than from the loudspeaker B. Also, the radiation strength of loudspeaker A in the direction P, represented by the vector AQ, is smaller than the radiation strength of loudspeaker B in the direction BP, as portrayed by the longer vector BR. Thus, the loudspeaker B has two advantages: The listener hears predominantly the sound of B and very little or no sound from the loudspeaker A. Furthermore, any sounds panned in between the two channels appear to move strongly towards B, because the Haas or "precedence" effect tends to credit the nearest loudspeaker with being the source of sound.

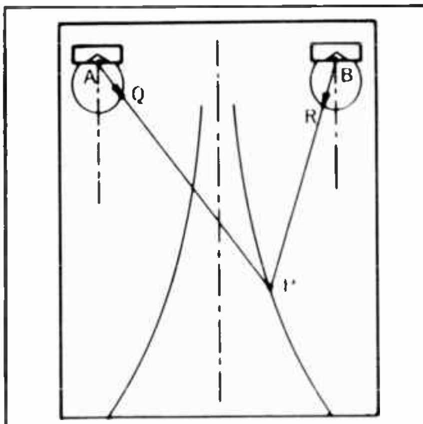


Fig. 6—Relatively narrow stereophonic listening area is obtained with directional loudspeakers placed parallel to the wall (*Courtesy AES.*)

Next, we examine the operation of the improved placement method in Fig. 7. Here the listener at point P again is at a greater distance from A than from B. However, because the loudspeakers are at an appropriate angle with respect to each other and with respect to the listener at P, the radiation vector AQ in the direction AP is greater than the radiation vector BR in the direction BP. Thus, the distance effect is, in part, compensated by the directional effect. The sounds arriving from the two loudspeakers remain in balance over a considerably broader area than is possible with the arrangement in Fig. 6. Also, the added

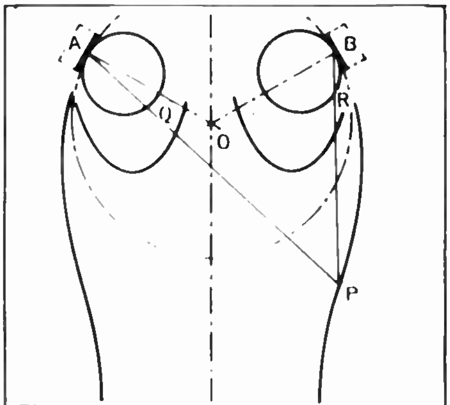


Fig. 7—Broadened listening area obtained with directional loudspeakers angled towards the center (*Courtesy AES.*)

signal strength from the farthest loudspeaker tends, in part, to compensate for the Haas effect thereby allowing a significant amount of common sounds to appear in between the loudspeakers avoiding the so-called "hole in the middle" effect.

The solid line contours in Figs. 6 and 7 represent the listening area within which the signal strengths from loudspeakers having radiation pattern as described remain within 3 dB of balance relative to each other. The advantage of the inclined orientation is evident. For an average bookshelf-type loudspeaker, the included angle between the loudspeaker axes, for proper orientation, turns out to be approximately 120-130 degrees.

Wall Reflections with Dipole Loudspeakers

We have shown, in a previous section, that omnidirectional loudspeakers under certain circumstances are significantly affected by reflections from the walls. Dipole loudspeakers, by contrast, are relatively free of this problem.

It has been seen from one of the preceding sections that directional loudspeakers normally are placed at an angle to the walls enclosing the listening area. Fig. 8(a) represents the polar pattern of a dipole loudspeaker placed, say, at 45° to a wall. It will be noted that a listener at P is subjected to its maximum output. This same listener is in a near-null orientation with respect to the virtual image caused by wall reflection. Furthermore, with the dipole loudspeaker placed in a corner, as shown in Fig. 8(b), two of three virtual images are oriented with the null planes toward the listener, thus contributing relatively little to the sound pressure at P. Thus, the response characteristic produced by a dipole loudspeaker is apt to be less affected by room acoustics than that produced by an omnidirectional unit. It should be noted, however, that the "back" radiation of the gradient loudspeaker does exist, and while it may not be significant on first reflection, it may become so for subsequent, later, reflections helping to create a desirable "ambiance" effect.

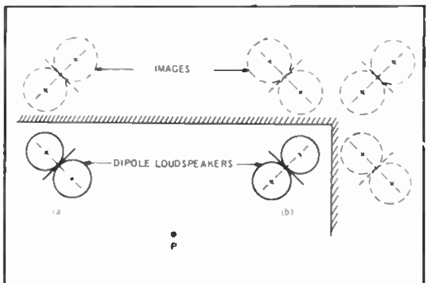


Fig. 8—Angled dipole units (a) near wall and (b) near corner.

Quadraphonic Arrays

Following the example given previously in connection with stereophonic arrays, the benefits of directional loudspeakers in quadraphonic listening will now be demonstrated. Fig. 9 portrays a quadraphonic listening area with 4 omnidirectional loudspeakers placed in the corners. For the sake of simplicity we assume for the moment that there are no walls to cause directional cancellation and reinforcement problems. Thus, the polar patterns of the loudspeakers are shown as four circles concentric with the corners of the listening area (which forms a dash-line perimeter). That portion of the listening area where the sound pressure from any of the four loudspeakers varies no more than ±3 dB is shown by the diamond-shaped outline.

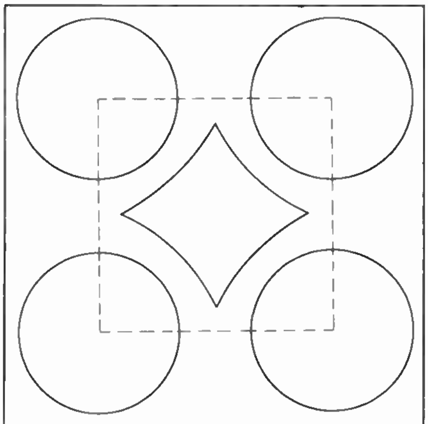


Fig. 9—Quadraphonic listening area with four omnidirectional loudspeakers placed in the corners.

In Fig. 10, dipole loudspeakers are used. The ±3 dB contour is now increased substantially, reaching all the way to the edge of the square; thus

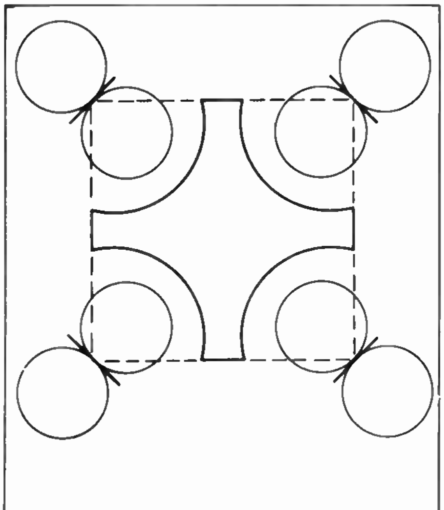


Fig. 10—Quadraphonic listening area with four dipole loudspeakers.

greatly increasing the positional freedom of the listeners. Similar, but perhaps not quite as dramatic improvement is obtained with semi-directional loudspeakers in the corners facing the center of the area. On the other hand, if these semi-directional loudspeakers were to be placed squarely against a wall (instead of being angled), their directional patterns would tend to augment the effect of the inverse distance law causing the optimum listening area further to be restricted.

The aforementioned analysis holds true even in conventional semi-reverberant listening rooms because directional localization depends principally on the sounds of first arrival.

Conclusion

Much remains to be learned about optimum design and placement of quadraphonic loudspeaker arrays. Omnidirectional loudspeakers in vogue today are a partial answer to this problem —albeit one troubled by excessive dependence upon the acoustical characteristics of the room boundaries. Also, omnidirectional loudspeakers produce a relatively limited area of quadraphonic perception. Directional loudspeakers—e.g. semi-directional or "bookshelf" types, and especially the dipole types, are apt to result in a more balanced sound field over a broader listening area, but usually require some experimentation with orientation and seating arrangements. Æ

In All Directions

*John Crabbe

A proper understanding of the mechanism of stereo perception requires extended reading, in general terms or at greater depth for those with a mathematical bent[1], but for my present purpose it can be safely stated that the accuracy with which stereo images may be localised by the listener depends on four factors:

(i) Clearly differentiated electrical information in the stereo signal, given either by Blumlein-inspired coincident microphone techniques, or by unambiguous amplitude pan-potting of discrete signals on to the soundstage.

(ii) Use of identical or near-identical loudspeakers.

(iii) An unobstructed sound path between each loudspeaker and the listener's ears.

(iv) Either an equal path length from the listener's head to both loudspeakers *or*, if the listener is placed to one side, a radiation pattern from the speakers which compensates subjectively for the resulting time differential.

We must assume that the first condition is satisfied, which is reasonable at least for the direct instrumental sounds in most modern recordings (almost invariably pan-potted), though not for the reverberation, which tends to be anomalous. Most good loudspeakers should satisfy the second point except for laboratory measurements, and the third requirement is a matter of common-sense usage.

With perfect two-channel stereo reproduction the full panoply of sound-sources is heard accurately displayed between and beyond the loudspeakers. This accuracy applies not only to the direction of individual instruments or voices, but also to their apparent widths. Now it so happens that in any system that is well balanced and has adequate electrical separation between signal paths, the performance with a central (double-mono) signal is a reliable indication of overall stereo accuracy. If a left-only signal produces a narrow sound image from the left-hand speaker, a right-only signal likewise from the RH speaker, and a double-mono signal produces a narrow image centrally placed between the speakers, then it follows automatically that a stereo signal will be reproduced accurately right across the sound-stage. Unfortunately, this perfect stereo can normally only be obtained if the listener is equidistant from both speakers —that is, if he is in the 'stereo set' placed on the apex of an isosceles triangle subtended by the speakers.

Any reader who doubts this can try it for himself: it will be found that there is a precise listening line along which a double-mono signal is heard as a very narrow and clearly detached sound-source. If this elementary first-step fails there is something faulty somewhere—either in the speakers, the room or the ears! Movement to one side from this ideal position normally causes two things to happen: (i) the image shifts more or less with the listener, and (ii) it broadens and is therefore less precisely located. In any system, insofar as mono does *not* sound as if it were coming from a separate central speaker, there is some falsification of stereo signals—an element of pseudo-stereophony. A major problem in domestic sound reproduction is to minimise this effect over a reasonable listening area, thus providing good stereo for practical use in the home.

The normal approach to this stabilisation of stereo images is to employ to best advantage any directional characteristics possessed by the speakers. Essentially, the central image (and everything else with it) becomes distorted when listening away from the bisecting line because one is then nearer to one speaker than the other, which gives its signals a time-lead. Because of Haas-effect (precedence-effect), this lead in time produces a subjective boost in loudness from that channel, which shifts and broadens the apparent sound-source in that direction. Now, if movement to one side resulted in a *lower* acoustic level at the listener's ears from the speaker on that side (and/or a higher level from the other side), the image-shift due to a time differential could be cancelled by a contrary shift due to the loudness change. This is the basis of the well-known Hugh Brittain loudspeaker placing[2], pursued more fully to overcome certain anomalies by Joseph Enock.

Practical loudspeakers vary enormously in the shape and frequency-dependence of their forward radiation patterns, and since an ideal 'Enock' speaker would have one particular lobe shape and no tendency at all to extra beaming at high frequencies, it is evident that the whole business is full of compromise. However, with patience most conventional speakers can be made to perform quite satisfactorily in most rooms. Setting up may be a tedious business[3], and it may sometimes involve very curious angling as advocated from time to time by Ralph West in his speaker reviews. But my experience is that if one is prepared to sit fairly well back from the speakers and not unreasonably out to the left or right extremities, it is possible to obtain good stereo over a sensible listening area. By 'good stereo' I don't mean the pin-pointed accuracy heard from the stereo seat, but a fairly consistent and well defined sound-stage of the sort associated with a double-mono signal that never shifts more than a third of the way towards one side or broadens to an angular width of more than about five degrees.

What has all this to do with omni-directional speakers or their advertising? Taking the second point first, it is extremely relevant, for we have been shown families of seven people ridiculously huddled around one chair in the middle of a room whose only other contents are a pair of conventional speakers, an amplifier and a player. This is a gross falsification of the domestic listening situation, attempting to create a myth that until recently it has been necessary to upset one's living arrangements in this manner in order to enjoy the benefits of stereophony. Even a hi-fi dealer wrote to me in support of this extremist position, conceding that 'there is a place for the lone listener in his throne the stereo seat' who can 'choose from a mass of direct sound speakers . . . but there are many more readers with a family and friends who like to sit round the fire-side', etc. Now it is true that sitting in a semi-circle around a fire does create difficulties for desiderata (iii) and (iv) listed earlier, but I suggest that this is only one special case among endless domestic possibilities, and that it is unfair to adopt such an extreme 'either—or' attitude about those who listen to music in their homes.

1. *Stereophony* by N. V. Franssen. (Philips Technical Library).
2. *Two-channel Stereophonic Sound Systems* by F. H. Brittain and D. M. Leakey. 'Wireless World', May/July 1956.
3. *Installation: Loudspeakers* pp. 223-229. 'Hi-Fi in the Home' by John Crabbe (Blandford Press).
4. *Two Channel Quadraphony* by David Hafler. 'Hi-Fi News', August 1970.
(See also 'A New Quadraphonic System' David Hafler, 'Audio' July 1970.)

*Editor, *British Hi Fi News*,

(abridged version

In any case, stereo is really a fairly subtle business and can only be appreciated fully by those who *listen* to music—it is hardly necessary for background while sitting around the fire!

The other important point about the adverts is their claim that omnis surround the listener with stereo sound wherever he or she is in the room, obviating the supposed need for 'stereo seat' listening and implying that the type of stereo obtained on the bisecting line with conventional speakers is achieved everywhere with omnis. This is where my earlier remarks about stereo perception come into the argument, for it can be shown both theoretically and practically that omni-directional loudspeakers distort the stereo sound picture more or less severely.

Firstly, they cannot by definition offer a sound intensity pattern that compensates for precedence-effect because they radiate equally in all directions; thus even in an anechoic room there would be considerable shifting and broadening of a centre-stage image as heard by an off-centre listener. Secondly, in a normal room there is relatively little direct sound from omnis of the Sonab type (without *any* forward radiating unit) so that the ears are presented with a very complex series of confusing reflected wavefronts which upset the localising faculty. This means that even in the stereo seat a nominally central sound-source seems vague and broad in most rooms, the only really precise directional information (if the room permits any at all) arising from extreme left or right sounds. In my own sitting room, which is acoustically rather 'dead' compared with most and therefore relatively disinclined to scatter the stereo sound-picture, a pair of Sonab OA-5s was quite incapable of producing anything remotely approaching a narrow sound-source from a double-mono signal. On a stereo recording of a harpsichord concerto on which a seemingly small solo instrument is contrasted nicely with a broad orchestral backcloth, the harpsichord stubbornly occupied the full space between the speakers as heard from any point in the normal listening area.

This is not good stereo—it is hardly stereo at all—and I must beg to differ most strongly with critics who state that omnis 'do provide a good stereo image virtually anywhere in the room'. They do not and they cannot. Neither can they provide a satisfactory and reasonably consistent frequency response from sample to sample, depending as they do entirely on the environment in which they are used; this is contrary to all good loudspeaker design criteria. Despite all this there are bound to be a few freak rooms in which it is impossible to obtain a satisfactory listening area with conventional speakers but which reflect the sound from omnis in a manner that happens to provide some compensation for Haas-effect in a pseudo-Brittain fashion. Any readers with such rooms (one was amongst my correspondents) may ignore the bulk of this article—but my general thesis stands.

Some people not in this special category may nevertheless *like* the sounds produced and many will welcome the fairly constant type of sound pattern throughout the listening room that was mentioned and praised by Donald Aldous in his review of the Sonab in November. Some have referred to this review as if it vindicated their viewpoint, apparently failing to notice that Donald did not claim that the relatively stable sound-field represented good stereophony. Indeed, he scattered a fair number of serious doubts, stating that 'there is loss of definition and precise images', that it is 'true that stereo is often anomalous . . . and this may prove disconcerting, especially to the more experienced listener', and that 'it is essential that the reader should be aware that the contention concerning directionality, at least, is fallacious when related to sound *reproduction*'. It is a case of distortion that remains equally distorted from all points of view!

I think that covers the objective side of the matter and explains why we commented so adversely on the Sonab advertising—though I see that more recently we have been asked to believe that these loudspeakers have some curious extra property enabling them to reproduce the quarter tone scale of Indian music that is 'too much for most systems'. It's certainly too much for me—I give up!

On the musical and subjective side there is much more room for argument and maneuvre. Once the supporters of omni-directional speakers have admitted that they generally lose a lot of directional information and suffer from rather extreme distortions of lateral perspective, then I will admit that they may indeed actually prefer this sort of sound and that they have every right to. But it must be understood that in terms of sound *reproduction*, of producing an accurate acoustic equivalent of the signals passing through the stereo amplifier, omni-directional loudspeakers represent a firm step backwards. Musically, this may not seem to be the case but if so this can only be due to other limitations of two-channel stereo which are receiving partial compensation via the loudspeakers. This indeed is part of the Sonab philosophy, emanating from Stig Carlsson, the argument being that in real life most of the sound energy arriving at our ears in the concert hall comes via reflections. This was outlined in the November review and is a point that has been made on many occasions when discussing the philosophy of stereo reproduction. It is basic also to the Bose loudspeaker, though this is in a rather different category to the Sonab, without the latter's flimsy construction and rather obvious colorations, and with at least one forward-facing drive unit. However, developments in quadraphony or pseudo-quadraphony promise a more satisfactory type of solution, taking us much closer to a live concert-hall atmosphere than the rather unreliable use of multiple short room reflections via omni speakers.

I am sure that it is this missing sense of all-round atmosphere that leads people to look beyond conventional stereo, with its sound-stage at one end of the room and no reverberation from around or behind the listener. But things are now on the move, and even limited experiments with 'difference' signals[3,4] can be a revelation in added spaciousness compared with the effects achieved by omni speakers. And there is no penalty to pay in the accuracy of spatial reproduction on the forward sound-stage.

Several of my correspondents were slightly offended by the phrase 'undifferentiated wodge of sound' used to describe the omni type stereo picture. The dealer whom I mentioned earlier pointed out that in his view this is just what many people want and that it gives a great deal of musical pleasure. Well, that may be so for some stereo beginners, especially if their taste is for big, lush orchestral music—Strauss tone-poems for instance—just as upward-facing column speakers were all the rage for a while when stereo reordings were first introduced. We have been through all this great debate before; but gradually, as people listened more carefully and became more critical, they came to realise that what they thought was stereo was really little more than mono thrown around somewhat by two speakers—in fact an undifferentiated wodge.

One reader claimed in a letter that omni speakers are 'as great an improvement over ordinary stereo speakers as stereo itself is over mono'. Well now, if this is so it would follow that to switch a pair of omnis from mono to stereo would be at least as revealing or dramatic as a similar switch using conventional speakers. But it is generally a good deal *less* revealing, for the simple reason that omnis dilute the stereo image and inflate a mono signal to the point where they are rather similar.

Finally, a few words in favour of the

musical subtleties of conventional stereo, subtleties not demanding bisecting-line listening accuracy, but simply ordinary loudspeakers and ordinary seating sensibly arranged in an ordinary room.

This was exactly what happened when I played the aforementioned harpsichord concerto recording: on conventional speakers in mono the whole orchestra and solo instrument appeared to occupy a fairly narrow band in the centre of the speaker wall, while in stereo the orchestra spread out correctly and grandly in its various sections with the harpsichord remaining of slender proportions at front-centre; on omni speakers in mono both harpsichord and orchestra appeared to occupy the whole wall, and in stereo the only change was a suspicion of upper strings more prominent on the left. The moral of this story is that if you want a stereo recording to make an impression on omni speakers you must exaggerate the left/right instrumental separation and minimise centrally placed sources for all you are worth—a thoroughly unmusical and reprehensible business, yet my same correspondent goes on to say that he 'looks forward to the record industry catching up with the equipment manufacturers by producing records suitable for reproduction on these omni-directional speakers'. God forbid! listen to the sound first from the stereo seat and then from a point far enough to one side to shift and stretch the sound image unreasonably. My ears register a change of tonal quality which seems to be independent of HF beaming effects. Tone-colours are part of music, so this sort of thing must affect musical pleasure at some level.

Much music demands, and some conductors use, spatially separated 1st and 2nd violins. Done discreetly, as on many recordings, the two string groups are placed to left and right of stage-centre, but not pulled apart ridiculously. A lot of delightful antiphonal effects are there for the hearing, but they are certainly less easily distinguished in a 'wodge' of sound. Solo instruments set against an orchestral backcloth sound quite unnatural if stretched out in the manner of the harpsichord already mentioned; in violin concertos, particularly, some of the musical drama is dissipated if the instrument's physical smallness is lost. This applies also to voices, especially in opera where both subtlety of movement or placing, and moments of high drama, may be lost or even contradicted in the proverbial sonic wodge.

Complex many-stranded counterpoint is sometimes difficult to follow without the aid of a score, especially when the music is for multiple divided strings and therefore unsignposted by a variety of instrumental timbres. Such music benefits from good stereo because of the audible but often subtle separation in space. Finally, chamber music, and particularly the string quartet, which can sound so very convincing when well reproduced but quite vague and silly when distorted by omni loudspeakers. Anyone with experience of listening to a real quartet at fairly close quarters soon realises the absurdity of the freakish quasi-stereo offered even by a moderately differentiated 'wodge'.

This all means that sooner or later people will get fed up with omni-directional loudspeakers—just as most people eventually abandoned their column speaker about ten years ago. (There is a possible analogy here with headphone listening, the present popularity of which—due to its consistently accurate stereo—could be a reaction against the vague stereo heard even from improperly used conventional loudspeakers.) Singers' mouths or solo violins several feet wide which cannot be placed at all certainly in an particular direction are tiring and irritating to live with. They will come home to roost. This I know from personal experience, having been a keen advocate of reflected sound not many years ago! Æ

SUMMING IT UP

Summing up: there is no doubt that omni-directional speakers or systems that specifically use walls for reflection do give a more spacious kind of sound. Under the right circumstances, one is less aware that one is listening to two loudspeakers. It is also true that this effect is achieved at the cost of definition. On the other hand, very directional loudspeakers give a sharp stereo image but the listening area is restricted. In the early days of stereo (two channel) I maintained that the optimum dispersion angle was 120 degrees but in these days of 16-channel mixers and multi-mic techniques I cannot be so dogmatic. Stereo itself is an illusion and the program material goes through many processes of mixing, dubbing, equalising and so on. Some producers exaggerate separation, some transport the listeners to the conductor's podium and others try and give him the impression of being in the middle of the 10th row back. Then again, most of today's music is recorded in the studios—not the concert hall at all! Finally, there is the question of room acoustics. The room must be considered acoustically as an extension of the loudspeakers and what sounds superb in one room can be incredibly bad in another.

Perhaps the best answer to some if not all of these problems lies with the intelligent use of the quadraphonic medium. This can give us a better sound image without relying on random room reflections or being so affected by room acoustics—especially standing waves. Moreover, as Jim Long stated in his recent article on microphones, "Four mic/four channel recording reduces the need for accent microphones. The ability of four-channel stereo to sort out a single event amidst complex aural confusion—if the recording is properly handled—can be downright uncanny!" The big question will be: What kind of loudspeaker radiation pattern will give best results with quadraphonic sound? My own tests indicate a dispersion of 90 degrees but I am reserving judgment for the moment. *G.W.T.*