Speaker directivity and sound quality

Effects of variation in the loudspeaker polar diagram with frequency

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The best examples of current loudspeaker design have reached the stage of development where only minor improvements in the overall sound quality can be achieved by further extension or smoothing of the frequency range, or by reduction in the well known effects of harmonic, inter-modulation and Doppler distortion. One distortion, using the word in its widest sense, that has not received its due share of attention is the effect on sound quality of the variation in the speaker polar diagram with frequency. This is discussed in the present article, and also methods of measuring the polar distribution of sound pressure and sound power. "Directivity index" is explained.

A TYPICAL single cone loudspeaker in a closed housing will radiate isotropically at low audio frequencies, the sound pressure being substantially constant at all points equi-distant from the loudspeaker. This is true even at the back of an enclosure that only employs a single forward facing unit. As the frequency is increased the solid angle into which the sound power is concentrated in front of the loudspeaker slowly reduces until it may not be more than 10°-15° at frequencies above 5kHz. This is a fundamental property of all plane surface disk radiators. The sound pressure level produced by an ideal solid disk diaphragm will be down by 3dB at 30° off axis at a frequency of 1kHz, the diaphragm being one wavelength in diameter at this frequency.

The sound pressure generated by a practical loudspeaker diaphragm does not fall off quite so rapidly with increase in the azimuthal angle as that from the rigid disk. Thickness and density graduation, the use of radial and circumferential ribs and similar design tricks can be used by the cone designer to reduce the effective diameter of the diaphragm with increase in frequency and this helps to maintain constant the sound pressure at points well off the axis. At first thought it would appear that the reduction in the off-axis output at high frequencies would be of little consequence to a listener seated on the axis, but experience shows that the effects on the sound quality are indeed obvious to a moderately experienced listener. A loudspeaker having a good (flat) axial frequency response but a poor off-axis response sounds 'hard and tiring' to a listener seated on the axis, while the stereo image tends to jump about with changes in the spectral content of the programme. It is interesting to consider the possible reasons for the effects of the polar distribution on the quality of the sound as this is a subject that is rarely discussed in greater depth than a comment that "cymbals sound better when you sit in front of the speaker, an aspect of the performance that is obvious and will not be further expanded."

The sounds emitted by a loudspeaker arrive at the listener's ears by three routes that require separate consideration if the overall acoustic performance is to be understood.

Group 1. In this group are the sounds that arrive at the listener's ears by the direct and shortest route from the loudspeaker and undergo little modification on the way, for the room boundaries have had no opportunity of affecting the characteristics of the sound. The room acoustics have no effect on these direct sounds.

Group 2. These sounds arrive at the listener's ears during the first few milliseconds after only one reflection from the room boundaries close to the loudspeaker. At each reflection from a boundary the frequency spectrum is modified by the acoustic characteristics of the area of room boundary from which the reflection takes place. In general the higher frequency components in the spectrum suffer greater attenuation at each reflection than do the lower frequency components but this is not inevitable. Thus the first reflections have frequency spectra almost identical to those of the direct sounds which they follow with a delay of only 2-5 milliseconds.

Group 3. These are the sounds that arrive at the listener's ears after many reflections, i.e. after at least ten to twenty reflections from the room boundaraies remote from the loudspeaker. This is the generally reverberant sound that is usually considered to be the 'room reverberation'. As was noted in the preceding paragraph the higher frequencies are generally more heavily attenuated at each impact with a boundary so the frequency spectrum of the reverberant sound gradually changes during the decay of the sound, the later reflections having reduced energy in the higher frequencies.

However, the reverberant sounds differ in another and very significant way. The sound field in a room does not become increasingly diffuse with the passage of time as is generally thought, but instead becomes increasingly ordered, with the sound energy concentrated in well defined spatial patterns even at the lower frequencies. The primary components of the reverberant sound energy are concentrated along the three axes of the room in the frequency bands for which the room length, width, and height are one half wavelength and at the harmonics of these frequencies. There are secondary components of the spatial pattern at frequencies that are determined by combinations of the axial dimensions of the rooms and further groups with frequencies determined by combinations of all three axial dimensions. Thus reverberation is not the decay of a diffuse sound field but the decay of a well defined pattern of sound distribution over the whole of the room volume. The sound field becomes *less* diffuse and more ordered as the decay proceeds, with the sound energy concentrated in the narrow frequency bands that constitute the modes of oscillation characteristic of the room. This is particularly true at the low frequency end of the spectrum.

Following this digression we can go back to consider the effect of the loudspeaker polar diagram on the resultant sound field in the room. There will clearly be no significant effect on the energy in the sounds that arrive first by the most direct path, for the room boundaries will have had no opportunity of reacting on the sound.

The sounds in group 2 that arrive by the second route during the first few milliseconds following the arrival of the direct sound will be affected by the polar distribution of the loudspeaker. At those frequencies at which the polar distribution is very narrow, generally the higher frequencies, the sound energy arriving during the first few milliseconds will be decreased, for less energy will strike the room boundaries in the vicinity of the speaker and be reflected from these boundaries. Thus the first effect of a narrow polar diagram is to minimise the intensity of the sound in the reflections occurring during the first few milliseconds. If the loudspeaker is pointing down the length of the room the sound energy in the reflection from the far end walls will be increased.

The sound energy in the 3rd group of reflections is more radically modified by a loudspeaker having a narrow polar diagram. Assuming the simplest possible case where the direct sound energy is all concentrated in a forward facing beam from a loudspeaker pointing down the room, there is then no energy fed directly into the resonant room modes other than the main length mode and its harmonics. Those modes of room resonance in which the sound energy oscillates along the width and height axes of the room receive no energy from the loudspeaker until it is scattered into these modes after many reflections from the boundaries at the ends of the room. In consequence the width and height modes will have no effect in colouring the early sounds but will colour the sounds arriving at the listener's ears 20 to 300ms after the direct sound.

In contrast a loudspeaker radiating isotropically will feed sound energy into all the room modes immediately it is excited. This energy will then be concentrated into all the mode characteristics of the room shape and the sound intensity in each mode will grow and decay at a rate controlled by the energy absorption in that particular mode. Each individual mode of resonance will have its own characteristic reverberation time with the important difference that all the room modes begin to be excited almost immediately the loudspeaker is excited.

Thus a listener sitting on the axis of a loudspeaker having a narrow polar diagram will hear sound that differs from that heard from a loudspeaker having a wide polar diagram, even though both speakers have a flat on-axis response. If the polar diagram is narrow the earlier reflection will be minimised and the later reflection will carry most of the sound energy. If the polar distribution covers a wide angle then the sound energy tends towards being uniformly distributed over all the early and late reflections, the sound energy/time distribution being determined by factors other than the loudspeaker polar diagram.

A loudspeaker having a "narrowish" polar diagram invariant with frequency will always tend to minimise the effect of the room acoustics on the quality of sound reproduced in the room. Dipole radiators such as the electrostatic speaker or a cone type loudspeaker in a flat baffle will sound rather 'dry' in some rooms, particularly those with a short reverberation time. A dipole radiator has no radiation in the plane of the diaphragm and thus provides the minimum excitation of the height and width room modes. Appropriate placement of the speaker allows one to vary the modal excitation to suit the room characteristics, an advantage not possessed by a speaker having a wider polar diagram.

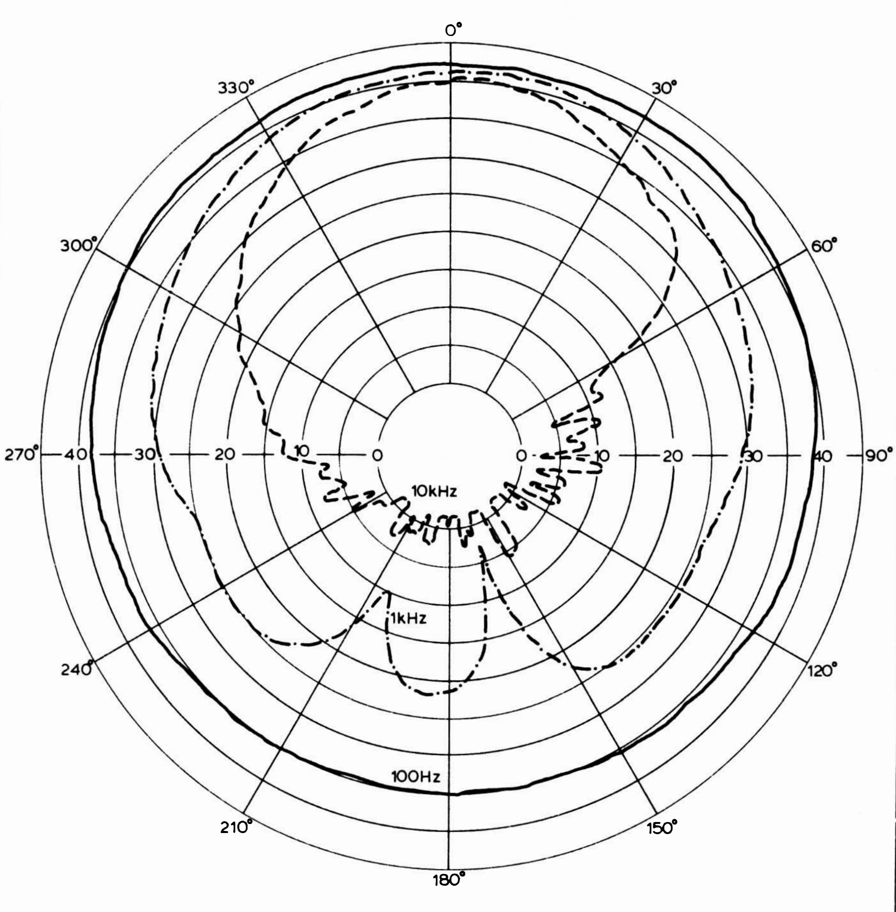

Fig. 1. *Typical polar diagram, giving variation in sound pressure level at points relative to the axis of a loudspeaker. Plots at three different frequencies are shown.*

The obvious alternative, the use of a loudspeaker system that radiates equally in all directions, proves to be almost equally unacceptable, the stereo image being diffuse and only vaguely located. It is significant that over the last twenty years many loudspeakers have appeared on the market with claims to a high degree of uniformity of the sound power distribution round the loudspeaker, but almost all of them have vanished from the field after a relatively short burst of popularity. This suggests that there is some optimum distribution of sound energy in front of a loudspeaker if the stereo image is to be well defined and the sound quality is to be 'soft and non-tiring' to the listener.

It would be of considerable value if the optimum polar distribution for a domestic speaker could be specified, but so far this has eluded definition, for it is difficult in the present stage of the art to design an experiment that will provide an even moderately unambiguous answer to the question, particularly in small domestic sized rooms. A start can be made by outlining the methods of defining the polar diagram of a loudspeaker.

The variation in sound pressure level at points off the axis of a loudspeaker is generally indicated by a polar point typified by Fig. 1, showing the sound pressure level round the loudspeaker at a few representative frequencies in the azimuthal plane. This plot does not make the performance particularly obvious when this has to be subjectively judged. The sound pressure level usually changes much more rapidly with change in the vertical angle than with changes in the azimuthal angle. Thus any specification of the polar distribution over the space in front of the loudspeaker requires polar diagrams in two planes at least, but even given this, it requires some mental gymnastics to visualise the distribution over the intermediate angles. It requires even more mental gymnastics to come to any reasoned decision about the subjective results of the variation in polar response with frequency. The off-axis frequency response of most speaker systems is markedly more irregular than the axial frequency response, but the irregularities may not be obvious for the standard form of polar diagram displays the performance at only a few frequencies.

An alternative presentation that has several advantages is to plot the frequency response on the speaker axis

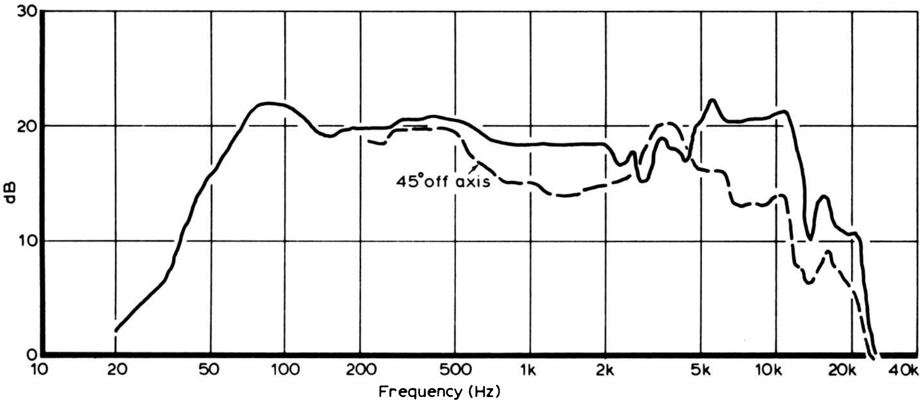

Fig. 2. *An alternative presentation of speaker directivity to that in Fig 1. The frequency response is plotted for the speaker axis and for other angular distances from the axis.*

and at 15° or 30° intervals off the axis, much as shown in Fig. 2. This makes the change in the frequency response off-axis easier to visualise, but it is still necessary to have a second set of response curves to illustrate the change in frequency response with change in the vertical angle.

During the past few years, a third possible presentation has appeared and as it has several advantages it deserves consideration. The basic change is the use of sound power rather than sound pressure as the parameter indicating the change in output with change in the angular displacement of the listener from the axis.

If the sound pressure distribution round the loudspeaker enclosure is not uniform at all frequencies execpt when measured on the axis of the system, it will be obvious that the total radiated sound power will decrease with increase in frequency. Thus a flat axial sound pressure/frequency response usually indicates that the sound power/ frequency response is not uniform but falls off with increase in frequency. Conversely a flat (uniform) sound power/frequency relation usually indicates that the axial sound pressure/ frequency response rises with increasing frequency.

The extent to which the sound power/frequency response varies with frequency can be conveniently indicated by quoting either the "Q" or the Directivity Index (DI = 10 log "Q") of the loudspeaker. As the use of sound power in specifying speaker directivity is probably a new concept to many readers (and "Q" an unfortunate choice of symbol) it will be explained more fully.

Sound power is proportional to the sound pressure squared so the parameter "Q" is the ratio of the total power actually radiated to the power that would be radiated if the axial sound pressure was maintained constant all round the loudspeaker. When this uniformity of distribution is achieved the loudspeaker has a "Q" of 1. It is a condition that is usually approximated at low frequencies. "Q" is the trans-atlantic term but the "Directivity Index" appears more appropriate in view of the prior use of Q to describe the performance of tuned circuits etc.

Fig. 3 shows the "Q"/frequency relation for a well-known three-unit system when measured in the open air. When measured in a room with the speaker back against a wall the "Q" will be increased in the low frequency range for the working "Q" is affected by the proximity of the walls. However, when considering the effect of the speaker directivity on the acoustic performance of the room it is the "Q" measured in the open air that is significant and not the "Q" that results from the speaker radiation being controlled by the room walls.

In the higher frequency band, and assuming that the speaker system has a flat frequency response when measured on the axis, the off-axis output will fall away and in consequence "Q" or "DI" will rise. A typical current speaker system will have a "Q" around 4 at frequencies in the 3-5 kHz region.

Omni-directional loudspeakers have been tried by several speaker manufacturers and are generally considered unsatisfactory but the reasons for this are hard to define with any real conviction. Increasing the directivity of a speaker system results in a design that has the radiated acoustic power concentrated in a solid angle less than 360°

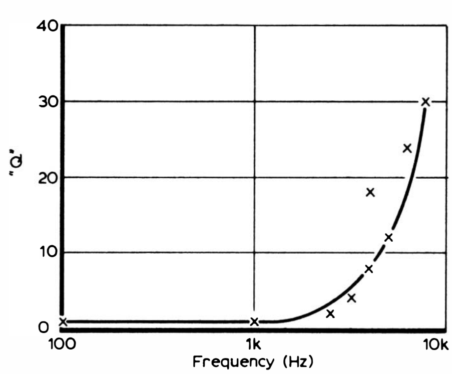

Fig. 3. *Plot of "Q" against frequency for a typical three-unit speaker system.*

and this has proved advantageous. It might even be said to be essential if a good stereo image is to be obtained. Unfortunately if has not yet proved possible to design a loudspeaker that has uniform directivity at all frequencies in the audio band. Though it has not proved possible to achieve this uniformity of distribution it is interesting to speculate on the reasons for thinking that it should be the target.

Achieving a good solid and firm stereo image requires a high ratio of direct to reflected sound, for it is only the direct sound that carries the basic information about the location of the stereo image in the space between the loudspeakers. The sound reflected from the room boundaries, particularly those in the vicinity of the speaker, can only serve to dilute the basic directional information. Thus to achieve a good stereo image we need to minimise the amount of reflected sound. One obvious way of achieving this is to design the loudspeaker and locate it in the room in a position that minimises the amount of sound falling on the room walls. The required result cannot be achieved by covering the room surfaces with sound absorbent, attractively simple though this solution may appear, for this reduces all the wall reflections, whereas an increase in speaker directivity increases the intensity of the direct sound and reduces the intensity of the early reflections and it is this we wish to achieve.

Room sizes

In large rooms of average proportions where the working "Q" is not significantly affected by the proximity of the room boundaries, experiments involving the subjective judgement of the acceptable loss in speech intelligibility suggests that a "Q" in the region of 20 at frequencies above 500Hz is about right. In domestic sized rooms a "Q" around 10 appears reasonable but more evidence on this aspect is required. This is not easy to obtain for design changes are necessary to change the "Q" and in the present stage of our knowledge it is impossible to change "Q" without affecting several other parameters that affect the sound quality. Uniformity of the "Q"/ frequency relation over the frequency band between 500Hz and 10kHz seems more important than the absolute value.

At present it appears fundamentally impossible to design a speaker with substantially constant directivity over the audio frequency band. Constant directivity demands a sound radiator having a diameter that is inversely proportional to frequency and this we cannot achieve in a practical design. However, though a direct solution appears impossible it may be possible to circumvent the problem, an aspect

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which will be considered in more detail later in the contribution.

There are no single unit loudspeakers that cover the whole of the audio frequency range in a fashion that is acceptable in the hi-fi field, two, three, four or more units being employed to achieve a flat frequency response. The diaphragm diameter of the unit is decreased as the frequency range covered by the unit is increased. Currently a 10in or 12in unit may be used to cover the range up to about 700/1000Hz, a 3in or 4in diameter unit used to deal with the band between 800Hz and perhaps 4000Hz with a 1in or 1½in diameter unit used to radiate the signal in the band above 4000Hz. In some more elaborate systems a super tweeter may be employed to extend the frequency range beyond 18 to 20kHz.

To a first approximation the use of three or four units allows the designer to adjust the "Q"/frequency relation by approximate choice of the frequencies chosen from the crossover points. However the speaker system designer does not have complete freedom to adjust the "Q" in this way for the choice of changeover frequencies is primarily controlled by the usable frequency range of each of the speaker units.

All domestic multiple-unit types of loudspeaker systems have generally similar polar distribution, for this is basically controlled by well established laws of physics. In the low frequency range the polar distribution is determined by the area of the front of the enclosure and the location of the speaker with respect to the walls and floor. At rather higher frequencies the polar distribution is controlled by the dimensions of the woofer cone, an increase in cone diameter decreasing the solid angle into which the acoustic radiation is concentrated. In the mid-frequency range the solid angle is again determined by the diameter of the mid-range speaker cone with the frontal area of the enclosure having influence that decreases with increase in frequency.

In the frequency range radiated by the tweeter cone diameter is the major controlling factor, but some effects are controlled by the enclosure geometry and the contours of the cabinet edges. Thus all multiple unit systems have a "Q"/frequency relation much as outlined in Fig. 3. Changing the cone and cabinet dimensions merely shifts the boundary region up and down the frequency scale without changing the general shape of the curves.

Sound power output

Lack of data on the "Q" of domestic loudspeakers is largely due to the difficulty there is in measuring the parameter. There is a British Standard in preparation that covers the method of measuring "Q" and "DI" but the technique described is really only of academic importance. A measurement of "Q" requires that the sound power output of the loudspeaker is determined, together with a measurement of the sound pressure level at a point one or two metres from the speaker and on its axis. Suitable techniques will be described in a later contribution.

This article can be summarised as suggesting that the polar distribution of sound energy round a loudspeaker has a more important effect on sound quality than a mere absence of top response at points of the axis of the loudspeaker. The ideal polar diagram would appear to confine the sound energy distribution ot something less than ±90 degrees in front of the loudspeaker but it is equally important that the angular distribution should not vary with frequency, particularly at frequencies above about 500Hz. At present this is an ideal that cannot be achieved but there are signs that technical skill may circumvent the apparent limitation imposed by basic physical laws. □