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COMPACT LOUDSPEAKERS WITH USEFUL DIRECTIVITY EVEN AT LOW FREQUENCIES

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1. INTRODUCTION

One way of making a directional loudspeaker is to use a structure which is comparable in dimensions to the wavelength of sound at the lowest frequency at which directionality is required . Examples of such structures are arrays, horns and columns. This is a consequence of the fact that the directionality is obtained through wave interference between sounds emanating from different elementary areas of the radiating surface. It is often assumed that this is the only practicable way of achieving useful directionality, but it is not. This paper explores an alternative approach which can produce useful results with modern drive units.

2. PRINCIPLE OF OPERATION

The principle of operation has been known for many years, but appears not to have been significantly exploited, probably because until recently the small drive units which the technique generally demands have not been capable of producing adequate sound pressure levels at sufficiently low frequencies, even for speech-only applications. Some of the requirements for the drive units are rather different from the usual, but they can be quite easily met.

Olson [1] appears to claim to have coined the term 'gradient loudspeaker' by analogy with 'gradient microphone', although the published definition seems to be somewhat difficult to interpret. Such a loudspeaker consists of two or more drive units, separated in space and operating with a difference of phase between them. In order not to be incomplete or misleading, this definition requires further qualification:

- the separation is along the reference axis, i.e. for two drivers, one is 'behind' the other

- the 'difference in phase' is actually a difference in polarity and/or a pure time-delay.

In contrast to the dimensions of directional loudspeakers depending on wave-interference, the dimensions of those depending on phase-differences have to be less than a fraction of the wavelength of the highest frequency for which the phase effects are relied on. In practice, other effects can take over the determination of directivity at still higher frequencies. Nevertheless, the dimensional limitations are quite severe.

3. ORDERS OF GRADIENT LOUDSPEAKERS

It is perhaps simpler to approach this subject by considering the sensing of sound pressures p by very small microphones in a one-dimensional sound field which decreases in intensity with distance x from some fixed point. Considering two points a very small distance δx apart, the difference in sound pressures, δp, tends to dp/dx, which is the *pressure gradient*, as δx tends to zero. We can define the 'position' at which this gradient is measured as $x_1 + \delta x/2$, which tends, of course, to x_1 as δx tends to 0. Similarly, if we take the difference between the two values of δp, measured at two positions x_1 and $x_1 + \delta' x$, and allow $\delta' x$ to go to zero, we obtain the second-order spatial differential coefficient of pressure d^2p/dx^2. This measurement, of course, would require four microphones if done in real time.

By reciprocity, an array of sources can generate a sound field whose appropriate differential coefficient is determined by the way in which the sources are energised. The *order* of a gradient microphone or loudspeaker is then the order of the differential coefficient of pressure to which it responds or which it determines.

4. ZERO-ORDER GRADIENT LOUDSPEAKER

This degenerate case simply consists of a drive unit in a sealed enclosure. It is omnidirectional at frequencies for which the dimensions of the box are much smaller than a wavelength. This means that a practical device for sound reinforcement certainly becomes directional above 1 kHz. The 'frequency response' is independent of frequency. It is necessary to explain why 'frequency response' is here in quotation marks. For a gradient loudspeaker we can identify two independent frequency responses, the first being the inherent pressure/voltage (or perhaps pressure/current) response of the drive unit(s) (and enclosure(s), if any) alone, which may be described as the primary frequency response. The second frequency response is that produced acoustically by the phase differences and spatial relationships in the array, and may be described as the secondary frequency response. The overall response is the product of these two elements. In this paper, the unqualified term 'frequency response' refers to the secondary frequency response.

5. FIRST-ORDER GRADIENT LOUDSPEAKERS

First-order gradient loudspeakers can be made in bidirectional or unidirectional form. The bidirectional form is, in principle, quite familiar: an unmounted, unenclosed cone drive unit approaches the theoretical performance at low frequencies, where the obstructions to the rearward radiation presented by the chassis and magnet assembly have little effect. In another form, two identical drive units are mounted in sealed enclosures, separated by a distance D in the axial direction, and are fed with identical signals, effectively in the same polarity. 'Polarity' in this context means that if the same voltage is applied to the voice-coils of the drive units with the same polarity, the cones move in the same direction (see IEC268-2 and -5). This means that, if the drive units face in opposite directions, they are connected with opposite polarity. It is important to recall that that if more than one drive unit is mounted in one overall enclosure, the acoustic coupling between them may produce unforeseen effects. The response of an individual drive unit may be considerably affected by radiation from other drive units in the same enclosure, and partitions may be required to eliminate unwanted coupling. Figure 1 shows the theoretical directional responses at various frequencies: these are normalised to D/λ (or Df/c), where D is as defined above, λ is the wavelength, f is the corresponding frequency and c is the speed of sound. The generating equations for all the Figures in this paper are quite well-known, but their graphical presentation at six (normalised) frequencies and with a logarithmic (decibel) radial scale for the directional responses may be helpful.The collapse of the (presumably) wanted lemniscate response at $D/\lambda = 1$ into serious lobing indicates that many designs have the drive units too far apart for comfort. This effect is theoretically 'mitigated' by the null in the (secondary) frequency response at this frequency, shown in Figure 2, but lobing occurs from $D/\lambda = 0.9$ upwards. Even for speech reproduction up to 6 kHz, the separation between the effective radiating centres of the drive units should therefore be no greater than 44 mm, which places severe constraints on drive unit depth. In practice, the situation is, for once, considerably improved by what is normally regarded as a disadvantage - the increased inherent directionality of drive units at high frequencies. However, this in turn implies that smaller drive units should be placed correspondingly closer together in the axial direction, since the inherent directional effect occurs only at higher frequencies. In practice, *with careful choice of drive unit*, serious lobing can be avoided.

Attention is also required to the frequency response (see Figure 2). The comb filtering at high frequencies may not be very important in many applications, in spite of its spectacular appearance on the graph. However, the 6 dB/octave low-frequency roll-off normally needs at least a partial remedy. In addition to some tailoring of the primary response (such as avoiding a presence peak), the drive unit Q_T and the enclosure volume may be chosen so as to produce a controlled low-frequency peak, whose upper flank tends to support the mid-range response.

The unidirectional form of the first-order gradient loudspeaker is perhaps more interesting from the theoretical point of view. The physical arrangement is the same as for the two-driver form of the bidirectional device, but the feed to one of the drivers includes a delay, which is conveniently described in terms of the distance d which sound travels in the delay time t:

$$d = ct$$

If the distance d is equal to the separation distance of the drive units, D, the directional response at low frequencies (D/λ less than 1/4) is a cardioid , and this and the theoretical directional responses at higher frequencies are shown in Figure 3. The provision of this delay does not represent a serious complication: a simple passive network can furnish a sufficiently close approximation to a constant delay over an adequate frequency range. The inherent directivity of the drive units at high frequencies improve the performance of this configuration as they do for the bidirectional form. In addition, it is possible to modify the relative drive levels to the two units in a frequency-dependent manner. A front-to back ratio of 16 dB to 20 dB can be obtained over the speech frequency range, at least.

The theoretical frequency response of the unidirectional device is the same as that of the bidirectional device, as shown in Figure 2, except for a change of horizontal scale: the first minimum is at $D/\lambda = 0.5$. The same compensation measures can be employed in both cases.

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6. HIGHER-ORDER GRADIENT LOUDSPEAKERS

It is possible to construct high-order gradient loudspeakers, and they become increasingly directional as the order increases, but the low-frequency roll-off also increases in steepness: it is 6n dB/octave, where n is the order of the gradient. For most purposes, even the 12 dB/octave slope of the second-order devices is too great, which could be a pity, because the unidirectional form has a directional response closely resembling half a lemniscate, and such a response could have applications in spatial sound systems.

7. EXPERIMENTAL WORK

Experimental first-order devices have been constructed, with encouraging results. However, the measurements of the frequency responses and directional responses are quite seriously affected by reflections which could be ignored in simple axial pressure response measurements. Further work is required to optimise drive units: those used in the experimental devices are no longer available and are of limited maximum sound pressure level capability. It is also necessary to investigate the optimum enclosure shapes and dimensions. It is hoped to present a further report of this work at a later date.

8. REFERENCE

H.F. OLSON. 'Gradient loudspeakers'. *Journ. Aud. Eng. Soc.*, **21:2**, p. 86 (March 1973)

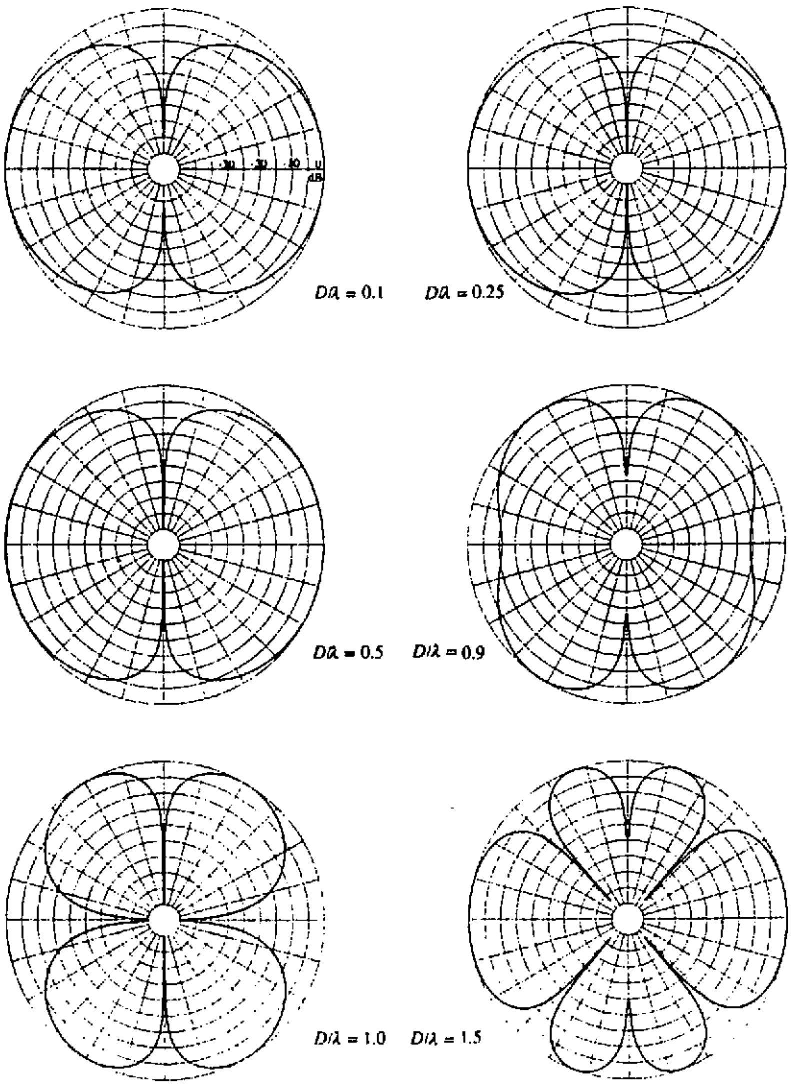

Figure 1 Theoretical directional responses of a first-order gradient bidirectional loudspeaker

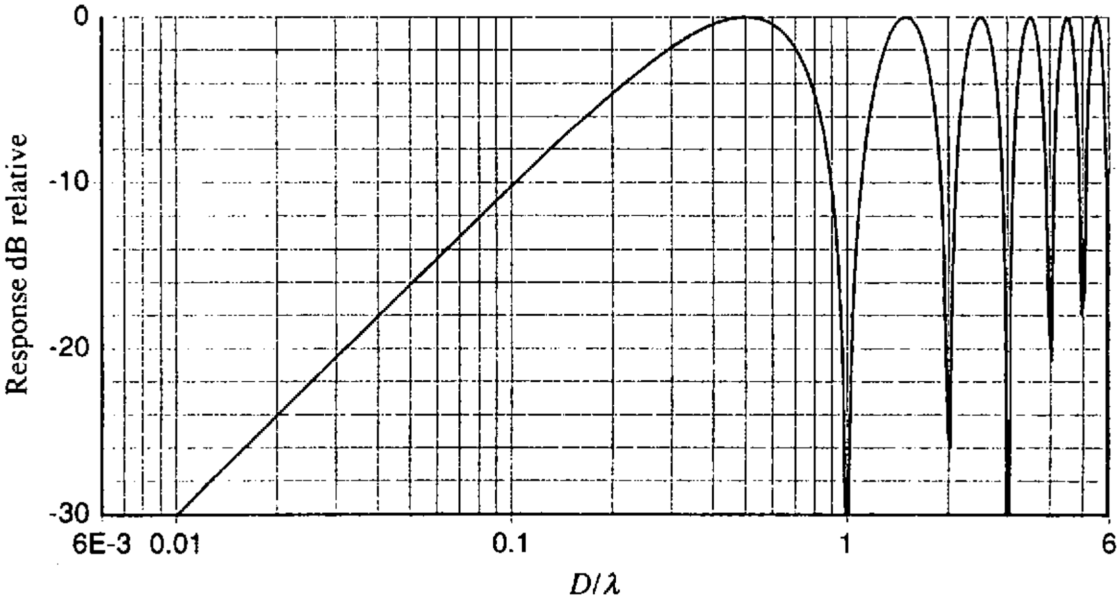

Figure 2 Theoretical (secondary) frequency response of a first-order gradient loudspeaker

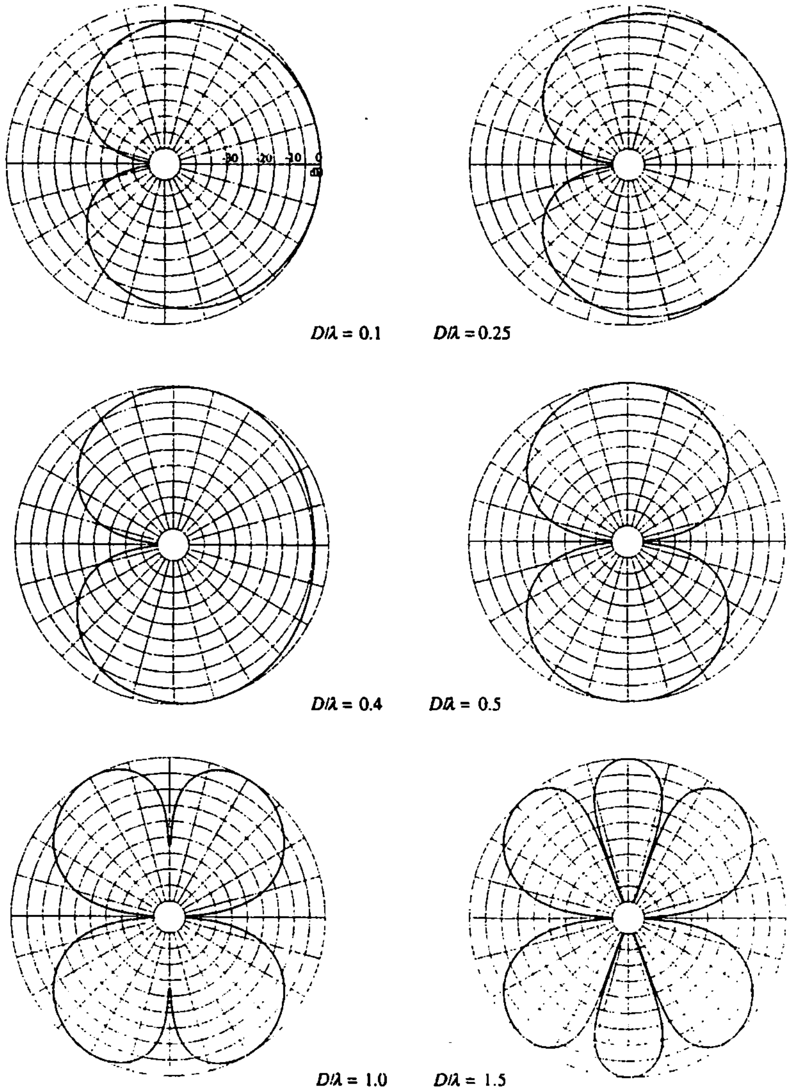

Figure 3 Theoretical directional responses of a first-order gradient unidirectional loudspeaker