A BI-DIRECTIONAL LINE-SOURCE LOUDSPEAKER WITH VON BRAUNMÜHL AND WEBER BAFFLE

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1. INTRODUCTION

Ordinary line-source loudspeakers, with enclosed boxes, have approximately circular horizontal polar characteristics at low and medium frequencies. In most speech-reinforcement applications, however, it is the forward radiation that is wanted, that in other directions merely increasing the reverberant sound level, leading usually to reduced intelligibility and a smaller margin against howl-back.

The simplest technique for obtaining horizontal directivity is to support the loudspeaker units in a vertical line, effectively without either box or baffle. A reasonable approximation to a cosine, or figure-of-eight, polar characteristic is then obtained over most of the audio range. If a casing is used to improve the appearance, it may be made, for example, from expanded aluminium. I installed two loudspeakers of this type in the main assembly hall at the Royal Radar Establishment, Malvern, in 1963. (Pat. Appn. No. 21,700/64). A similar scheme is described by John K. Hilliard(1).

2. PROS AND CONS OF UNBAFFLED LINE-SOURCE LOUDSPEAKERS

The obvious disadvantage of operating the drive units in an unbaffled state is a reduction in the bass output capability of the system. Ignoring the usual minor response irregularities, the frequency response of a single unbaffled 9 ins. x 5 ins. elliptical unit as here employed is approximately level down to just under 1 kHz, below which it falls off at 20 dB/decade (6 dB/octave) until the resonance frequency (about 80 Hz) is approached. Even with a single unit, however, the frequency response as such may readily be made level by means of electrical equalization, leaving the disadvantage of reduced bass output capability. Nevertheless, in a line-source loudspeaker with, say, eight similar units, all equally energised, it will be supposed, at low frequencies, the curtailment of bass output capability is much less serious. For an on-axis listening point at a reasonable distance, the bass outputs from the various units add in-phase, so that the maximum total pressure that can be produced without serious distortion is eight times as great as one unit could produce, i.e. the acoustic power level (intensity) at the listening point is up by a factor of sixty four. A further useful improvement in bass output capability may be achieved, as described later, by the use of a Von Braunmühl and Weber acoustic-resistance baffle, without spoiling the shape of the horizontal polar characteristic at any frequency.

In a normal line-source loudspeaker, it is quite usual to employ "tapering", i.e. the voltage fed to the various units is reduced as one moves from the centre of the column towards the ends (2, 3). This is done in order to reduce the magnitude of the side-lobes in the vertical polar characteristic. It should not be forgotten, however, that the usual theoretical derivation of the polar response is based on a parallel-ray theory, the listening point being assumed to be "at infinity". In fairly small-scale indoor installations, most of the listeners may well be at a distance of only several times the length of the line-source, and the effect of side-lobes is then much reduced(3).

Though the desirability of tapering is, perhaps, sometimes exaggerated, it can nevertheless be claimed as an advantage of unbaffled line-sources that the side-lobe magnitude, even without tapering, is less than in a normal type of line-source. This is because each unit has an approximately figure-of-eight polar characteristic vertically as well as horizontally.

A matter of some importance in many applications of line-source loudspeakers is the amount of sound output that occurs along the direction of the column, for the microphones are often placed more or less below a suspended line-source loudspeaker. In a normal, boxed, line source, at frequencies where the spacing between the loudspeaker units is one or more wavelengths, the outputs from all the units will add in phase at a position immediately below the loudspeaker, a condition likely to lead to serious howl-back difficulties. This is one reason why, in some line-source loudspeakers, a crossover network is employed to transfer the operation at high audio frequencies to a shorter line of closely-spaced miniature units. With unbaffled units, the figure-of-eight polar characteristic helps us again, and this difficulty does not arise.

A further attractive feature of unbaffled line-source loudspeakers is the complete absence of colouration attributable to cabinet effects; in particular, there is no tendency towards boominess on male speech.

3. DESIGNING FOR LEVEL AXIAL RESPONSE

In the original RRE line-source loudspeakers, already mentioned, all the units in each 7-ft. column were equally energised, at any given frequency. The axial frequency response was measured out-of-doors at a range of 25 ft., and an equalizer was built to provide approximately the inverse of this response. This gave such remarkably natural results on speech reinforcement when installed in the assembly hall, and also on music when augmented by woofers, that earlier intentions to progress to a more subtle arrangement, in which the effective length of each column was reduced with rising frequency, were not carried out. An interesting observation made when measuring the frequency response was that the signal strength received by the microphone sometimes varied with time in a manner very comparable to a fading short-wave radio station. The cause of this appears to be variations in propagation velocity along various paths from the units to the microphone, resulting from the movements of warmer and cooler air currents. This is another reason for not taking the polar characteristic derived on a parallel-ray basis too seriously.

The axial frequency response at 25 ft. of the above loudspeakers exhibited a peak of nearly 10 dB at approximately 1000 Hz. At this frequency the signals received by the microphone from the various units were adding almost in phase. At higher frequencies, both because of the differing distances to the various units, and because of the effect of temperature variations, the signals tended to arrive with random phasing, giving power rather than pressure addition. Below 1000 Hz, the response fell at 20 dB/decade because of the lack of baffling, reaching the same level at about 400 Hz as it had above 3 kHz. Equalization for the loss below 400 Hz was provided by bass lift ahead of the loudspeaker amplifier.

For general use it is clearly much more convenient if such loudspeakers can be designed to give approximately level frequency response without the need for external equalization, preferably with a bass response good enough to provide pleasing music reproduction of adequate volume. Recent efforts have been directed to achieving this.

First it was decided not to adopt tapering, it being felt that with a 6 ft. column (about the maximum convenient length for ordinary use) one was likely to want every bit of vertical directivity at low frequencies that could be obtained. From Olson (4), a line source one wavelength long gives a vertical polar response 6 dB down at approximately 35^{o} off axis. For a 6 ft. length, this corresponds to 180 Hz. Though, as mentioned, a line-source with all units equally energised at any given frequency - even a high frequency - was found to be surprisingly satisfactory in a particular application, it was again felt that, for general use, the principle of shortening the effective length of the column with rising frequency should be adopted, thus maintaining a more nearly uniform vertical polar characteristic and making the high-frequency response less dependent on temperature gradients in the air. Shortening the line with rising frequency is, of course, quite a separate issue to that of tapering.

Thus, in the new design, which employs eight Elac Type 59RM/109 15-ohm units, the whole of the input voltage to the loudspeaker, at frequencies above about 2.5 kHz, is applied to just one unit, near the centre of the column. The design aim is to arrange that additional units come into action as the frequency falls, making the effective length of the line source approximately proportional to wavelength and also, if possible, holding the axial frequency response level.

The circuit employed is shown in Fig. 1, and is a considerably simplified version of that originally adopted, which had four inductors. The units are numbered in sequence from the top of the column to the bottom.

When the frequency has fallen to about 1.5 kHz, the input is divided almost equally between units 4 and 5. At a distance of many feet in front of the column, on axis, the acoustic pressures produced by these two units add to produce a total pressure which is ideally the same as would be produced by either unit on its own if it had the full input voltage applied to it. Thus there is nothing critical about either the capacitor value or the exact manner in which the excitation changes over from one unit to two units. Note that, with two units in operation, the same axial pressure is being produced with only half the input current that would be required with one unit alone.

As the frequency falls, units 3 and 6 next come into operation, with a corner frequency at 700 Hz, the units being positioned one on either side of units 4 and 5. The resistor and capacitor shunted across the units make the total impedance in series with the inductor a nearly constant resistance of about 30 ohms over the significant frequency range. Thus the voltage across units 3 and 6 is given closely by:-

$$V_{3+6} = V_{in} \times \frac{1}{1 + pT} \qquad (1)$$

where $T = L/R$ $\quad p = j\omega$ $\quad R = 30\Omega$ $\quad L = 6.8$ mH

Thus, below 700 Hz, a state is approached in which each of the units 3, 4, 5 and 6 has a voltage of $V_{in}/2$ across it. If each unit had a flat frequency response, the total acoustic pressure at a good distance from the column on axis would then be 6 dB up on what a single unit with V_{in} across it would produce, i.e. 6 dB up on the high-frequency response level of the system. However, this rise in response is approximately balanced by the falling response of the unbaffled units at frequencies well below 1000 Hz.

At a corner frequency of 200 Hz, the remaining four units are smoothly brought into action, further increasing the effective line length and thus tending to maintain the vertical polar characteristic more nearly constant. With all eight units fully in action, each with $V_{in}/2$ across it, the total axial output at a good distance, if the frequency response of the individual units was flat, would be 12 dB up on that given by one unit with V_{in} across it, and the input impedance of the complete system is then nominally 7.5Ω. Once again this rise in response is counteracted by the falling response of the individual unbaffled units, causing the overall response to fall off below about 200 Hz.

Fig. 2 shows a simple electrical analogue circuit which may be used to predict the long-distance axial frequency response of the above loudspeaker system. The measured frequency response of this circuit is shown in Fig. 3. The acoustically-measured frequency response of the loudspeaker is in reasonable agreement with this, the microphone distance being about 20 ft.

To improve the response at low frequencies, a Von Braunmühl and Weber acoustic-resistance baffle (5) has been added. Such a device is also used in BBC ribbon microphones (6). Ideally it consists simply of a stiff sheet of thin acoustically-resistive material, but may be made in practice by sticking one or more layers of cloth to a sheet of wire mesh.

The principle exploited is that at distances of a wavelength or less from a sound source, the ratio of particle velocity to pressure becomes greater than at large distances, where it has the value ρc. A curve showing this effect is given on page 16 of reference 4. A high ratio of velocity to pressure means a low value of acoustic impedance. Thus if we surround a loudspeaker unit with a baffle which is small compared with the wavelength considered, the effective source trying to drive air through the baffle is one of low internal impedance. Consequently a baffle of quite low impedance is sufficient to offer effective obstruction to the flow of air from one side of the loudspeaker unit to the other. The baffle used in the present loudspeaker has an acoustic resistance value of just over half ρc, i.e. about 250 MKS mechanical ohms per m^2. At higher frequencies this baffle, whose resistance is independent of frequency, is driven by a source of higher internal impedance than its own, and it therefore causes relatively little obstruction.

The construction used is shown diagramatically in Fig. 4, from which it will be seen that thin cloth is held taut by spring tension over the curved surface of galvanized steel mesh. That used has openings 1 ins. x ½ ins., but this is not critical and calculation shows that the cloth need not be very tight to prevent significant movement.

As originally made, the cloth was stretched over the front of the units as well as the side-panels, which was a more convenient form of construction. I was then very puzzled to find that adding the cloth made almost no difference to the loudspeaker output at 100 Hz, and thought for a time that there must be something wrong with the theoretical argument! By using a capacitive displacement-monitoring arrangement, involving a piece of copper-foil stuck to one of the diaphragms, it was established that placing the stretched cloth over the front of the unit reduced the diaphragm amplitude by about 6 dB, just about annulling the advantage conferred by the Von Braünmuhl and Weber baffle. The acoustic resistance of the cloth used is much higher than for typical loudspeaker grill covering materials.

When the above difficulty had been overcome, the expected result was obtained. The axial frequency response, measured with the microphone at about 20 ft., is shown in Fig. 5. When this curve was obtained, slight additional equalization was in use, involving a very low-Q tuned circuit to reduce the response a little in the region centred on 600 Hz. The desirability of this was evident from careful listening tests, and is consistent with the analogue curve of Fig. 3.

4. HORIZONTAL POLAR CHARACTERISTICS

Fig. 6 shows measured polar characteristics at 250 Hz, 1 kHz and 4 kHz. A theoretical cosine curve, plotted to the same decibel scale, is also shown for comparison.

5. POWER-HANDLING CAPABILITY

Only at high frequencies is the whole of the amplifier output voltage applied to a single unit, and at these frequencies the coil impedance is considerably higher than at lower frequencies. The units will withstand a continuous high-frequency input of about 20 V rms without thermal damage. This corresponds to full sinusoidal output from an amplifier rated at about 25 watts into 15 ohms or about 50 watts into 8 ohms.

At lower frequencies, the input voltage is divided between pairs of units, but the larger amplitudes will increase the thermal resistance for heat loss from the coils. Nevertheless a continuous input level similar to that mentioned above can be withstood.

On music with hefty bass content, the limit is likely to be set by intermodulation considerations rather than by any danger of thermal damage.

Music tests in a school hall of volume approximately 150,000 cu. ft. (4250 m^3), using an amplifier rated at 50 watts into 15 ohms, showed that peak SPL's of about 90 dB could be produced at a point about half way back in the hall from the loudspeaker. Reproduction of a piano recorded in the hall was quite impressively realistic.

REFERENCES

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(5) H. J. von Braunmühl and W. Weber, "Kapazitive Richtmikrophone", Hochfrequenztechnik und Elektroakustik, Vol. 46, pp. 187-192, 1935.

(6) D. E. L. Shorter and H. D. Harwood, "The Design of a Ribbon Type Pressure-Gradient Microphone for Broadcast Transmission", BBC Eng. Monograph No. 4, December 1955.

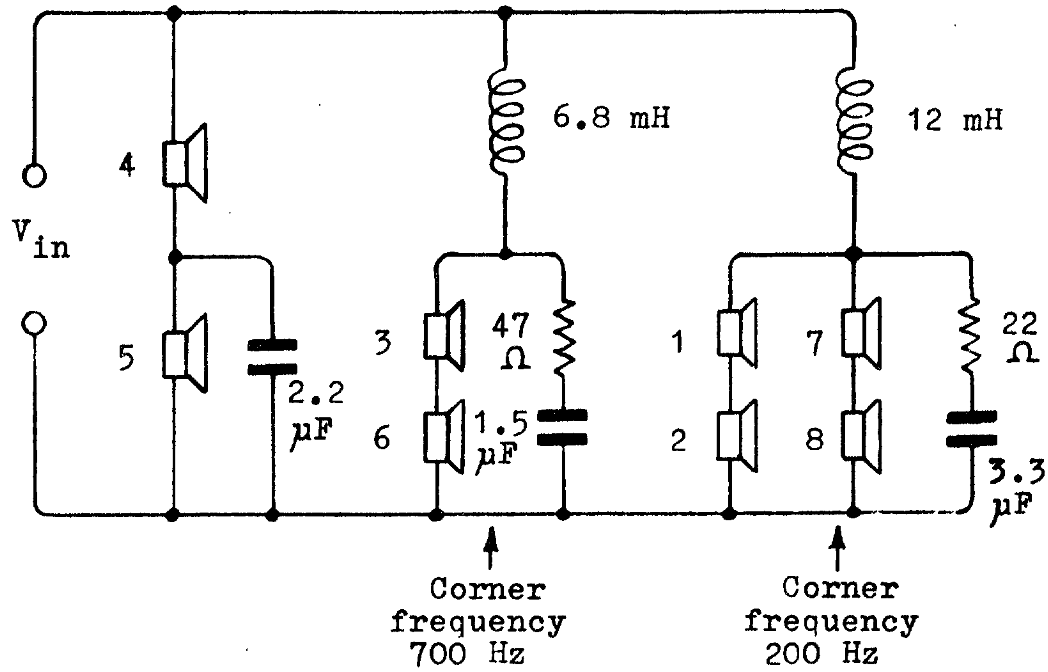

Fig. 1. Internal circuit of loudspeaker.

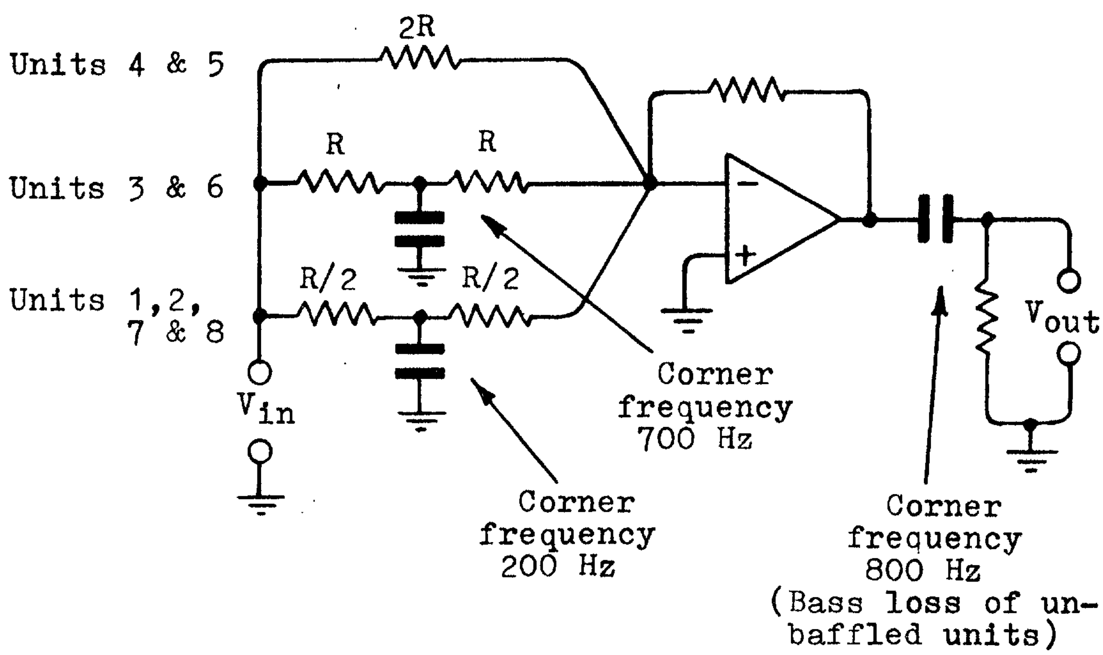

Fig. 2. Electrical analogue circuit for predicting long-distance axial frequency-response of loudspeaker without baffle. Effect of diaphragm suspension stiffness is ignored.

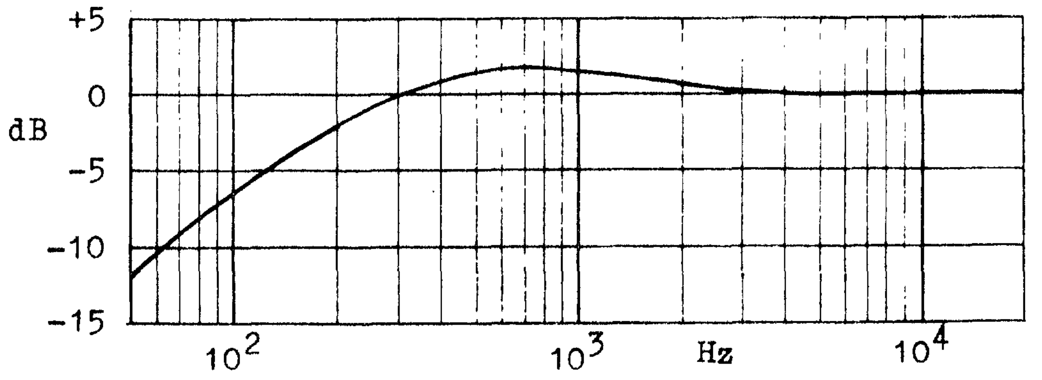

Fig. 3. Measured response of the Fig. 2 analogue circuit.

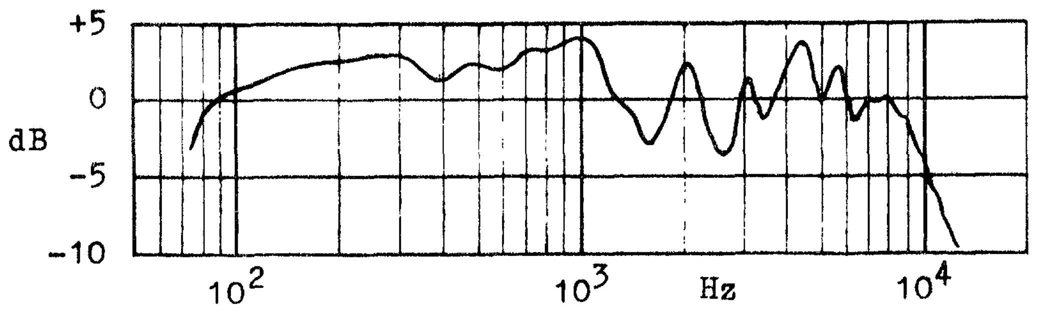

Fig. 5. Axial response of complete loudspeaker. Outdoor measurement with microphone at 20 ft.

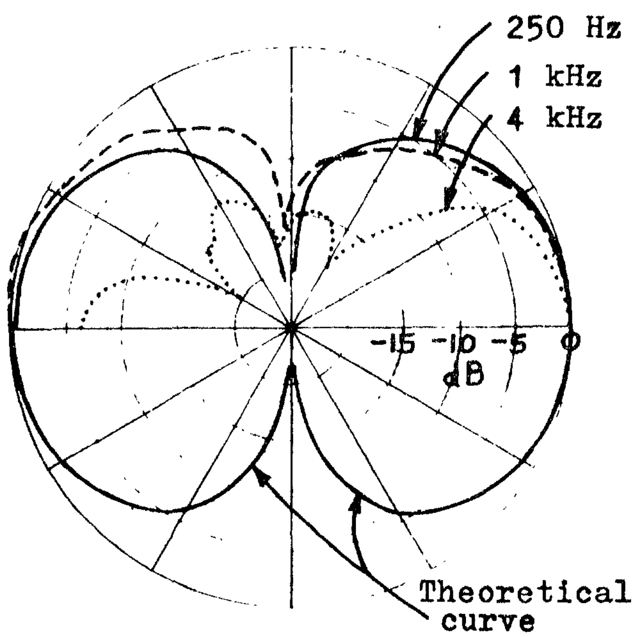

Fig. 6. Polar characteristics for complete loudspeaker.

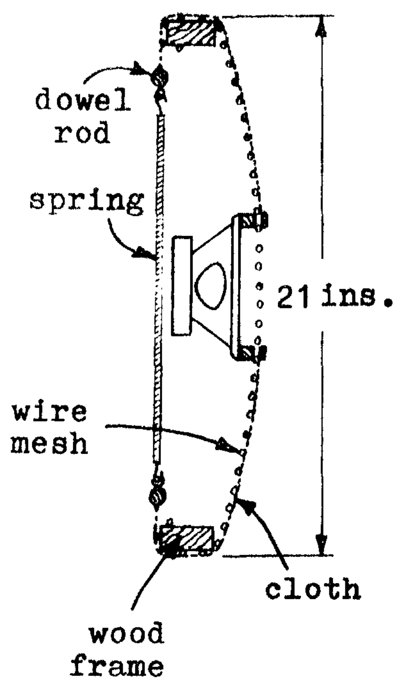

Fig. 4. Construction of experimental model.