70/04

BRITISH ACOUSTICAL SOCIETY

Electroacoustics in Air and Water, January 1970

Loudspeaker Developments by H.D. Harwood, B.Sc.

At low frequencies loudspeaker cones behave as rigid pistons and since the radiation resistance of air is shown in slide 1 to vary as the frequency squared the cone should be mass controlled to give a uniform axial response/frequency characteristic. From this information we can deduce two important factors. These are that the amplitude of the cone varies inversely as frequency squared, i.e. the amplitude is large at low frequencies but small at medium and higher frequencies. The second point is that, as can be seen from the figure, the radiation resistance at low frequencies is, surprisingly, independent of the area of the piston

Now the maximum sound level which can be radiated by a cone is determined by the amplitude permissible before excessive distortion sets in and this occurs, as we have seen above, at low frequencies. The usual procedure employed to overcome this effect is to load the rear of the cone acoustically by resonating the air stiffness of the loudspeaker cabinet with an acoustic inertance in the form of a vent, thus forming a Helmholtz resonator. The instructions given in the textbooks is that the area of the vent should be equal to that of the cone and in order to obtain the required value of inertance a tube has to be constructed inside the cabinet. However we have seen that the radiation resistance is independent of the piston, or vent, area and this instruction is therefore false. The vent can be made quite small with two provisos. Firstly that the r.m.s. air velocity in the vent does not exceed the limits for linearity, about 1 m/s, and secondly that the vent is not so small that the Q of the inertance is seriously affected. In practice a hole of about 6 in^2 can be employed successfully and is of course cheaper and simpler to construct than the usual tube.

The next point concerns the non-linearity caused by the magnetic field. When the amplitude of the voice coil is great enough to exceed the linear portion of the magnetic field so that it enters a much weaker portion of the field it might be expected that clipping of the waveform would take place. In fact, however, we have seen that the maximum amplitude takes place at low frequencies and it will be appreciated that at these frequencies the motional impedance is the predominating factor in deciding the current in the voice coil. Now when the coil moves into a region where the average flux density is half the rest value the motional impedance is reduced to one quarter. From a constant voltage source, four times the current will flow in the voice coil and this in a field of half the intensity will give twice the driving force that was obtained in the centre field. The amplitude, far from being clipped, is therefore expanded as the field is reduced. Of course it should be noted that this state of affairs only occurs when the motional impedance is the predominating factor in deciding the current flow. When the flux density is reduced so much that this is not so, clipping of the waveform does take place. Now it may be thought that expansion of the driving force is just as bad as compression from the point of view of distortion but this is not so. The stiffness of the spider is itself non-linear and increases with amplitude too. This can be made to match the expansion of the driving force giving a linear displacement over a much greater amplitude than would otherwise be possible. In this way a loudspeaker has been designed which, with an amplitude four times greater than the linear magnetic field still has distortion products almost 40 dB below the fundamental.

We next come to the problem of directivity. If we use only one unit to cover the whole frequency range it is found that the radiation at high frequencies is highly directional. The obvious next stage is to use two units, one for low and the other for high frequencies. However even this is not free from snags for if the axial response is made uniform the off-axis response will be as shown in slide 2. Still further improvement can be obtained by using three units for low, middle and high frequencies respectively but the same fundamental problem remains.

The directivity of the low frequency units can be improved by placing a slit over the cone provided the resonance of the air in the cone with the inertance of the slit is placed sufficiently high in frequency not to be troublesome. The effect of the slit is not however as simple as would appear at first sight. For the purpose of calculating the directivity, a slit in front of a loudspeaker can be likened either to a line source, or somewhere between a piston in an infinite baffle and on the end of a cylinder. Now if we calculate the difference between the axial and 60° responses for these three cases we get the curves shown in the slide.[3] It is not surprising that for ratios of slit width to wavelength up to 0.7 the three curves are closely in agreement, and it would appear that if we take a value of $\frac{1}{3}$, the off-axis curves should approximate closely to the axial ones. In fact this is not the case, the measured results are given in curve d. Now it is possible that the slit is not uniformly illuminated with sound and if we calculate the extreme case where all the sound is concentrated at the edges of the slit we get curve e. This is better but still not in good agreement and in any case measurements of the sound pressure show it to be almost uniform across the slit with a slight excess at the centre. The next stage was to repeat the measured results, taking the width of the cabinet as the slit width, see curve f, and it will be seen that the agreement with the theoretical results is very good up to a ratio of 0.7. It appears then that the radiation from the slit flows along the front of the cabinet until it meets the discontinuity of the sides and is then re-radiated from the corners. This is confirmed in the next slide which shows that a slit has no effect on the directivity up to a frequency of about 700 Hz corresponding to $\frac{a}{\lambda}$ of 0.7 in the previous slide. Of course above this frequency it has a marked effect.

Now we come to the question of cone material. In the past the customary cone material has been paper pulp. This has the advantage of being cheap once the expensive tools have been paid for, but the reproducibility is poor and the sound quality is marked by middle frequency colouration. Some attempts have been made to use expanded polystyrene, with and without reinforcing metal skins, with varying degrees of success. The difficulty with this material is that it has a high internal Q and is thus difficult to damp or terminate mechanically. More recently use has been made of a solid polystyrene material whose internal damping has been increased by the addition of a synthetic rubber. Wave motion in the cone is thus relatively well damped but to eliminate standing wave effects it is still necessary to provide the correct mechanical termination for the cone. The mechanical impedance of the cone is different for radial and circumferential waves and the surround must act as a correct termination for both, and that in a distance which is small compared with a wavelength. At the same time the surround must permit appreciable amplitudes and must not resonate itself. Resonance of the surround can often result in irregularities of 10 dB in the middle frequency range, with corresponding colouration. A successful design is shown in the slide 5 where it will be seen that effectively an RC element is placed in series with the LCR components of the surround proper.

During the design of a high grade monitoring loudspeaker a small middle frequency unit was made using the thermoplastic material mentioned above. It had a very smooth axial response frequency curve but on listening was found to have marked colouration in the 1 kHz to 1.5 kHz range. Examination with chopped tone showed that there were three resonances close together but the maximum value of the decay was 40 dB below the steady state; they did however have a Q of about 500. It should be noted that if these resonances were in phase with the remainder of the output the effect on the steady state response would only be 0.1 dB whilst if at 90° they would have even less effect. As they caused sufficient colouration to cause the loudspeaker to be rejected the importance of this source of trouble is underlined. In fact it was possible to cause the subjective effect to disappear almost completely by damping the cone with a layer of a p.v.a. compound.

In the light of this, other cones in use were tested for colouration by driving them with pink noise in the free field room and recording the output of the measuring microphone. They were then painted with the same damping compound and pink noise again recorded. The two recordings were then played consecutively and any effect of the additional damping was immediately apparent.

A complete loudspeaker has been produced using a 12" unit with a plastic cone for the frequency range up to 400 Hz, an 8" unit again with a plastic cone for the middle frequencies from 400 Hz to 3 kHz and a small pressure type unit about 1¼" diameter with a plastic impregnated cone for the remainder of the frequency range. The two larger units have 10 cm slits in front to improve the directivity and in common with all BBC designs over the last twenty years the crossover networks incorporate frequency correction networks to produce the required axial response/frequency characteristic. The different units are connected to the taps of an auto-transformer to permit adjustment of the levels exactly. The spread in response/frequency characteristics at various angles in the horizontal plane is shown in slide No. 6 and will be seen to be very small. The range in axial response/frequency characteristics for six specimens is shown in slide No. 7 and will be seen to be within ±1 dB. This has been fixed as the permissible range for production models and should be compared with a range of 5 dB for middle and high frequencies for high grade capacitor microphones and 7 dB at the bass. Loudspeakers have no longer the widest spread in response.

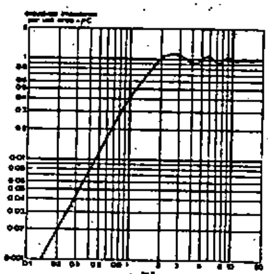
Slide No. 8 shows the mean spherical response of this loudspeaker and also the directivity as a function of frequency. This varies quite smoothly with frequency.

The harmonic distortion measured at a sound pressure of 1 N/m^2 at a distance of 1.5 m in the free field room is shown in slide No. 9. For those unaccustomed to assessing such curves two points should be mentioned. Firstly, compared with the fundamental curve note the extreme irregularity of the other curves, particularly at the higher orders of distortion, even at low frequencies. For example at 82 Hz the level of the eighth harmonic is 10 dB above that of the sixth, but at 85 Hz the eighth is 28 dB below the sixth, a difference of 38 dB in 3 Hz! It is clearly essential therefore to measure distortion as a continuous function of frequency rather than at a few spot frequencies as with electronic equipment.

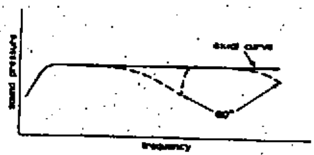
The second point is that these levels of distortion are quite inaudible.

The corresponding intermodulation distortion curves are shown in slide No. 10.

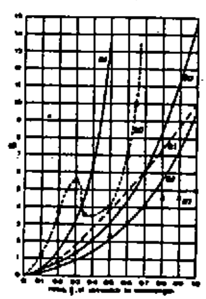
Finally this loudspeaker is not only highly reproduceable but also is remarkably free from colouration and represents a major step forward in the art of loudspeaker design.



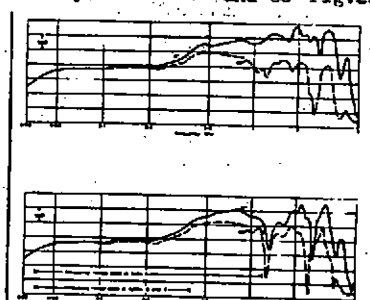
Radiation resistance of piston in infinite plane Fig. 1.



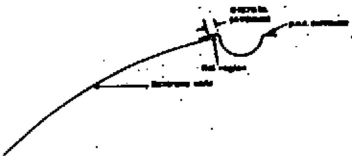
Theoretical response/frequency characteristic of 2 unit loudspeaker at 0° and 60° Fig.2.



Response at 60° with reference to axial response of various sources Fig. 3.

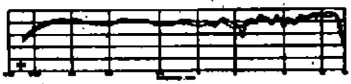


Response/frequency characteristic of 305 mm unit without & with 100 mm slit. Curves at 0° and 60° to axis. Fig. 4.

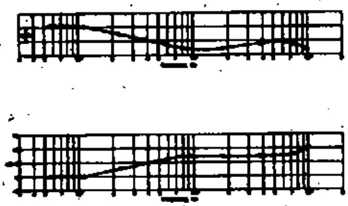


Shape of cone p.v.c. termination. Fig. 5

Response/frequency characteristic of 2 and 3 unit loudspeakers in horizontal plane.

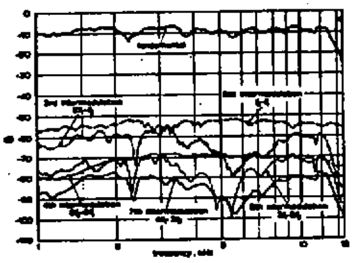


Spread in axial response/frequency characteristics of six 3 unit loudspeakers. Fig. 7.



Mean spherical response and directivity index of 3 unit loudspeaker. Fig. 8.

Harmonic distortion of loudspeaker at sound level of 1 N/m^2 at 1.5 m. Fig. 9.



Intermodulation distortion of loudspeaker at sound level of 1 N/m^2 at 1.5 m. Fig. 10.