Loudspeaker coloration

Eliminating unwanted sources of resonances

by **D. A. Barlow**, Ph.D

Loudspeakers have always been the weakest link in the chain of sound reproduction. The tone is coloured by the presence of unwanted resonances, which may still be audible in spite of considerable damping. The already-reported limits of audibility of resonances on white noise and music over a range of frequency and Q are discussed in relation to loudspeakers. The white noise test was severe and few if any speakers meet this "peak criterion," even over part of the audio range. Sources of unwanted resonances and methods of elimination are discussed and a design proposed for a speaker in which coloration is inaudible.

In LOUDSPEAKERS, there are many causes of coloration or spurious effects not present in the electrical input signal. These usually take the form of resonances or anti-resonances. In bad cases, they show on a frequency response curve; less severe cases may be found by transient tests, or by watching the motion of the moving parts by holographic methods.[1,2] Resonances may be present in the diaphragm, surround, rear suspension, voice coil, dust cap, chassis, cabinet walls, etc. Other resonances are the fundamental ones of the drive units and of air cavities, including the air enclosed by the cabinet. Other effects, not necessarily audible, include acoustic interference between units in multiple speaker systems, phase differences between units, phase distortion in the crossover, diffraction at the edge of the cabinet, speaker frame, etc.

I have long thought that listening tests should be used where possible to determine the limits below which the various forms of distortion or imperfection in audio equipment become inaudible. Effort could then be concentrated on the most serious defects, and those which are inaudible can be ignored. In particular, listening tests were proposed to determine the limit of audibility of peaks, by introducing resonances of various frequencies and Qs electrically.[3]

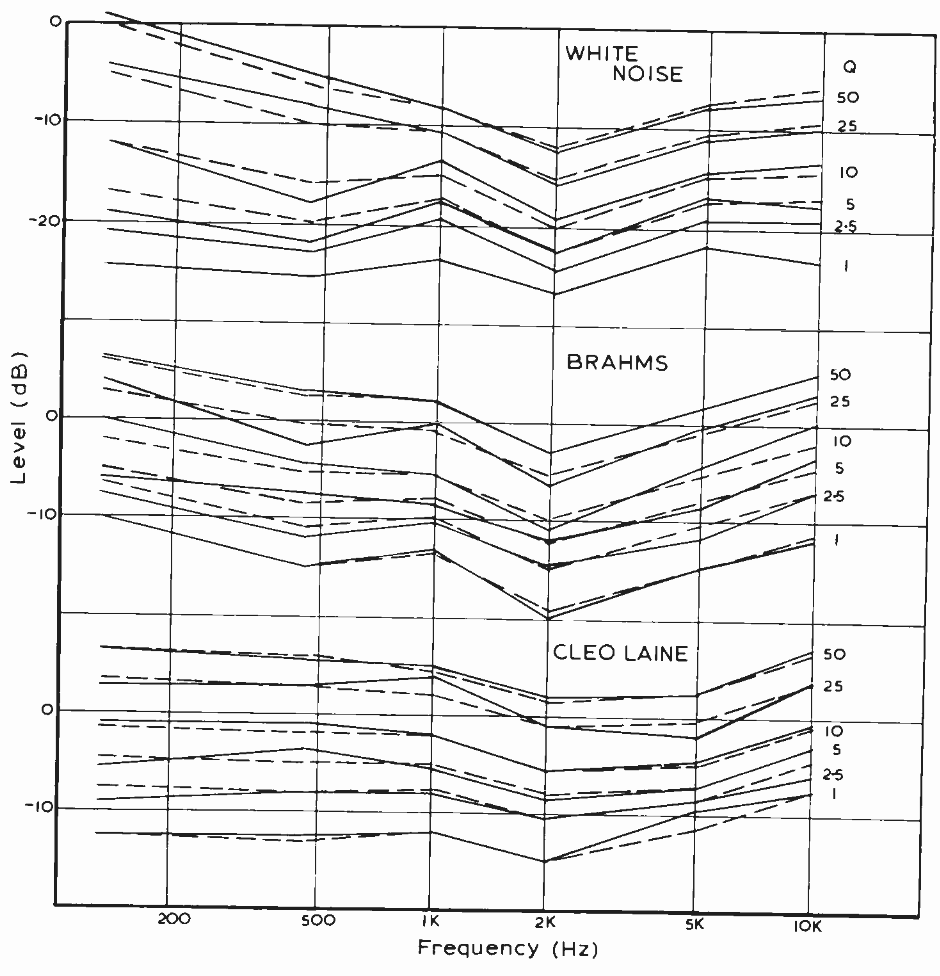
Peak listening tests

Preliminary tests were made in 1972, using an Altec Room Equaliser. This has a number of resonant circuits covering the audio range. Each may be varied to be either a peak or a dip. Listening tests were carried out, using two makes of high quality headphones, thus avoiding the effect of room acoustics. Using white noise a single peak of 2dB in the mid-range was clearly audible, giving the noise a definite pitch. At the extremes of frequency, the ear was less sensitive, as might be expected. A 2dB dip in the mid-range equally gave a definite pitch to the white noise.

The main listening tests were carried out by Fryer[4]. A number of frequencies were used with a Q of 50, 25, 10, 5, 2.5, and 1. Three sources were used, white noise, the opening bars of Brahms first Piano Concerto, and Cleo Laine singing 'Peel me a grape'. The unbroken lines in Fig. 1 show the level at which the peak becomes inaudible. A-B tests were used with compensation for the increase in loudness caused by the addition of the peak. A large number of listeners took part, and were of various ages and occupations. Each listener listened alone, with no knowledge of other listeners' results.

White noise is the most sensitive, followed by the Brahms. As the Q is lowered, the level at which the peak can be detected is also lowered. A hump of given height, covering a large bandwidth is more noticeable than a spike of the same height, which affects only a very small bandwidth. The ear evidently detects mainly the energy or area under the peak. In some cases, at high Q, the peak can be well above the general level

Fig. 1. Levels at which response peaks become inaudible for six values of Q and frequency, using three source signals. Broken curves indicate adjusted values (see text).



before being detectable, but in other cases a low Q resonance, well below the general level, is still detectable. Damping a resonance may not give as great an improvement as hoped for, especially at low frequencies. It follows from these curves that a flat response, containing peaks damped down to the general level, is no guarantee of freedom from coloration; also that two speakers with smooth frequency response curves may have quite different degrees of coloration. Low-Q resonances near the extremes of frequency are similar in effect to tone controls, and alter the character of the sound rather than make it unpleasantly coloured.

There is naturally some scatter in results; for example the gap between the levels for Q of 25 and 10 for white noise at 450Hz appears excessive. There is good reason for thinking this. Reducing the Q from 25 to 10 by damping means reducing the level by 8dB, yet the detection limit drops 10dB. Thus damping the resonance would appear to make it slightly *more* audible! This is highly improbable. I felt justified therefore in smoothing the curves, removing this one anomaly. Values were adjusted so that the differences between the dB drop in reducing the Q, and the drop in detectable level followed a smooth curve in each case. This was done for all points, the change in actual values being kept to a minimum. The smoothed curves are indicated by the broken lines.

These curves agree in general with similar tests reported by Bowsher[5]. Under certain unstated conditions, Harwood[6] obtained different results. It can only be concluded that these conditions were unrepresentative of normal listening.

Application of results

The present curves, especially for white noise, represent a very severe demand on the loudspeaker; we may call this the peak criterion. Few if any commercial speakers meet the criterion, even over part of the frequency range. There are two basic ways of making a speaker

- by using a relatively large light diaphragm driven all over, for example by electrostatic, piezoelectric or electrodynamic means
- by using a relatively small diaphragm driven from a very small area, for example by a moving coil.

For satisfactory operation, the first type must have a very limp diaphragm, operating well above the fundamental frequency, in the hope that the overtones will be sufficiently damped as to be undetectable. There is very little information on this. The second type must operate at frequencies well below the diaphragm resonances. Most speakers fall between the two stools.

Thin cones made of paper, metal, plastics, carbon fibre, inevitably resonate over almost all of their working range. The object in designing such cones is to find a profile in which none of the resonances is pronounced. There is no way of calculating this, and a suitable shape can only be found by trial and error, a process which is still going on after nearly 50 years, and could go on ad infinitum. For this reason, it is always possible that a beginner may by chance produce a cone with a smooth response. In some plastic film diaphragms, the profile is known to be very critical and small deviations may give serious peaks. Even if a smooth response is obtained, resonances will be present. Such cones cannot be expected to meet the peak criterion.

If a cone is to operate below its breakup resonances, it must have the highest possible stiffness/weight ratio. As deformation is mainly in bending, the structure with the maximum bending stiffness must be used, viz. sandwich construction[7,8]. The maximum stress in bending is taken by the outer layers; these are therefore made in a material with the highest ratio of Young's modulus/density. The skins are glued to a core, which must be as thick and light as possible. Aluminium foil and expanded polystyrene are the obvious materials to use.

Possible speaker to meet the peak criterion

By using sandwich construction, it should be possible to meet the peak criterion except at the ends of the frequency spectrum, where the ear is less sensitive and where further tests are desirable. Sandwich cones are usually of high Q, but the breakup resonances can be damped down to the general level by means of suitable damping material applied to the cone neck[2]. If the white noise criterion is used, these resonances must be about 24dB down, assuming a Q of 1.

It is known from holographic examination that a 25cm diameter sandwich cone of 105° included angle has a first resonance, the umbrella mode, at 1300Hz, which is often difficult to detect acoustically or by impedance curves. Such a cone would meet the peak criterion by crossing over at about 300Hz with a 12dB/octave crossover. A 6dB/octave crossover would be of little value where a limit of —24dB is to be met.

The mid-range could be handled by a 7.6cm diameter cone. The first breakup would be at about 6kHz, allowing crossover at 1.5kHz. Damping of the resonances may require a rather large weight of damping compound. Driving from the periphery by means of a 7.6cm diameter voice coil may give higher breakup frequencies, although the mass of the voice coil former would be greater than for a smaller diameter coil. Furthermore, diffraction at the cone edge and resonance of trapped air may be problems. If beryllium or carbon fibre were available in suitable form, the breakup frequencies could be raised considerably, thus easing the design.

The treble cone could be 3.8cm diameter, again perhaps driven from the periphery. To raise the first breakup above 20kHz, beryllium or carbon fibre skins would be necessary. Smaller cones than this are difficult to construct and the maximum permissible weight for smaller cones is very low. The optimum cone angle is 90 to 105°. The use of a smaller included angle should raise the circumferential mode frequencies but decrease the radial mode frequencies. As there are no radial modes in sandwich cones, unlike paper, a small included angle could be used. However, this raised the first frequency, but lowered the frequency of the second mode, so that there was no advantage in going to smaller angles than 90°.

The suspensions of the mid and treble units should be designed to coincide with the planes of the centre of gravity and centre of inertia, thus avoiding any tendency to non-axial motion. Likewise, the leads must be brought out at 180°, as it is known from holography studies that if they are brought out together, the unbalanced mass will cause rocking of the cone. The fundamental resonances of the two units when mounted must be at least two octaves below crossover, assuming good damping.

Very little can be done about the fundamental resonance of the bass unit. Most speakers show the effect of the fundamental resonance in the slow decay of the bass in delayed resonance tests. The principal types of enclosure are the reflex and the totally enclosed. The full theory of the reflex has been given by Thiele[9]. With correct design, with correct coil and cone weights, flux density, etc, the bass response can be extended well below that for a similar totally enclosed cabinet. Thiele's work has been translated into practical terms by Garner and Jackson[10] and by Collinson[11] at my suggestion[3]. However, the reflex cuts off at 18dB/octave compared with 12dB/octave for the enclosed cabinet. In the present context, a sharp cut-off is to be avoided. It might be better to use an enclosed cabinet with enough acoustic and magnetic damping to be critical (Q=½), the response being —6dB at resonance. This represents some loss of bass, but as the cabinet is likely to be placed against a wall during use, there will be acoustic reinforcement of the bass.

The only other enclosure of interest is the folded pipe or labyrinth, now called the transmission line. This has the advantage of not increasing, or even slightly decreasing the fundamental resonance. Apart from any possible extension of the bass, this would place the fundamental resonance sufficiently low in frequency to be inaudible. Unfortunately, the finite length of the pipe and the necessary folds give rise to resonances of the enclosed air[12], and these are audible as 'bumbling', even when damped with long-fibre wool[13].

Resonances of cabinet walls

The conventional rectangular cabinet inevitably suffers from bending resonances of the flat walls. In certain cases, especially with large cabinets, the sound output of the cabinet walls at the frequency of panel resonance can exceed that of the speaker by several decibels[1]. These resonances may be damped by thick layers of damping material glued to the panels, the weight of the damping compound being comparable the the panel weight. Bituminous damping felt is the most practical material [8, 10]. Damping compounds readily suppress the overtones, but are less effective at the fundamental. The answer is to use a cabinet of constant curvature, where there are no bending resonances, only resonances in direct stress[14]. This has now been utilised in two recent commercial designs. Such cabinets are so stiff in operation that almost any material may be used for bass cabinets. A cardboard tube of 30cm diameter has no resonances below 2kHz, and the radiation level at lower frequencies is 30 to 40dB below the signal. It is fully equal to brick and concrete and easily meets the peak criterion.

The obvious method of mounting a bass unit in a tubular cabinet would be at one end. The tube could be 60cm long × 30cm diameter with the bass unit facing upwards. A long pipe may give trouble with organ pipe resonances. With a crossover at 300Hz, the bass unit would be almost omnidirectional over its working range. This would avoid any possible apparent loss of mid-frequencies due to listening off-axis. Diffusers could not be used to increase the spread of the upper frequencies because they give irregularities in the response curves and audible effects at lower frequencies. Inverting the speaker unit so that the rear faced upwards, the rear face of the cone being clearly visible from the listening position, did not alter the directional properties. Mounting the speaker at one end of the tube, facing the longest direction has the advantage that the rear reflected wave will be at the lowest frequency; it is less likely to be audible and has the maximum thickness of acoustic absorbent through which to travel. Re-radiation of the reflected wave is thus at a minimum. A sandwich cone gives much less re-radiation than a conventional paper cone[15].

The mid and treble units could be mounted in the cylindrical surface, without unduly affecting the performance of the cabinet; if necessary, the cutouts could be stiffened up with additional material. The diffraction effects at the sharp edges of a conventional cabinet are avoided, and provided the units are not at centre height, a cylinder was found to be almost as good as a sphere or ellipsoid for avoiding diffraction. That diffraction effects can be audible in the worst case is shown by the following test.

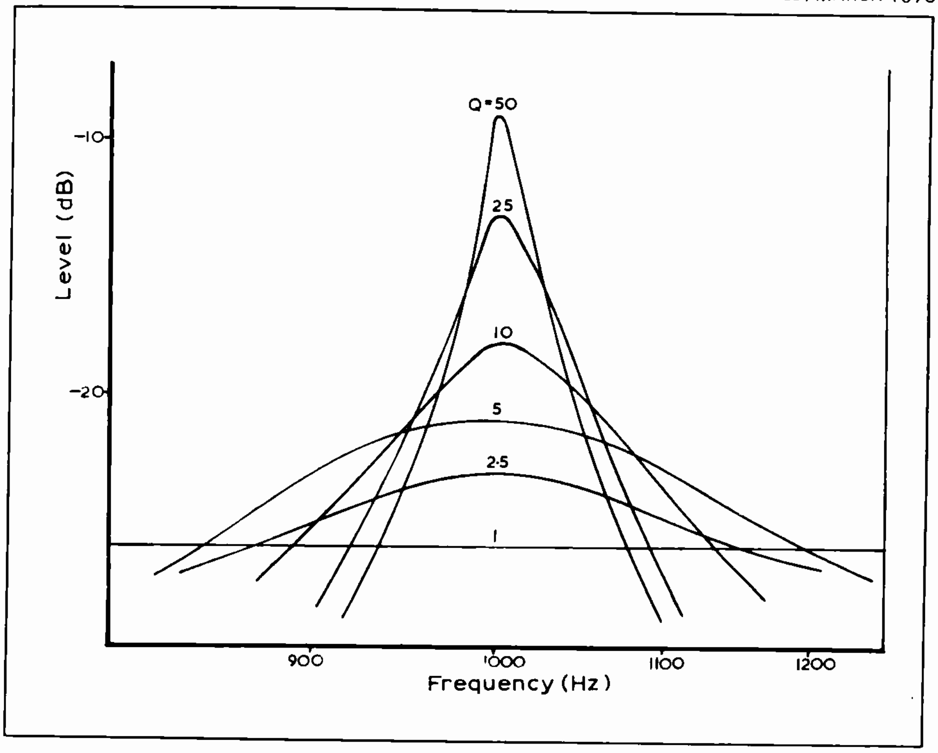


Fig. 2. In the listening tests discussed resonance peaks with Q of 1 to 50 were switched in and out in establishing level of inaudibility. Detectability decreased by 3dB for each doubling of Q.

A single speaker was used, as no two units sound the same on white noise, and differences due to position in the room are avoided. The speaker was mounted in a 30cm diameter sphere and fitted with a 30cm diameter removable flat baffle. On white noise, the difference with and without the baffle was quite clear. The effect of the baffle on the frequency response was to introduce a hump of 4dB at 1kHz and a hollow of 4dB at 1.8kHz.

In addition to spurious external radiation by the cabinet walls, there is the possibility of sound being transmitted from the bass into the treble cavity and vice versa. Tests in 1974, which unfortunately I could not complete, suggested that this transmission may not be negligible in all cases.

Crossover networks

It has been known for many years that there is phase distortion in most crossover networks, the 6dB/octave quarter section being the only common one free from this. Crossover filters have been studied by Wall[16] at my suggestion.[3] He devised a three-way filter without phase distortion. This uses a two-way half section with a mid-section to correc the phase. Baekgaard[17] has devised a similar filter. Although the mid-speaker operates only over a narrow band, the cut-off on each side is only 6dB/octave. If it is to meet the peak criterion, it must be free from resonances over eight octaves. Such a speaker would be a full range one and would hardly need crossovers. It might be possible to make an acceptable unit by rolling off both bass and treble acoustically by suitable design.

Another possibility is a linear-phase filter of the Gaussian or Bessel type, i.e. beyond cut-off the phase angle is proportional to frequency, although design data is scarce. Nomoto et al[18] have demonstrated the wavefront from speakers by means of measurement over a large number of microphone positions, using a computer. A two-way system using a Bessel filter showed a wavefront corresponding to the input signal, in contrast to a Butterworth filter.

A number of commercial speakers have been produced recently, in which the mid and treble units have been set back behind the plane of the bass unit. The acoustic centres should thus be in the same plane and acoustically in phase — the "linear phase" system. Some of these have crossovers without phase distortion, others have conventional crossovers. If in a two-speaker system, the treble unit is placed on top of the cabinet and moved back and forth, there is a slight difference in sound with position on white noise. This is clearly heard from above the speakers and is obviously due to reflection off the top of the cabinet. The test was repeated with thick absorbent on the top of the cabinet and with the treble unit mounted in a sphere to avoid diffraction effects. The difference with position was still present on white noise, again clearly so from above the speakers and was reflected from the top of the cabinet. Setting mid and treble units back necessitates steps in the front face of the cabinet, and these may be bevelled to reduce reflection. A treble unit was mounted off centre in the usual way near the top of the front panel of a typical rectangular cabinet. The edges of the cabinet were bevelled to reduce diffraction. A removable 7.8cm thick panel with a 45° bevel was fitted below the treble unit. On white noise, there was a small but definite difference with and without the panel. The effect of the panel on the frequency response was to create a small dip at 2kHz. It seems that any audible effect due to the acoustic centres being in the same plane is very small and is masked by reflection.

Other sources of spurious radiation

Other components of the speaker besides the cone may give spurious radiation. The surround in particular is of appreciable area and tends to move out of phase with the diaphragm, especially at large excursions at low frequencies. Also, it is well known that an insufficiently damped surround will give a dip and a peak in the response curve. The units could operate without surrounds. The moulded edge of the expanded polystyrene could be a clearance fit in the chassis rim. The clearance would be filled with a suitable magnetic fluid, a retaining magnet being incorporated in the rim of the chassis. The outer edge of the cone and inner edge of the chassis would need to be rounded to reduce diffraction. Two rear suspensions would probably be necessary for centering the bass unit.

Dust domes are another possible source of spurious radiation. There are two possible forms

- A rigid airtight continuation of the cone. This must meet the peak criterion; on an area basis, the radiation will be about 14dB below that of the cone.
- An open structure, allowing free passage of air. This assumes that the acoustic resistance offered by the magnet gap is sufficient to avoid losing bass. Rather than being strictly dust-tight, this prevents most foreign bodies from entering the magnet gap. Measurements showed that the conventional undoped impregnated fabric dome and plugs of (flexible) open-cell urethane foam were satisfactory. Any radiation by these components would be largely cancelled acoustically because of their open structure.

Voice coils are another possible source of resonance. The compliance of the neck of the former may resonate with the mass of the cone. The neck will deform by direct tension and compression, but is unlikely to buckle except for very long formers in thin material. It can be easily shown that the load needed to cause elastic buckling of the former far exceeds the load due to the driving force. A typical 2.5cm diameter former in kraft paper may resonate around 8kHz, and in many moving coil tweeters, the output consists mainly of cone and coil resonances. In the present case, short 3.8cm diameter formers in epoxy-glass fibre and in carbon fibre were stiff enough to avoid resonance in the audio range.

Another source of coloration is reflection from obstacles behind the cone or resonance of air cavities created by such obstructions, for example the chassis. It is well known that the rear radiation from a speaker is seldom as clean as that from the front. Listening tests were made with white noise fed to the unit with a very open chassis. On a flat baffle, the slightest obstruction at the rear was immediately audible from the front. The speaker was then mounted in the wall of a room and obstructions introduced at the rear. Small obstructions corresponding to a chassis were detectable, but gross obstructions, for example a shallow enclosing box were clearly audible. Providing the enclosure was fairly deep and filled with absorbent, it was very difficult to detect.

Acoustic interference between units is noticeable on sine wave in bad cases for example where two treble units are used in parallel, perhaps to increase power handling capacity. The loudness varies on moving the head. In more typical cases, the transient test results are poor at crossover frequencies, but whether this produces an audible effect is not known. It may be desirable to avoid crossing over in the mid-range where the ear is most sensitive to coloration. It might be passible to reduce interference by means of careful co-axial design.

D. A. Barlow, B.Sc. M.Sc. Ph.D. F.A.E.S. . . . unemployed

Don Barlow left Fane Acoustics when they closed down their laboratory last year, reluctantly joining the unemployed. And it was another closure that forced him to leave the Rank Leak Wharfedale research laboratory three years before that. At RLW, he worked on a viscous-filled sphere suspension for turntables, also developing a lightweight tubular enclosure designed to be free from panel resonances. But perhaps his most well-known contribution to audio is the sandwich loudspeaker that he developed and produced whilst with H. J. Leak & Co. in the 1960s. He actually conceived the idea (*WW* Dec 1958, pp 564-9) in his spare time, his job then being concerned with the properties of aluminium alloys following graduation in metallurgy at Birmingham University back in 1943, and through which he gained an external M.Sc. 12 years later. Two other *WW* articles which reflected another spare-time interest — groove deformation in records — were published in May 1957, pp. 228-30 and April 1964, pp. 160-6.

Fallibility of listening tests

In production, the sensitivity of units will vary due to variation in mass of diaphragm, mass of dope applied, mass and resistance of voice coil, and magnetic flux. In a multiple speaker system, it is well known that if the units are not carefully matched for sensitivity, the whole character of the sound is altered. Furthermore, we have already seen that the character is altered by small differences in shape of response curve. Again, in listening tests on amplifiers in 1972, it was found that a gradual slope of +2dB from bass to treble due to slight inaccuracy of equalization gave a different character from the reverse slope. Speakers may well be judged on the character of sound which the listener prefers, rather than on the quality. Speakers used by the British Broadcasting Corporation have to meet very close tolerances, perhaps in order to maintain the same character of sound. Harwood[19] has described errors which can arise in listening tests. The question arises: if a speaker were built to be free from coloration, would it be recognised as such?

References

1 Stroboscopic holographic interferometry for transducers. *Wireless World*, vol.73, 1967, p.471.
Barlow, D.A. Rank Leak Wharfedale Research Report 1970.
Fryer, P. A. Lecture to A.E.S. London, 12 June 1973.

2 Fryer, P.A. Holographic investigation of speaker vibrations. 50th A.E.S. Convention, London, 1975.

3 Barlow, D. A. Rank Leak Wharfedale Proposed Research Programme, 17 Sept., 1971.

4 Fryer, P. A. Intermodulation distortion listening tests. 50th A.E.S. Convention, London, 1975.

5 Bowsher, J. M. 47th A.E.S. Convention, Copenhagen, 1974.

6 Harwood, H. D. Audibility of phase effects in loudspeakers. *Wireless World*, vol.82, 1976, pp.30-2.

7 Barlow, D. A. Rigidity of loudspeaker diaphragms. *Wireless World*, vol.64, 1958, pp.546-9.

8 Barlow, D.A. Lecture to Brit.I.R.E. (now I.E.R.E.), 24 Jan., 1962.
Barlow D. A. Development of a sandwich-construction loudspeaker system. *J.A.E.S.*, vol.18, 1970, pp.269-81.

9 Thiele, A. N. Loudspeakers in vented boxes. *Proc. I.R.E. (Aust.)*, vol.22, 1961, pp.487-508. Reprinted in *J.A.E.S.*, vol.19, 1971, pp.382-91 & 472-83.

10 Garner, A. V. & Jackson, P. M. Theoretical and practical aspects of loudspeaker bass unit design. 50th AES Convention, London, 1975.

11 Collinson, J. D. Lecture to A.E.S., London, 2 March 1976.

12 Barlow, D.A. Letter, *Wireless World*, vol.71, 1965, pp.614-5.

13 Falkus, A.E. Private demonstration, April 1975.

14 Barlow, D. A. Sound output of loudspeaker cabinet walls. 50th A.E.S. Convention, London, 1975.

15 Cooke, R. & Fincham, L. Lecture to Brit. Kinematography, Sound & Television Soc., London, 16 March, 1969.

16 Wall, P. K. Active and passive loudspeaker crossover networks without transient distortion. 50th A.E.S. Convention, London, 1975.

17 Baekgaard, E. Loudspeakers – the missing link. 50th A.E.S. Convention, London, 1975.

18 Nomoto, I., Iwahara, M. & Onoye, H. Demonstration film to A.E.S., London, 11 May 1976.

19 Harwood, H. D. Some factors in loudspeaker quality. *Wireless World*, vol.82, 1976, pp.45-54.