Bookshelf loudspeaker Mk II

Improvements to the October 1977 design

by **Jim Wilkinson,** Sony Broadcast

Following the publication of the original loudspeaker article[1] KEF ceased production of the T15 tweeter used in the design. Although existing stocks would meet the initial demand, in order to ensure the usefulness of the loudspeaker for several years to come an alternative tweeter had to be found. A unit which meets the performance criteria is the Audax HD13D34H. This unit is now being fitted to several new commercial designs and thus is going to be around for some time to come. Introducing this new unit initiated further rounds of measurements which revealed some shortcomings in the original theory and this article reveals the details of the new design.

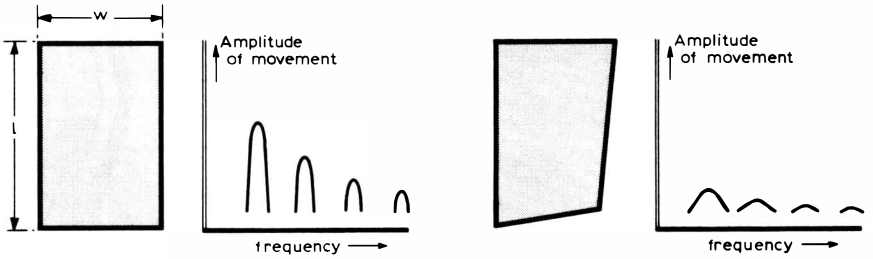


Fig. 1. *Cabinet resonance factors, comprising the effects of parallel and non-parallel sides*

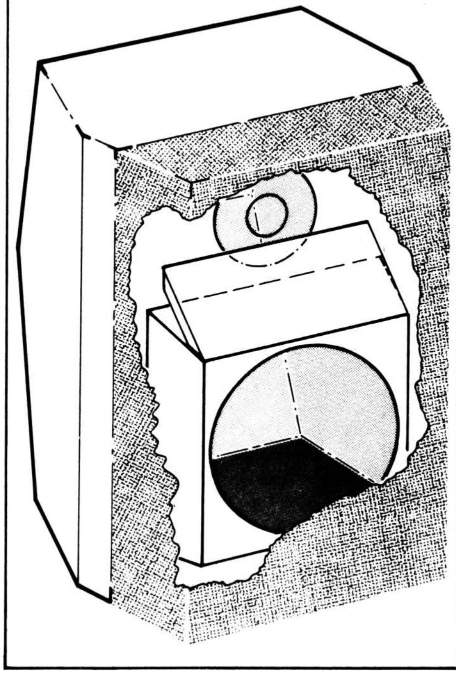


Fig. 2. *Shape of the completed cabinet*

THE ORIGINAL loudspeaker included a number of features which are retained, one of these being the use of the 4th order crossover network. The high rate of cut-off (24dB per octave) ensures that the response of each unit does not have to be maintained more than one octave beyond the crossover frequency. Unlike the more common 3rd order Butterworth filter, the 4th order network is instrumental in obtaining a symmetrical vertical polar pattern, by ensuring that the phases of signals fed to the bass and treble units are identical and independent of frequency. Although the crossover network is one of the most complex available today, the trend towards more involved networks is continuing as designers realise that simpler networks cannot achieve the same performance. Even so, the total cost of one network is less than the cheaper drive unit. This particular network also has the advantage of being exceptionally easy to drive.

Another retained feature is that of staggered drive units. This method is the second stage in obtaining a totally symmetrical polar pattern. Essentially required to align the voice coils of bass and treble units, the time shift must also account for any additional errors introduced by these units. It is accepted that a high quality loudspeaker should have a wide (and symmetrical) horizontal dispersion for realistic performance. It follows, therefore, that such a loudspeaker should also have a wide and symmetrical vertical dispersion and since even the 4th order crossover is active over a frequency range of two octaves then inserting the correct time delay is essential. Finally, the technique of diagonal bracing of the cabinet walls is retained. There are essentially two methods for building a cabinet. The first is to make the box as rigid (which includes as much mass) as possible and the second is to use light walls which are heavily damped with thick felt panels. This latter method allows some antiphase sound to be radiated but attenuates panel resonances significantly.

The approach in this design is to adopt the rigid box method using a combination of techniques (diagonal bracing being one) to reduce panel resonances.

The cabinet design

The internal dimensions of the original cabinet were 440 × 270 × 180mm which results in a system resonance of 55Hz. No change is required in the enclosure volume, but considerable thought has been given to the internal shape.

A simple box with rectangular sides and parallel walls quite readily allows a whole series of resonant modes. The formation of standing waves in such a cabinet is well documented and it is normal to fit large amounts of acoustic wadding to absorb the energy, thus attenuating the standing waves. Solutions to the cabinet wall resonances commonly involve bracing techniques but often they only succeed in raising the frequencies of the resonant points rather than attenuating the level of vibration. A mathematical study of the modes of vibration is complex but a useful starting point is given in ref. 2. The modes of vibration of a panel of length l, and width w, are a function of these two dimensions and give rise to preferential frequencies of vibration proportional to $1/l$ and $1/w$. There is no practical way of eliminating panel vibrations for a cabinet of this size. On the other hand, if these modes could be distributed over a band, then the Q of each resonance would be lowered. Consequently, the panel frequencies would be more evenly distributed and this can be achieved by using non-rectangular cabinet walls.

A cabinet which employs non-parallel sided walls will, in a like fashion, lower the Q of each standing wave. By combining these two techniques, a significant improvement in cabinet resonances can be achieved. Some considerable time was spent creating and

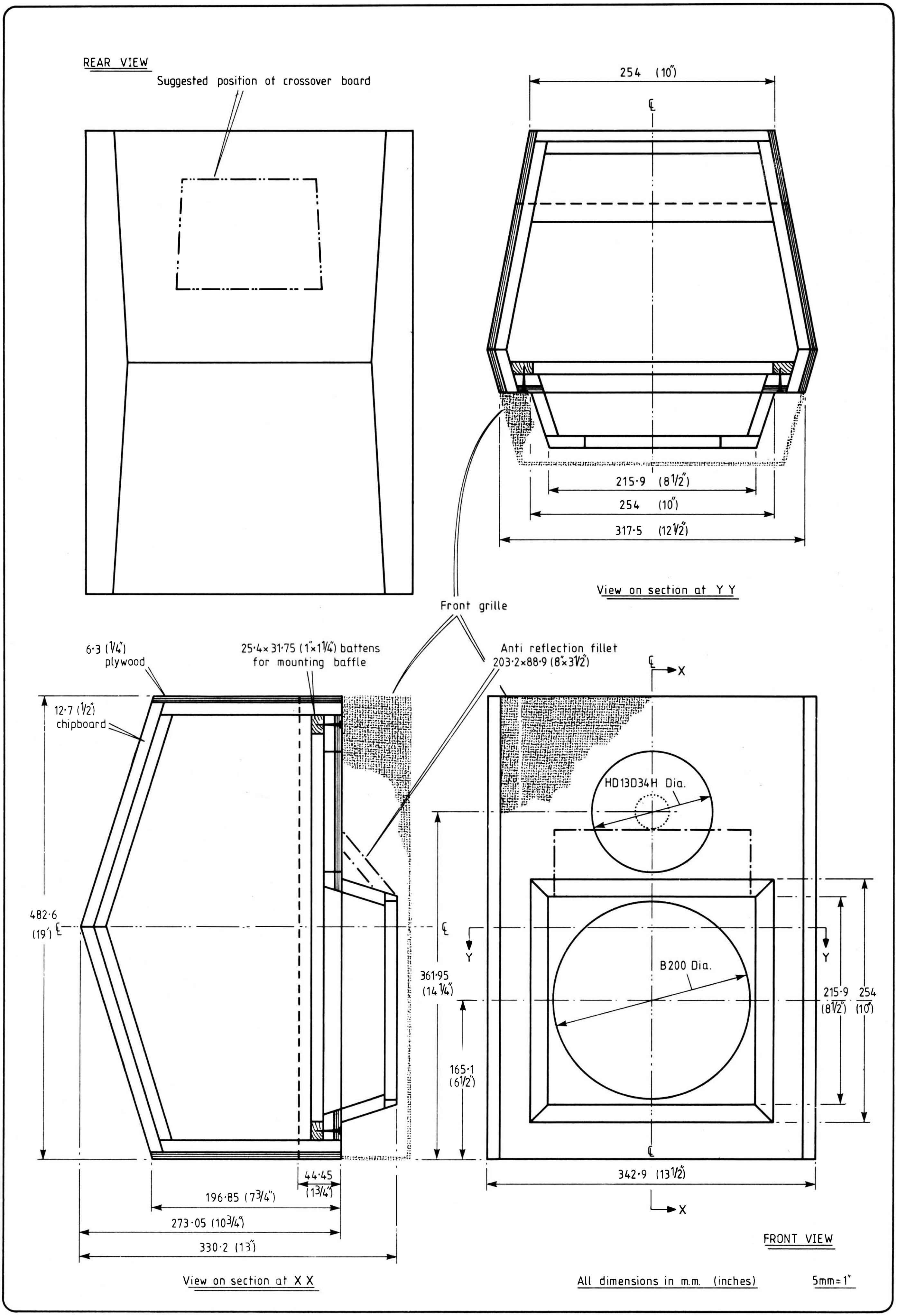

REAR VIEW
Suggested position of crossover board
254 (10″)
215·9 (8½″)
254 (10″)
317·5 (12½″)
View on section at Y Y
Front grille
6·3 (¼″) plywood
25·4×31·75 (1″×1¼″) battens for mounting baffle
Anti reflection fillet 203·2×88·9 (8″×3½″)
12·7 (½″) chipboard
482·6 (19″)
X
X
HD13D34H Dia.
B200 Dia.
Y
Y
361·95 (14¼″)
165·1 (6½″)
215·9 (8½″)
254 (10″)
44·45 (1¾″)
196·85 (7¾″)
273·05 (10¾″)
330·2 (13″)
342·9 (13½″)
FRONT VIEW
View on section at X X
All dimensions in m.m. (inches)
5mm=1″

Fig. 3. *Full engineering drawing of cabinet (see left)*

evaluating various cabinet shapes, concentrating on those which could be build by the amateur and which would be pleasing to the eye. Further points of consideration are cabinet diffraction effects and the need for staggered drive units. The only rectangular panel is the baffle but here the drive units themselves break up the standing wave patterns. The chamfered corners at the front of the cabinet help reduce acoustic reflections which naturally occur at sharp boundaries.

A cabinet based on this shape was built and compared directly against the original. The latter cabinet never showed any signs of boxiness, indeed the triangular bracing and extra thick rear wall should have eliminated any such possibility. The new cabinet definitely sounds better and experiments have shown that it is not a simple diffraction effect. The difference seems particularly audible on male speech, the new cabinet being slightly more mellow in character. Interchanging the drive units and crossover proved that the cabinet itself was providing the difference. NB: Those readers who wish to retain the original cabinet whilst updating the tweeter can easily do so provided, of course, the new crossover network is installed. The improvement is still worthwhile.

Construction of the cabinet is much the same as the original design, but the use of non-rectangular joints means that a multi-angled power saw and circular sander are almost mandatory. The overall method of construction is essentially the same as the original article. There is, however, an additional bracing piece which is placed between the centres of the two side walls of the cabinet, these two walls being the weakest. This bracing piece should be a tight fit which is glued prior to hammering into place. The internal walls of the cabinet are coated with a layer of car underseal (or Rubberoid mastic, available from builders merchants), then about 75% of the available wall area is further damped by pinning on bitmus felt panels. The recommended acoustic wadding consists of two rolls of 2in BAF, each roll formed from a piece 3ft × 9in (914mm × 228mm). The rolls are fitted into the top and bottom halves of the cabinet, separated by the centre brace.

When the drive units are fitted to the baffle a new piece of timber (12mm thick) is fitted to present a continuous surface between the bottom of the tweeter diaphragm and the top edge of the bass unit, which functions as an anti-reflection fillet. This prevents unwanted acoustic reflections from the top of the bass unit sub baffle (Fig. 4).

The crossover circuit

This is the most complex area of any loudspeaker design and is in this case the result of considerable thought. Over the past few years, several manufacturers have produced loudspeakers which preserve waveform fidelity, claiming that waveform distortion is audible. The 4th order crossover network produces gross waveform distortions (Fig. 5) which should be audible were the ear sensitive to phase shifts. A simple test was arranged in order to make listening tests of this distortion and an active network of the type shown in **Fig. 5** was built to simulate the effect of such a circuit. This was inserted into the feed to a studio monitor loudspeaker via a switch. By switching the network in and out, this waveform could be introduced. The loudspeaker used in the test had its own minor waveform distortion, but further distortion should still show up as a difference. None of the three listeners (all experienced hi-fi enthusiasts) could detect any difference using either music or white noise sources, although, when a square wave at 500Hz was applied a slight tonal change could be heard. Further tests showed that there was a 0.25dB gain difference between the high and low pass filters. This error was corrected and the tests resumed. Now no difference could be heard at all with any type of source, emphasing just how carefully any test should be controlled before attaching significance to the result.

At least one other designer has arrived at the same conclusion for the 4th order crossover network. This in no way implies that phase distortion of any kind cannot be heard since gross errors have been proved audible, but that the level introduced by this type of crossover is inaudible.

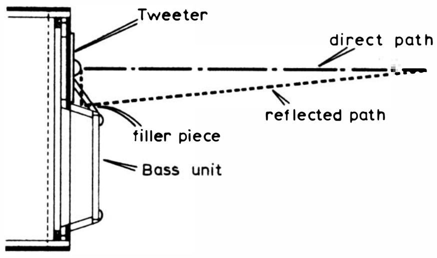


Fig. 4. *Location and effect of filler piece*

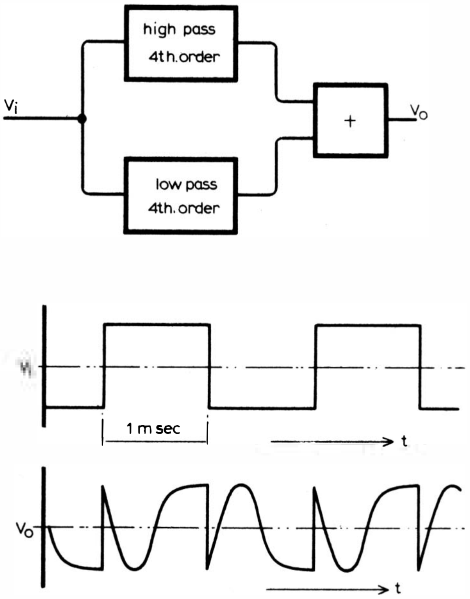


Fig. 5. *Active filter network showing typical 4th order waveform distortion*

One of the most important parts of any crossover network is the method of compensating for drive unit deficiences. Early theoretical work showed that the on-axis pressure response of a direct radiator would rise with increasing frequency (tending towards 6dB/octave), this being coupled with a reduction in the radiation angle. The exact frequency at which this effect starts to become significant is a complex function of the effective cone diameter, the shape of the cone and the velocity of wavefront propagation across the cone surface. The rising response is coupled with cone resonance effects (the drum effect, also known as "bell modes," is explained mathematically in ref. 2), cabinet diffraction effects, roll surround reflections, the voice coil inductance and the high frequency cut-off between the voice coil and the cone. All these effects will combine to produce an on-axis pressure response which is complex and difficult to understand.

Any practical crossover will attempt to compensate for the overall effect rather than for individual effects, and

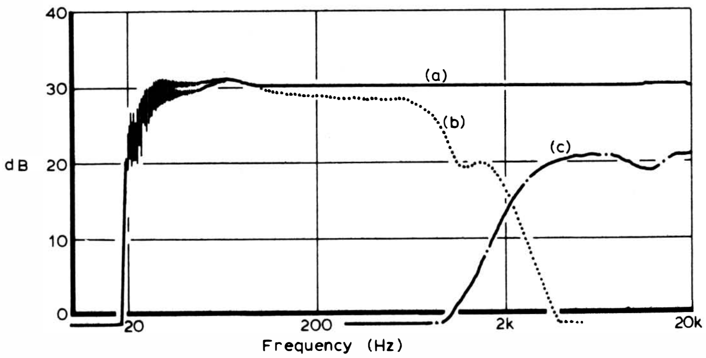


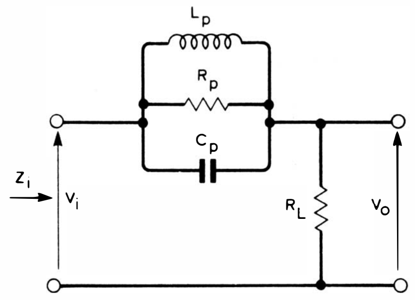
Fig. 6. *The signals applied to the B200 and HD13D34H*

(a) signals to crossover

(b) signal to B200

(c) signal to HD13D34H

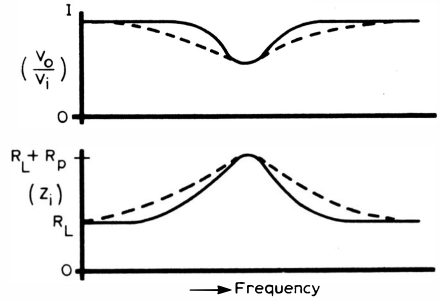
no single network has been found which will give the desired response. However, a combination of two cascaded functions helps to solve the problem. The first is the addition of a suckout filter, the second a modification of one of the Butterworth low pass filter sections. The crossover frequency has been set at 2.2kHz, but one of the low pass Butterworth filters has been lowered to give a −3dB point at 1.3kHz. This results in the voltage applied to the terminals of the bass unit emerging as shown in the left-hand response of Fig. 6. The tweeter needs only one compensating network for a peak of 3.5dB at 11kHz. The suckout is evident from the right-hand response of Fig. 6 which is the signal applied to the tweeter.



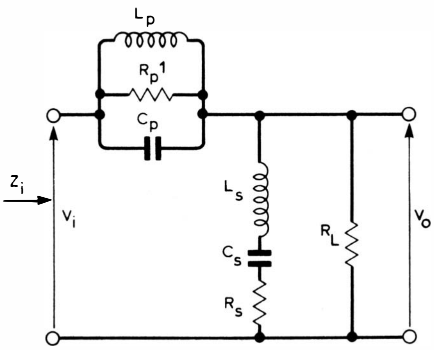
$$\frac{V_o(s)}{V_i} = \frac{s^2 + {}^{s}/_{C_pR_p} + {}^{1}/_{L_pC_p}}{s^2 + {}^{s}/_{C_pR_x} + {}^{1}/_{L_pC_p}}$$

$$\text{where } R_x = \frac{R_L R_p}{R_L + R_p}$$

Fig. 7. *Suckout filter circuit and related equations*



The principle of cascading 2nd order Butterworth filters to produce the 4th order high and low pass filters was explained in the original article. However, in this network there is a requirement for cascading the Butterworth filters with the suckout filter and the basic suckout filter is shown in Fig. 7, the related equations being in the 's' domain. The dotted line shows the effect of increasing the value of the inductance (the capacitance being decreased by the same factor). The response showing the input impedance of the network displays clearly that this is far from resistive and is, therefore, unsuitable for cascading. Adding a second tuned circuit can completely solve this problem provided the set network conditions are met (Fig. 8). This network is used to compensate for a broad peak (at 1.2kHz) in the bass unit response. A simple network based on Fig. 6 is used to compensate for this response anomaly in the tweeter. Figs. 9 and 10 show four pressure response curves for the loudspeaker. All were measured on a dry, warm day. A framework, some 3m high, supported the loudspeaker, with the microphone supported on its tripod. Some reflections are bound to occur at this height and cancellation effects can be seen at 120Hz, 170Hz and 260Hz. Fig. 9 shows the on-axis response of the bass unit, which also indicates the effectiveness of the compensation networks. Fig. 10, parts a, b and c show the response of the completed loudspeaker on axis, 30° horizontally off axis and 45° horizontally off axis respectively. Lowering the crossover frequency from 3kHz to 2.2kHz has ensured a wide horizontal response which is evident from these readings. www.keith-snook.info



(1) $\mathrm{Loss}_{(max.} - \dfrac{R_s R_L}{p \quad s \qquad s}$

(2) $R_p^{1} + \dfrac{R_s R_L}{R_s + R_L} = R_L$

(3) $C_s = \dfrac{L_p}{R_L^{2}}$ (4) $L_s = C_p R_L^{2}$

Fig. 8. *1.2kHz filter circuit and network conditions*

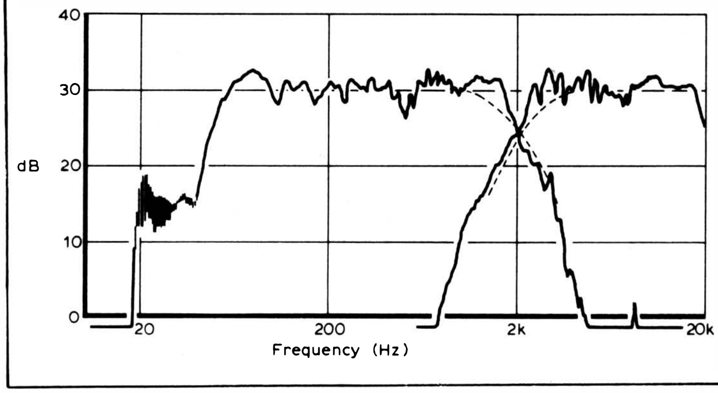


Fig. 9. *Pressure response of B200 unit with filter included – the dotted line shows the ideal response*

One point which could cause trouble is that, in lowering the crossover frequency, the tweeter could possibly run into frequency doubling problems.

The power to the tweeter is reduced by a factor of 0.25 so that it matches the sensitivity of the bass unit. This means that the loudspeaker can accept at least 25W at any frequency. A level of 25W was applied, sweeping the frequency over the full audio range. With the bass unit replaced by a load resistor, no obvious frequency doubling occurred in the tweeter.

The suggested amplifier power rating is 25 to 100W r.m.s. into 8Ω. A higher power amplifier can actually be safer for the tweeter since the onset of distortion in a lower power amplifier produces high levels of harmonics which can easily destroy a tweeter, although in this particular design there is sufficient power headroom to make this eventuality extremely unlikely.

As one of the design objectives of this loudspeaker was to produce a symmetrical vertical polar response, it is possible to measure the phase error between the two units. Such a measurement has been performed and indicates that, for ±0.5 of an octave either side of the crossover frequency, the phase difference between the two drive units is better than 30°. Measurements beyond ±0.5 of an octave are difficult as the level of one signal becomes unusable. The complete crossover network is shown in Fig. 11 and three values of attenuator for the tweeter are given. If required, a simple switch can be used to give two variations on the nominal setting. Note that no Zobel network is needed for the tweeter as this has a very well controlled impedance over the frequencies of interest. To obtain the best performance from the crossover network, high grade 5% tolerance components should be used throughout. Some leeway is permissible on the components marked with an asterisk.

The resistor power ratings allow for a continuous 25W to be applied to the loudspeaker. No significant distortion (in the general sense) is introduced by the network at this power level at any

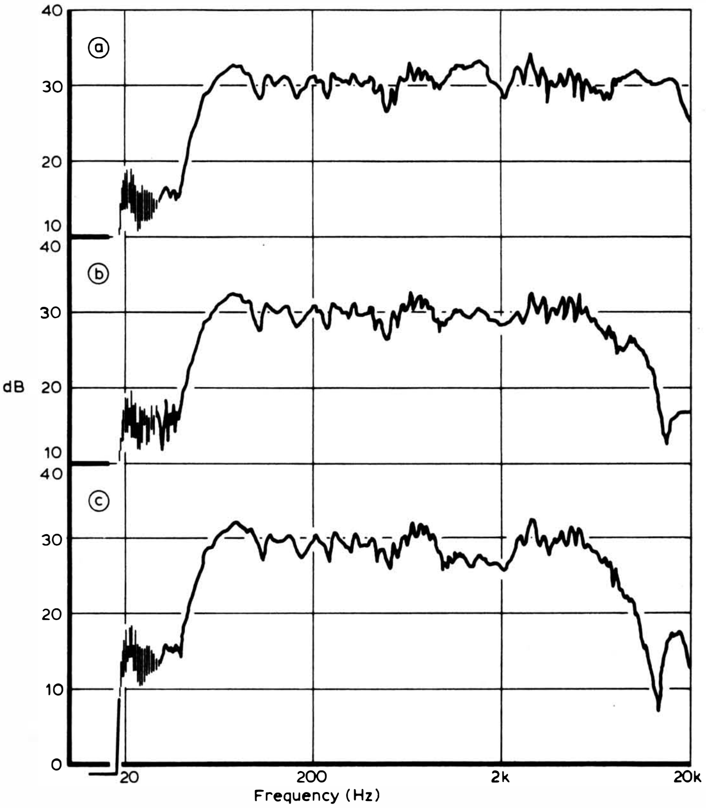
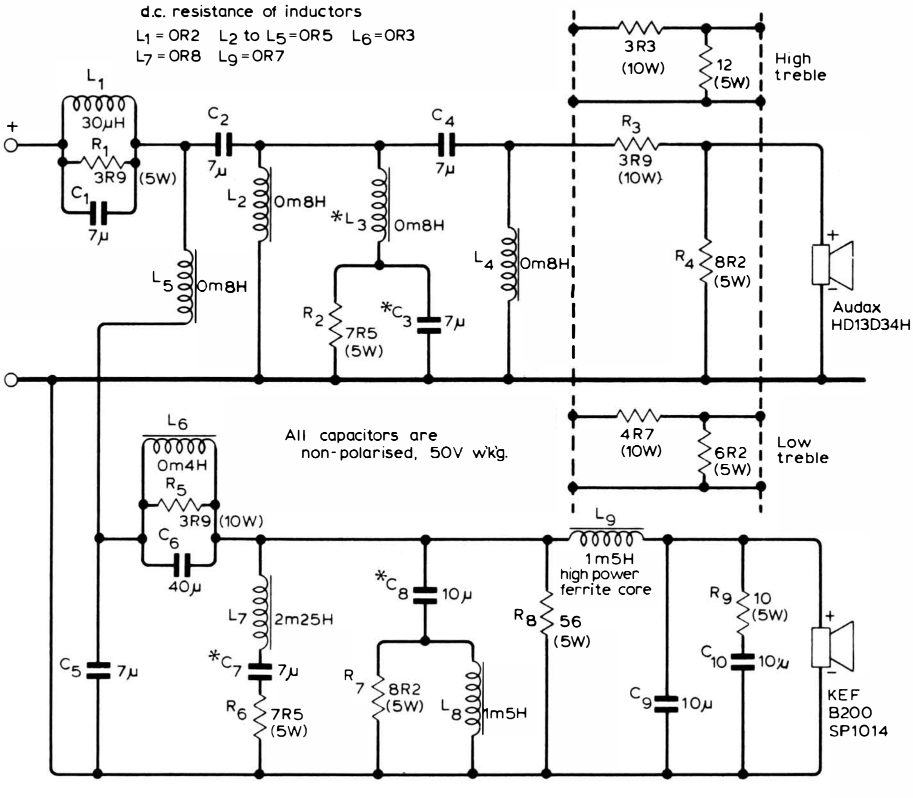
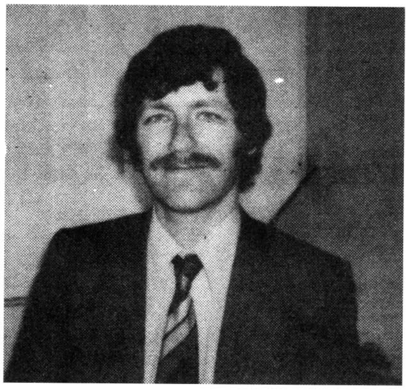


Fig. 10. *Three pressure responses of the complete loudspeaker*

(a) on axis (b) 30° off axis (c) 45° off axis

Fig. 11. *Full schematic of the c*





Jim Wilkinson studied at Sheffield Polytechnic prior to joining Marconi Elliott Avionics where he worked on raster-based avionic display systems. Subsequently he joined the IBA, working for over four years on digital video equipment, specialising in phase-locked-loops and differential p.c.m. coders. He is currently a project engineer in the advanced development laboratories of Sony Broadcast.

frequency in the audio band, using inductors from the recommended supplier. The network's design accounts for each inductor's resistance and the use of air-cored inductors is not recommended unless similar resistance values could be achieved. Further, the effect of using an active crossover network has been simulated and no real advantage emerged over the use of passive components apart from a slight improvement in the damping of the system resonance. Furthermore, the cost penalty for using an active network is quite high and does not have the flexibility of a passive network.

The author recorded the terminal impedance between 100Hz and 20kHz, which emerged as 8Ω (+3Ω or −1Ω) and 0° ±10° for magnitude and phase respectively, showing that the loudspeaker is easily driven by any amplifier.

Frequency traces were made using a Brüel and Kjaer frequency response recorder. The materials for acoustic damping of the cabinet comprise three bitumenised felt panels, approximately 9in by 7in and two pieces of BAF wadding, 36in by 9in. Where difficulties are experienced in obtaining the specified components and materials, these are all available from Falcon Acoustics, Tabor House, Norwich Road, Mulbarton, Nr. Norwich, or any of this company's suppliers.

References

1. Wilkinson, J. H. "A high quality bookshelf loudspeaker," *Wireless World*, October 1977, pp.42-46.
2. Kreyszig, Erwin. Advanced Engineering Mathematics, Wiley International, pp.440-453. www.keith-snook.info

Further reading:

Linkwitz, Siegfried. "Loudspeaker system design," *Wireless World*, May & June, 1978.

Schroeder, Manfred R. "Models of Hearing," *Proc. I.E.E.E.*, Vol. 63, No. 9, September 1975.

Baranek, Leo L. "Acoustics," McGraw Hill, Chapter 4.

$$\text{or } R=R_o 1-\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t$$

The current is given by:

$$i=\frac{v_{ntc}}{R}$$

$$=\frac{\sqrt{2}v_o\cos\omega t}{R_o\left(1-\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t\right)}$$

which is nearly equal to

$$\frac{\sqrt{2}v_o}{R_o}\cos\omega t\left(1+\frac{BP_o}{2\omega HT_o^2}\sin 2\omega t\right)$$

$$=\frac{\sqrt{2}v_o}{R_o}\left(\cos\omega t+\frac{BP_o\sin\omega t}{2\omega HT_o^2}\ \frac{\sin 3\omega t}{2}\right)$$

The current is thus composed of the fundamental and of a third harmonic. This would be the same if a voltage, composed of a fundamental and a 3rd harmonic, were applied to a fixed resistor R_o. For the fundamental component, the term is negligible with regard to the term cosωt; so, the third harmonic distortion can be approximated by

$$d_3=\frac{BP_o}{4\omega HT_o^2}$$

$$\text{or } d_3=\frac{B\delta\Delta T}{4\omega H(T_{amb}+\Delta T)^2} \quad (9)$$

Table 1. *Distortion measurement results.*

Frequency (Hz)		110	263	520	1092	2636	5224	9564
Harmonic components (dB)	H2	−104	−112	−117	−122	−119	−113	−108
	H3	−117	−124	−121	−117	−116	−115	−114
	H4	−121	−124	−124	−123	−125	−123	−123
	H5	−119	−120	−121	−120	−118	−118	−119
	H7	−125	−128	−130	−126	−128	−126	—

Measurements were made using an HP3580A spectrum analyser preceded by a passive notch filter, giving a measuring limit of −130dB.

This function is zero for $\Delta T=0$ and $\Delta T=\infty$. Its maximum is reached for $\Delta T=T_{amb}$ (in K). For small values of ΔT, the distortion is almost proportion to ΔT. The expression $B\delta/H$ can be seen as a measure for the distortion proper to a certain type. For the used n.t.c., $B=3900$k, $\delta=0.11$mW/K and $H=0.5$mJ/K.

Using (1), expression (9) can be transformed to:

$$d_3=\frac{1}{4\omega\tau}\left(-\frac{T_{amb}}{B}\ln\frac{R_{amb}}{R_o}\right)\ln\frac{R_{amb}}{R_o} \quad (10)$$

Where $\tau=H/\delta$ thermal time constant of the n.t.c.

R_{amb}=n.t.c. resistance at the ambient temperature

R_o=n.t.c. resistance at the operating point.

In the particular case when R_o is only slightly less than R_{amb} we have

$$\ln\frac{R_{amb}}{R_o}=\ln\left(1+\frac{R_{amb}-R_o}{R_o}\right)$$

$$\approx\frac{R_{amb}-R_o}{R_o}$$

and (10) becomes $d_3=\frac{1}{4\omega\tau}\ \frac{R_{amb}-R_o}{R_o}$,

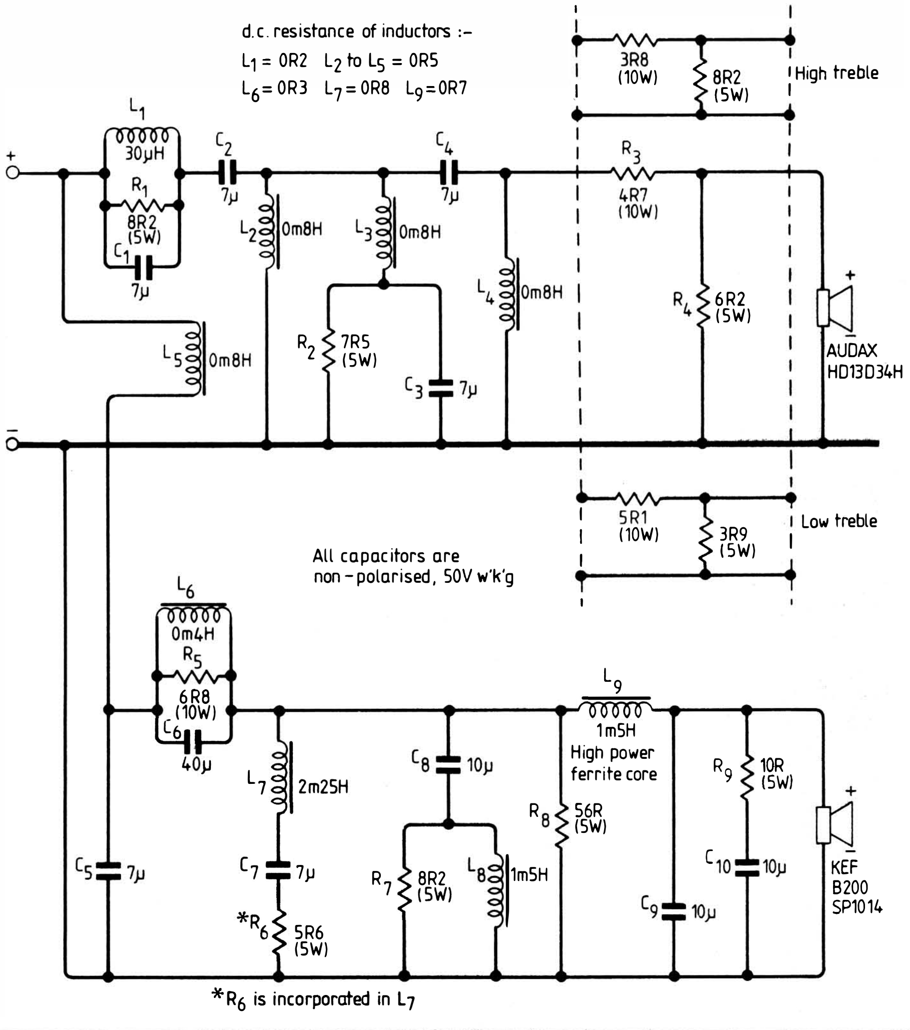
which conforms to the analysis of Dr F. N. H. Robinson (*Int. Journal of Electronics*, No. 2, 1980). In our circuit, the calculated n.t.c. distortion is about 0.13% at 20Hz which would give a distortion figure of 0.05% at the output of A₃. The measured distortion is 0.1%. The reason for this difference has not been determined exactly, though it looks as if H decreases at increasing frequency. This could be explained by the spherical shape of the n.t.c. material which causes a non-uniform current density and hence, especially at higher frequencies, a non-uniform temperature variation inside the n.t.c.

Book-shelf loudspeaker improvements

An article by J. Wilkinson describing the design and construction of a high-quality book-shelf loudspeaker was originally published in the October 1977 issue and improvements to the design followed in the June 1979 issue. Subsequent testing has prompted further small improvements.

Three small component changes in the crossover circuit have been made. One of these, namely changes in value of R₃ and R₄, has resulted from critical listening and comparison tests and gives a few dB attenuation in all three switch settings to compensate for room reflections of the tweeter's output. Changes in the values of R₅ and R₆ give a little extra dip in the crossover's output response curve at around 1kHz to compensate for a peak in the woofer's response curve at this frequency. Connecting the input of the low-pass filter before, instead of after L₁ gives a virtually inaudible improvement in performance but is nevertheless the best option from a theoretical viewpoint.

Extensive listening tests have also revealed a slight deterioration in sound quality caused by the 'anti-reflection' fillet attached to the bass-unit sub-baffle. The best solution is to replace the wood with 1/2in bituminous felt or similar material. A modified printed-circuit board, all the necessary components and the speakers can be obtained from Falcon Acoustics Ltd, Tabor House, Norwich Road, Mulbarton, Nr Norwich, Norfolk NR14 8IT.



*R₆ is incorporated in L₇