Horn loudspeaker design

Three articles summarizing the development of design theories and concluded with two systems for construction

by J. Dinsdale, M.A., M.Sc. *Cranfield Unit for Precision Engineering*

Reprinted from WIRELESS WORLD, June 1974

The two designs which follow are specific examples derived from the design data and tables provided in parts one and two of this series. Guidelines for construction are given, although it is intended that the constructor devise his own variations, using the design data, to suit his particular requirements.

Much has been written about the best methods of constructing loudspeaker enclosures, especially regarding rigidity and the prevention of resonances and leaks, and as far as the horn is concerned, these points are equally important. The horn enclosure has to stand up to considerable acoustic stress, and any shortcomings in its manufacture are liable to cause more serious aural distress than would be the case with some other enclosures.

Ideally, the horn should be cast in circular section, but this form of construction is only practical with small middle and high frequency horns. The technique best adopted by the home constructor is to cast in plaster-of-Paris using a plywood mould and reinforcements as necessary. The calculated profile should be set out using plywood plates held in place by stringers, which [illegible] be buried within the casting itself as "reinforcement". It is also a good plan to provide a $\frac{1}{2}$in panel at the throat end for mounting the loudspeaker, and a further panel surrounding the mouth which will help in securing the complete horn assembly and fixing any decorative cloth finish.

Bass horns are almost invariably constructed of flat panels cut so as to approximate to the correct flare profile. Plywood, chipboard or blockboard are satisfactory, either $\frac{3}{4}$ or $\frac{1}{2}$in thick. Composite sand-filled panels consisting of two thin walls of $\frac{1}{8}$in plywood spaced $\frac{3}{4}$ or 1in apart and filled with dry sand provide extremely rigid resonance-free enclosures. Great care should be taken to prevent any particles of sand, sawdust, etc. from entering the speech-coil gap of the loudspeaker; a recent demonstration mounted by the author at St. Albans was spoiled by distortion caused by a minute particle of wood in one of the treble loudspeakers. Care must also be taken to ensure that the sand is dry, otherwise the wood panels will rot. It is advisable to bake the sand on shallow trays in an oven to ensure that all moisture is removed. After filling, a few minutes of organ music will help the sand to settle down ready for "topping-up".

The wooden panels should be fixed together using wood-screws and with a liberal application of a liquid glue along all mating faces. This not only adds strength, but also makes all the joints air-tight. Further strength should be provided by triangular corner fillets and "glue-blocks" placed at intervals along the longer joints. In addition, smaller reflecting plates should be placed at the outside of all sharp corners to "ease" the wavefronts around bends, and to help preserve the steady exponential increase in horn area, as indicated in Fig. 10. Manufacturing tolerances should not exceed $\pm\frac{1}{16}$in at the throat but errors of $\frac{1}{2}$in at the mouth of the bass horn are unlikely to have any noticeable effect on the performance. It is worth bearing in mind that the velocity of sound, on which all design calculations are ultimately based, itself varies by as much as 5% at climatic extremes.

A vital detail is to ensure that the loudspeakers can be fitted and removed easily, maintaining an overall air-tight construction by means of thin rubber gaskets if necessary. It should of course be remembered that the highest pressures occur at the throat, and the greatest effort to ensure rigidity and absence of leaks should be made in this area. As the cross-sectional area of the horn increases, it is a good plan to fit longitudinal stiffening panels, made of $\frac{1}{4}$in plywood, across the centre of the horn, thereby converting the horn into two symmetrical adjacent ducts. This reduces air turbulence effects at bends and makes the bends themselves less critical in addition to providing extra cross-bracing between panels that might otherwise resonate. It is worth fitting longitudinal stiffeners for the final 25% of each bass horn.

Unlike the majority of loudspeaker enclosures, there is no need to provide any sound absorbent material within the enclosure itself (except within the compression chamber, if fitted, which may be lined with acoustic wadding, long-hair wool, etc., to absorb high frequency sound). The interior of the horn should have all sharp edges removed with sandpaper and all internal corners filled with putty or a similar setting plastic compound and smoothed down by means of a finger. This practice, which is not mandatory, also has the effect of sealing any remaining air leaks. The whole interior surface should be treated with a thick coat of gloss paint.

Design of a "mini-horn"

The intention of the mini-horn is to provide as many as possible of the benefits of horn-loading within an enclosure which is sufficiently small for use in a small living room, where the overall size is of course especially important when a quadraphonic or even a stereophonic installation is under consideration. The room for which this particular mini-horn was originally designed imposed limitations of 20in as the maximum intrusion into the room, and an overall height of 4ft; fortunately, corner positioning was acceptable.

It was clear that only one loudspeaker could be used, and after some thought, the Eagle FR65 was chosen. This is a co-axial twin-cone loudspeaker in which the inner (tweeter) cone is itself shaped as a small horn. This subsidiary cone will handle the extreme top of the frequency range and beam it out axially through the treble horn. The loudspeaker has a nominal diameter of 6·5in, a frequency range of 35 to 18,000Hz and power handling capacity of 10 watts. It is clear that, since top frequencies will be dealt with by the tweeter cone, the bass horn need only cover 3 octaves, i.e. from 70Hz to 560Hz, and the middle-frequency horn can take over at (say) 500Hz. This middle-frequency horn will be most efficient for 4 octaves, i.e. up to about 8kHz, at which point the tweeter cone will already be taking over. The complete frequency spectrum will therefore be:

Bass horn	70Hz to 550Hz
Middle horn	500Hz to 8000Hz
Top horn (tweeter cone)	8kHz upwards

The other design consideration at this stage is the power handling capacity. A bass power of 0·3 watts at a distortion level of up to 1% was decided.

Bass horn

In order to derive the greatest benefit from corner-positioning, the mouth of the bass horn should be at floor level and should stretch horizontally from wall to wall. A mouth consisting of a quadrant of a circle of 19in radius was considered, giving a horizontal arc of 2·48ft. Examination of Table 3 (Part 2) shows a minimum mouth area of 2·56 sq.ft for a horn capable of reproducing down to 70Hz, and dimensions of 2·48ft × 1·03ft (29·7in × 12·5in) were therefore chosen for the bass horn. Table 7 suggests a throat area of 0·048 sq.ft (i.e. 45 sq.cm) and Fig. 9 indicates that for 1% distortion at 7 times the cut-off frequency (i.e. 490Hz) the power at the throat will be 0·007 watts/sq. cm, giving 0·3 watts total, which is the specified value.

Table 9 shows that the bass horn will have a length of 6·18ft (exponential contour) or 5·24ft (tractrix contour). It was decided to adopt the tractrix so as to give a shorter overall length, and the complete contour has been constructed in Fig. 12.

Treble horn

The treble horn will load the front of the loudspeaker, commencing at the nominal diaphragm area of 23 sq.in, which is thus the throat area for this horn. The lowest frequency to be handled is 500Hz, and from Table 4 the mouth area is 130·4 sq. in, which may conveniently be realized as 10·1in × 12·9in. Table 10 now gives the horn length as 4·42in.

It is also possible to adopt a circular format for this horn, in which case the mouth diameter will be 12·9in or alternatively some degree of horizontal directivity may be introduced by adopting an aspect ratio of 2·5:1 (larger dimension horizontal). In this event the mouth dimensions become 18·08in × 7·23in, and the flare contours should be arranged to give the appropriate expansion (see Fig. 13).

Integration and complete design

Radiation at the throats of the mid-frequency and bass horns will be in anti-phase, since these horns load the front and back respectively of the single loudspeaker. Since the mouths of both horns will be in the same vertical plane, the combined length should be an *odd* number of half-wave-lengths at the crossover frequency to ensure that radiation from both mouths is in phase at this frequency. The total length is 5·24ft plus 0·37ft, i.e. 5·61ft. At 500Hz this length corresponds closely to five half-wavelengths as shown by Table 11. This design thus includes a satisfactory combination of horns.

The cavity which couples the rear of the loudspeaker diaphragm with the throat of the bass horn should now be designed to cut off radiation from the bass horn at 550Hz.

$$V = cS_t/2\pi f$$

where V = cavity volume, S_t = throat area,

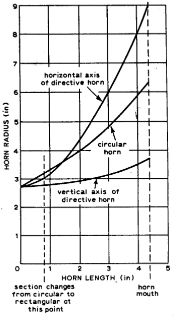

Fig. 13. Flare contour for the treble section of the mini-horn.

f = cut-off frequency, whence V = 27·23 cu.in. The volume taken up by the magnet, etc, of the loudspeaker is approximately 21 cu.in (obtained by direct measurement) and thus the overall cavity volume will be some 48 cu.in. The parameters of the mini-horn have been summarized in Table 12.

Finally, the bass horn should be folded into a suitable shape, and the two horns integrated together. In view of the limited space available and the desire for simplicity,

Table 12
Summary of mini-horn parameters

Bass horn	
Frequency range	70Hz to 550Hz
Driver unit	Eagle FR65
Position	Corner
Mouth area	2·57 sq.ft
Throat area	0·048 sq.ft
Contour	Tractrix
Length	5·24ft
Cavity volume	48 cu.in (including 21 cu.in loudspeaker volume)
Treble horn	
Frequency range	500Hz upwards
Driver unit	Eagle FR65
Mouth area	130·7 sq.in
Throat area	23 sq.in
Contour	Exponential
Length	4·42in

a design with only one major fold may be adopted, shown in Fig. 14(b) (*overpage*). The mouth of the bass horn is at the bottom of the enclosure between the two walls, making contact with the floor. The mouth of the mid-horn is placed immediately above this, in the same plane, leading back to the loudspeaker itself. The loudspeaker is mounted on a small baffle board which supports the middle-frequency horn at the front and the cavity coupling to the throat of the bass horn at the rear. The bass horn bends vertically upwards almost immediately after the throat to a point some 4ft high at which it doubles back on itself down the corner of the room to form the mouth. The cross sectional area may conveniently be made trapezoidal, but the design shown will not preserve "plane-ness" of wavefronts around the bends. Fig. 14(b) (*overpage*) illustrates the general arrangement only, as readers may well wish to make modifications for personal reasons. The material used should be ½in chipboard, etc, except the side and front panels of ¼in plywood.

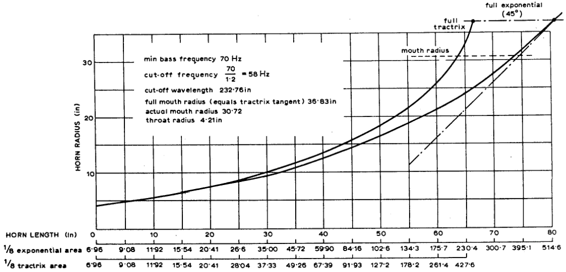

Fig. 12. Flare contour for the bass section of the mini-horn.

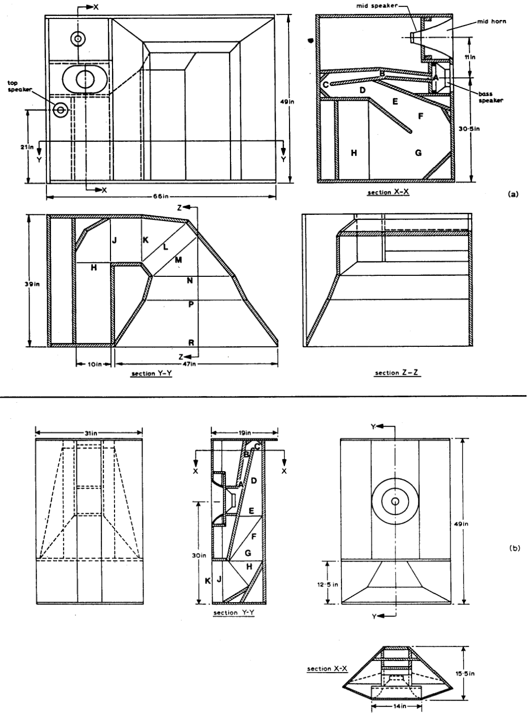

Fig. 14 (a) Suggested realization of the no-compromise horn (b) suggested realization of the mini-horn. Cross sectional details for the mini bass horn are given in Table 14 and for the no-compromise bass horn in Table 15.

Design of a no-compromise horn

Following the many qualifications already stated in this article, it must be clear that "no-compromise" is in itself a misnomer —horn design consists largely of making the most effective compromises between conflicting requirements. However, this design is aimed at the situation where the best possible practice can be followed without being unduly hampered by limitations of either size or position. Nevertheless, it would be somewhat pointless to design an enclosure which cannot be built without professional tools, facilities and materials, so the design has been conducted with a large living room (or small hall) in mind, and directed towards the competent do-it-yourself enthusiast.

In order to cover a wide frequency range, a three-horn design has been adopted, using three separate loudspeaker units.

Bass Horn	40Hz to 440Hz
Mid-frequency Horn	400Hz to 3·8Hz
Treble Horn	3·5Hz to 20Hz

A total acoustic power handling capacity of 1W at a distortion level up to 2% has been chosen as being more than adequate for the situation envisaged. A wall-mounting design is adopted, using a tractrix bass horn, to simplify the eventual positioning of the system. (Of course, there is no reason why a design intended for wall-mounting should not be placed in a corner but it is not recommended that corner designs be placed against a wall.)

The choice of loudspeaker drive units is not straightforward; there are many commercial units worth using in horns, although individual designers inevitably have their own favourites. For this design it was decided to use:

Horn	Unit	Power(W)	Frequency Range (Hz)	Diaphragm Area (Nominal sq.in)
Bass	KEF B139	30	20–1k	42
Middle	KEF B110	15	30–5k	13
Treble	KEF T27	6	3k–30k	1·5

Bass horn

The mouth area for a minimum frequency of 40Hz is given in Table 2 as 15·73 sq.ft, realized as 47in by 48in. The diaphragm area of the B139 loudspeaker is approximately 42 sq.in (the diaphragm is oval in shape) which corresponds closely with the 8in speaker of Table 7. This table gives a recommended throat area for the bass horn of 0·073 sq.ft (68 sq.cm). The highest frequency to be handled by this horn will be 440Hz, i.e. 11 times the cut-off frequency. Fig. 9 shows that for 2% distortion at 11 times the cut-off frequency, the throat will handle 0·01 watts/sq.cm, which for a mouth area of 68 sq.cm gives 0·68 watts total power. The length of the bass horn, from Table 8, is 13·1ft using the tractrix contour, and this curve may be constructed to a suitable scale in the same way as that produced for the mini-horn. The form of the tractrix should commence with a throat radius equivalent to four times the chosen throat area (eight times in the case of the corner horn) and terminate at a mouth radius giving a perimeter equal to the cut-off wavelength. The area at a series of points along the horn (e.g. every 6in) may be obtained by reading the radius from the graph and taking one quarter of the corresponding area.

Middle horn

Attention should now be directed to the mid-frequency horn. The cut-off frequency of 400Hz, together with the area of the chosen loudspeaker (13 sq.in) result in a mouth area of 203·6 sq.in, a throat area of 13·75 sq.in and a length of 8·78in (exponential contour). Again the contour should be constructed to a suitable scale (which may be 1:1 for the mid-frequency and treble horns). Since the throat areas of the middle and treble horns are made equal to their respective loudspeaker diaphragm areas, there is no problem regarding air overload distortion—one could do little if there were.

Treble horn

In view of the throat area of 1·5 sq.in for this horn, it is suggested that a mouth area of (say) 30 sq.in is adopted, giving an exponential length of 1·1in.

However, at these frequencies it is quite acceptable to mount the loudspeaker directly onto a flat baffle board without any horn.

Integration and complete design

The three loudspeaker drive units should drive their respective horns in phase. Initially it will be assumed that, whereas the middle and treble horns must load the front of the loudspeakers (to avoid diffraction effects caused by the frame and magnet assembly at the rear), the bass horn will in fact load the rear of the loudspeaker. This implies that the bass loudspeaker must be connected in anti-phase to the middle and treble loudspeakers. If examination of the behaviour of the bass and middle horns at their mutual crossover point reveals that the radiation is in anti-phase, the bass horn can be arranged to load the front of its loudspeaker, which will then have to be connected in phase with the other two. In fact the total length of the bass and middle horns is 13·8ft and Table 11 shows that this is nearly equivalent to an even number of half-wavelengths at 400Hz, the crossover frequency. The bass loudspeaker may therefore be reversed so that the horn loads the front of the diaphragm; this will also make the design of the acoustic cavity much simpler.

The cavity between the bass loudspeaker and its horn should be designed to give a cut-off frequency of 440Hz. Applying the aforementioned formula gives a volume of 51 cu.in. There is no real need to employ a similar cavity at the crossover between the middle and treble horns; the fact that these horns are not folded, together with their large throats, reduces distortion at high frequencies to negligible proportions.

Finally, the three horns must be combined into a composite enclosure. As with the mini-horn there are many ways of achieving this, and it would be invidious to specify a particular design to the exclusion of all others. However, certain basic rules apply, and the following suggestions may be of value.

The rectangular mouth of the bass horn should be placed at floor level, with the mouths of the middle and treble horns placed above it, in the same plane. If the back-to-front depth of the complete structure is at a premium, the middle and treble horns may be mounted on top of the complete folded bass horn, giving a very high cabinet. If, however, height is at a premium, then the bass horn may be folded behind the middle and top horns, thus minimizing the overall height but increasing the width. This latter approach is shown in Fig. 14(a), and the complete design of the no-compromise horn is summarized in Table 13. Material used for construction is 1in blockboard, plywood, etc, and all joints should be screwed and glued to make them air-tight.

When converting from a basic parameter design, as described in this section, to complete working drawings, the temptation is often to press on rapidly and adopt certain compromises. Unfortunately, the final construction is a "once only" event, and horn structures cannot easily be modified if major audio deficiencies (e.g. resonances or "holes" in the frequency spectrum) become apparent during listening tests. It

Table 13
Summary of no-compromise horn parameters

Bass horn	
Frequency range	40Hz to 440Hz
Driver unit	KEF B139
Position	Wall
Mouth area	15·73 sq.ft
Throat area	0·073 sq.ft
Contour	Tractrix
Length	13·1ft
Cavity volume	51 cu.in (directly at front of loudspeaker)
Middle horn	
Frequency range	400Hz to 3·8kHz
Driver unit	KEF B110
Mouth area	203·6 sq.in
Throat area	13·75 sq.in
Contour	Exponential
Length	8·78in
Treble horn	
Frequency range	3·5kHz upwards
Driver unit	KEF T27
Mouth area	30 sq.in
Throat area	1·5 sq. in
Contour	Exponential
Length	1·1in

Table 14
Cross section details for the mini bass horn

Sec.	Length (in)	Area (sq.in)	Realized (in)
A	0	7·0	1
B	10	11·9	1·7
C	15	15·5	2·2
D	25	28	4
E	35	49	7
F	40	67	complex section
G	45	92	complex section
H	50	127	complex section
J	60	261	26 x 10 high
K	63	370	29.7 x 12.5 high

Table 15
Cross section details for the no-compromise bass horn

Sec.	Length (in)	Area (sq.in)	Realized (in)
[illegible]	0	10·6	1·06
[illegible]	15	17·0	1·7
C	30	27·8	2·78
D	40	38·0	3·8
E	50	54·0	5·4
F	60	75·0	7·5
G	75	122	12·2
H	94	230	23
J	104	316	13·5 × 23 high
K	113	426	13·5 × 31·5 high
L	120	540	17 × 31·5 high
M	125	630	17 × 37 high
N	132	790	21 × 37 high
P	139	1125	28 × 40 high
R	153	2265	47 × 48 high

is therefore strongly recommended that the final design takes place over an extended period, with several alternative approaches being worked on simultaneously until one of them emerges as the right solution for the parameters and overall concept in mind.

The three loudspeaker units must be connected via suitable filters so that each handles frequencies only within its appropriate pass-band. The simplest way of achieving this is by means of passive crossover networks at the output of the power amplifier. However, this method reduces the beneficial effects of electromagnetic damping of the loudspeaker movement afforded by the low output impedance of the amplifier, and a better method is to use three separate power amplifiers whose inputs are fed via active high and low pass filters, as outlined in Part 2.

It is well-worth experimenting over an extended listening period until the optimum bandwidth and sensitivity of each horn has been realized, paying particular attention to the crossover points.

Conclusions

This article has taken the form of a critical review of work which took place largely between 20 and 50 years ago. The author of such reviews benefits from hindsight, but inevitably loses much of the excitement and impact of the original work. I have been in contact with many individuals who were personally involved with the development of horns, in both amateur and professional capacities; I thank them all for their advice and comments, and hope that I have done justice to their suggestions.

In spite of the obvious disadvantages of large size and high cost, and the difficulties of realizing an adequate design, the exponential horn loudspeaker still has many enthusiastic users, the present author among them. The clear advantages conferred by the horn in terms of presence, clear bass, low distortion and sheer realism, combine to make horn enthusiasts redouble their efforts to design a better horn rather than to adopt an alternative type of enclosure.

It will be clear to readers of this article that, with the possible exception of straight horns of circular section constructed in a very stiff material, the simple horns described here can only approximate to the ideal performance offered by this genre of reproducer. Although the pioneer development work was conducted between 50 and 70 years ago, engineers are continuously designing new horns and investigating different aspects of their performance, often with the aid of computers to construct a mathematical model for the analysis of conditions in a practical horn (38, 39). It must be emphasized again that first-class results may be obtained by following the basic design data and constructional advice given in this article. Loudspeakers in general, and horns in particular, are controversial subjects, and I have no doubt that many will wish to challenge some of the statements I have made. I hope that this article, together with any discussion, will stimulate many audio enthusiasts to design and make their own horns, and to write about the results so that all may benefit from their findings.

Finally, I acknowledge with thanks the helpful advice given by Mr Gilbert Telfer, whose experience of the design and manufacture of horns has been a constant encouragement.

JACK DINSDALE was educated at Trinity College, Cambridge and later at Cranfield. After a craft apprenticeship in mechanical engineering he joined the Elliott Automation Group where for nine years he was concerned with missile guidance, digital computer design and latterly with on-line applications of computers to industrial and military control systems. Mr Dinsdale is now Principal Research Engineer with the Cranfield Unit for Precision Engineering, a commercial department of the post-graduate Cranfield Institute of Technology, engaged in the design and manufacture of high precision machine systems for industry. He is responsible for all aspects of electronics, automation and computing.
Mr Dinsdale is married and has three sons. His spare time activities include sound reproduction, music-making and horticulture.