

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

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After a period in the infancy of the gramophone when it was universally employed, the horn loudspeaker has fallen from popularity, due probably to its relatively large size, complexity of manufacture and hence high cost. Although full-range horn systems are used today only by a small number of enthusiasts, most experts are unanimous in acclaiming their virtues as loudspeaker enclosures, especially their high degree of realism and "presence". These articles examine briefly the history of the exponential horn loudspeaker and discuss the theory of horn-loading and the technical requirements of a good design. Comprehensive data are included for a wide range of horns, together with outline designs for a large and a small horn, suitable for domestic use.

The ideal exponential horn consists of a straight circular tube whose cross-sectional area increases logarithmically along its length from a small throat (at which is mounted the loudspeaker) to a large mouth. Extreme bass notes demand a mouth of very large area (20 to 30 sq. ft) and a horn at least 20ft in length, whereas extreme treble notes require a horn with dimensions of only a few inches. For this reason most wide-range horn systems will incorporate a number of separate loudspeakers, each with its individual horn of appropriate length and mouth area. To accommodate these horn combinations within a cabinet of reasonable size, the bass and middle horns are generally of square cross-section and are "folded" into a complicated pattern. Unfortunately, the inevitable restrictions and compromises introduced by these departures from a straight axis and circular section can cause serious variations in the frequency response, and much of the art of horn design is concerned with achieving a product of reasonable overall size and cost, without sacrificing any of the astonishing realism which is obtainable from the ideal horn.

The efficiency of a horn system will be typically between 30 and 50%, a figure to be compared with 2 or 3% for a bass-reflex enclosure and less than 1% for a totally enclosed box.

The principal reasons for the evident lack of popularity of the horn probably lie in its dimensions and cost. The overall size of a bass horn, even when folded into a cabinet of reasonable shape, will be larger than a bass-reflex or infinite baffle enclosure of

comparable specification. But although one reads occasionally of straight horns up to 20ft long, excellent results may be obtained from horns of more moderate dimensions; for example a complete horn system may be folded into an attractive cabinet of volume only 6 cu. ft, a not unreasonable size for domestic listening. The cost of horn enclosures is often considered to be prohibitive, and it is true that there is considerably more work in constructing a folded horn than in other enclosures; furthermore, this is work best performed by craftsmen and not easily adapted to "production-line" methods. Nevertheless, the building of a folded horn is by no means outside the capability of a competent do-it-yourself enthusiast, and it is to these individuals that the practical designs will be directed.

Although the early acoustical gramophones or phonographs employed horns of one type or another to couple the diaphragm to the listening room, and the early electrical reproducers of the 1920s and '30s also used horns, thereafter the horn suffered a setback from which it has never recovered. Certainly, a few companies market horn loudspeaker enclosures, and the occasional articles in the technical press^{1,2} stir up a passing interest, but unless one resorts to the masterly academic treatises by Olson³ or Beranek,⁴ or reverts to pre-1940 publications, there is very little information available for the enthusiast who wishes to both design and construct a horn. Recent experience gained by Telfer and others^{5,6} has reinforced the author's opinion that there are many audio enthusiasts who would be interested in constructing a horn enclosure.

After a brief historical survey, these articles examine the theory behind the horn-loaded loudspeaker enclosure and explain the basic points to consider when designing horns. The various compromises adopted by different workers are discussed, especially in the area of folding techniques, and the effects of these compromises on audio quality are studied. Finally, outline designs for two domestic horns are given: a "no-compromise" horn to suit the most fastidious (and enthusiastic) listener, and a "mini-horn" which provides a more limited performance for those with smaller living rooms (and bank balances), and which, while no more obtrusive than most commercial loudspeaker cabinets, will provide extremely clear and natural reproduction.

Background

It has been known for many thousands of years that when sound is passed through a tube with a small throat and a large mouth, it experiences an apparent amplification, and from Biblical times man has used rams' and similar naturally occurring horns both as musical instruments and as megaphones. Thomas Edison attached a tin horn to his primitive phonograph in 1877 to couple the minute vibrations of the diaphragm to the air load in the listening area, and to the majority, the term "gramophone horn" conjures up an image of the early gramophones or phonographs designed between about 1890 and 1912, all of which utilised an external horn.

A variety of expansion contours were employed for these early horns, mainly straight conical horns in the earliest machines, but the later gramophones of this period employed large flaring horns with either straight or curved axes depending on the overall length of the horn and the general design of the complete equipment. An analysis of these early horns, carried out in the light of modern acoustic knowledge, reveals a lack of understanding at that time of the operation of the horn as an acoustic transformer. This is surprising since Lord Rayleigh had analysed the "transmission of acoustic waves in pipes of varying cross-section" in Articles 265 and 280 of his classic treatise "Theory of Sound", published in 1878.⁷

Lord Rayleigh gave the analysis in Art. 281 for the passage of sound through a conical pipe, and he also made the interesting statement that "when the section of a pipe is variable, the problem of the vibrations of air within it cannot be generally solved". For some years after publication, Lord Rayleigh's results were purely of academic interest, but more general interest was aroused about the turn of the century by the early gramophones, most of which used external conical horns, as in the early HMV "dog" models.

After 1912, a number of manufacturers introduced internal horns with a degree of folding to enable cabinets of reasonable size to be used, and these models held the consumer market during the following 12 years, on account of their compactness and suitability as pieces of furniture. (Even in those early days, the enthusiast must have had

problems in persuading his wife to provide house-room for a large unfolded external horn.)

In the early 1920s a number of designers carried out theoretical analyses based initially on the work of Lord Rayleigh, but extending the work to be more applicable to the full audio range at domestic listening levels. Among these early analyses must be mentioned the work in America by A. G. Webster⁸ in 1920, by C. R. Hanna and J. Slepian⁹ in 1924 and by P. B. Flanders¹⁰ in 1927. In Britain independent analyses were carried out by P. Wilson in 1926 writing in *The Gramophone* magazine and later with A. G. Webb in "Modern Gramophones and Electrical Reproducers", and also by P. G. A. H. Voigt¹² in 1927.

All of these analyses, except the last, were based on an exponential contour, and were derived from a statement in Art. 265 of Rayleigh's treatise. Webster had worked out an approximate theory for other types of horn and had deduced that the exponential was the optimum contour. All these analyses made the assumptions that (a) the cross-section is circular, (b) the axis is straight, and (c) all wavefronts are plane.

However, while it may be reasonable to assume plane wavefronts at the throat of the horn, it is clear that the wavefront at the mouth will be curved (as if a balloon were emerging from the horn, being inflated at the same time). Wilson, who had independently derived the analysis of the exponential horn in 1926 working from Rayleigh's treatise, later published a modified form on the assumption that the wavefront would assume a spherical shape always cutting the

contour of the horn and its axis at right angles.

This assumption, that the curvature of the wavefront would gradually increase from zero (the initial flat wavefront at the throat), satisfies also the condition specified by Hanna and Slepian and later by I. B. Crandall¹³ that the wavefront as it emerges from the open end will be equivalent to that provided by a spherical surface, as opposed to that produced by a flat piston. Voigt, however, had commenced his analysis on the assumption that wavefronts within the horn will be spherical and of the same radius throughout their progression through the horn. This assumption leads to a tractrix curve for the horn contour, and both theoretical considerations and very careful listening tests by the author and others tend to support the claims of the tractrix as the optimum horn contour. The mathematical basis of the exponential and tractrix curves is discussed in a later section of this article.

During the 1920s, 30s and 40s a large number of experimenters investigated methods of folding horns into small enclosures for domestic gramophone reproducers, and the records of the Patents Office bear witness to the ingenuity of man at overcoming conflicting conditions in the search for perfect sound reproduction. These designs for folded horns enjoyed a greater or lesser degree of success according to a number of factors including the performance of the loudspeaker motor. Nevertheless, it must be repeated that they were almost invariably of square or rectangular cross-section, and the axis was no longer straight and thus any resemblance between their actual perform-

ance and theoretical considerations was to some extent coincidental.

The advent of the moving coil loudspeaker in 1927 and electrical amplification stimulated further advances in the design of horns, which, because they now no longer had to be connected to the acoustical tone-arm, were freed of many of the earlier constraints. Many loudspeaker motor units were designed specifically for horn loading, and it was not until World War II that interest in the horn lapsed in favour of the bass reflex, infinite baffle and other types of loading systems which, although they had the peripheral advantages of smaller physical size, greater ease of design and manufacture and hence lower cost, were decidedly inferior in terms of musical realism.

During this time the designs of Voigt in Britain and of Klipsch¹⁴⁻¹⁸ in America continued to attract considerable support, especially the ingenious method evolved by the latter in adapting a doubly-bifurcated bass horn design to utilize the acoustic advantages inherent in corner positioning, a design which has now become a classic. Others at this time were experimenting with horn-loaded loudspeakers, notably J. Enoch and N. Mordaunt (whose design was subsequently incorporated in the Tannoy "Autograph" and "GRF" enclosures). Lowther (using a modern version of Voigt's high-flux motor unit) and J. Rogers (whose horn-loaded mid-frequency ribbon is still regarded by many as the ultimate in sound reproduction in this range) and one must not overlook the contributions of H. J. Crabbe¹⁹ and R. Baldock²⁰ in more recent times.

However, it must be emphasised that the multiple reflections, absorptions, resonances and changes of direction inherent in folded horns, together with the uncertainty of function of non-circular sections must inevitably alter the performance of such horns from that of the straight, circular-section horn on which the design may have been based.

Recent years have seen a minor resurgence in the popularity of the horn, caused perhaps by the search for "perfect sound reproduction", and there are many who hope that this trend will continue.

A very readable account of the early history of the horn loudspeaker has been given recently by P. and G. L. Wilson.²¹

General theoretical principles

The following section deals principally with the exponential contour, which is the basic expansion curve used in most high quality horn loudspeakers, and the tractrix, which has a more complicated formula, but with a dominant exponential component—indeed the two curves are virtually identical from the throat to about midway down the horn.

Determination of flare contour

The theory of the conical horn was originally worked out by Lord Rayleigh, but the first serious attempts to establish a practical working formula for the exponential horn were not made until 1919 and the years following. The basic formulae for the transmission of sound waves through horns have been given in modern terms by V. Salmon²²

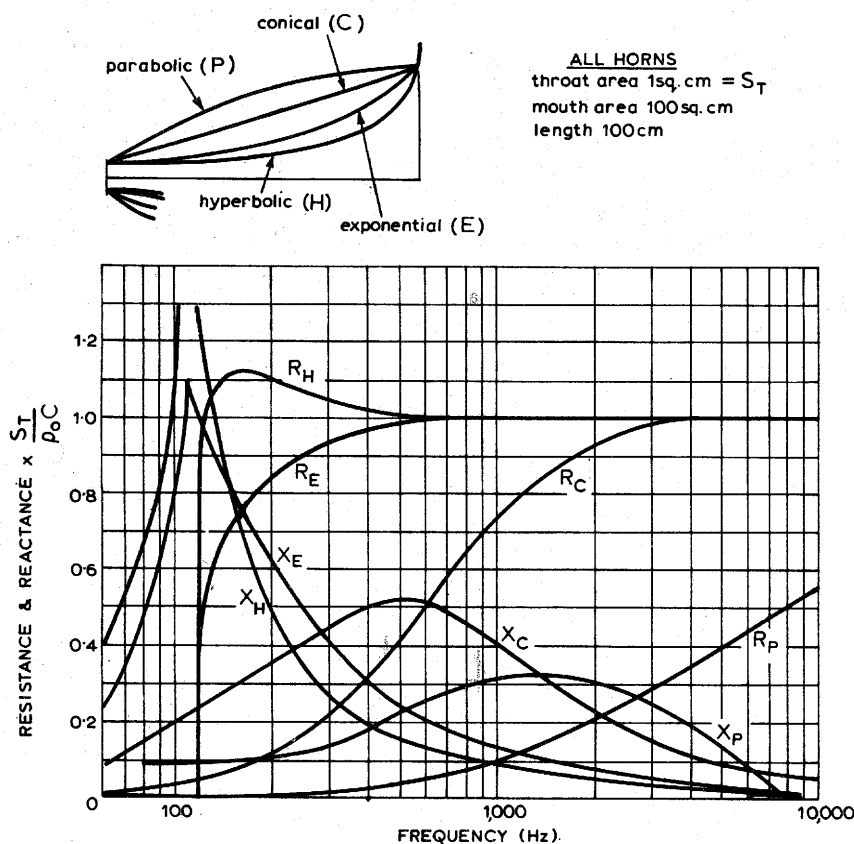


Fig. 1. Acoustical resistance and reactance against frequency at the throats of a series of infinite horns of different contour.

and others. Beranek⁴ has plotted the acoustical resistance and reactance against frequency at the throats of a series of infinite horns of different contour with identical cross-sectional areas at the throat and at a given point along the axis of the horn, and the resulting curves are shown in Fig. 1. For optimum loading of the loudspeaker motor, it may be shown that the impedance presented by the throat of the horn should be entirely resistive and of constant value throughout the working frequency range, i.e. the sound transmission should be of unity "power factor". Examination of the curves in Fig. 1 shows that the exponential and hyperbolic contours satisfy this condition most closely.

However, a further condition to be satisfied is that of minimum distortion at the throat of the horn, caused by "air overload". When a sound wave is propagated in air, a series of harmonics will be produced, thereby distorting the waveform. This occurs because if equal positive and negative changes in pressure are impressed upon a mass of air, the resulting changes in volume will not be equal; the volume change due to an increase in pressure is less than that due to an equal decrease in pressure. The rapid expansion and compression of air caused by the propagation of sound waves takes place adiabatically, i.e. there is no net transfer of heat, and the pressure and volume are related by the formula $pV^\gamma = \text{constant}$, where

p = pressure
 V = volume
 γ = adiabatic gas constant (approx. 1.4 for air under normal room conditions)

This curve has been plotted in Fig. 2, together with a superimposed large sinusoidal change in pressure to illustrate the corresponding distorted change in volume.

If the horn were a long cylindrical pipe, distortion would increase the further the wave progressed towards the mouth. However, in the case of a flaring horn, the amplitude of the pressure wave decreases as the wave travels away from the throat, so for minimum distortion the horn should flare out rapidly to reduce the pressure amplitude as early as possible after the sound wave has left the throat. From this viewpoint it is apparent that the parabolic and conical contours will generate the least distortion due to air overload, and that distortion will be highest for the hyperbolic horn, because the sound wave must travel a further distance before the pressure reduces significantly.

Further inspection of Fig. 1 shows that the acoustical resistance of the hyperbolic horn lies within 10% of its limiting value over a larger part of its working frequency range than that of the exponential horn, and for that reason the hyperbolic horn provides rather better loading conditions to the loudspeaker motor. However, in view of the considerably higher air-overload distortion of the hyperbolic horn, the exponential or one of its derivatives is generally chosen as a satisfactory compromise between the hyperbolic and conical contours.

In cases where the advantages of a long

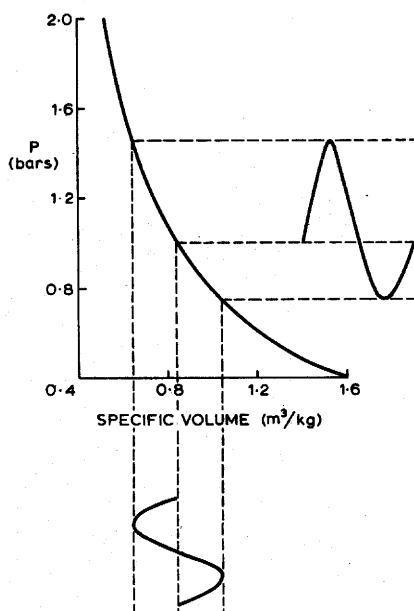


Fig. 2. Adiabatic pressure/volume relationship for air.

slow flare rate are required without the attendant high air-overload distortion, Olson³ has shown that a horn can be made up of a series of manifold exponential sections, commencing with a very short stub of high flare rate at the throat (to minimize distortion) which leads into a longer section of lower flare rate and thence to the main horn of very low flare rate. Klipsch has referred to this technique as the "rubber throat" in his paper on corner horn design.¹⁴ The mouth acoustical impedance of each exponential section is designed to match the throat impedance of the preceding section, right along the chain. Practically any acoustical impedance relationship with frequency may be obtained by this technique, but the procedure is complicated, and the additional effort cannot generally be justified for domestic horns.

Determination of mouth area

The acoustical resistance and reactance of the exponential horn have been plotted on a normalized scale in Fig. 3, which shows that

the acoustic impedance is entirely reactive below a frequency given by

$$f_c = \frac{mc}{4\pi}$$

where c = speed of sound; m = flare constant which appears in the basic exponential horn formula

$$S_x = S_T e^{mx}$$

where S_x is the area at distance x from throat; S_T is the area at the throat.

The frequency f_c , known as the cut-off frequency, is the lowest frequency at which the horn will transmit acoustical power, and thus the flare constant defines the lower frequency of transmission by a given horn. The flare constant may be calculated for any given cut-off frequency, and the horn profile may then be constructed. The above statement refers strictly only to horns of infinite length. In horns, as in cylindrical tubes, wavefronts of sounds whose wavelength is large compared with the mouth diameter tend to be reflected back into the horn where they interfere with successive wavefronts. Just as the loading of the loudspeaker motor by the throat of the horn must be largely resistive over the working frequency range for the smooth efficient transfer of acoustical energy, so must be the loading presented to the mouth of the horn by the surrounding air. Beranek has shown⁴ that for the radiation impedance of the mouth to be mainly resistive, the relationship $C/\lambda > 1$ must hold, where C is the circumference of the mouth of the horn and λ is the wavelength of the lowest note to be transmitted. If the mouth of the horn is not circular, it will behave in a similar way for equal mouth areas, i.e. if $C = 2\pi r_m > \lambda_c$ is the limiting condition

$$\text{and } S_m = \pi r_m^2 > \frac{\lambda_c^2 c}{4\pi} r_m > \frac{\lambda_c}{2\pi}$$

where λ_c = cut-off wavelength; r_m = mouth radius; S_m = mouth area.

Thus a horn of square section may be employed provided the mouth area exceeds $\frac{\lambda_c^2}{4\pi}$. Hanna and Slepian had examined from

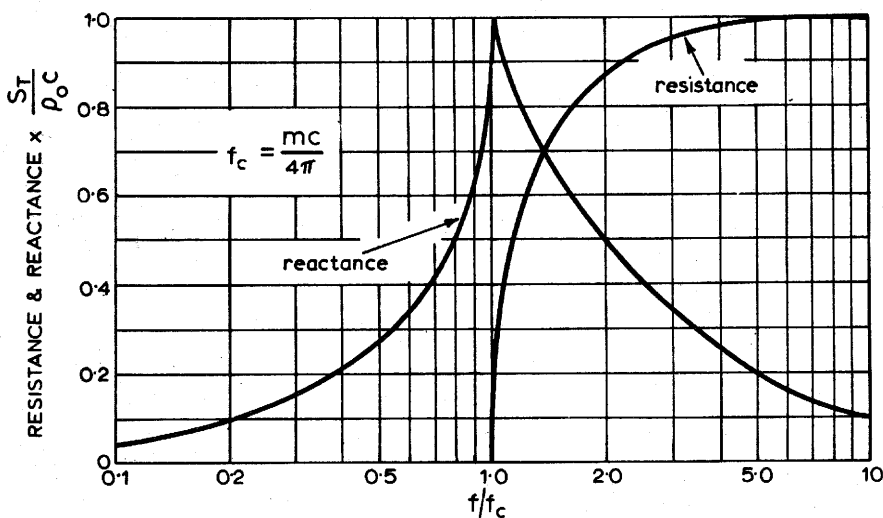


Fig. 3. Acoustical resistance and reactance of an exponential horn.

a different standpoint the behaviour of wavefronts at the mouth of the horn, and deduced that reflection was a minimum when the slope of the profile was 45° (i.e. included angle of 90°). This will be so where the mouth circumference equals the cut-off wavelength of the horn. It also illustrates the importance of distinguishing between the values of flare constant used for calculating exponential increase in area, and in plotting the profile of the actual horn. Fig. 4 (after Olson) illustrates the effect of foreshortening the horn to a length less than

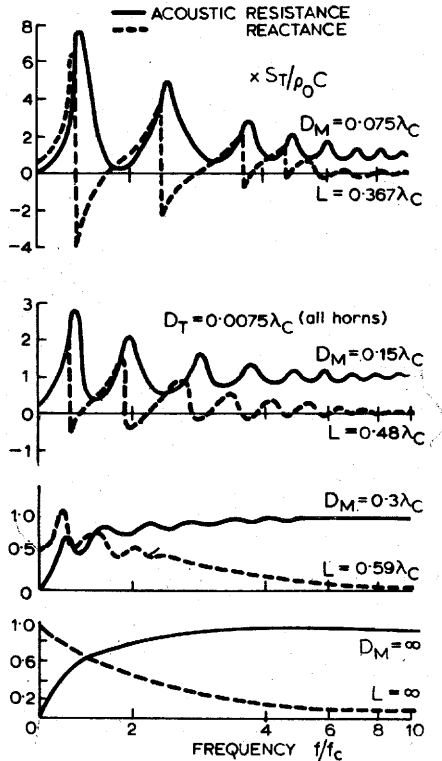


Fig. 4. Performance of foreshortened horns. Reflections at the mouth cause peaks and troughs in the frequency response near to cut-off.

the ideal. When the mouth circumference becomes less than the cut-off wavelength, reflections at the mouth cause objectionable peaks and troughs in the frequency response at frequencies near to cut-off, and if, in a given design, the mouth dimensions are restricted, it is generally preferable to increase the cut-off frequency to a value which allows the correct mouth area to be adopted, rather than to accept the uneven bass response illustrated in Fig. 4.

Plane and curved wavefronts

Hitherto, the assumption has been made that successive wavefronts remain plane throughout their propagation through the horn. However, along a straight circular section horn the wavefront must be normal to the axis, and also normal to the walls. (If the wavefront were either approaching or receding from the walls, energy would be either absorbed or supplied; alternatively, the composite wavefront resulting from the original wavefront and its reflection will itself be normal to the walls.) Thus wavefronts transmitted along a cylindrical tube will be plane, while wavefronts transmitted down a conical horn will be spherical. It is therefore clear that the wavefront emerging from an exponential horn will possess a degree of curvature, and that the conventional calculations made on the assumption of the exponential increase of plane wavefronts will be in error (in practice, the actual cut-off frequency will be somewhat altered from that derived theoretically, and the profile errors of the horn are not excessive).

The correct approach to the design of a horn in which the areas of successive wavefronts expand according to a true exponential law is not certain, since any horn profile chosen will *per se* determine the contour of the wavefronts within it, and in general this contour will be different to that originally assumed. Wilson¹¹ decided to assume spherical wavefronts of increasing curvature from zero (plane wavefronts) at the throat of the horn, and on this basis he calculated a modified contour which lies just inside and very close to the true exponential.

Fortunately, if a papier mâché horn is made on a solid former designed to a true exponential contour, the shrinkage of the papier mâché when drying converts the horn very closely to Wilson's modified form. Nevertheless, the prime assumption has been made that wavefronts are spherical and of changing curvature, and it is by no means certain that this is the case.

The tractrix contour

Voigt, in his 1927 patent, had proceeded on the more elementary assumption that the wavefronts within the horn must be spherical and of the same radius throughout their propagation through the horn. He based this assumption on the reasoning that if the curvature increases from plane waves (zero curvature) at the throat to a certain curvature at the mouth, then a point on the axis must travel at a faster rate than a point at the wall. Since the entire wavefront must travel at the speed of sound (assumed to be constant throughout the horn) the wavefront has no alternative but to be spherical and of constant radius. This requires that the horn contour should be the tractrix.

The tractrix is the involute of the catenary (the curve adopted by a uniform heavy chain suspended between two points at the same level) and is the curve traced out by a load being dragged along by a man moving in a straight line not passing through the load. It is not the "pure pursuit" curve traced by a missile which always travels towards an escaping target, as is often mistakenly supposed. The length of a tractrix horn of mouth circumference λ_c , may be expressed as the cut-off wavelength

$$x = \frac{\lambda}{2\pi} \log_e \frac{\frac{\lambda}{2\pi} + \sqrt{\left(\frac{\lambda}{2\pi}\right)^2 - y^2}}{y} - \sqrt{\left(\frac{\lambda}{2\pi}\right)^2 - y^2}$$

where y is the radius of what? of mouth of throat

$$x = \frac{\lambda}{2\pi} \log_e \left(\frac{\lambda}{2\pi y} \right)$$

Both these curves are shown in Fig. 5.

It will be seen that the tractrix has a dominant exponential term which becomes less significant towards the mouth; in fact for the first 50% of their length the exponential and tractrix contours for a given cut-off frequency and throat area are virtually identical, but thereafter the tractrix flares at an increasingly greater rate until it attains its fully developed mouth at 180° included angle. In view of the complex nature of the formula, the best way to construct a tractrix is by graphical means, as shown in Fig. 6. The curve thus derived may be used to provide ordinates for the tractrix horn, after some smoothing of the slight discontinuities inherent in the graphical construction.

Whereas the tractrix terminates when the angle between the horn and the axis is 90° (180° included angle), the true exponential goes on to infinity in both directions. The

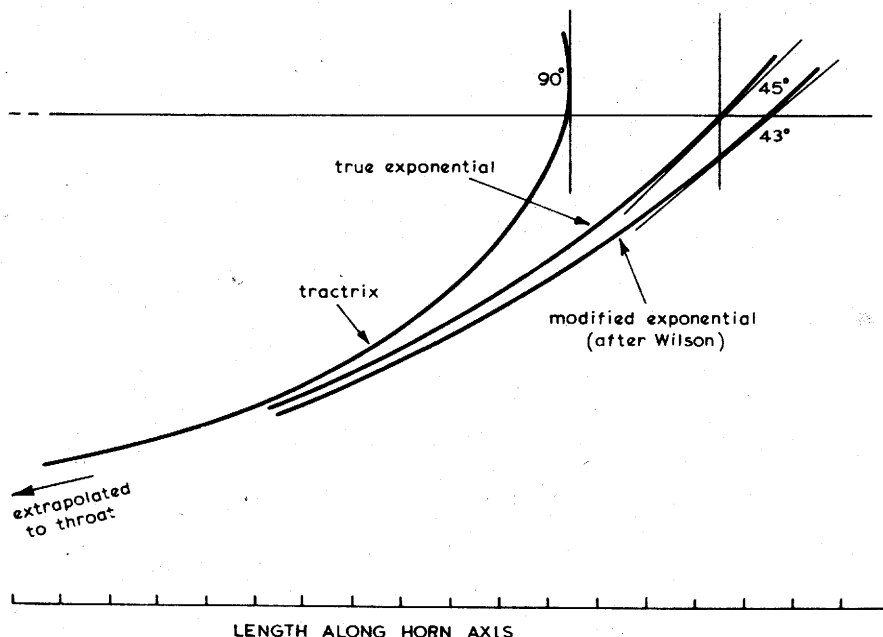


Fig. 5. Comparison of the exponential and tractrix contours.

tractrix horn for given throat and mouth dimensions is thus shorter than the equivalent exponential. It has been suggested that with the full tractrix terminating in a mouth of 180° included angle, the sound appears to originate from a point just inside the mouth, where the included angle is only 90°. There is thus some evidence that the tractrix may be terminated prematurely at this point, and if this is done, the mouth perimeter will be 90% of the wavelength at cut-off, as shown in Fig. 5, which compares the true and modified exponentials and the tractrix contours.

Efficiency

The efficiency of an exponential horn loudspeaker is determined by a large number of parameters, and a comprehensive treatment has been provided by Olson.³ Typical efficiencies of bass horns can be as high as 50%, while mid-frequency and treble horns can have efficiencies of over 10%, and these figures compare very favourably with bass-reflex enclosures (efficiency 2 to 5%) and infinite baffles (efficiency generally less than 1%). The extremely high efficiency of the horn is not necessarily of value in enabling amplifiers of lower output power to be used. Indeed, some class B output stages may produce a higher distortion level in horns because they need only be operated within the first 10% of their capability, at which low levels the effects of crossover distortion are more pronounced.

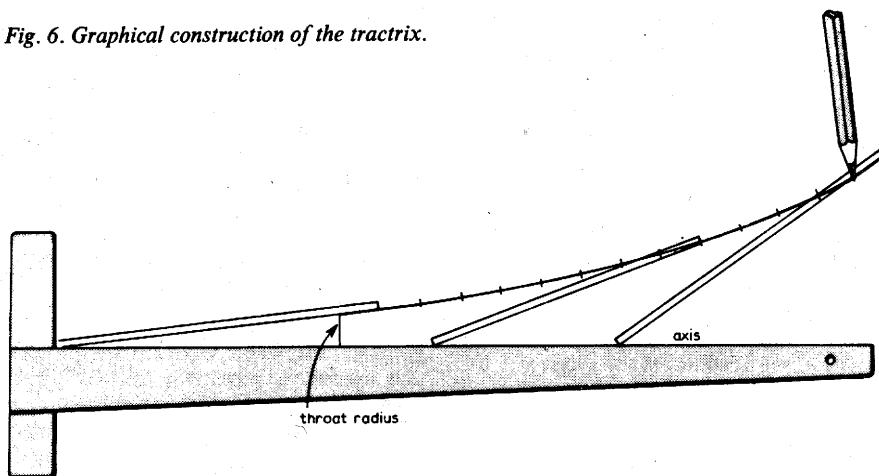
The principal advantage conferred by the horn's high efficiency is that for a given loudness the amplitude of movement of the loudspeaker motor is appreciably less than with other enclosures. The effects of nonlinearities in the magnetic field and suspension are therefore greatly reduced, and there is less tendency for "break-up" of the cone to occur. Thus the relatively high distortion products normally produced by the loudspeaker motor will be minimized, and, provided the horn itself does not introduce distortion, extremely high quality sound can be radiated.

A further advantage resulting from this reduction in amplitude of movement of the cone is that a form of inter-modulation distortion, caused by variation of the volume of the cavity between the loudspeaker cone and the throat of the horn, may be reduced to negligible proportions.

Tuning the throat cavity

The cavity, which must inevitably exist between the loudspeaker diaphragm and the throat of the horn, plays an important function in the design of horn systems, since it can be used to limit the maximum frequency to be transmitted. Although the lower frequency limit may be set with some precision by the flare rate of the horn, in conjunction with the mouth area, the upper frequency limit is ill-defined, being determined by a combination of (a) unequal path lengths between different parts of the diaphragm and the throat of the horn, (b) internal cross reflections and diffraction effects within the horn, especially when the horn is folded, (c) the high frequency characteristics of the motor unit itself, and (d) the effective low-pass filter characteristic presented by the cavity between diaphragm and throat.

Fig. 6. Graphical construction of the tractrix.



Using a straight edge of length equal to the final mouth radius, the tractrix curve is constructed of a series of tangents, length not greater than $\frac{1}{10}$ the mouth radius, starting at the throat.

It may be shown that a cavity of fixed volume behaves as an acoustic reactance of value

$$\frac{S_D^2 \rho c^2}{2\pi f V}$$

where S_D = area of diaphragm, V = volume of cavity, ρ = density of air, c = speed of sound, f = frequency.

When the cavity is placed between the diaphragm and throat, it behaves as a "shunt capacitance" across the throat itself, and thus by choosing the correct parameters, the cavity/throat combination acts as a low-pass filter at a frequency which may be set by making the cavity impedance equal to the throat impedance at the desired frequency,

$$\text{i.e.} \quad \frac{S_D^2 \rho c^2}{2\pi f V} = \frac{\rho c S_T^2}{S_T}$$

where S_T = throat area, f = desired upper frequency limit, whence

$$V = \frac{c S_T}{2\pi f}$$

The volume of the cavity may therefore be calculated to provide high-frequency roll-off at a point before the poorly-defined effects (a) to (c) stated above become significant (Fig. 7).

A further benefit resulting from the use of a cavity tuned to prevent mid and high frequencies from entering a bass horn at the rear of a loudspeaker is that the efficiency of transmission of these frequencies by the opposite side of the loudspeaker is greatly increased, thus improving the performance of a mid/high frequency horn mounted at the front of the loudspeaker.

The considerations affecting the practical determination of the upper and lower frequency limits of a particular horn will be considered in more detail.

Loading the rear of the loudspeaker motor

Mention has already been made of distortion resulting from the non-linear expansion/compression characteristics of air. This effect is accentuated when a loudspeaker is horn-loaded on one side only, because the

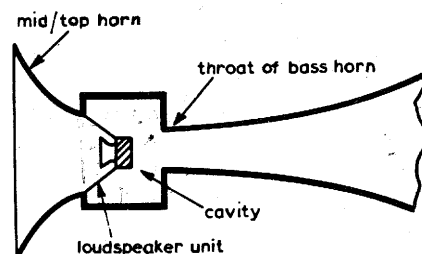
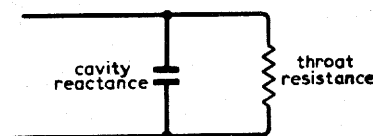


Fig. 7. Effect of the throat cavity in limiting high frequency performance.

constant resistance characteristic of the throat acts only against excursions of the cone in the forward direction; when the cone moves back it is against a far lower load and hence the excursion will be larger. The ideal way of eliminating this distortion is to load both sides of the loudspeaker by equal horns, or to employ a bass horn for loading the rear of the cone and a middle/top frequency horn to load the front. The design of the mini-horn, to be described, utilizes this feature.

An alternative solution favoured by many designers is to load the rear of the loudspeaker by a sealed compression chamber, the effect of which is to provide a loading similar to the horn. The compression chamber thus reduces the effects of non-linearity due to uneven loading on each side of the loudspeaker diaphragm, and also presents a better resistive load to the diaphragm because a closed chamber on the opposite side of the diaphragm to the horn itself acts as an "inductive" reactance which tends to balance the "capacitive" reactance presented by the mass reactance of the throat impedance at low frequencies.

Klipsch states¹⁴ that the volume of this cavity is given by the throat area multiplied

by the speed of sound divided by 2π times the cut-off frequency. This is readily shown as follows:

The air chamber reactance is given by

$$\frac{S_D^2 \rho c^2}{2\pi f_c V}$$

where S_D = diaphragm area, V = volume of air chamber.

The throat reactance at cut-off is

$$\frac{\rho c S_T^2}{S_T}$$

where S_T = throat area.

Equating these,

$$V = \frac{c S_T}{2\pi f_c}$$

However, some observers claim that the use of a compression chamber detracts from the realism of the reproduced sound, and advocate either double horn-loading or a combination of horn-loading with direct-radiation from the other side of the diaphragm; in other words, the most realistic reproduction occurs when both sides of the diaphragm are allowed to radiate.

Summary

In summarizing this section, it is clear that there is no universal formula applicable to any aspect of horn design. The reason for mentioning the alternative approaches and for providing a comprehensive list of references is to stimulate others to experiment in those areas where to a large extent results must be evaluated subjectively by very careful comparative listening tests *a posteriori*.

To quote Wilson:²¹ "It cannot legitimately be assumed that a horn incorporated in a cabinet has the precise characteristics of any particular type of straight horn, whether exponential, hyperbolic, catenary or tractrix, even though their dimensions have been used as guides in its construction. The multiple changes of direction, coupled with reflections and absorptions and internal resonances, are always such as to destroy any legitimate comparison. Every internal (horn) enclosure construction must be judged on its merits as revealed by measurement and by listening tests."

(To be continued)

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Horn loudspeaker design—2

Continuing the development of design theories and techniques

by J. Dinsdale, M.A., M.Sc.

Cranfield Unit for Precision Engineering

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The previous sections have outlined the physical principles underlying the operation of horns, and have shown how, provided certain basic rules are followed, sound reproduction of startling clarity and realism is possible from horns. However, it will also be clear by now that, unless one is prepared to accept extremely large and costly structures, it is all too easy to lose many of the potential qualities of horns through attempts to reduce the size to more acceptable proportions. This section now considers the procedures to be adopted in designing a domestic horn enclosure.

It has already been stated that the horn behaves as a transformer, converting acoustic energy at high pressure and low velocity at the throat to energy at low pressure and high velocity at the mouth. As with the analogous electrical transformer in which electrical voltage and current correspond to acoustical pressure and velocity, the basic requirements of the acoustical horn are that: (a) the primary (throat) should be correctly matched to the signal source (loudspeaker motor); (b) the secondary (mouth) should be correctly matched to the load (listening room); (c) the horn should be designed to handle the specified power level and frequency range. There are four principal parameters of the horn, namely mouth area, throat area, flare contour, and axial length. Any three of these will determine the fourth, and hence the characteristics of the horn itself. Once non-circular cross-section and non-linear axes are adopted, the problem becomes far more complex, and mathematical and physical concepts are no longer sufficient to design a horn. Nevertheless, the basic characteristics even of folded horns are determined to a large extent by known acoustic principles, and the most effective method of design is to work from these principles, ensuring that any deviation from theory is made on scientific grounds where possible.

Flare profile

Previous sections discussed the most commonly considered flare profiles, and it was concluded that a contour which allowed an exponential increase of the area of the wavefront as it travelled from throat to mouth provided the best compromise between the extremely gradual expansion of the hyperbola (giving optimum loading of the motor, but excessive throat distortion) and the

rapid expansion of parabolic and conical horns (giving minimum throat distortion but poor loading of the motor). However, the exact shape of the wavefront within a horn of curved profile is uncertain, and therefore assumptions have to be made, ranging from Wilson's modified exponential (lying a little inside the true exponential) to Voigt's tractrix, (which commences in a virtually identical manner to the true exponential, but departs substantially outside it in the region of the mouth). Which contour one adopts must be largely a matter of personal preference based preferably on careful listening experience.

Mouth geometry

The mouth of the horn couples the horn itself to the listening room. One of the commonly raised disadvantages of horns is that they require a very large mouth area if bass notes are to be properly reproduced. To some extent this is true; one cannot get a double bass out of a piccolo. However, there are a number of ways in which the mouth area may be reduced to manageable proportions without significantly sacrificing bass response.

As a sound wavefront travels up the steadily increasing bore of the horn, it should not meet any major discontinuity. However, it is clear that, unless the length and mouth diameter of the horn are infinite, there must be some discontinuity as the wavefront emerges and is no longer constrained by the walls of the horn. Although the cut-off frequency of the exponential horn is determined by the flare constant, the linearity with frequency of the acoustical resistance and reactance are determined by the mouth area, which, for a given throat area and flare constant will also determine the overall length of the horn. Strictly speaking, for no

discontinuity, the mouth should have infinite area. However, Olson³ has shown that provided the perimeter of the mouth of an exponential horn is greater than four times the cut-off wavelength,

$$\text{i.e. } p_m > 4\lambda_c$$

there will be no significant deviation of mouth resistance from that of the infinite horn.

A more important result is that for only 6dB variation in acoustic resistance, the mouth perimeter may be made equal to the cut-off wavelength, i.e. mouth area = $\lambda_c^2/4\pi$ where λ_c is the cut-off wavelength. As the mouth area is reduced below this value, the non-linearity of the acoustical resistance and reactance will increase.

Now these figures refer to the situation where the horn is suspended in free space, i.e. it radiates into an angle of 4π solid radians. In practice, this situation never occurs: even if the horn were placed on the ground at the centre of an infinite field, the mouth would only radiate into half a solid angle, or 2π solid radians; against the centre of a wall the mouth would be loaded by π solid radians, and in a corner formed by two walls and the floor the mouth will be loaded by only $\pi/2$ solid radians. The significance of this is that, whereas the minimum mouth area for a circular horn has been shown to be $\lambda_c^2/4\pi$ when loaded by 4π solid radians, *this value may be divided by a factor of two each time the solid angle is halved*. Thus the mouth area may be reduced to a size more in keeping with domestic conditions, e.g. a horn with a cut-off frequency of 56Hz (wavelength 20ft) would require a mouth area of 32 sq ft in space, but only 8 sq ft against a wall and 4 sq ft in a corner position, to give variations in loading of less than 6dB.

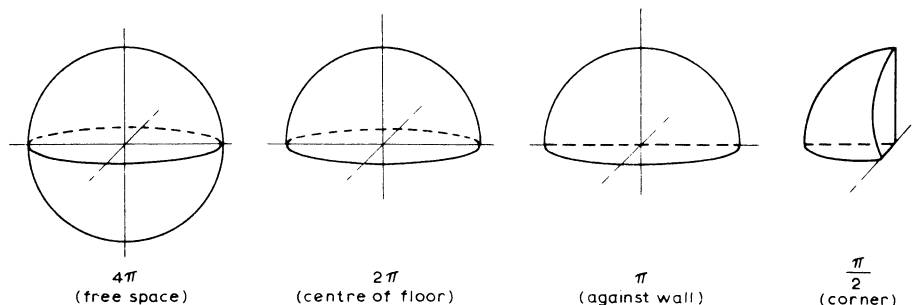


Fig. 8. Solid angles presented to a horn in different positions.

This situation which is illustrated in Fig. 8 may be compared with the mouth of a single horn placed at the intersection of eight rooms: four on the ground floor and four on the first floor. The bass response of the original horn will not be impaired, even though a listener in each room will see only one eighth of the total mouth area. One seldom gets anything for nothing in this world, and those who adopt corner speaker positioning in order to obtain a purer extended bass response from as small an enclosure as possible, may have to live with the eigen-tones such a position produces.

A plan view of a corner horn shows that the room itself provides a natural extension of the horn mouth. Many listeners have observed that corner horns can provide bass notes from fore-shortened horns, well below the limit dictated by the mouth area²⁵. It is tempting to reduce the mouth area still further below the 3dB limit established earlier and rely instead on the corner placement itself to supply the additional mouth area and horn length. In the author's experience, this technique cannot be justified because although the bass response is undoubtedly there, careful listening reveals an uneven response over the first two octaves above the cut-off frequency which will often detract from the realism offered by the horn. It is therefore recommended that in cases where overall enclosure size is a limitation, a correctly-designed horn with a cut-off frequency of (say) 80Hz will give a more satisfying and linear response than a fore-shortened horn whose expansion constant has been set to 40Hz but whose length has been limited to give a mouth area corresponding to 80Hz.

Most domestic horns will be of rectangular cross-section for ease and cheapness of manufacture. The foregoing comments regarding horns of circular section apply also to rectangular sections, although it is clear that the wavefront must behave in a most complex way at the corners, thereby reducing slightly the effective cross-sectional area. Provided that the ratio between the major and minor axes at the mouth does not exceed 4:3, rectangular horns may be employed to good effect.

Tabular design data is given for horns of both round and square section, with mouth areas computed for both corner positioning ($\pi/2$ solid radians) and wall positioning (π solid radians).

Throat geometry

The throat of the horn couples the wavefronts from the loudspeaker, which should ideally be plane at this point, to the horn itself. It has previously been shown that the horn is an acoustic transformer, converting acoustic radiation of high pressure/low velocity at the throat to low pressure/high velocity at the mouth. It is clearly of advantage to have a high pressure (and hence a low velocity) at the throat, because the low velocity will result in smaller movement of the loudspeaker cone, thus reducing the distortion produced by non-linearities in the magnetic field and the suspension. One way of increasing the pressure, and also of ensuring a higher degree of "plane-ness" of the wavefronts is to employ a throat area

substantially smaller than that of the loudspeaker itself. Tests carried out on a number of loudspeakers have shown that the "equivalent piston area" is approximately 70% of the speech cone area, i.e. the loudspeaker diaphragm in the shape of a truncated cone gives the same acoustic output as a plane piston with 70% of its area.

There are a number of practical reasons why modern loudspeakers are not manufactured as plane pistons; one of the unfortunate results of employing conical diaphragms is that the resulting wavefronts are in general not planar. However it has been found empirically that a throat area of between one quarter and one half the "equivalent piston area" of the loudspeaker provides satisfactory coupling between the loudspeaker and the horn, and also gives an approximation to plane wavefronts at wavelengths well in excess of the throat dimensions. It must be emphasized that for higher frequencies, where the wavelengths are of the same order as the physical dimensions of the loudspeaker diaphragm, the throat area should be made the same as that of the loudspeaker, and the horn should be of circular section, at least at the throat, so as to minimize standing waves across the horn itself.

The phenomenon of air overload distortion is caused by the non-linear relationship between pressure and volume of the air in the throat of the horn as it undergoes adiabatic compression and expansion. Beranek⁴ has derived the relationship for 2nd harmonic distortion at the throat of an infinite exponential horn as:

$$\begin{aligned} \% \text{ 2nd harmonic distortion} \\ = 1.73(f/f_c)I_t \times 10^{-2} \end{aligned}$$

where f = driving frequency f_c = cut-off frequency I_t = intensity (watts/sq in) at the throat.

This expression is also closely correct for finite horns because most of the distortion occurs near the throat. This expression has been plotted in Fig. 9 from which the throat area for given power and distortion may be obtained.

It is important to appreciate that the acoustic power radiated by musical instruments is extremely small²⁶, and that the higher the frequency the lower is the acoustic power to give the same subjective effect at the human ear. With the exception of full orchestra and pipe organ, which in the author's view it is futile to attempt to reproduce in domestic surroundings at anything

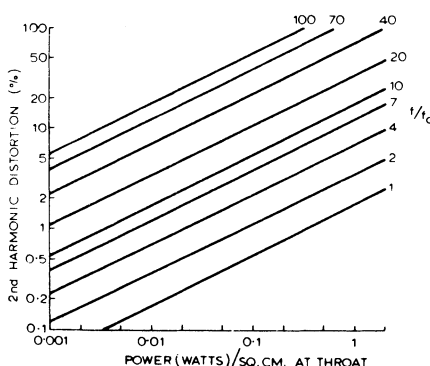


Fig. 9. Distortion caused by air overload at the throat.

approaching normal volume level, the acoustic power levels are extremely small, and an aim-point of (say) 3 watts and 1% distortion at the cut-off frequency, reducing to 0.05 watts and 0.5% distortion at four times the cut-off frequency, is likely to prove entirely satisfactory for domestic listening²⁷.

The above proposals for power and distortion give a throat area of around 10 sq cm, from Fig. 9, which compares not unfavourably with the effective piston area of 43 sq cm for a 3½ in loudspeaker, one quarter of which is a little over 10 sq cm. Of course, if the throat area is increased, as would be the case with larger loudspeakers, the available power for a given level of distortion will also increase.

Having established the throat and mouth areas and the flare profile, the length of the horn and hence its area at any point may be obtained mathematically or graphically.

The horn as a filter

The foregoing sections have indicated how the horn can act as a bandpass filter—the lower pass frequency of which is determined by the expansion coefficient and the upper by the volume of the cavity between the loudspeaker and the throat of the horn. It is important that the response should be as linear and free from distortion as possible over this passband, and as far as the lower frequencies are concerned, careful choice of mouth area, in conjunction with a knowledge of the solid angle into which the horn will radiate and the flare constant, can ensure that non-linearities in the frequency response are kept to a satisfactorily low level.

However, with regard to higher frequencies, non-linearities of increasing amplitude become apparent at frequencies exceeding about four times the cut-off frequency, due to internal cross-reflections and standing waves set up within the horn itself. These non-linearities will be more serious if the material of which the horn is constructed can resonate, and they are also accentuated if the horn is folded, when wavefronts at the higher frequencies will be distorted at bends. In fact, there is also a practical limit beyond which folding becomes undesirable: folding should not occur beyond the point at which the lowest wavelength (highest frequency) to be transmitted exceeds 0.6 of the diameter of the horn. More will be said of this limitation during the discussion on folding, but it clearly points to a practical limit on the highest frequency a horn may accurately transmit.

Yet a further limitation becomes apparent from the graph of throat distortion versus frequency (Fig. 9). As the frequency increases, the percentage distortion for a given power density at the throat will also increase, and although it is generally true that in the majority of complex musical sounds the energy level reduces with increasing frequency there will still be a frequency above which throat distortion becomes unacceptable.

A commonly used and quite adequate rule of thumb is that a horn should not handle frequencies higher than four octaves above its cut-off frequency, although purists may prefer to limit at only three octaves in order to ensure lower distortion levels.

The complete multi-horn system

The maximum frequency range to be handled by a wide-range high-quality loudspeaker is about 9 octaves, i.e. 40Hz to 20kHz. This is clearly too wide a range to be handled by a single horn, for the reasons already noted, but it can conveniently be divided into three ranges, i.e. 40Hz to 320Hz, 320Hz to 2.5kHz and 2.5kHz to 20kHz. In practice, a 10% overlap should be allowed to ensure that there are no troughs in the response at the crossover points, and a case could be made for a four-horn system to cover a wider range.

It is worth considering a more modest instrument. If the cut-off frequency is limited from 80Hz to 18kHz and a two-horn system is considered with each horn handling a little under four octaves, the frequency ranges become 80Hz to 1.2kHz and 1.2kHz to 18kHz. Again, about 10% frequency overlap should be allowed.

The great attraction of a two-horn system is that only a single loudspeaker is required: the bass horn will be loaded from the rear of the loudspeaker; while the middle and treble horns will be loaded from the front of the loudspeaker, to eliminate interference and diffraction effects caused by the frame and magnet assembly at lower wavelengths. It has already been emphasized that the throat of the horn should match exactly the loudspeaker dimensions at these higher frequencies, and this arrangement is particularly attractive if a twin-cone speaker is employed. Treble wavefronts may be prevented from going down the bass horn by the cavity. To show the ease and utility of this approach, this article will include the design of a "mini-horn" utilising both sides of a single loudspeaker in a cabinet of reasonable size and cost for small domestic living rooms.

Purists may claim that the curtailed frequency range of 80Hz to 18kHz is inadequate. It is however the author's experience that the flat relatively distortionless response between these limits, together with

the sense of presence afforded by the horn's transformer action, make the mini-horn sound more attractive than many commercial loudspeaker systems of similar size but two or three times its price.

Once one adopts a multi-horn approach, there will be a number of frequencies which fall within the compass of two horns, i.e. 320Hz and 2.5kHz in the case of the three-horn system, and 1.2kHz for the two-horn system. It is essential that the radiation from the relevant pair of horns should be reasonably in phase at the crossover frequency, to avoid the presence of troughs in the frequency response, because the bass horn will be folded to bring its mouth adjacent to the other horns (it is not normally necessary or desirable to fold the middle and treble horns). This requirement places a restriction on the length of the horn, which has until now been regarded as a parameter to be determined solely by the throat and mouth diameters and the flare constant, and it is now apparent that the length of the lower horn of each pair should be either an odd or even number of half wavelengths of the crossover frequency, depending on whether the radiation wavefronts at the throats of the two horns are respectively in or out of phase.

Thus, if separate loudspeakers are used and the voice coils are connected in phase, the combined length of the horns from the loudspeakers to the plane of the mouths should be an even number of half wavelengths. Conversely, if a single loudspeaker is used to feed two horns, the radiation from the front and rear of the cone will be out of phase and the combined length of the two horns should be an odd number of half wavelengths. In practice, the lower horn will be considerably longer than the upper, and will effectively determine the design.

Folding, cabinets and room placing

Hitherto, discussion has been confined to ideal horns, of circular cross-section and straight axis, constructed of very stiff ma-

terial. Although typical dimensions for practical horns have not been calculated formally, it will be clear from many of the tables and diagrams that the dimensions of bass horns are almost certainly too large for comfortable accommodation in an average living room. Two further points must therefore be added to the design procedure, adoption of rectangular sections and folding the horn into a compact size.

Rayleigh showed that bends in tubes of constant cross-section will have no effect on transmitted sounds if the wavelength is large compared with the diameter, but that any cross vibrations set up will have a fundamental wavelength of 1.7 times the tube diameter. Wilson¹¹ has summarized the three principal rules of folding horns as follows: the wavefronts must not be twisted across the horn; the horn diameter (or width if rectangular) must be less than 0.6 times the lowest wavelength to be transmitted by that horn; the wavefront should be accelerated round bends to preserve its form.

As soon as one departs from the straight horn of circular cross-section, the scientific design principles described cease to be so relevant and become of more approximate value, although the three basic rules quoted above, together with the choice of a suitably stiff material for construction, provide very acceptable results.

A folding technique which twists the wavefront across the horn is difficult to achieve in practice, and may be eliminated by folding always in one plane. The requirement to "accelerate the wavefront around bends to preserve its form" is difficult to achieve when more than one fold is involved, since it requires a rectangular cross-section before the bend to become trapezoidal around the bend itself¹¹, and then revert to a different rectangular section after the bend. If one considers a multi-fold horn, concertina-fashion within an overall rectangular enclosure, this is not really a practical proposition, and is unnecessary because

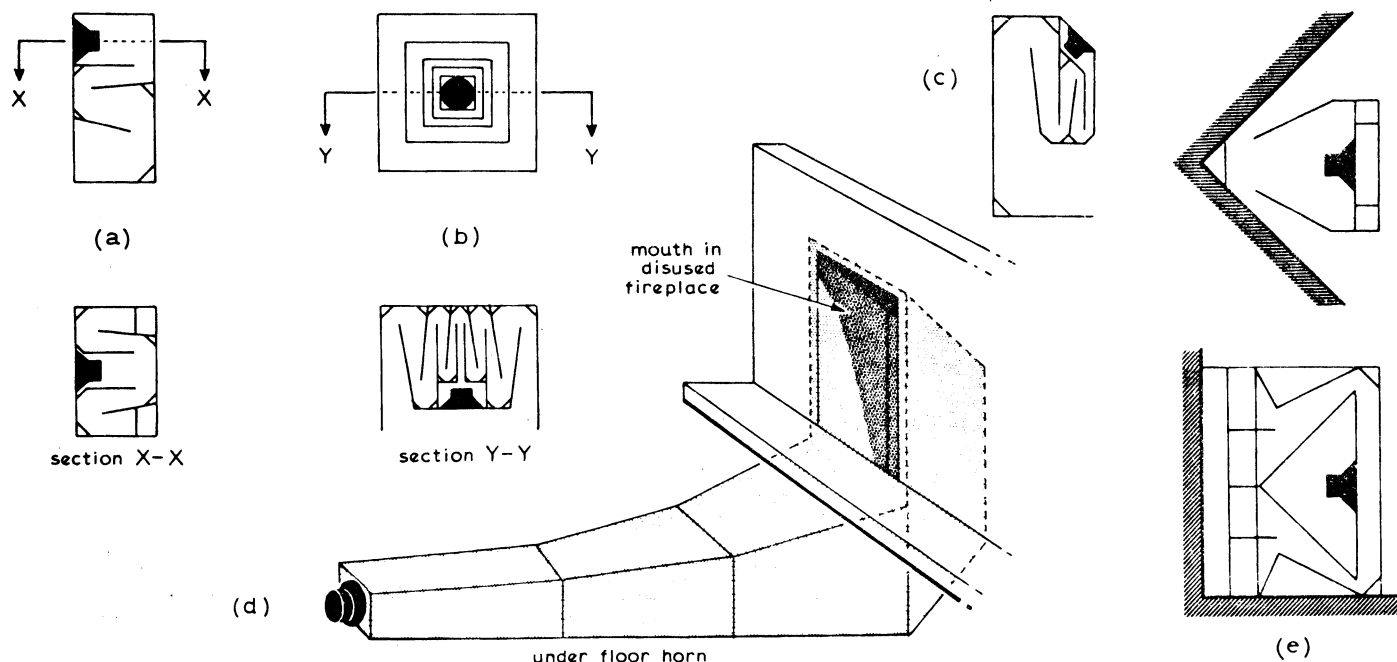


Fig. 10. Methods of folding horns (a) Olson, (b) Olson and Massa, (c) Lowther, (d) Newcombe, (e) Klipsch.

subsequent bends correct the waveform. But for single bends it can be adopted, and the mini-horn design described later could utilize this feature.

Examination of the Patent Office records for folded horn designs registered during the 1920s and 30s provides a fascinating monument to the ingenuity of acoustical designers, and Fig. 10 illustrates a number of the more well-known methods of folding. The restriction of horn width at a bend to 0.6 times the highest wavelength to be transmitted suggests initially that folding can only be attempted over the first few feet of the length of a horn; after that point the width will have reached the limiting value. However, this limitation may be overcome by bifurcating the horn (splitting into two equal channels) at each point when the width limits. Thus the mouth of a horn may comprise four equal mouths (brought together for convenience and to ensure audio realism) and the four "quarter-horns" may be folded far closer to the mouth than would otherwise be possible. Rayleigh has shown⁷ in Art. 264 that bifurcating a conduit will have no effect on the transmission of sound provided the lengths of the two portions are equal and the sum of their areas at corresponding points is equal to that of the original conduit.

In many cases, the front side of a loudspeaker, whose reverse side is horn loaded, will be physically close to the mouth of the horn itself, and it is commonly feared that there will be cancellation at certain frequencies caused by interference between the two radiations in anti-phase. However, the direct radiation from the unloaded front of the cone is only a few percent of that through the horn, and so the amount of cancellation is negligible.

Frequency handling

Although it has been shown that each horn acts as an acoustic bandpass filter, the lower cut-off frequency being determined by the expansion coefficient and the upper cut-off frequency by the throat cavity, there are important reasons why the full audio signal should not be applied directly to all horns regardless of their frequency handling capability. At the low frequency end of the spectrum, examination of Fig. 3 (Part 1) shows that the horn provides the loudspeaker with no resistive acoustic loading below its cut-off frequency. Thus any applied signals below this frequency will cause excessive movement of the loudspeaker diaphragm, which will be constrained only by the mechanical and electro-magnetic factors. This excessive movement can cause unpleasantly high intermodulation distortion, and can also lead to further non-linear distortion when the loudspeaker moves outside its linear range. At the upper frequency end, signals of excessive power can also give rise to distortion products due to deficiencies in the cavity/throat relationship. It is therefore beneficial to restrict the bandwidth of the electrical signal reaching each loudspeaker to match the acoustic bandwidth of its corresponding horn.

Although most commercial multi-unit loudspeaker systems use passive LC cross-over networks between power amplifier and

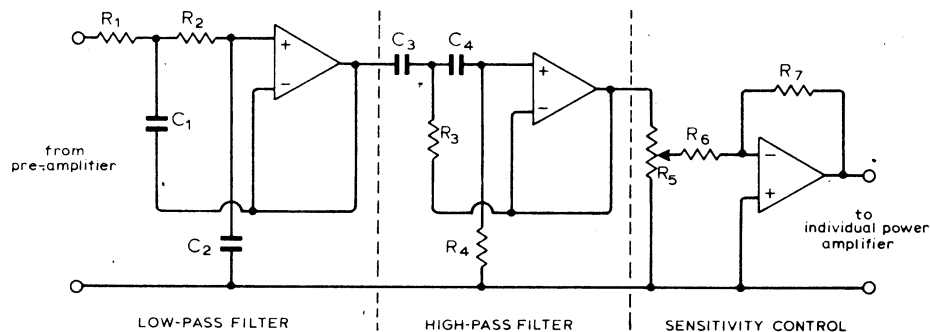


Fig. 11. Circuit for an active filter network. See appendix for component details.

loudspeaker to route signals of the appropriate bandwidth to each loudspeaker, careful comparative listening tests show that these units undoubtedly introduce a "dullness" or loss of "brilliance" into the audio output. Many explanations have been offered for this situation; in the author's opinion, the most likely reason being the loss of "direct drive" from the output of the amplifier, allied with a significant reduction in the degree of electro-magnetic damping afforded by the low output impedance of the amplifier.

Recent correspondence in *Wireless World*²⁸ and elsewhere has extolled the virtues of splitting the frequency range at low signal level, and employing a separate power amplifier directly coupled to each loudspeaker. The author has devised such a circuit, which consists of three (or four) parallel frequency-selective channels comprising Sallen & Key active filters giving preset low and high-pass characteristics in series in each channel, together with some gain adjustment to allow for the inevitable differences in sensitivity of each loudspeaker/horn combination. The active filters provide 2nd order Butterworth characteristics, a response which appears to give the least displeasing effects at the cross-over frequencies. (There will inevitably be phase-shifts associated with any filter circuit, and the effects of these on transients can produce a marked difference in their character.) This circuit is in Fig. 11 and the Appendix.

Thus, some form of electrical cross-over is generally necessary in addition to the acoustic cross-over provided by the horn itself. An exception is of course the case where a single loudspeaker drives two horns: one loading the front and one loading the rear of the diaphragm. In this situation, some compromise will be necessary in the acceptable distortion level and bandwidth of the loudspeaker system.

Directional horns

This article has extolled the ability of the horn to propagate wavefronts that are nearly plane at its mouth. However, there are situations where it is desirable to propagate wavefronts with different characteristics in the vertical and horizontal planes, particularly when middle and treble horns are used in stereophonic systems; it is often desirable to spread the wavefronts in the vertical plane while preserving more of a "point-source" in the horizontal plane. There are a number of different techniques

for achieving this, based on diffraction and refraction effects at the horn mouth with the comparatively short wavelengths (a few inches or less) with which these high frequency horns are concerned.

The design and manufacture of multicellular horns, distributed-source horns, diffraction horns and reciprocal-flare horns is beyond the scope of this article, and with the exception of the first two mentioned is probably outside the capability of most amateur constructors. Those interested should refer to the papers by Smith²⁹, Winslow³⁰ and to the relevant chapters by Olson³ and Cohen⁵.

Klipsch^{16,17} has described the design of his high frequency horn, in which the length/breadth ratio of the (rectangular) mouth assumes a value in excess of 4:1 c.f. the ratio of near unity advocated for bass horns). The optimum dimensions, length/breadth ratio, and apportionment of flare to the long and short axes depend on a number of complex factors, however, an aspect ratio between 2:1 and 4:1 with the flare apportioned in similar ratio has been found to give good practical results, and these parameters have been adopted for the "no-compromise horn" to be described. Although the high frequency horn of the "mini-horn" system is specified as circular (in view of its handling the relatively large wavelengths at 1kHz) an alternative rectangular mouth with aspect ratio of 2.5:1 has also been described.

Detailed design procedure

The previous sections have dealt in some detail with the basic theory of the horn, and the essential design procedures have been outlined for a series of horns which can cover the complete audio range. The final sections will consider the detail design of two horns: a "mini-horn" and a "no-compromise horn".

Because all horns are designed to slightly different requirements, and inevitably many readers will wish to "bend" the specification to a greater or lesser extent in order to satisfy their own needs, the designs are presented here by means of tables so that they represent a comprehensive design code for a wide range of horns.

Bass horn design

The bass horn should be examined initially, commencing with the mouth. Tables 1, 2 and 3 indicate the relationship between

continued over page

Table 1

Freq. (Hz)	Wave-length (ft)	Diameter (ft)	Area (sq. ft)
30	37.5	11.94	111.98
40	28.13	8.95	62.92
50	22.5	7.16	40.27
60	18.75	5.97	28.0
70	16.07	5.12	20.59
80	14.06	4.48	15.77
90	12.5	3.98	12.44
100	11.25	3.58	10.07
110	10.23	3.25	8.30
120	9.38	2.98	6.98

Table 1. Minimum mouth dimensions for bass horn (free loading).

Table 5

Freq. (Hz)	Cut-off freq. (Hz)	Flare coeff. (ft ⁻¹)	Area increase (% ft ⁻¹)	Doubling dist. (ft)
30	25	.278	32	2.49
40	33	.366	44	1.89
50	42	.466	59	1.49
60	50	.555	74	1.25
70	58	.644	90	1.08
80	66	.733	108	.945
90	75	.833	130	.832
100	84	.932	154	.744
110	92	1.02	178	.679
120	100	1.11	205	.624

Table 5. Exponential constants for bass horn.

Table 7

Nom. dia. (in)	Area (sq. in)	Effective area (sq. in)	Throat area (sq. in)	Throat area (sq. ft)
3½	9.62	6.74	2.02	.014
5	19.64	13.75	4.12	.029
6½	33.19	23.23	6.97	.048
8	50.27	35.19	10.56	.073
10	78.55	54.99	16.50	.114

Table 7. Throat dimensions.

Table 2

Freq. (Hz)	Area (sq. ft)	Dia. (ft)	Sq. side (ft)	Rect. sides (ft)
30	28	5.97	5.29	4.69 5.97
40	15.73	4.47	3.96	3.52 4.47
50	10.07	3.58	3.17	2.81 3.58
60	7.0	2.98	2.64	2.34 2.98
70	5.15	2.56	2.27	2.01 2.56
80	3.94	2.24	1.98	1.76 2.24
90	3.11	1.99	1.76	1.56 1.99
100	2.52	1.79	1.58	1.41 1.79
110	2.07	1.62	1.44	1.27 1.62
120	1.74	1.49	1.32	1.17 1.49

Table 2. Minimum mouth dimensions for bass horn (wall position).

Table 6

Freq. (Hz)	Cut-off freq. (Hz)	Flare coeff. (in ⁻¹)	Area increase (% in ⁻¹)	Doubling dist. (in)
200	166	.155	17	4.48
250	208	.193	21	3.59
300	250	.233	26	2.97
350	292	.271	31	2.56
400	330	.307	36	2.26
450	375	.349	42	1.98
500	420	.391	48	1.77
550	458	.426	53	1.63
600	500	.465	59	1.49
700	580	.539	71	1.29
800	660	.614	85	1.13
900	750	.698	101	.993
1000	840	.781	118	.887
1100	920	.855	135	.810
1200	1000	.930	153	.745
1300	1083	1.01	175	.686
1400	1166	1.08	196	.642
1500	1250	1.163	218	.596
2000	1660	1.54	368	.450
2500	2080	1.93	590	.359

Table 6. Exponential constants for mid/top horn.

Table 10

Freq. (Hz)	3½	5	6½	8
200	30.9	26.3	22.9	20.3
250	22.5	18.8	16.1	14.0
300	17.1	14.0	11.8	10.0
350	13.6	10.9	8.98	7.46
400	11.1	8.78	7.07	5.73
450	9.09	7.05	5.55	
500	7.58	5.77	4.42	
550	6.51	4.84		
600	5.56			
700	4.24			
800	3.31			
900	2.58			

Table 10. Length of mid/top horn (in), free loading. Since the mouth perimeter equals 1.5 times the highest working wavelength, the tractrix cannot be used. Tractrix contours can however be incorporated if the mouth perimeter is reduced to one wavelength.

Table 3

Freq. (Hz)	Area (sq. ft)	Dia. (ft)	Sq. side (ft)	Rect. sides (ft)
30	14.0	4.22	3.75	3.32 4.22
40	7.87	3.16	2.81	2.49 3.16
50	5.03	2.53	2.24	1.99 2.53
60	3.5	2.11	1.87	1.66 2.11
70	2.57	1.80	1.60	1.42 1.80
80	1.97	1.58	1.40	1.24 1.58
90	1.55	1.41	1.25	1.10 1.41
100	1.26	1.27	1.12	0.995 1.27
110	1.04	1.15	1.02	0.904 1.15
120	0.87	1.05	0.93	0.829 1.05

Table 3. Minimum mouth dimensions for bass horn (corner position).

Table 4

Freq. (Hz)	Wave-length (in)	Dia. (in)	Area (sq. in)	Sq. side (in)	Rect. sides (in)
200	67.5	32.2	815.4	28.6	25.3 32.2
250	54.0	25.8	522.9	22.3	20.3 25.8
300	45.0	21.5	365.1	19.1	16.9 21.5
350	38.57	18.4	265.9	16.3	14.5 18.4
400	33.75	16.1	203.6	14.3	12.6 16.1
450	30	14.3	160.6	12.7	11.3 14.3
500	27.0	12.9	130.7	11.4	10.1 12.9
550	24.55	11.7	107.5	10.4	9.2 11.7
600	22.5	10.7	89.9	9.5	8.4 10.7
700	19.28	9.2	66.5	8.2	7.2 9.2
800	16.88	8.1	51.5	7.2	6.3 8.1
900	15	7.2	40.7	6.4	5.6 7.2
1000	13.5	6.4	32.2	5.7	5.1 6.4
1100	12.27	5.9	27.3	5.2	4.6 5.9
1200	11.25	5.4	22.9	4.8	4.2 5.4
1300	10.38	4.9	18.8	4.3	3.9 4.9
1400	9.64	4.6	16.6	4.1	3.6 4.6
1500	9	4.3	14.5	3.8	3.4 4.3
2000	6.75	3.2	8.0	2.8	2.5 3.2
2500	5.40	2.6	5.3	2.3	2.0 2.6

Table 4. Minimum mouth dimensions for mid/top horn (free loading).

Table 8

Freq. (Hz)	3½		5		6½		8		10	
	Ex	Tr	Ex	Tr	Ex	Tr	Ex	Tr	Ex	Tr
30	27.3	25.1	24.7	22.5	22.9	20.7	21.4	19.2	19.8	17.6
40	19.2	17.6	17.2	15.6	15.8	14.2	14.7	13.1	13.5	11.9
50	14.1	12.8	12.6	11.3	11.5	10.2	10.6	9.3	9.62	8.30
60	11.2	10.1	9.88	8.78	8.98	7.88	8.22	7.12	7.42	6.32
70	9.17	8.23	8.05	7.11	7.25	6.31	6.60	5.66	5.92	4.98
80	7.69	6.83	6.70	5.84	6.01	5.15	5.44	4.58	4.83	3.97
90	6.48	5.75	5.61	4.88	5.00	4.27	4.50	3.77	3.97	3.24
100	5.57	4.91	4.79	4.13	4.25	3.59	3.80	3.14	3.32	2.66
110	4.90	4.30	4.18	3.58	3.69	3.09	3.28	2.68	2.84	2.24
120	4.34	3.79	3.68	3.13	3.23	2.68	2.85	2.30	2.46	1.91

Table 8. Length of bass horn (ft) for different flare constants, wall position. Ex-exponential, Tr-tractrix. N.B. The tractrix lengths are approximate.

Table 9

Freq. (Hz)	3½		5		6½		8		10	
	Ex	Tr	Ex	Tr	Ex	Tr	Ex	Tr	Ex	Tr
30	24.8	22.6	22.2	20.0	20.4	18.2	18.9	16.7	17.3	15.1
40	17.3	15.7	15.3	13.7	13.9	12.3	12.8	11.2	11.6	10.0
50	12.6	11.3	11.1	9.8	9.98	8.66	9.08	7.76	8.12	6.80
60	9.95	8.85	8.64	7.54	7.73	6.63	6.97	5.87	6.17	5.07
70	8.10	7.16	6.96	6.02	6.18	5.24	5.53	4.59	4.83	3.89
80	6.75	5.89	5.75	4.89	5.07	4.21	4.50	3.64	3.89	3.03
90	5.65	4.92	4.78	4.05	4.17	3.44	3.67	2.94		
100	4.83	4.17	4.05	3.39	3.51	2.85				
110	4.22	3.62	3.51	2.91						
120	3.72	3.17								

Table 9. Length of brass horn (ft) for different flare constants, corner position. Ex-exponential, Tr-tractrix. N.B. The tractrix lengths are approximate.

minimum frequency and mouth dimensions for horns positioned in free air (4π solid radians) at a wall (π solid radians), and in a corner ($\pi/2$ solid radians). In table 1, the speed of sound has been taken as 1125 ft/sec, and the mouth perimeter as the wavelength. The mouth areas in tables 2 and 3 are equal to $\frac{1}{4}$ and $\frac{1}{8}$ respectively of the mouth area in free air, and the dimensions for the circular, square and rectangular mouths are derived from these areas. It is tempting to reduce the areas of the square and rectangular horns so as to give a perimeter equivalent to the wavelength (suitably scaled for wall or corner positioning) but this is not recommended. However, the shorter side of the rectangular horn has been derived in this way (i.e. a square horn with this side would have the appropriate perimeter).

After settling the mouth dimensions, the throat may be determined from the chosen loudspeaker unit. Table 7 gives suggested throat areas for five typical mean loudspeaker sizes. In some designs, the choice of loudspeaker will be influenced by considerations of overall size (the length of the horn is greatest for the smallest loudspeaker) and whether the loudspeaker is to perform as both bass and mid/top driver, using two separate horns on either side. Many loudspeakers will possess different dimensions, and in these cases table 7 will be of little value. The effective area (piston area) has been taken as 0.7 of the area derived from the mean (quoted) diameter, and the throat area as 0.3 of the effective area. Although there is obviously scope for experiment here, the quoted dimensions should give very acceptable results.

Having decided the throat and mouth areas, tables 8 and 9 give the overall lengths of horns with true exponential and tractrix contours for both wall and corner placing for horns with the five derived throat areas at each of the cut-off frequencies specified in table 1. The factor of 1.2 applied to the cut-off frequency in table 5 when calculating the flare coefficient is to ensure a fairly linear frequency relationship throughout the working range of the horn. The flare coefficient m is thus given by

$$m = (4\pi/c)(f/1.2)$$

where c is the speed of sound (1125ft/sec) and f is the lowest frequency to be reproduced.

The area increase is given by $(e^m - 1)\%$ and the doubling distance by $(\log_e 2)/m$ for each frequency. The length of the exponential horn is given by $(1/m) \log_e S_m/S_T$ for each specified set of areas, and the length of the tractrix horn will be $r_m(1 - \log_e 2)$ shorter than the true exponential, where S_m = mouth area, S_T = throat area, r_m = mouth radius.

N.B. The tractrix lengths given in tables 8 and 9 are approximations, being based on the fully developed tractrix referred to the flare cut-off frequency, whereas the mouth radius is referred to the lowest bass frequency to be reproduced.

Middle top horn design

Attention should now be directed to the middle and high frequency horns. The

mouth perimeter should not be less than the wavelength of the lowest working frequency, and in practice a perimeter of 1.5 times the lowest working frequency has been found to give good results. Table 4 is based on this factor of 1.5, and gives the recommended minimum mouth dimensions for free air loading. It is safest to assume free air loading to apply at these higher frequencies, because diffraction and reflection effects at short wavelengths prevent true wall or corner loading from being achieved, and it is for this same reason that the perimeter has been specified at 1.5 times the wavelength of the lowest working frequency. The dimensions of square and rectangular horns have been derived in the same way as those in tables 2 and 3. The throat dimensions of middle and high frequency horns should match the drive unit directly, and may be taken as the mean diameter and area of the chosen loudspeaker, shown in table 7. Tables 6 and 10 give the flare constants and lengths of exponential horns assuming the throat and mouth dimensions of tables 7 and 4 respectively.

Integration of multiple horns

It has been emphasized that the radiation from the mouths of each pair of horns at their common crossover frequency should be in-phase. Assuming that the mouths of all the horns will lie in the same plane, the total length of each pair of horns should be compared with the multiples of half wavelengths of the crossover frequency set out in table 11. If the drive signals at both throats are in-phase (separate loudspeakers), the total length should be an even number of half-wavelengths; if the drive signals are out-of-phase (single speaker horn-loaded at both front and rear) the total length should be an odd number of half wavelengths. If necessary, small changes may be made to the crossover frequency (with subsequent re-design of the higher frequency horn) to ensure optimum conditions at crossover.

The complete design

The bass horn will generally be folded. Originally it was intended to provide a table giving the maximum permitted length of horn before folding should cease because the horn diameter has become equal to 0.6 times the lowest wavelength to be transmitted. However, examination has shown that at frequencies up to five times the bass cut-off frequency (i.e. 4 octaves bandwidth) this restriction does not apply to the corner-positioned horn (due to the small mouth dimensions) and with the wall-positioned horn the limitation lies between 92% and 95% of the full exponential length. It may therefore be assumed that provided the wall-positioned horn is not folded within the final 10% of its length, the problem of cross reflections will not arise.

Finally, the cavities at the throats of the lower frequency horns should be designed in accordance with the formula already given, remembering to allow for the loss of cavity volume due to the frame, magnet and cone assembly of the loudspeaker itself.

The design procedure laid down in this part has been applied to two different designs of horn to follow, and further examples

of overall horn design are given in refs 34 to 37, and also in ref. 5.

Appendix

A variable bandpass active filter for feeding a 3 horn loudspeaker system (see Fig. 11):

Low-pass filter

Frequency (Hz)	R_1 (kΩ)	R_2 (kΩ)	C_1 (pF)	C_2 (pF)
200	59	59	20,000	10,000
1k	12	12	20,000	10,000
2k	59	59	2,000	1,000
10k	12	12	2,000	1,000
6k	59	59	680	330
30k	12	12	680	330

N.B. R_1 & R_2 to be realized as 12k in series with 47k log pots.

High-pass filter

Frequency (Hz)	R_3 (kΩ)	R_4 (kΩ)	C_3 (pF)	C_4 (pF)
25	28	57	160,000	160,000
100	7	14	160,000	160,000
250	28	57	16,000	16,000
1k	7	14	16,000	16,000
4k	28	57	1,000	1,000
16k	7	14	1,000	1,000

N.B. R_3 to be realized as 6.8k in series with 22k log pot. R_4 to be realized as 12k in series with 47k log pot.

All i.c.s to be Signetics N5741V, etc. R_5 10k log, R_6 22k, R_7 100k.

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Construction

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

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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 will 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 $1\frac{1}{2}$ in thick. Composite sand-filled panels consisting of two thin walls of $\frac{1}{2}$ in plywood spaced $\frac{1}{2}$ 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 $\frac{1}{4}$ 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 $\frac{1}{2}$ 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 coaxial 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 $\times$ 1.03ft (29.7in $\times$ 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 130.7 sq.in, which may conveniently be realized as 10.1in $\times$ 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 $\times$ 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-wavelengths 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,

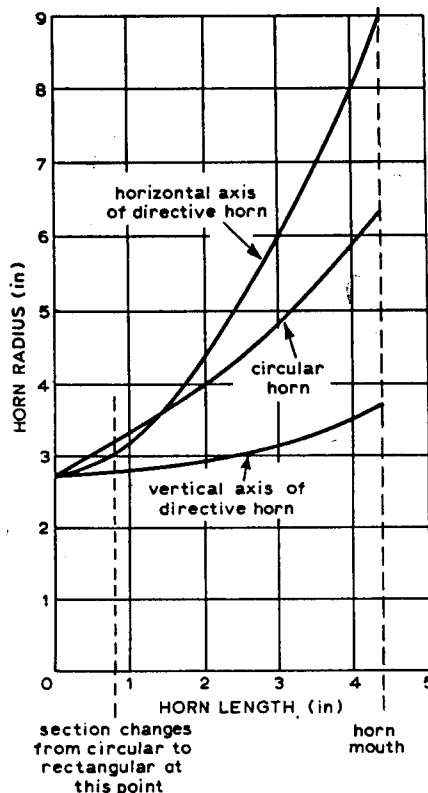


Fig. 13. Flare contour for the treble section of the mini-horn.

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 $\frac{1}{2}$ in chipboard, etc, except the side and front panels of $\frac{1}{2}$ in plywood.

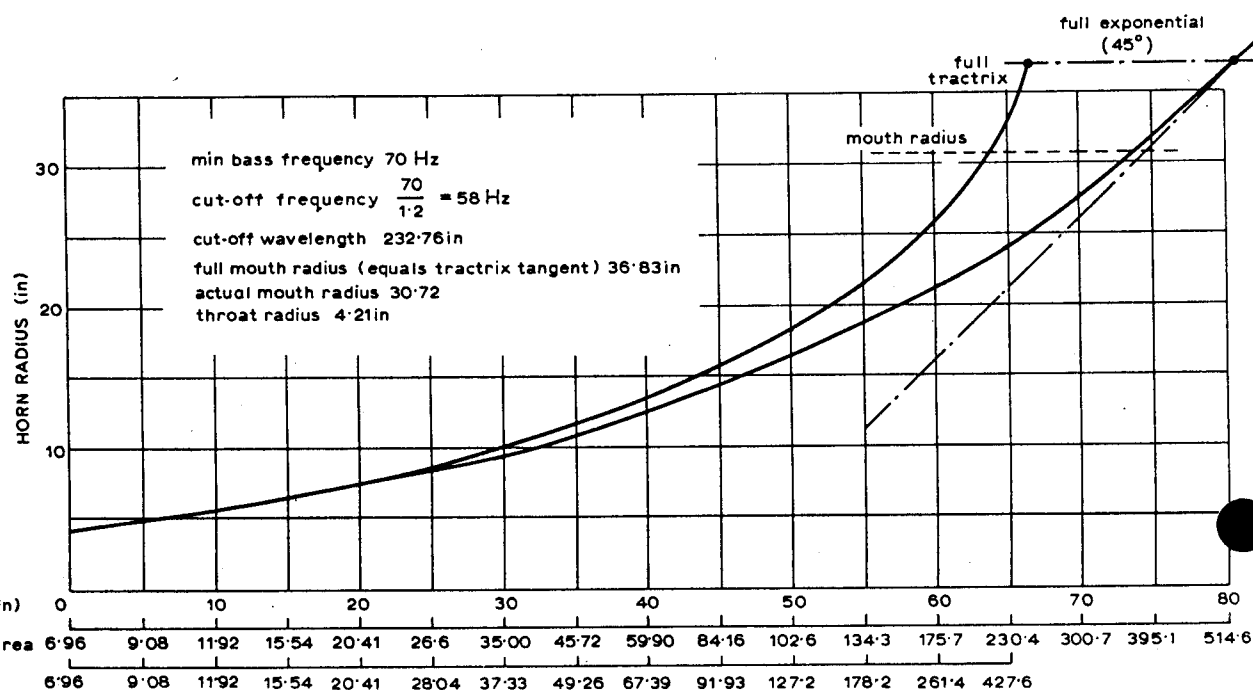


Fig. 12. Flare contour for the bass section of the mini-horn.

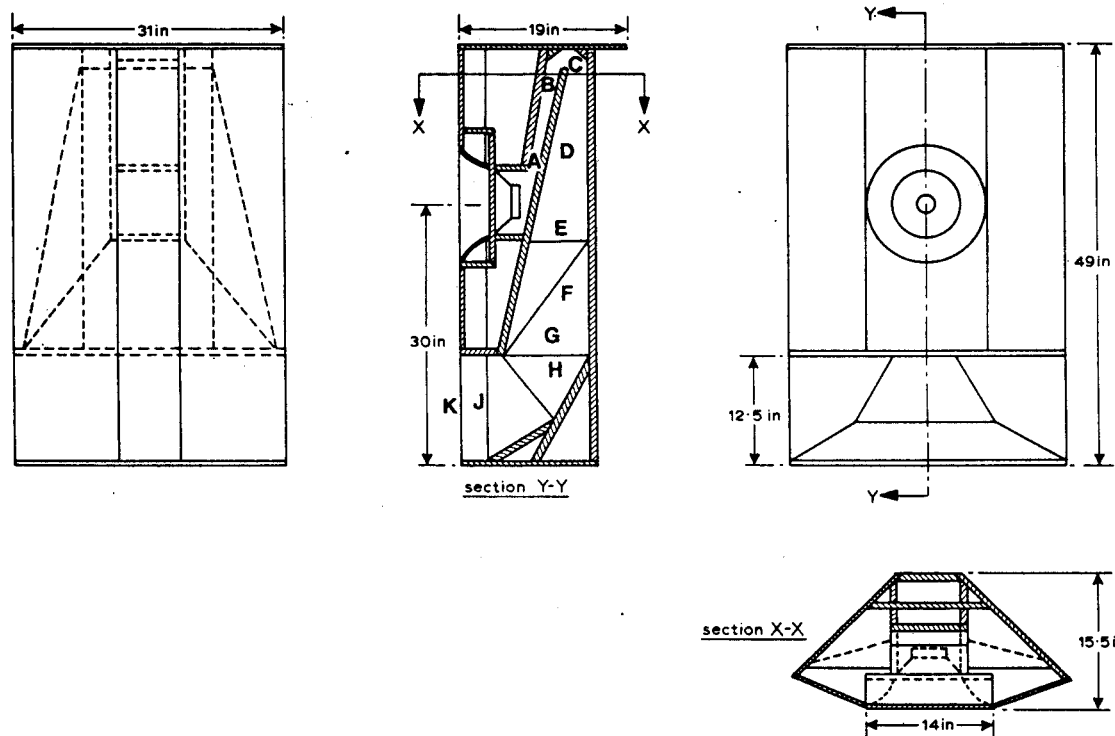
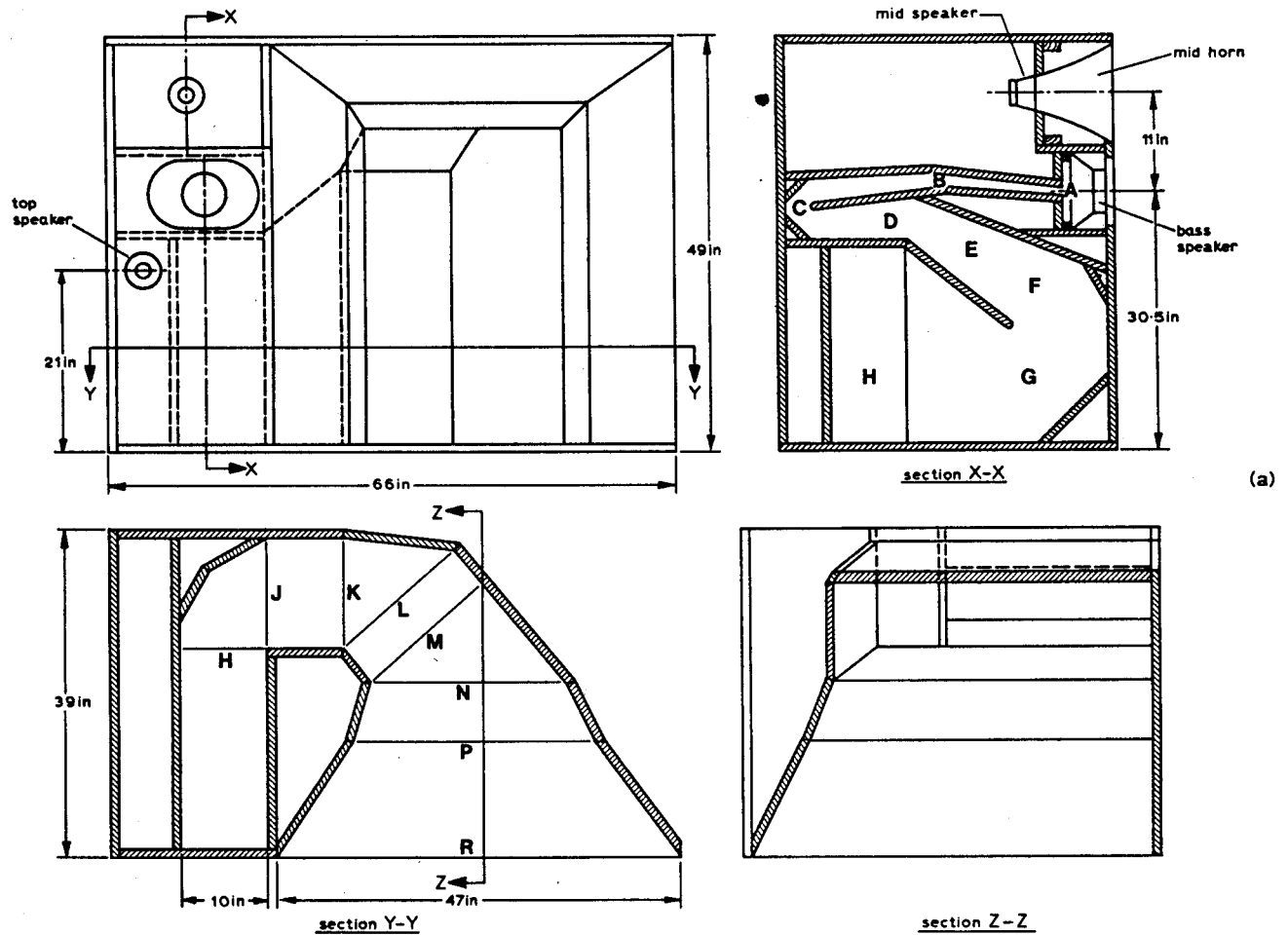


Fig. 14 (a) Suggested realization of the no-compromise horn (b) suggested realization of the mini-horn. Cross sectional details for the mini bass horn are given in Table 14 and for the no-compromise bass horn in Table 15.

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 3.8kHz
Treble Horn	3.5kHz to 20kHz

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 peri-

meter 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 block-board, plywood, etc., and all joints should be screwed and glued to make them airtight.

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	
H	50	127	
J	60	261	
K	63	370	26 x 10 high 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)
B	0	10.6	1.06
C	15	17.0	1.7
D	30	27.8	2.78
E	40	38.0	3.8
F	50	54.0	5.4
G	60	75.0	7.5
H	75	122	12.2
I	94	230	23
J	104	316	13.5 x 23 high
K	113	426	13.5 x 31.5 high
L	120	540	17 x 31.5 high
M	125	630	17 x 37 high
N	132	790	21 x 37 high
P	139	1125	28 x 40 high
R	153	2265	47 x 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.