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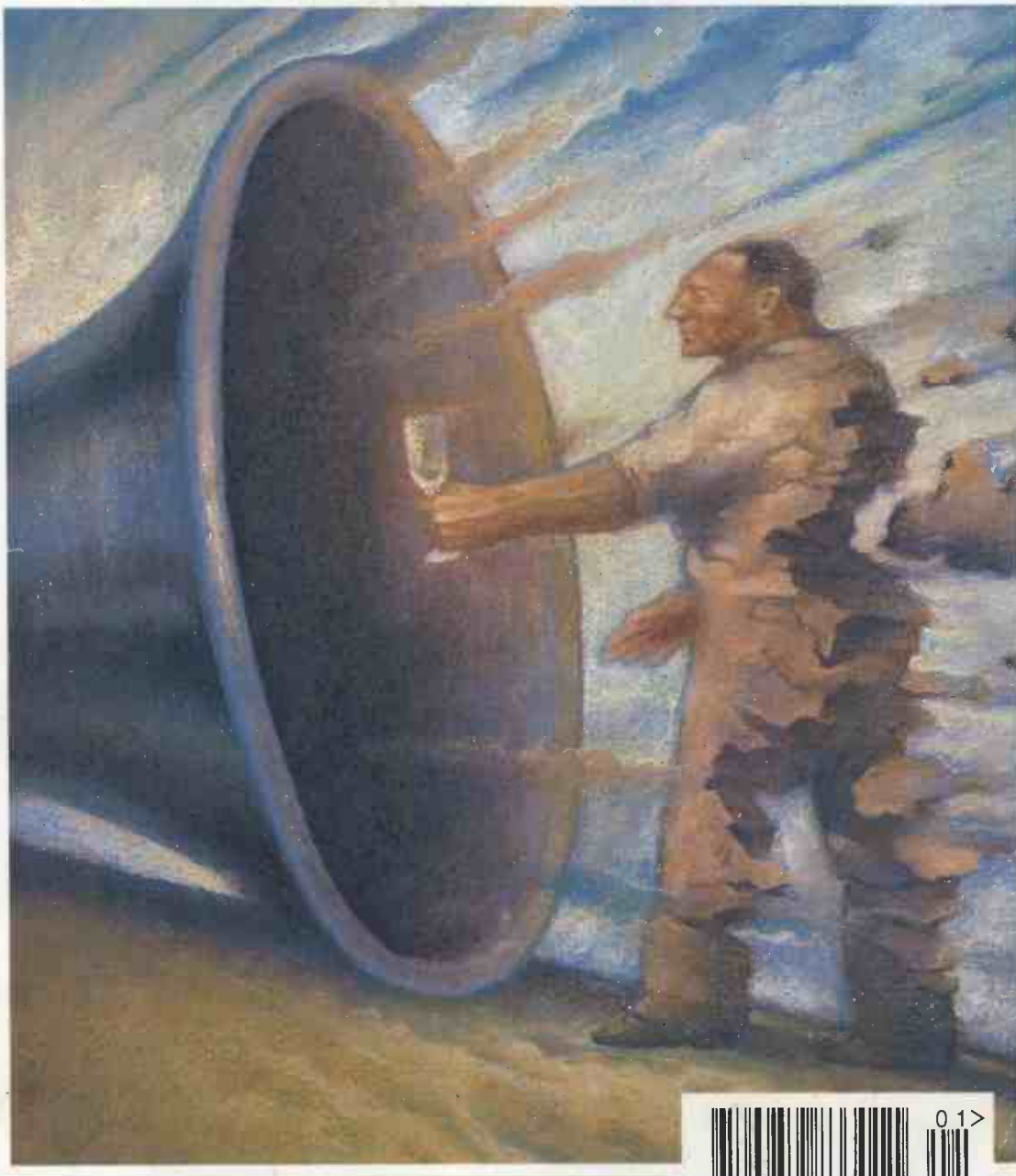

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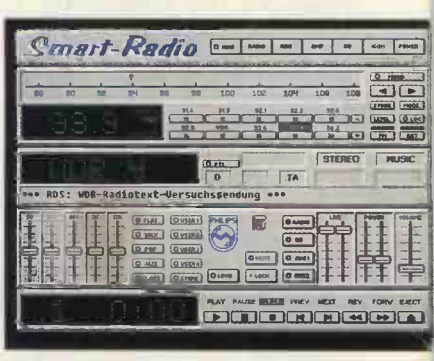


Its now possible to view broadcast Radio Data on the PC – page 4.

Designing a horn loudspeaker



Ketil Parow details how to design a no-compromise, full-range tractrix horn loudspeaker featuring the combined benefits of high efficiency and crossover-free operation.

Why a horn? Much has been written about horn speakers over the years, and I am not going to repeat all of it here. I will however point out the obvious advantages, and my points of view. First, I will kill some of the myths about horn loudspeakers.

- Bass reproduction from a horn is not tinny. Some poorly-designed systems may have a tendency to produce 'empty' bass. In these cases, chances are that the designer compromised too much, foreshortened the horn in order to reduce the physical size. Poor wood quality may also have contributed to the poor quality.

- You do not need a vinyl record player and valve amplifiers to make a horn sound good. Advantages of a horn system are noticeable – regardless of equipment technology.

- Treble is not poor from a one-way horn system. There is a number of 'full-range' drivers available that are not truly range. This is not so with the Lowther drivers I used.

There is wide agreement on the following pros of horn loudspeakers.

- A horn system is far more efficient than an infinite baffle of bass reflex system. This offers not only more sound per input watt. For a given signal peak level, spl, the driver's excursion is accordingly smaller. As a result, the driver operates with more linear excursions so distortion is lower.

- Sound from a horn is more dynamic and more life-like than that from closed or vented boxes.

- In my experience, multi-way systems in vented or sealed enclosures can be seriously compromised by sloppy construction. A horn is less sensitive to enclosure materials and wood-working accuracy.

- Crossover networks are difficult to design, expensive, and the end results are unpredictable. A one-way horn removes these problems and produces a single sound source.

Design goals

Does the world need a new horn design? There is a number of well-designed horn systems in existence. However, on reviewing some of the existing designs, they did not appeal to me for various reasons.

The modern designs seem to compromise too much in order to limit their physical dimensions. Older designs are no doubt good, but they *look* old fashioned. I want my speakers to look modern.

When I set out on this project, the only goal that was well-defined was that I wanted a back-loaded horn. Bass reproduction was to go well below 40Hz. Physical size was not an absolute restraint.

Horn theory overview

This section merely scratches the surface of horn theory. Those of you wanting to design your own horn are referred to the literature list. I will however provide all the theory relevant to the horn that I designed in enough detail to allow you to duplicate my work.

A horn is an acoustic transformer coupling the speaker cone movement to the air. It transforms a small volume of air moving with high energy into a low-energy, large movement of air. This is where the efficiency comes from.

The horn forms a funnel starting at the throat, closest to the driver and ending at the mouth. Cross-sectional area of the funnel expands along the length of the horn at a rate depending the formula used. This is known as the contour.

Any given horn is only effective down to its cut-off frequency, f_c. To calculate the horn, you need to know the mouth and throat area, the cut-off frequency, and the chosen contour.

Mouth dimensioning

Mouth area is calculated from f_c. Circumference of a circular mouth should be

List. Pseudo code for calculating the horn's tractrix contour.

```
;Sample code
Def var r       as decimal . ;See the above formula
Def var x       as decimal . ;See the above formula
Def var a       as decimal . ;See the above formula
Def var  r_throat       as decimal . ;Radius at throat
Def var  r_ fe_mouth    as decimal . ;Radius for a Fully
                        ;Expanded mouth (free space loading)
Def var  hl_ feas decimal . ;Horn Length when Full Expansion
                        ;(free space loading)
Def var  Size_factor    as integer .          ;See below
Def var  step           as integer initial 1 . ;See below
Def var oldx            as decimal initial -1 .
Def var  xfromthroat    as decimal .
Def var  prec           as decimal initial 0.001 .
               ;simulate radius growth with prec(ision) of…
Input r_throat          ;Get the radius of the throat
Input Size_factor       ;Get the size factor
                        ;(1 for free loading,
                        ;2 for the middle of a floor,
                        ;4 for wall placement, 8 for corner placement)
Input r_fe_mouth        ;radius for free loaded mouth
Input step              ;Get the desired step value
                        ;(output for every <step> length units)

r = r_throat * sqrt(Size_factor).
               ;Start at the size-factor adjusted r.
a = r_fe_mouth.                    ;End at the fully expanded mouth.
hl_fe = a * log((a + sqrt(a * a - r * r)) / r) - sqrt(a * a - r * r).
                        ;Calculate the length of the horn
do while r <= r_fe_mouth: ;Leave the loop when we're at the mouth.
  x = a * log((a + sqrt(a * a - r * r)) / r) - sqrt(a * a - r * r).
               ;Calculate the x (dist from mouth)
  xfromthroat = hl_fe - x.          ;Find dist from throat
  If trunc(xfromthroat / step, 0) > oldx then do:
                        ;Did we just step over to a new value of x?
    display             ;Yes, print the line out...
      xfromthroat at 1                  column-label "Dist. throat"
      sqrt(r * r * M_PI / Size_factor)  column-label "Square"
      r / sqrt(Size_factor)             column-label "Radius"
      (r * r * M_PI / Size_factor)      column-label "Area".
    oldx = xfromthroat / step.        ;And keep current step value
  End. ;New step value
  r = r + Prec.                       ;Increase radius by Prec
end.
;End Sample code
```

Performance

I don't have the tools to measure frequency response, but bass response seems reasonably flat in the deep end. I suspect, however, that there's a small dip in the response in the high bass region. It may be possible to reduce this with experimentation on cavity-damping/room-placement.

One of the most amazing things about these speakers is the sound output they are capable of. Out of interest, I tried powering them up using a Walkman, and they actually filled my basement – which is a big room. According to my measurements, 2-3W driving these speakers should suffice. At 1W, they are loud enough for most people to start holding their ears.

Horn speakers require tweaking to perform at their best. Seemingly insignificant adjustments in room placement can shift the sound from beautiful to dreadful. At this point, I am still not 100% sure that my speakers are optimally placed, and some of the above noted problems may still go away.

Lowther drivers are often criticised for having peaks in the high mids/low treble regions. I think the critics are, to some extent, right on this. There is a pronounced peak somewhere in that region, making some vocals/guitars sound a little harsh. There are some common tweaks to remedy this. Loosely stuffing some clean, long-hair wool between the whizzer-cone and the main cone is one of them.

equal to one wavelength of f_c, which gives,

$$r_m = \frac{c}{2\pi f_c}$$

where, c is the speed of sound, at 34290cm/s or 1125ft/s.

If you try inserting a sample value in the formula of, say, 30Hz, you will get an outrageous mouth radius of 182cm. This, however, is a mouth size calculated for free space loading. That means that the dimensions are good if the horn is hanging from the roof, radiating into all eight quadrants of the space. For wall placement, the horn will be radiating into only two quadrants, so you can safely reduce the size by a factor of $^8/_2$, or four.

For corner placement, the situation is even better. The horn will be radiating into one quadrant only, and you can reduce the size by a factor of eight. In this example, that will bring the mouth down to $r_m/\sqrt{8}$, which is 64cm. In a square horn, this corresponds to a square side of 114cm – which is still large.

It is possible to reduce the mouth size still further, even without compromising the overall design, as explained later.

This horn's f_c was set at 32Hz, and calculated for corner placement.

Throat dimensioning

Theory here is somewhat more obscure. However, there are some valid thumb rules in calculating the throat area. In his 1974 article (see recommended reading) Dinsdale said, "For maximum bandwidth of a horn, one uses throat-to-driver ratios of 0.50 to 0.30; for maximum efficiency one uses ratios of 0.50 to 0.70."

Personally, I chose the throat area of my horn empirically. I browsed through 10-20 comparable horn designs, and decided on the basis of the designs most resembling mine. The driver I chose has an effective area of 211cm^2. This indicates that the throat area should be somewhere between 63cm^2 and 148cm^2. I decided on a throat area of 100cm^2. That gives a throat radius, t_r of 5,65cm.

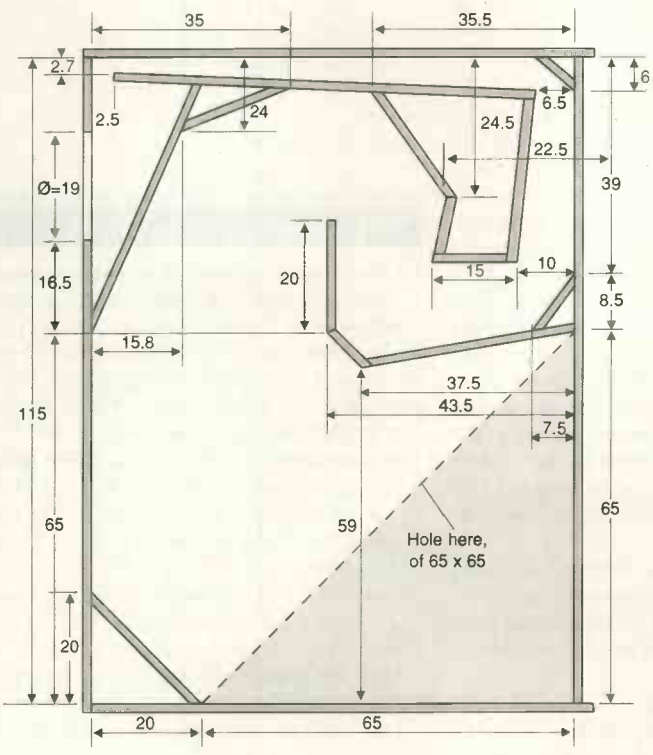
Horn contouring

Common contours for horn loudspeakers include conical, exponential, hyperbolic, and the tractrix. Of these, the conical is the easiest one to calculate and convert into a physical unit, but it is also the least efficient. Conical contours are never used for bass horns, because of the poor response and the impossibly long horns that result.

The exponential is the most common, and is easy to calculate. The hyperbolic contour is a variety of the exponential, and is the most efficient type. The trade-off is more distortion in the deep bass region. Hyperbolic horns are

Tractrix horn expansion from the throat

Distance	Radius	Square	Area	Const. width	L. straight	Dist, inch	Const. w, inch	L. straight inch
				37.00			14.6	
0	5.64	10.00	100.00	2.70		0.00	1.06	
10	5.99	10.61	112.53	3.04	9.93	3.94	1.20	3.91
20	6.35	11.25	126.64	3.42	9.93	7.89	1.35	3.91
30	6.73	11.94	142.48	3.85	9.88	11.82	1.52	3.89
40	7.14	12.66	160.36	4.33	9.89	15.76	1.71	3.90
50	7.58	13.43	180.48	4.88	9.87	19.70	1.92	3.88
60	8.04	14.25	203.03	5.49	9.80	23.62	2.16	3.86
70	8.53	15.12	228.61	6.18	9.85	27.57	2.43	3.88
80	9.05	16.04	257.31	6.95	9.78	31.50	2.74	3.85
90	9.61	17.03	289.85	7.83	9.81	35.45	3.08	3.86
100	10.19	18.07	326.35	8.82	9.73	39.37	3.47	3.83
110	10.82	19.17	367.65	9.94	9.72	43.31	3.91	3.83
120	11.48	20.35	414.22	11.20	9.67	47.25	4.41	3.81
130	12.19	21.61	466.81	12.62	9.63	51.18	4.97	3.79
140	12.94	22.94	526.27	14.22	9.59	55.12	5.60	3.78
150	13.75	24.36	593.56	16.04	9.54	59.06	6.32	3.76
160	14.60	25.88	669.75	18.10	9.48	63.00	7.13	3.73
170	15.51	27.50	756.05	20.43	9.41	66.94	8.04	3.70
180	16.49	29.22	853.78	23.08	9.32	70.88	9.08	3.67
190	17.53	31.06	964.84	26.08	9.23	74.81	10.27	3.64
200	18.64	33.03	1090.96	29.49	9.11	78.75	11.61	3.59
210	19.82	35.14	1234.48	33.36	8.99	82.68	13.14	3.54
220	21.10	37.40	1398.57	37.80	8.86	86.62	14.88	3.49
230	22.47	39.82	1585.84	42.86	8.68	90.56	16.87	3.42
240	23.94	42.44	1800.80	48.67	8.50	94.50	19.16	3.35
250	25.53	45.25	2047.51	55.34	8.25	98.43	21.79	3.25
260	27.25	48.30	2333.01	63.05	8.01	102.37	24.82	3.15
270	29.12	51.61	2663.60	71.99	7.68	106.30	28.34	3.03
280	31.16	55.23	3049.89	82.43	7.33	110.24	32.45	2.89
290	33.40	59.20	3504.50	94.72	6.91	114.18	37.29	2.72
300	35.88	63.59	4043.91	109.29	6.40	118.11	43.03	2.52
310	38.66	68.52	4694.61	126.88	5.83	122.05	49.95	2.30
320	41.82	74.13	5494.64	148.50	5.15	125.98	58.47	2.03
330	45.54	80.71	6514.42	176.07	4.37	129.92	69.32	1.72
340	50.14	88.87	7898.07	213.46	3.43	133.86	84.04	1.35
350	57.04	101.10	10221.90	276.27	2.17	137.80	108.77	0.86



Prototype enclosure design, cross section. Front and back panels are 37cm wide. Note these dimensions apply for 22mm mdf.

Table 1. Inside dimensions of the horn. Note that the mnemonics are referred to in Table 2.

Dimension	Mnemonic	cm
Width	IW	37cm
Depth	ID	85cm
Height	IH	115cm

also somewhat longer than exponential horns. Combinations of all these types can also be found.

The tractrix is a curve well-known in the world of mechanics. In a stroke of genius, the late Paul Voigt applied the tractrix to horn speaker acoustics in 1926. The tractrix contour has characteristics similar to the exponential, but has the advantage of being shorter since the curve expands faster. The disadvantage is that it is somewhat awkward to calculate. This is because you cannot directly calculate the area $A(x)$ at a distance x from the throat.

In this design, I decided to employ the tractrix contour to save space and wood.

Calculating the tractrix

The formula for calculating a tractrix contour is as follows,

$$x = \frac{a\log(a+\sqrt{a^2-r^2})}{r} - \sqrt{(a^2-r^2)}$$

Where x is the distance from the mouth of the horn, a is the radius at the mouth and r is the radius at distance x from the mouth.

The tractrix curve can also be constructed using two straight rulers.

However, if you have access to a computer and some form of compiler, the most convenient method is to write a small program to calculate the curve. Pseudo code outlining how this is done is presented in the **List.**

Coupling horn and driver

Before designing the enclosure, some attention needs to be directed to the volume of air – the cavity – between the driver's back side and the horn throat. It is best to keep higher frequencies out of the horn.

A good thumb rule is to let the horn handle 3-4 octaves or fewer. You should therefore dimension the cavity in such a way that it will act as a low-pass filter with an upper cut-off 3-4 times the horn's cut-off frequency. Also, the upper cut-off should be set at a point where the horn's length equals an odd multiple of the wavelength. This is because the horn is loaded from the back of the driver, 180° out of phase. In this way, cancelling of the frequencies around the upper cut-off is avoided.

Calculate the volume of the cavity V_c using,

$$V_c = \frac{C \times \text{throat area}}{(2\pi \times \text{upper } f_c)^3}$$

In my design, this was not considered. This is because I wanted to leave plenty of space available for experimenting with different upper cut-off frequencies and damping of the cavity. However, I advise would-be constructors to take advantage of this equation.

Folding a bass horn

This is by far the most difficult part of constructing a bass horn. Horn length should be measured along the middle of the duct. Through a bend, the length should be measured along the middle of the duct, all the way around the bend. That makes it a little difficult to construct the bend correctly, but by employing a pair of callipers and a ruler, it is possible.

At first glance, the most convenient method appears to be to keep one wall of the horn straight, while expanding the horn with the other wall. This provides for a convenient way of making the cross-sectional areas match the distance. However, it also makes it harder to measure the distance, since the distance will be on an angled line.

The formula gives you values for x measured along a straight centre line in the middle of the duct, while the radius – and calculated squares/rectangle heights – will expand in both directions from the centre line.

I solved this trigonometrical problem with a spreadsheet. I inserted output from the tractrix contour program into the spreadsheet, and added a number of columns. One of the columns contains the length along the straight wall of the horn, corresponding to the length along the centre line, x. This makes it a lot easier to draw the horn.

In this spreadsheet, the first four columns are created by the tractrix calculation program. These are, distance, radius, square and area. Height of the duct with a width of 37 is shown in the next column, entitled Const. width. In the L. straight column, length of the straight duct wall over the corresponding distance is shown. This has been found by applying simple trigonometric functions to the angles given by the increase in height *versus* the length increase shown in the Distance column.

In the spreadsheet that I used, I also calculated the minimum space requirements for each row of the table. This gave a good indication of the final overall size, given the horn length.

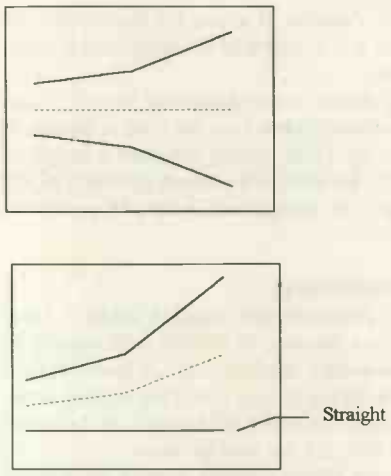
And a time to compromise...

Comparing the spreadsheet to the drawing reveals that the mouth area of horn appears small. It has been foreshortened, i.e. terminated at a mouth smaller than the actually calculated mouth area.

An accepted method of foreshortening the horn, is to base the mouth opening on a higher frequency than the fc used to determine the flare rate. Normally, a horn's 'true cut-off' will be at a frequency of around $1.25f_c$. This allows the horn to be terminated at an area of 7314cm^2. This corresponds to a duct height of 198cm in our 37cm constant-width horn.

Purists will tell you not to foreshorten the horn any more than this, and they are right. However, reviewing a large number of bass horns, I've found that even some of the most acclaimed designs are foreshortened more than this – and in some cases a lot more. The resulting design theoretically yields an uneven response versus frequency curve in the 1-2 octaves above the f_c. However, so will any speaker located in any room. Depending on the acoustical damping characteristics of the speaker's surroundings, this natural reflection phenomenon may, or may not, be in excess of the irregularities of the horn.

After having done some thorough research on the subject, I have found a number of thumb rules for foreshortening horns. One of them is that the mouth area should be at least five times the area of the throat. This rule is probably best-employed for front-loaded



Folding the horn. In order to transfer the horn from paper to woodwork, it can help to draw one side flat and double the curve on the opposite side. But this also has the disadvantage of making the distance more difficult to measure since the horn axis is no longer a straight line.

Mounting the drivers – caution

Take great care when handling the Lowther drive units. The magnetic gap is open, and small metal objects, swarf and dust can easily be drawn in to the gap. If that happens, the unit will need to be serviced. A useful tip is to cover the whole unit with thin tights as soon as you remove the plastic bag it is shipped in, and then mount the driver with the tights in place.

Table 2. Dimensions of panels required for the horn. In the interests of flexibility, the choice of wood thickness has not been fixed.

Qty	Board	Width	Depth	Height
2	Top	IW	ID + front panel thickness + back panel thickness + 1	
2	Bottom	IW	ID + rear panel thickness + 1	
2	Front	IW		IH + bottom panel thickness
2	Rear	IW		IH
4	Sides		ID + front + back thicknesses	IH + top + btm thicknesses

horns. Another is to cut the horn when the length is at a quarter of the theoretical f_c wavelength.

My design's foreshortening is well within these thumb rules. I cut the horn at an area of 91cm by 37cm, giving the horn a length of 288cm. Because of the mouth geometry of this design, the mouth will in fact be somewhat larger.

Dimensioning

Inner dimensions are listed in **Table 1**. Since there's a number of options with regards to wood quality, thickness, etc., I have left final dimensioning to you. Using the original drawing, the outer board dimensions can be calculated like this, for two speakers.

I used 22mm medium-density fibre-board for the top/front and side panels, and 16mm MDF for the back/bottom and inner boards. My advice however is to use marine plywood, as thick as you can afford. Also, if I were to build these speakers again – which I am sure I will, incidentally – I would cut some boards for bracing the cabinet, between the top panel and the topmost inner board, between the front board and the middle (vertical) inner board, and between the side panels toward the mouth opening. ■

Recommended reading

Dinsdale, J., Horn Loudspeaker design, *Wireless World*, Mar-June 1974. Note, there are errors in the tables of tractrix horn lengths.

Edgar, BC, The Show Horn, *Speaker Builder*, 2/90.

Edgar, BC, The Monolith Horn, *Speaker Builder*, 6/93.

Edgar, BC, The Edgar midrange horn, *Speaker Builder*, 1/86.

Edgar, BC, Solving the Klipschorn throat riddle, *Speaker Builder* 4/90.

Edgar, BC, The Klipschorn throat revisited: Or, Oooops, *Speaker Builder*, 6/90.

Hanna CR and Slepian, J, The Function and Design of Horns For Loudspeakers, *JAES*, Sep 1977 Vol. 25, No. 9, pp. 573-585. (Reprint of 1924 article).

Discussion: The Function and Design of Horns For Loudspeakers, *JAES*, Mar 1978, Vol. 26, No. 3, pp. 131-138. (Reprint of 1924 article).

Ketil Parow is a 30 year old programmer / software analyst at RADAR Software AS in Norway. His hobbies include loudspeaker design and building, wood-working and scuba diving. Ketil is also a part-time musician.

Lowther's renowned PM6C – 20% discount for *EW* readers

For a limited period*, Lowther Voigt is making available one pair of PM6C drivers per reader at a 20% discount on the normal retail price. This makes the pair £253.80 including VAT, instead of the normal price of £317.25. Please add £10 postage and packing.

*Closing date for receipt of orders 9 February.



Driver details

Lowther's PM6C driver was specially developed with back-loaded horn applications in mind.

Even though designed for high-efficiency horn enclosures, the PM6C is still capable of handling 100W. It is a full-range, twin-cone unit specified at 30Hz to 20kHz and with a free-air resonance of 36Hz. Sensitivity is 96dB and flux density achieved from the driver's ferrite magnet is 1.75 tesla.

The PM6C is an 8Ω unit with an overall diameter of 23.2cm and a a depth of 7.6cm. A baffle hole of 19cm is needed, with 4 equidistant holes on a 20.8cm pitch-circle diameter.

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