

A Hegeman Subwoofer

Here's an unusual subwoofer design that follows a different path to achieve good low-frequency sound. **By Cornelius Morton**

In 1969 the late A. Stewart Hegeman, of Harman-Kardon Citation fame, introduced a unique speaker bearing his name, the Hegeman Model 1 (*Photo 1*). It consisted of a handmade 8" bass/midrange driver firing upwards into a spherical reflector, resembling a ball cut in half, resulting in a circular horizontal pattern. The dome tweeter was mounted in the flat top of the reflector and fired into a similar smaller reflector mounted to the underside of a metal grille. Because the vertical spacing of the two driver-reflector assemblies was small, the two sources merged into a point source at listening distances greater than 4'.

The inside of the box was even more interesting. Instead of being open, it consisted of six tubes of various lengths opening just under the bass driver with the far end of the tubes closed off so that each tube became a quarter wavelength resonant stub. Each stub presented the driver cone with a high acoustical impedance around the center frequency of the stub. By centering the stub frequencies about the resonance frequency of the driver, the stubs provided a controlled damping to the driver, virtually eliminating the driver resonance peak and associated impedance fluctuations.

Stewart continued producing the Model 1 along with a few Model 2s—a 10" driver—until 1977, when failing health and finances forced him to cease production. At that time he gave Don Morrison, of Toronto, Canada, a six-week course in speaker building along with a truck load of cabinets, driver parts, and so on. Don resumed production in Toronto and continues

to produce a much improved version today. See his website at <http://www.donmorrisonaudio.com/>.

IMPRESSIONS

Several years ago a friend found several Model 1s on eBay and shortly after our audio club auditioned them. The first impression was of very good quality sound reproduction, so we moved on to the sound stage.

I was seated about in line with the left speaker and another member was about 6' away in what should be the sweet spot. A female vocalist was singing and I had her placed just up on a staircase behind the speakers and about 3' to the right of the center line. I asked the member in the sweet spot to point to the vocalist—we both did and it was the same spot! At the time I was using a pair of Magnepans, which were nice but had a very confined sweet spot.

The next impression was of the bass, which was very articulate, with no sense of overhang and no bass boom, just the sound of instruments. I was hooked.

I had some understanding of quarter-wave stubs from a long-term association with radar systems. Quarter-wave waveguide stubs are very similar in function to quarter-wave acoustical stubs. While searching for additional information, I located Don Morrison and explained what I was attempting. Don was very friendly and helpful. After providing history and a ton of information and hints, he commented that only a nitwit and masochist would try to build these things, wished me luck, and said to keep in touch.

The Magnepans are now gone, re-



PHOTO 1: Hegeman Model 1.

placed by what looks like a pair of flying saucers on top of small boxes. But the tight bass response of these clones was what led to thoughts of subwoofers. To date I have built three 12" models and two 10" units. This has been an evolutionary experience with improvements added to each.

One of the 12" versions resides with a friend in Texas, another with the owner of the Hegemans, and I have the third.

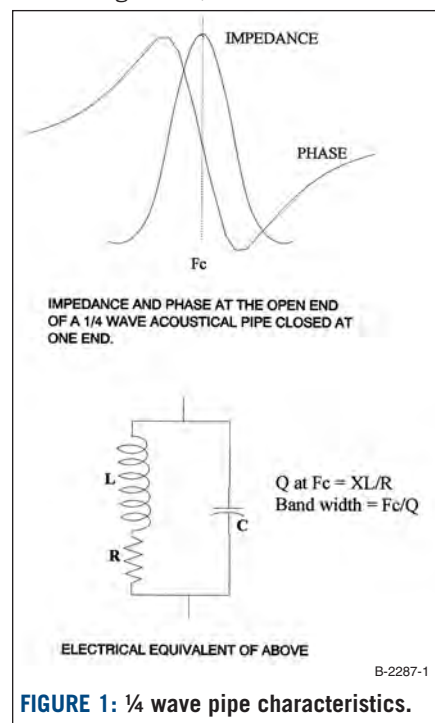


FIGURE 1: 1/4 wave pipe characteristics.

The first 10" model is also gone. The 10" units are the latest and probably the best of the crop in terms of detail. They are also the subject of this construction article.

The drivers are MCM 55-2325 or Audiomobile MASS 2010 devices. The MCM version has an X_{MAX} of 12.75mm and an 8 lb magnet. They also have horrendous impedance peak at f_s . The Audiomobile MASS2010 has an X_{MAX} of 21mm, nearly 2" peak-to-peak and an even more horrendous peak at f_s . *Photo 2* shows the subwoofer with the Audiomobile driver installed.

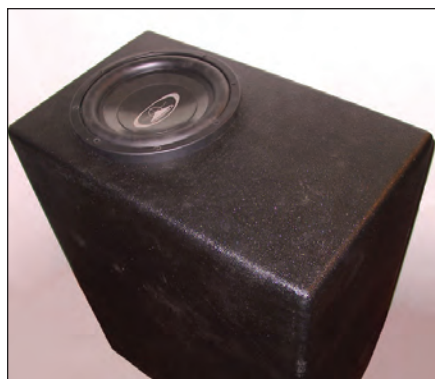


PHOTO 2: Sub with Audiomobile driver.

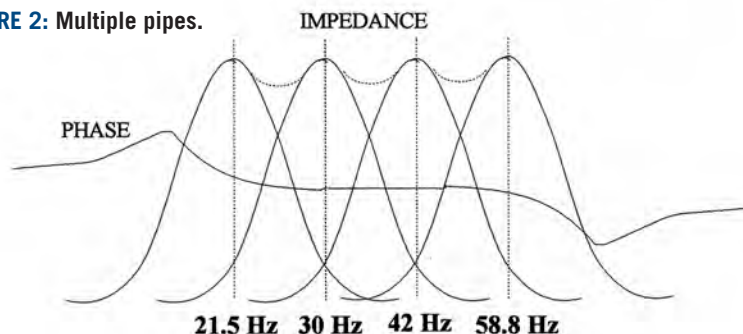
HOW IT WORKS

Most bass and subwoofer speakers depend on the driving amplifier to damp the speaker resonance and control unwanted cone movement. Modern amplifiers very closely approach the concept of a constant-voltage generator. The amplifier sees peaks in the speaker impedance curve as changes in loading, which they are, and it responds by reducing the output current so that the current times impedance remains constant. Note that at the center frequency

of the impedance peak the impedance is purely resistive and the output power is reduced accordingly.

To either side of center the impedance has a reactive component, which the amplifier will try to control, sometimes with interesting results. If an impulse is applied to the speaker, that excites a resonance mode of the driver/cabinet combination, that response is coupled into the voice coil and controlled by the amplifier feedback. For example, an amplifier with 20dB feed-

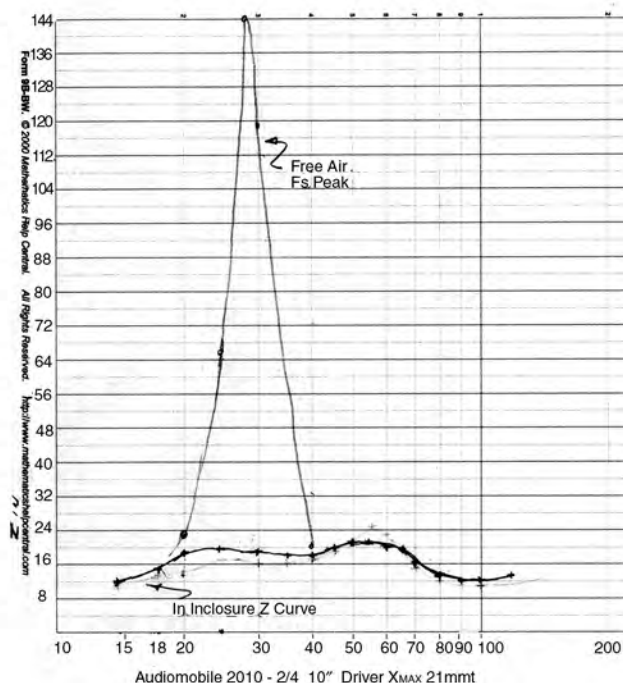
FIGURE 2: Multiple pipes.



IMPEDANCE AND PHASE CHARACTERISTICS OF THE FOUR QUARTER WAVE PIPES USED IN THE SUB WOOFER. THE DOTTED LINES SHOW THE IMPEDANCE ADDITION OF ADJACENT PIPES. PHASE SHIFT BETWEEN PIPES IS OPPOSITE AND CANCELS.

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resonance is to apply a frequency selective resistance to cone movement over the entire surface of the cone. This would effectively damp the cone resonance, and since the voice coil is firmly



B. AUDIOMOBILE MASS 2010

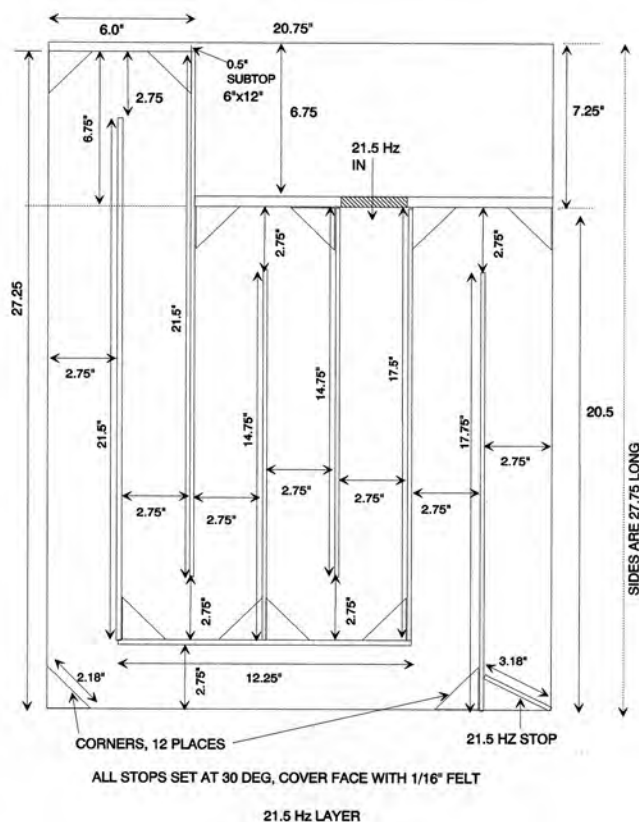


FIGURE 5: 21.5Hz layer detail.

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attached to one end of the cone, the voice coil is also damped and the amplifier is presented with a rather benign load. This selective acoustical loading was the secret of the Hegeman Model 1s.

OVERVIEW

Figure 1 illustrates the impedance characteristics at the open end of a quarter-wave pipe closed at one end and the equivalent circuit, a parallel resonance R, L, C combination, where the Q of the circuit is set by R. (See Harry F. Olson's *Elements of Acoustical Engineering* for a more thorough discussion of resonance pipes.) Figure 2 shows the relationship of the four tuned pipes used in this subwoofer. The response of the pipes merges into a bandpass filter response representing the resistance applied to the driver cone. The Q of the individual pipes is adjusted by varying a resistive element placed in the mouth of each pipe.

Standard stuffing materials are not very effective at very low frequencies, but an open cell foam is. The materials used for this sub are a number of utility sponges, such as those sold by Ace

Hardware. Coupling between the pipes and the cone is accomplished with a relatively small plenum into which the rear of the driver projects. Sealing this box is a must.

Figures 3A and 3B show the driver impedance in free air superimposed upon the impedance response of the finished unit for the MCM and Audiomobile drivers. The finished response for the MCM unit indicates a center frequency of about 54Hz and a corresponding bandwidth of 73Hz, resulting in a Q of about 0.74, which results in an excellent transient response. The Q for the Audiomobile driver is 0.78—again, excellent transient response. Now for the “no free lunch” part.

The nominal impedance of the MCM driver is listed as 8Ω and the maximum input power as 175W. The MASS 2010 maximum input is 600W. The impedance curves of Fig. 3 indicate an impedance of approximately 18–20Ω over the operating range. To fully drive these speakers, an amplifier must be able to put out about 200 to 600W into 16Ω. I am using a Hafler DH220 operating in

the bridged mode with good results. A 4Ω driver would result in a better match to lower power amps.

DESCRIPTION

The cabinet is built up of three layers, similar to a triple-decker sandwich. The two outer layers contain the two lower frequency pipes, 21.5Hz and 30Hz. The center layer contains the 42Hz and 58.8Hz pipes. Each pipe is a rectangular tunnel that is folded several times to achieve the proper acoustical length. The acoustical path of the 21.5Hz tunnel is shown in Fig. 4.

Two walls of the outer layer tunnels are the cabinet sides and the near sides of the separators; the inner sides of the separators provide the same function for the center layer. Seven 3.75” high walls of various lengths, corner pieces, and a stop (acoustical short) define the rest of the tunnel structure in each layer. Figures 5, 6, and 7 show the wall lengths and wall, corner, and stop locations for each layer.

Figure 8 illustrates the layer positions and the location and build-up of the 21.5Hz layer. Note that this layer

has seven walls, 12 corners, and one stop. It is the only one that utilizes the maximum available tunnel length; the 30Hz tunnel has three fewer corners and does not use the last two lengths of

the tunnel. The center layer divides the available tunnel into two sections and does not use the last length of the tunnel, leaving space for the lead-in wiring for the speaker.

honeycomb-like structure, which results in an acoustically dead cabinet over the operating frequency range. The open mouth of each tunnel opens under the driver into a small plenum. A divider reduces the plenum volume to improve the coupling between the tunnels and the driver. *Figure 9* details the plenum; the divider is not shown so that the divider support structure may be detailed.

Each layer preserves the same basic structure of seven walls to

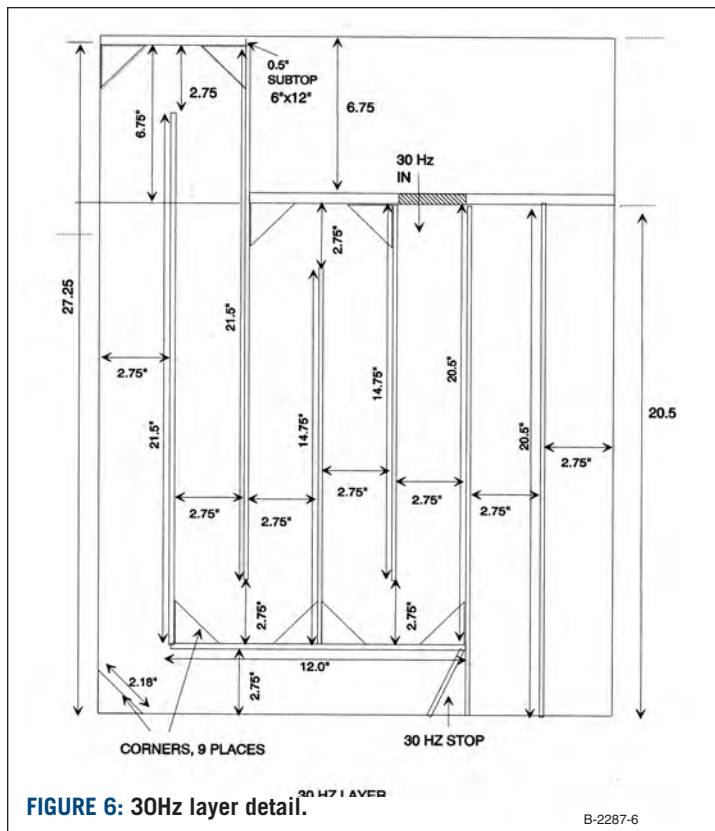


FIGURE 6: 30Hz layer detail.

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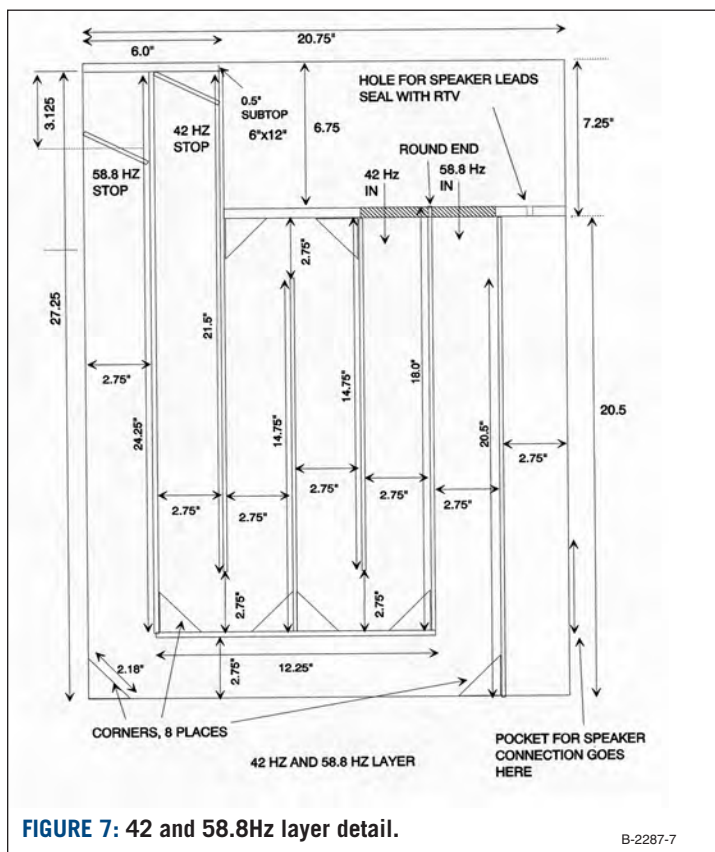


FIGURE 7: 42 and 58.8Hz layer detail.

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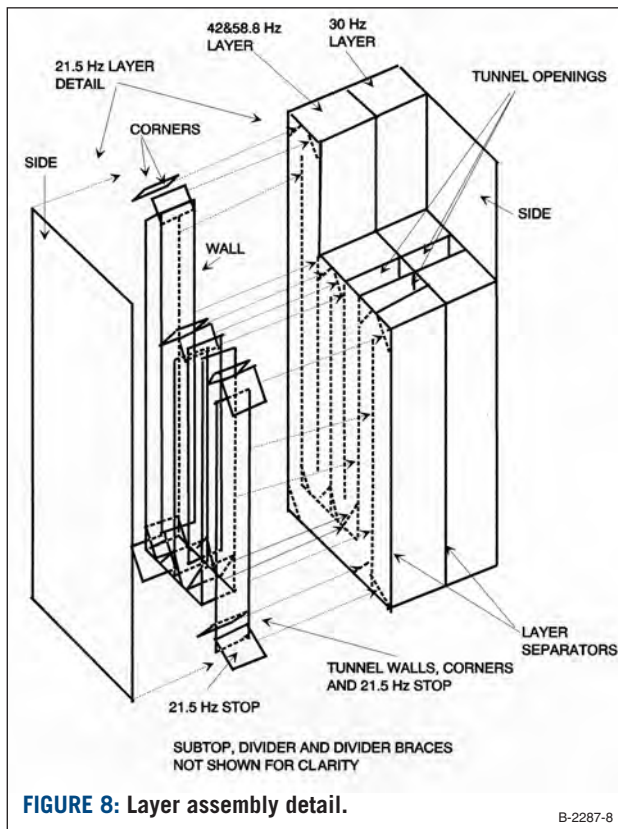


FIGURE 8: Layer assembly detail.

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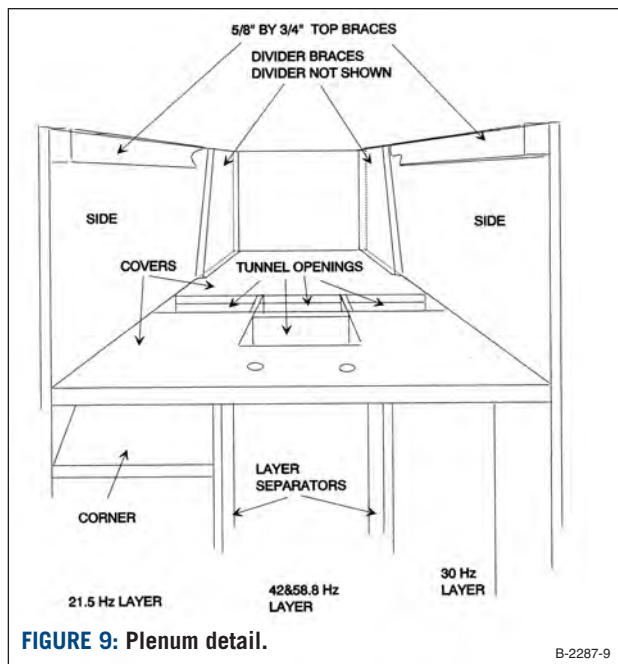


FIGURE 9: Plenum detail.

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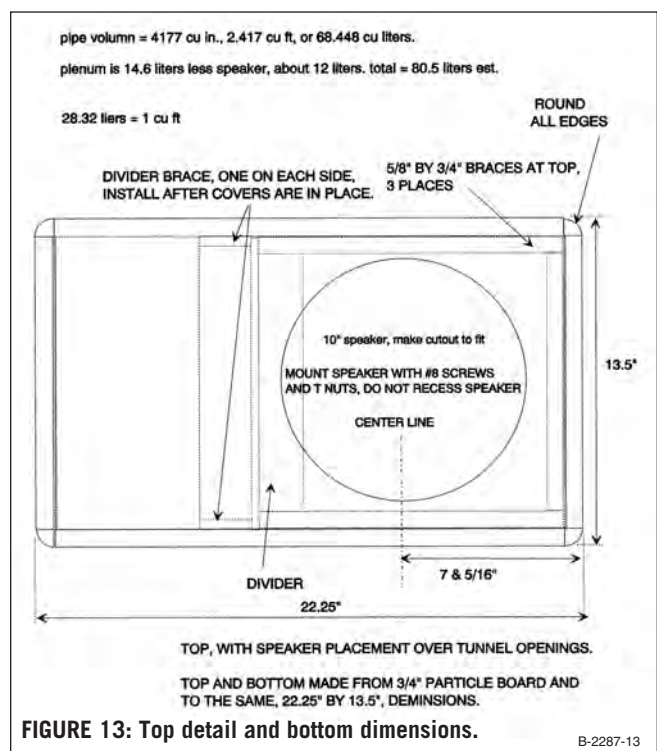
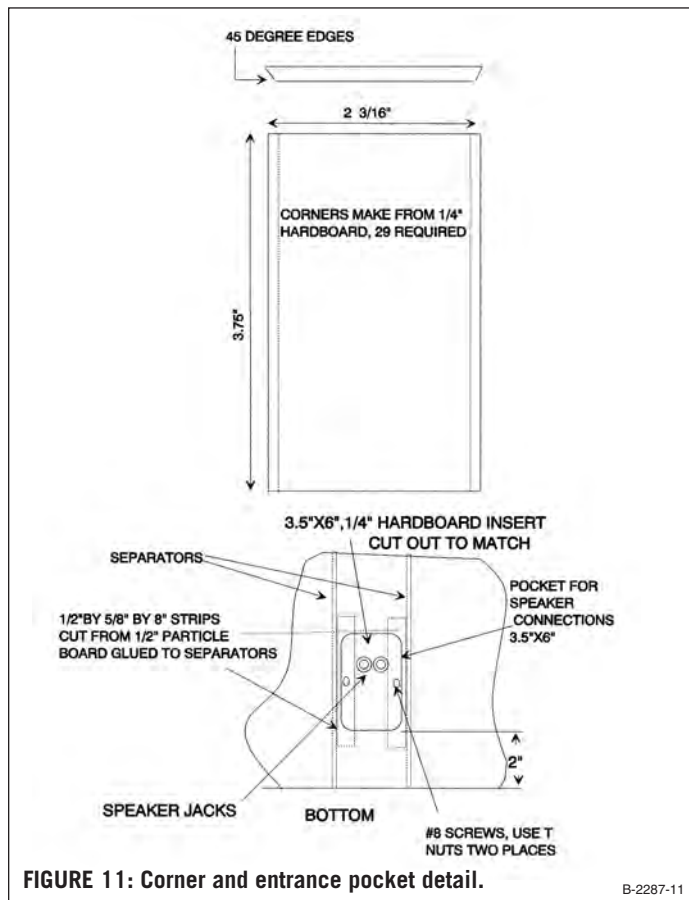
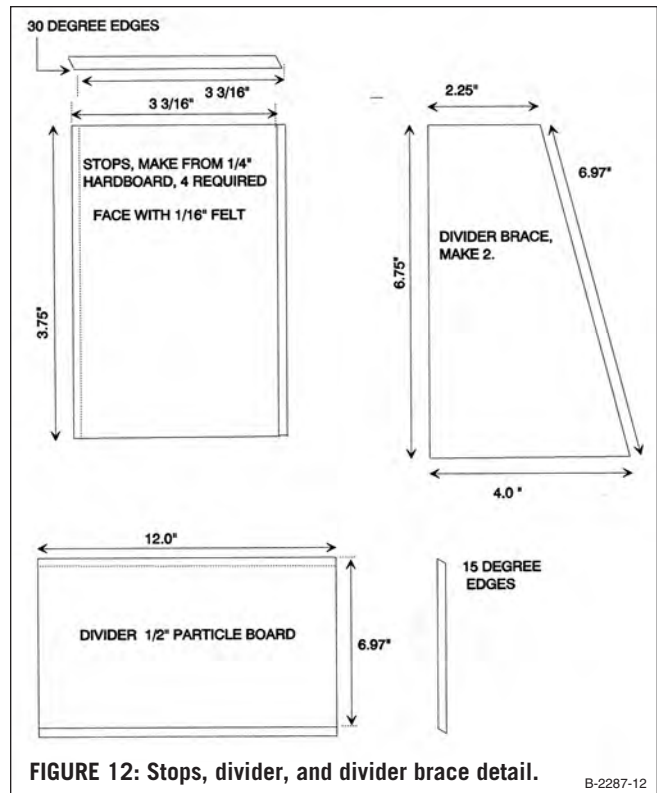
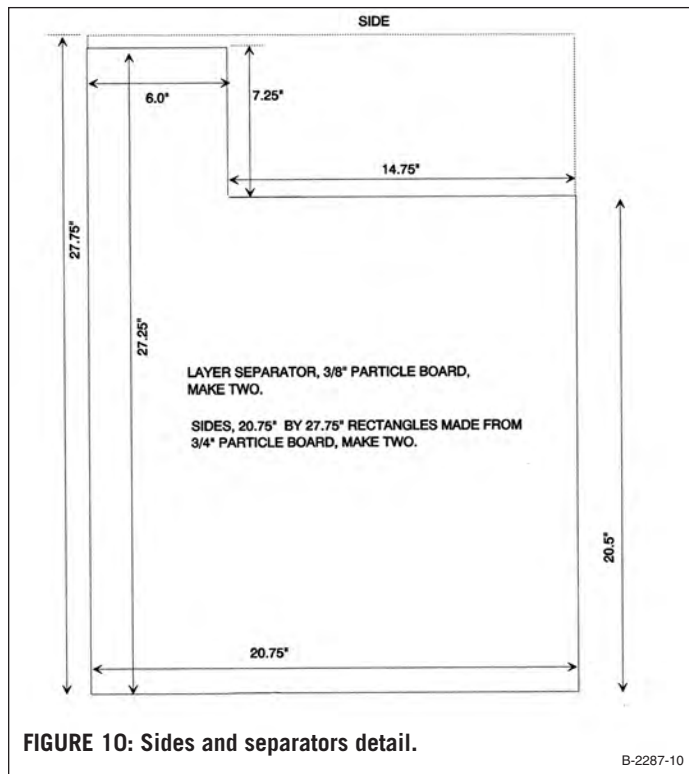
CONSTRUCTION

Have your supplier cut the two $\frac{3}{4}$ " sides and two $\frac{3}{8}$ " separators to 27.75" by 20.75". You can then cut the separators to their final shape and size on a stan-

dard 10" table saw (Figure 10). Have one 48" by 48" $\frac{1}{4}$ " hardboard cut in half; the two 24" by 48" pieces will make all of the walls, corners, and stops. Stores such as Home Depot will cut these as

and bottom pieces at this time, but because their actual size depends on the build-up of the layers, I like to do those after the three-layer core is complete.

Cut the separators to shape (Figure 10). Then set the table saw to make a 3.75" cut from the fence to the fence side of the blade and start cutting 3.75" by 24" strips of $\frac{1}{4}$ " hardboard, convert-



ing all of the hardboard to strips. You will cut the walls, corners, and stops from these strips.

Figures 5, 6, and 7 detail the three layers. Starting with Fig. 5, the 21.5Hz layer, cut the seven walls to the lengths shown. I label each one with the layer frequency and wall length. Do the same for the remaining two layers and keep the walls for each layer separate. Note that one wall of the 42/58.8Hz layer is 24.25" long; cut a short length and glue it to the 24" piece to make the full 24.25".

Make the 29 corners as shown in Fig. 11 and the four stops as shown in Fig. 12. Cut the 6" × 12" sub top from ½" particleboard. Refer to Fig. 12 and cut the divider and divider braces from ½" particleboard. You can find felt for the stops at a local craft store. Attach the felt to the stops with a line of white glue around the edge and a dot in the middle, leaving most of the felt glue free. After the glue has dried, trim the edges with a sanding block.

Note, when cutting the walls, to cut seven for each layer. You must install all seven walls in each layer to ensure the integrity of the box. Leaving out a wall—even though that section of tube is not used—will cause the box to be less rigid and subject to resonance effects.

ADHESION

Photo 3 shows the start of the first layer. I generally begin with the 30Hz layer, which starts out on a ¼" side. Use a fine point magic marker to draw the outline of the walls and label the length, corners, stops, and, in this case, the sub top.

Photo 3 also shows what I built to aid construction: a right-angle jig that I clamp on the wall to position it during gluing and a larger jig consisting of a 30" × 36" sheet of plywood with four up-rights affixed to it. The up-rights, which are positioned in a right-angle "L" to engage two sides of the core, are about 15" tall and are carefully set to right angles to the base. When adding a separator or the last side to the core you snug the core tightly into the "L" and use the up-rights to align the new piece. Use a good grade of polyurethane glue for construction. This glue expands as it sets and will fill any small gaps.

Be generous with the glue, using large beads, especially when covering a

layer with a separator or side. If you use enough glue, the excess will run down the walls, which will decrease the Q

only a little bit, but the Q will be decreased much more when the system is tuned and there are no leaks.

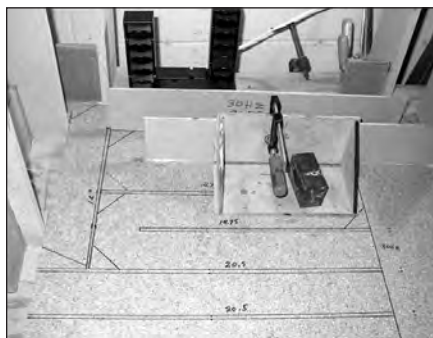


PHOTO 3: Starting the first layer.



PHOTO 4: 30Hz layer ready for separator.

Polyurethane glue does not easily come off, but will only wear off human skin. So wear gloves or keep paper towels handy to wipe fingers and clean up spills.

Start by gluing the sub top making sure that it forms a right angle with the side. *Photo 3* shows the setup for the second wall. Do not rush—it takes about two hours or so for the glue to set enough to remove the clamp. After the walls are in place, you can glue the corners and stop. The bottom edges of the corners may require trimming to fit the glue bead at the base of the walls. About the time you finish the first layer, you may be wondering why you started this project in the first place (please see Don's comments at the beginning of the article).

Photo 4 shows the completed first layer ready for the separator installation. Note the freestanding corner in the upper left. I made a little jig to mount that with, too. Also, on the freestanding corners I used a small scrap of hardboard about $\frac{5}{8}$ " by 2" as a brace glued to the back so it would remain rigid during handling.

When you reach this point, check to see that everything is at the same height and use lots of glue and install the separator. To ensure a good bond,

use lots of weight to hold the separator in place while the glue sets. Sand bags, gallon cans of paint, or anything else heavy and handy will do. Repeat the preceding for the next two layers.

The next, center layer, is the 42/58.8Hz layer. After you have finished the last layer, with the side on, let the core set overnight to fully cure before handling. See *Figure 11* for the speaker connector pocket details. After you have glued the $\frac{1}{2}$ " \times $\frac{5}{8}$ " \times 8" strips in place, check to ensure that the front, back, top, and bottom openings are flush and without high spots. Cut the top, bottom, front, and back pieces to size (*Figs. 13 and 14*). To make the pocket cutout in the back, I made a template from $\frac{3}{8}$ " material and used a template guide and $\frac{1}{4}$ " straight router bit.

Glue the front, back, and bottom in place using clamps and/or weights to keep the joints tight. Install the covers as shown in *Fig. 15*. Drill the holes for the speaker wires for a tight fit. I used 12-gauge stranded wire for mine. Install the divider braces and divider as shown in *Figs. 9 and 13*. Cut the $\frac{5}{8}$ " by $\frac{3}{4}$ " braces to fit and glue in place, again referring to *Fig. 13*. Note that these should be flush with the top edge.

Make the speaker cutout as shown in *Fig. 13*—9.125" diameter for the MCM

driver or 9.25" diameter for the MASS 2010 driver. Check the fit of the driver and mark the location of the mounting holes. Drill mounting holes for #8 T-nuts and install them. Check to ensure that everything is flush and without high spots, then glue the top in place, using lots of glue.

When everything is well set—ten to 12 hours at least—sand the edges flush and use a router with a $\frac{1}{2}$ " round-over bit to round all edges. Start with the long edges, then you can do the top and bottom by following the edges around. Give the box a final sanding. Install the speaker wires and use an RTV sealant around the wires where they pass through the cover, and your favorite connector on the pocket insert. Leave

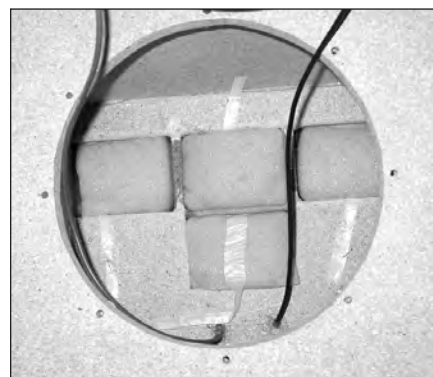
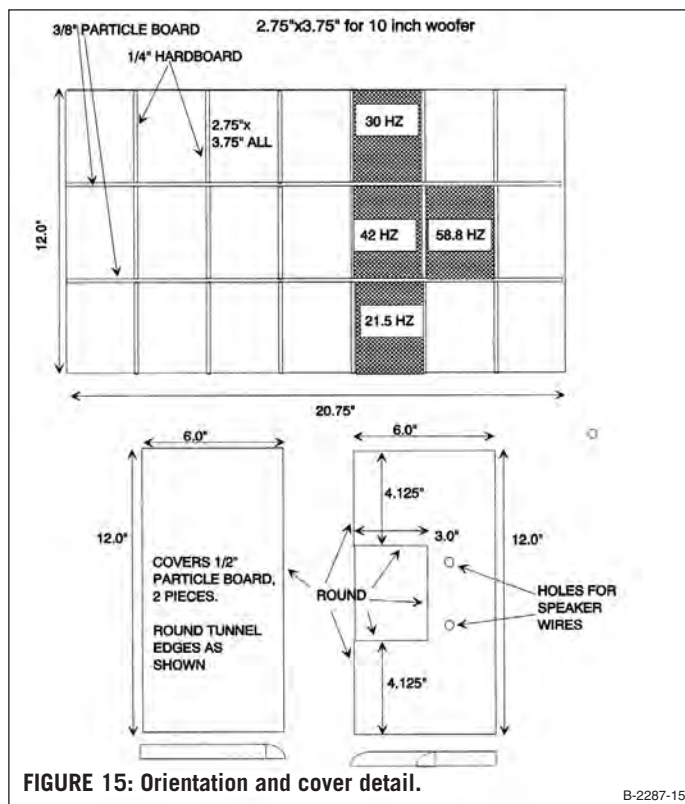
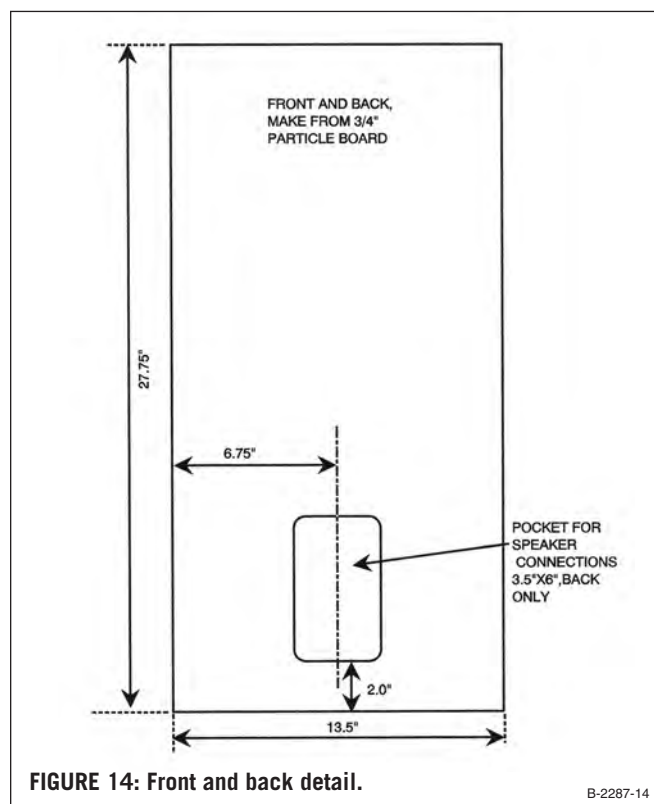


PHOTO 5: Stuffed pipes.



about 15" of wire outside the cover so that you can set the speaker up on the top of the cabinet while connecting or removing the leads.

TUNING

Tuning consists of adjusting the Q of the four pipes so that the impedance of the pipes dissipates the stored energy in the driver around Fs, resulting in a relatively flat impedance curve as shown in *Figs. 3A and B*. *Figure 16* illustrates a simple means of measuring speaker impedance. The little battery-

operated digital VOMs usually have an AC range that is flat to 5kHz or so. My old Radio Shack unit is good beyond 10kHz.

If you use the MCM driver, you must apply a gasket to the bottom of the mounting flange. The Audiomobile driver has a molded rubber mounting gasket that works fine. I used a $\frac{3}{8}$ " weather strip foam tape from Ace Hardware on my MCM driver. Use masking tape to cover the mounting screw holes to seal the cabinet. Hook up the driver and set it into the cabinet. The driver weight on the gasket will provide an adequate seal.

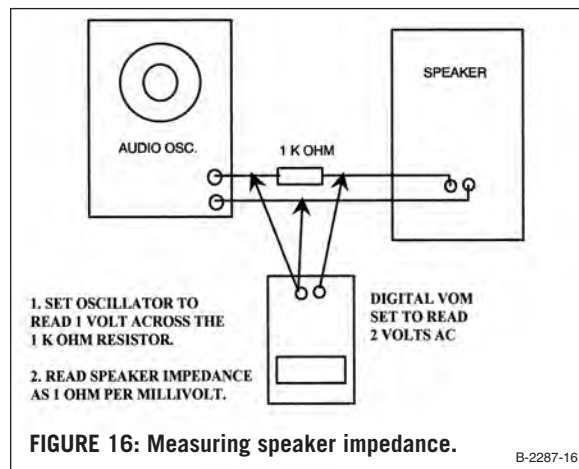
Set the speaker up for test as shown in *Fig. 16*. Adjust the generator to provide 1V RMS across the 1k Ω resistor and make a test run measuring the voltage across the speaker (1mV = 1 Ω), maintaining a constant output level from the signal generator. I used one cycle steps from 15Hz to 30Hz, two cycle steps from 30Hz to 50Hz,

and 5Hz steps beyond. The results will be a bit jagged but will show the effect of the tunnels on the driver response.

I used five 7" by 4.5" by 2.375" polyester utility sponges from Ace Hardware to adjust the Q of the pipes; similar sponges should work as well. Cut two of the sponges in half so that you have four pieces 3.5" by 4.5" by 2.375".

Remove the driver from the cabinet and place it to the rear of the mounting hole. Wrap a strip of $\frac{1}{2}$ " strapping tape two-thirds around the length of the three whole sponges, centered on the 4.5" sides leaving a 6" tail. Insert the sponges into the 21.5, 30, and 42Hz tunnels with the tails pointing up and the 4.5" sponge width corresponding to the 3.75" width of the tunnel. Place the half sponges into each tunnel so that the 4.5" and the 3.5" dimensions of the sponges correspond to the 3.75" and 2.75" tunnel dimensions (*Photo 5*). Replace the driver and repeat the impedance measurement, plot it on semi log paper. The plot should look like *Figure 3A* or *3B*, depending on the driver.

You may make minor adjustments by rotating the half sponges by 90°, chang-



ing the compression of the sponge, or larger changes by adding or subtracting half lengths to the full sponges. Do the adjustments one at a time. Adding sponge material or increasing compression of the sponge in a tunnel will generally increase the measured impedance at the tunnel frequency, and decreasing the sponge material or compression in a tunnel will decrease the measured impedance.

The low frequency tunnels also affect frequency areas where the tunnel is one half wavelength long, twice the tuned frequency. A half wavelength pipe, closed at one end, reflects a closure at the open end, effectively removing the volume of the pipe from the system. The magnitude of this effect is determined by the Q of the pipe. Thus, increasing the Q (removing the sponge) from the 30Hz tunnel will increase the efficiency of the 58.8Hz tunnel.

ASSEMBLY JIGS

Figure 17 illustrates two jigs that I used to ease assembly. Sizes given are approximate. Critical measurements are the 90° angles shown and the height of the layer assembly jig uprights (not less than 15"). The wall-mounting jig or a commercial equivalent is a must. The layer assembly jig makes layer alignment accurate and easy and is highly recommended. A jig for the freestanding corners was mentioned in the text and is nothing more than a mini version of the wall-mounting jig.

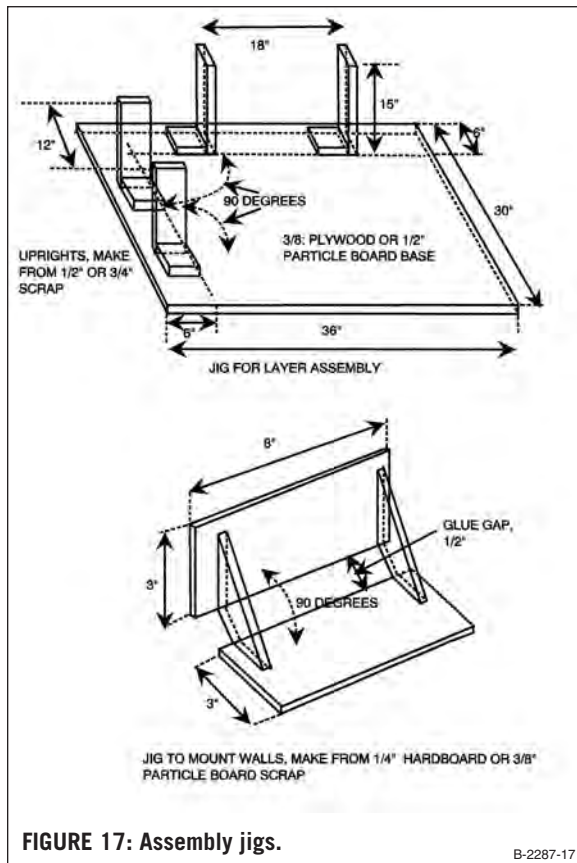


FIGURE 17: Assembly jigs.

Once the tuning is satisfactory, remove the driver, put a tail on the sponge in the 58.8Hz tunnel, and staple the tails to the bottom or sides of the plenum. Loosely fill the plenum with fiberfill, check the connections to the driver, remove the tape over the mounting holes, and screw the driver in place.

FINISH

I had the finished unit sprayed in a bedliner shop. This finish, which has become popular with small bands for their equipment, is extremely durable and easy to care for, and the black crinkle finish looks good. Mine was done by Inyati of Phoenix and ran about \$4.50 per square foot. Lacquer or paint finishes should be applied before tuning.

The bedliner coating only requires that the driver and the connector insert be removed and can be done after tuning. You can stuff the insert inside so you do not need to remove the wires. The shop will cover the holes so that the inside is not sprayed.

SETUP

Set your crossover to sum the low-frequency outputs. Set the crossover frequency in the range of 50–100Hz.

The subwoofer has a sensitivity of 88–89dB. If your stereo pair has a sensitivity of 90–92dB, set the output of each high-frequency channel to 5 or 6dB below the output level of the summed low-frequency channel. For frequencies below 130Hz or so, you will see a 3dB gain from the stereo speakers at your listening location so these settings should result in a channel balance within a few dB. Note that a 12–18dB per octave crossover is recommended.

Center the sub between your stereo pair and the same distance from your listening location; I generally start with the driver pointing up. Put on some music that contains a fair amount of bass and midrange or your favorite

alignment and test CD and try it out.

Because the LF and HF channels of many second- and third-order crossovers are 180° out of phase around the crossover point, you may choose to try switching the phase to the subwoofer for effect. If required, readjust the channel gains so that the subwoofer disappears in the sound stage.

The integration of the subwoofer and the stereo speakers should be seamless; the only noticeable change in sound should be that the low-frequency range has found a lower octave. When set up properly, the low bass may almost sound a little thin but very articulate, just like a live concert! ❖

PARTS LIST

One 4' × 8' sheet of ¾" particleboard—sides, front, back, top, and bottom.

One 2' × 4' sheet of ½" particleboard—covers, divider braces, divider, and subtop.

One 4' × 4' sheet of 3/8" particleboard—separators.

One 4' × 4' sheet of ¼" hard board—walls, corners, stops, and free corner braces.

16 oz bottle of polyurethane wood glue.

Small bottle of white glue.

1ft² of craft felt.

Ten #8 T-nuts.

Ten #8 cap head or Phillips head screws, 1.25" long.

Ten #8 steel washers.

Two 6' lengths of #12 stranded wire, one red and one black, or your favorite colors.

One dual binding post with ¾" centers for single or dual banana plugs.

1⅝" × ¼" self-adhesive weather proofing tape, MCM driver only.

1ft³ fiberfill.

Five 7" × 4.5" × 2.375" polyester utility sponges from Ace Hardware or equivalent.

MCM 55-2325 or Audiomobile MASS 2010 2/4 driver. If the MASS 2010 series is no longer available the new MASS 2410 2/4 is the replacement and has ±3mm more throw.

The ⅝" × ¾" braces and the ½" × 8" strips are cut from the ¾" sheet scraps.

REFERENCES

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<http://www.audiomobileinc.com/main.htm>.

MCM,
www.mcmelectronics.com.

Elements of Acoustical Engineering, 2nd Edition, Harry F. Olson, E.E. Ph.D., D. Van Nostrand Co. 1947.

Don Morrison Audio,
<http://www.donmorrisonaudio.com/>.

NOTES ON DRIVERS

The MCM driver will make a very good subwoofer that will be well worth the time spent for a very reasonable cost. The Audiomobile driver will be outstanding at a higher cost. The following set of distortion measurements are made at a 91dBi level at one meter.

Frequency	MCM	Audiomobile	Adire Audio Brahma 10
40Hz	6%	2.2%	1.5%
30Hz	12%	5.5%	1.75%
25Hz		12%	4.5%

Many other drivers will work in this cabinet; the general requirements are: X_{MAX} = 12mm or greater, Q_{TS} of 0.4 or greater, Q_{ES} of 0.4 or greater, Q_{MS} of 3 to 15, and an f_s between 25Hz and 35Hz. Here's a short list of available drivers (an "*" indicates drivers installed and tested).

Dayton Titanic MKII, X_{MAX} = 16mm and f_s = 28Hz, Parts Express PN 295-412

Audiobahn AW1008Q*, X_{MAX} = 20mm, f_s = 35Hz.

Audiobahn AW1008T (This year's model of the above).

Rockford Fosgate RFR 3110, specs similar to the Audiomobile.

Adire Audio model Brahma 10*, X_{MAX} = 27mm, f_s 35Hz (measured 28Hz). Extremely linear, see URL.

<http://www.acoustic-visions.com/brahmaseries.htm>

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PIPE DESIGN

I'm working through a design based on Cornelius Morton's article "A Hegeman Subwoofer," published in the December 2003 edition, and have two questions.

If I wanted to extend the design to six pipes from four, as originally published, should the resonant frequency of the additional pipes be placed at the square root of 2 multiple? This would give a set of frequencies at F_0 , $1.414F_0$, $2F_0$,

$2.83F_0$, $4F_0$, and $5.65F_0$. Or would it be better to use something different, such as the third root of 2 for a multiple, which would yield a set of frequencies at F_0 , $1.26F_0$, $1.59F_0$, $2.00F_0$, $2.52F_0$, $3.17F_0$?

Would it be better to scale the area of the tunnel such that the pipe Q_s occur over a narrower range, which might make tuning easier? I realize that this would complicate the construction of the cabinet.

Rob Weinstock

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Cornelius Morton responds:

Thanks for your interest. The original Hegeman model ones were a six tube design that was subsequently changed to a four tube configuration to accommodate ease of tuning the Q of the individual tubes. If you examine the typical free-air impedance curve for a subwoofer driver, the area from one octave below F_s to one octave above F_s is the area that requires control to properly damp the value of Q below one.

Considering this range, then, a four tube

design requires that the individual Q_s be 2.5 to 3, and for a six tube design the Q_s should have a value between 4 to 5, the value of Q being inversely proportional to the spacing between the tube frequencies. The Q values required for the six tube design approach the maximum values that are obtained in a tube of this design leaving little room for adjustment; the Hegeman ones did not use lossy material to control the Q values. The required Q value may be decreased slightly by increasing the frequency range that the tubes control, usually at the high end.

For example, if the driver requires control from 17Hz to 57Hz, the range of tuning could be from 20Hz to 75Hz. But doing this comes at a price. Resonance control is accomplished by inserting controlled resistance into the electromechanical circuit of the driver. When this is extended past the resonance hump, the efficiency of the driver at frequencies beyond the hump is decreased.

Determining the frequency spacing for a six tube design. As an example, I will use the 20 to 75Hz range mentioned before and an F_s (free-air resonance) of 28Hz. Let

$20x^0 = 20\text{Hz}$ and $20x^5 = 75\text{Hz}$. Then $x^5 = 75/20 = 3.75$ and $x = 3.75^{(1/5)}$. Then $x = 1.3026$. The frequency values of the tubes are, starting with x^0 , 20Hz, 26.05Hz, 33.94Hz, 44.2Hz, 57.58Hz, and 75Hz. Typical Qs will be 3.7, which will allow for some adjustment. The value of Fs is very close to the lower edge of my target range, which is $0.8 \times 33.94\text{Hz}$ to $1.2 \times 33.94\text{Hz}$. This is easily adjusted by lowering low frequency from 20Hz to 19Hz, which sets the third tube to 32.24Hz and the last tube to 71.25Hz, or x may be re-evaluated using 19 and 75Hz.

Tube area. I have found that setting the total mouth area of the tubes to 80% of the effective cone area of the driver provides good results. The general effective cone area for a 10" driver is around 60 in², which would result in a tube area of 10 in² for a six tube design and 15 in² for a four tube design.

General. The free-air resonance, Fs, has been used throughout this discussion. As the impedance of the tubes as seen by the driver is a resistance instead of a reactance as seen in most other designs, the resonant value does not change when the driver is mounted in the box, thus Fs is the proper design value. A small increase in damping efficiency may be obtained by adding another divider in the plenum. Use a divider similar to the one in the design but on the opposing wall, from a line just clearing the outer edge of the 58.8 tube up to the top edge of the plenum.

The original corner reflectors were made slightly narrow to increase the tube bandwidth—I found this to be unnecessary as the angled stops are sufficient. Increase the design width from 2.18" to 3.888". The tuned tubes also operate as a resistance that is an odd harmonic of the design frequency, phantom tubes.

For example, the 21.5Hz tube acts as a phantom tube at 64.5Hz, and the 30Hz tube shows a phantom tube at 90Hz. Both of these phantom tubes provide an additional bit of damping, dependent upon the Qs at which the parent tubes are set. At even harmonics, primarily the second, the tubes act as though the mouths have been closed, reducing the volume that the driver is working into. The 21.5Hz tube shuts off at 43Hz and the 30Hz tube shuts off at 60Hz. This increases the efficiency of the tubes operating near or at those shutdown frequencies. Because these effects depend

on the Qs of the parent tubes, they result in interactions during tuning.