Alpha Transmission Lines

This author challenges some of the mystery and myth by using TSPs in transmission-line design. **By Rick Schultz**

Quarter-wave loudspeaker designs are mystical and mythical creations from the ancient past of loudspeaker design. They go back at least to Voigt's tubes (1934) and Olney's Acoustic Labyrinth (1936), about ten years after the invention of voice-coil drivers. Much later (1965), Bailey stuffed the entire pipe and called it a transmission-line.

Over the years, some people have built successful quarter-wave systems, but many more have failed. It is now possible to build a reliable α-transmission line derived from any driver's Thiele/Small parameters (TSPs). To get past the myths and mysticism, let's look outside the lines.

This design system takes some mystery out of transmission line (TL) construction. Later, I will cover how transmission line myth has hampered past designs. Even with this design system, the art of speaker building remains. You may decide to add or remove some stuffing as you listen to your α-TL. You may choose to build a longer or shorter α-TL for comparison.

TL DEFINED

A quarter-wave loudspeaker is a broad group of designs that rely on pipe resonance frequency to assist the driver's output. For example, when you blow across the top of an empty bottle, the bottle hums. If the bottle is partly filled, the hum sounds different.

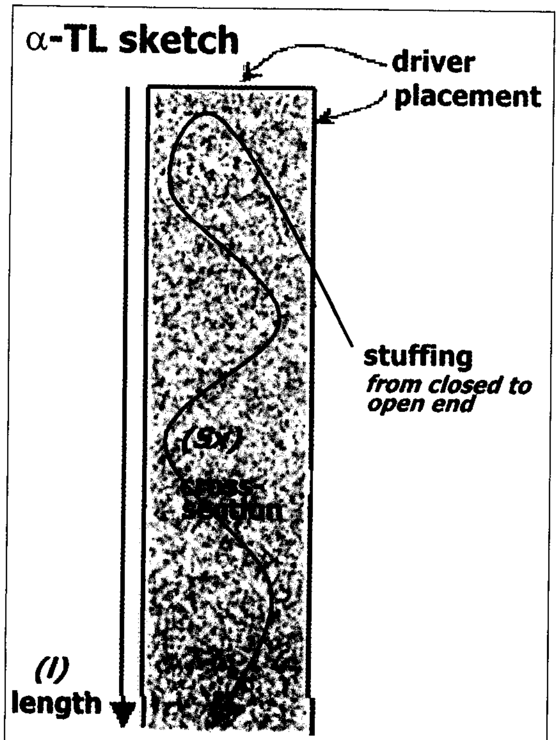


FIGURE 1: α-TL sketch.

B-2215-1

The common element of quarter-wave design is a long narrow pipe, which is closed at one end and has an opening at the opposite end, just like the bottle. A driver is placed at or near the closed end. Most are stuffed with loose fibers.

Pipes and bottles with one end closed have unique resonant properties. An unstuffed pipe resonates at a frequency directly related to pipe length. A pipe of a certain length is often referred to by its quarter-wave frequency. For convenience, I label the pipe frequency fΘ. This resonance frequency is at the speed of sound divided by four times the length. I write this as fΘ = c/4l = 13560/(4 × inches).

Simply, if a closed pipe is 100″ long, its first resonance occurs at 13560/(4 × 100) = 34Hz. Interestingly, a 34Hz sound has the wavelength of 400″. The 100″ pipe is one-quarter of the 34Hz wavelength. Hence the name quarter-wave loudspeaker. (See the sidebar for more.)

TL DESIGN

This article focuses on transmission line design (*Fig. 1*). TLs are special quarter-wave systems. Specific TL properties are:

- Driver attached to the closed end of the pipe
- Opposite end of the pipe is completely open
- Internal stuffing fills the entire length
- Pipe is straight and not tapered
- Q-neutralized impedance curve
- Critically damped, transient perfect driver response

In an α-TL, the driver is critically damped every time. I have run many simulations, and driver rolloff is usually near 10dB per octave. Group delay is consistently quick and smooth. Traditional TLs perform very much like a Q_B = 0.5 acoustic suspension sealed box. Shorter α-TLs are also critically damped with great group delay, but offer additional low-frequency output. α-TLs are just as easy to build as a sealed box.

Here are the steps to design an α-TL for your driver.

1. Choose the pipe frequency fΘ (between f_S and two times f_S).
2. Decide whether you will use fiberglass stuffing, polyester, or AcoustaStuf.
3. Refer to *Fig. 2* or *Fig. 3* to read pipe length from the curve marked "length inches" line and left axis.

4. Refer to *Fig. 2* or *Fig. 3* to read stuffing density from the stuffing density line and right axis.
5. Refer to *Fig. 4* or *Fig. 5* to read the value of Z, at the same fΘ used in steps 3 and 4.
6. Calculate α equals $\sqrt{(1 + (f\Theta/f_S Q_{TS}))}$. Be careful to take the square root.
7. Cross-section area (Sx) equals $Z \times f_S \times f\Theta \times V_{AS}/(10{,}000 \times \alpha)$. V_{AS} must be in cubic inches.
8. Material needed equals length times cross-section times density.

Start by reviewing TSPs of the driver—any driver works. Important TSPs in this design system are resonance frequency (f_S), quality ratio (Q_{TS}), and equivalent volume (V_{AS}). One of my

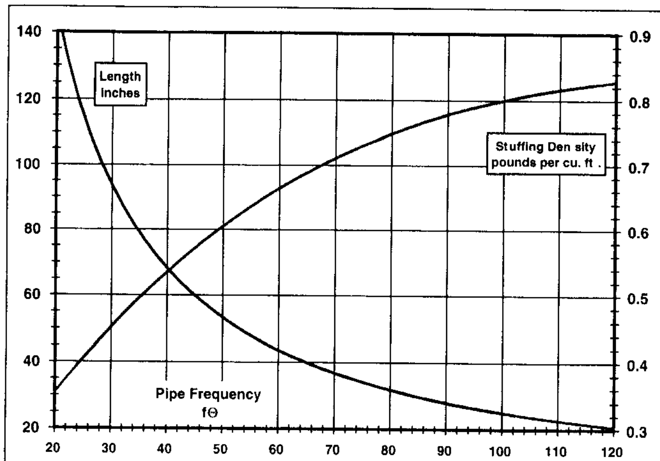


FIGURE 2: α-transmission line length and stuffing density—fiberglass. After you decide which pipe frequency fΘ you want to use for your project, use the length line to read the proper length. The length is in inches on the left axis. At the same fΘ, read the fiberglass stuffing density and the recommended stuffing amount on the right axis. Stuffing is given in pounds per cubic foot. To convert to metric units: inches divided by 39.35 equals meters. Pounds per cubic foot times 16 equals grams per liter. B-2215-2

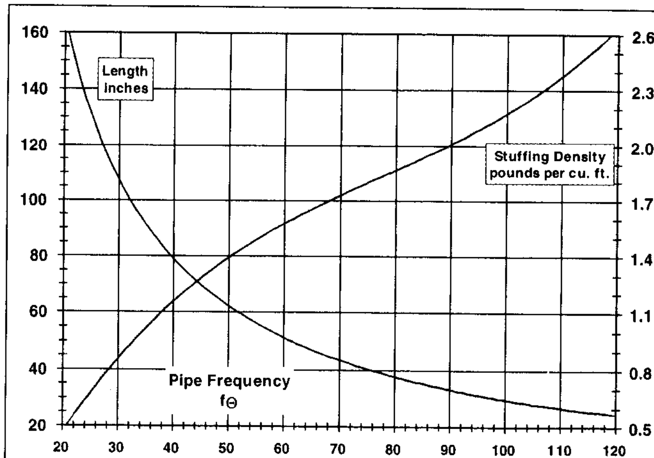


FIGURE 3: α-transmission line length and stuffing density—polyester, cotton, AcoustaStuf. After you decide which pipe frequency fΘ you want to use for your project, use the length line to read the proper length. The length is in inches on the left axis. At the same fΘ, read the fiberglass stuffing density and the recommended stuffing amount on the right axis. Stuffing is given in pounds per cubic foot. To convert to metric units: inches divided by 39.35 equals meters. Pounds per cubic foot times 16 equals grams per liter. B-2215-3

personal favorites is Jordan's JX92S (about $120). From Jordan's website at http://www.ejjordan.co.uk/92S.html, f_S is 45, Q_{TS} is 0.40, and V_{AS} is 15.28 ltr.

Notice whether V_{AS} is measured in liters (l), in cubic feet (ft^3), or in cubic inches (in^3). V_{AS} must be in in^3 to get proper results in my equation. If V_{AS} is in liters, multiply by 61.02 to convert to in^3. If V_{AS} is in cubic feet, multiply by 1728 to get in^3. For this driver, V_{AS} is 932 in^3.

Going through the steps:

1. I choose to set pipe $f\Theta = 80$.
2. I will use fiberglass stuffing. I prefer the size and sound of fiberglass pipes, but polyester or AcoustaStuf is much easier to work with. I need to use *Figs. 2* and *4* for the next steps.
3. Referring to *Fig. 2*, my pipe must be 32″.
4. Refer to *Fig. 2*; the recommended stuffing density is at least 0.75 lb per cubic foot.
5. Refer to *Fig. 4*; the value of Z at 80 is 0.34.
6. α equals $\sqrt{(1 + (80/(45 \times 0.40))} = \sqrt{(5.44)} = 2.33$.
7. Cross-section area (Sx) = $0.34 \times 45 \times 80 \times 932/(10{,}000 \times 2.33) = 49\ in^2$.
8. Material = $32 \times 49/1728 \times 0.75 = 0.68$ lb or 11 oz. I need to divide by 1728 to convert in^3 to ft^3.

About 32″ is a very reasonable speaker height. If the $f\Theta$ you want to use requires a long pipe, there is more to follow about shorter TLs. The cross-section of this pipe is about 49 in^2. Cross-section shape of your TL is up to you. For the JX92S, cross-section could be a 7″ square, an 8″ diameter circle, or a 9 × 5½″ "golden ratio" rectangle.

Although you may consider this Jor-

QUARTER-WAVE LOUDSPEAKERS

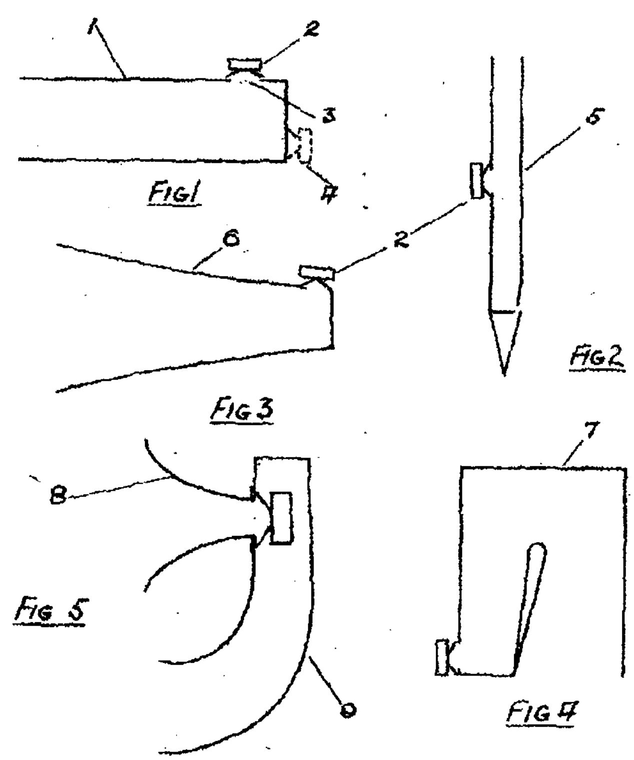
Quarter-wave systems are a group of loudspeakers that rely upon the resonance of a pipe. The fundamental resonance of a quarter-wave pipe is based on the length of the pipe. I refer to this resonance frequency as $f\Theta$.

The closed pipe frequency is expressed mathematically as $f\Theta = c/(4 \times \text{length})$, where c is the speed of sound. This is the same equation used to calculate one-quarter wavelength of a certain frequency. If length is in meters, speed of sound is 342m/s. If length is in inches, speed of sound is 13560 inches/sec. A pipe 42″ long resonates at 80Hz, the fundamental.

Unfortunately, bare pipes also resonate at odd multiples of $f\Theta$ (three times $f\Theta$, five times $f\Theta$, and so on, which I refer to as 3Θ, 5Θ, 7Θ, . . .) The 80Hz pipe will also resonate at 240Hz, 400Hz, 560Hz . . ., the harmonics. These extra harmonics are unpleasant and destroy the valuable sounds a loudspeaker is meant to deliver. Quarter-wave systems rely on stuffing to control unwanted resonances at 3Θ, 5Θ, 7Θ, and beyond.

Tapered Quarter-Wave Tube (TQWT)—The first quarter-wave system published was the Voigt (pronounced vote) Patent 447,749 submitted Oct. 17, 1934. In it he lays claim to a wide variety of quarter-wave schemes. However, nowhere does he mention fibrous stuffing. Without it, his pipes undoubtedly produce a series of unpleasant harmonics. His tapered design (*Fig. 3*) and folded tapered design (*Fig. 4*) have an ongoing cult-like following. Today, stuffing is always used in the tapered pipes.

Voigt describes his pipes as "closed at one end and excited by means of a loudspeaker diaphragm . . . [the] length just under one quarter of the lowest frequency at which efficient working is desired, the diameter being about ⅓ or ¼ the length, and the tube being closed at the one end." (Paul Gustav Adolphus Helmuth Voigt, Patent Specification 447,749, Application date: Oct 17, 1934.) His quarter-wave pipes place the driver on the closed end or on a side immediately adjacent to the closed end. He points out "in practice it is desirable to taper the bass chamber slightly . . ." TQWT is commonly referred to as the "Voigt pipe."



From "Improvements in Means for Converting Electrical Energy into Sound" Paul Voigt, U. S. Patent 447,749 (1934)

B-2215-sb

Acoustic Labyrinth—"It consists essentially of an absorbent walled conduit having one end coupled tightly to the back of the loudspeaker cone and the other end open. This conduit is in effect folded within the interior of the cabinet."[3] The photo accompanying Olney's article shows a pipe folded into three sections within a furniture-styled cabinet of that time. He places the driver at the closed end and the open end is near the floor.

Although no dimensions are given, the pipe appears to be several feet long and perhaps a half-foot square in cross-section. One side of the pipe is lined with thick felt, perhaps 2″ or 3″ thick. "However, by lining the tube with material whose sound absorption rises suitably with frequency, we can suppress entirely these higher resonances . . ." Just two years after Voigt's pipes, Olney understood the importance of absorbent lining to suppress the 3Θ, 5Θ, and other harmonics.

Transmission Line—A long pipe with parallel sides, stuffed the entire length. Bailey writes more about the transmission line in 1972[4], "Radiation from the back of the driver cone flows down a pipe filled with a low-density sound-absorbing material. Fibrous absorbents such as loose wool, cotton wool, and kapok can be used." He also notes "[t]he effect of wool filling in the pipe is to slow down the wave relative to its velocity in free air." Stuffing not only attenuates the rear wave but also slows the speed of sound within the tangle.

dan JX92S example a large box, the amount of room it takes up on your floor is not that big, just 7 × 7″ plus the width of your wood. α-TLs have a very reasonable "footprint" compared to a corresponding sealed box. Going through the eight steps has given three critical bits of information: length, cross-section, and stuffing amount. Now you can build the α-TL. The sidebar describes construction. See *Fig. 6* for results of this 80Hz α-TL.

Since this is your first view of an α-TL, I need to point out some features in *Fig. 6*. Driver rolloff is near 9dB per octave. I have run many simulations, and the α-TL driver is critically damped every time. Though not on the graph,

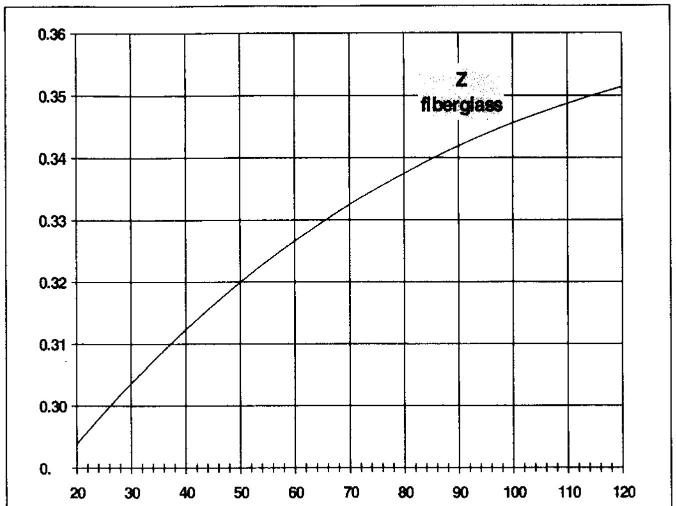


FIGURE 4: α-transmission line Z value—fiberglass. The Z value is needed to determine the cross-section area. Using the same pipe frequency, read the Z value from the curve. Use Z in this equation to set proper cross-section: Sx equals $Z \times f_S \times f\Theta \times V_{AS}/(10{,}000 \times \alpha)$, where α equals $\sqrt{(1 + (f\Theta/f_S \times Q_{TS}))}$. The shape of the cross-section is up to you. B-2215-4

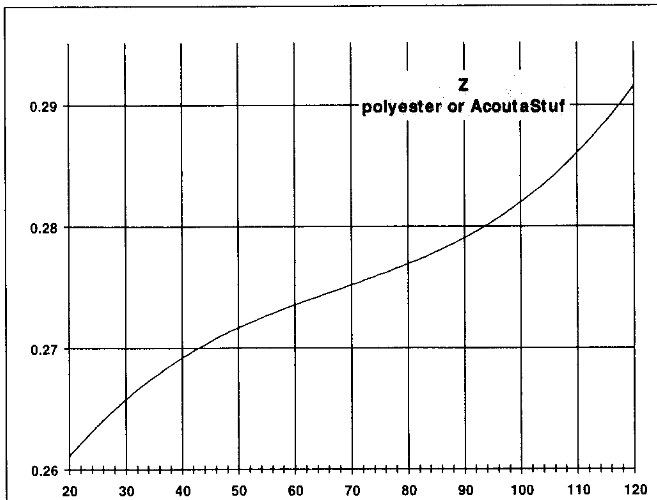


FIGURE 5: α-transmission line Z value—polyester, cotton, AcoustaStuf. The Z value is needed to determine the cross-section area. Using the same pipe frequency, read the Z value from the curve. Use Z in this equation to set proper cross-section: Sx equals $Z \times f_S \times f\Theta \times V_{AS}/(10{,}000 \times \alpha)$, where α equals $\sqrt{(1 + (f\Theta/f_S \times Q_{TS}))}$. The shape of the cross-section is up to you. B-2215-5

group delay is consistently quick and smooth, normally between 4 and 6ms.

Notice how flat the impedance curve is in *Fig. 6.* α-TL impedance curves are noticeably flatter than the driver's free-air curve. Impedance curves of α-TLs are much flatter than the curve of the driver in a sealed box or bass reflex. If you like tube amps, this is an attractive property of α-TLs.

Lastly, output from the opening adds about 3dB to the low-frequency response of the driver. The low-frequency cutoff of the driver alone is at 93Hz. The opening output extends cutoff to 66Hz, one-half octave.

TRADITIONAL TL

Reviewing TL properties: they have straight sides; they are not tapered. The driver is always at the closed end of a TL. At the open end, the entire cross-section is open. Stuffing is uniformly packed along the entire length of the pipe, from closed end right to the open end. Traditional TLs have one additional, unique property:

- Pipe frequency fΘ is set near f_S

Let's examine a traditional TL, using the same JX92S for this example. The only prerequisite for making a traditional TL is setting fΘ equal to f_S. For the JX92S, fΘ = f_S = 45. Using fiberglass stuffing as before, *Fig. 2* shows the traditional JX92S TL is 60″ tall, while proper packing is just 0.57 #/ft^3. Doing the rest of the math, cross-section is 17 in^2, and 5.4 oz of fiberglass is needed to stuff the pipe.

Figure 7 shows the performance for this pipe. Notice the small output from the opening (dashed line). At 200Hz, opening sound is −21dB compared to the driver. That is 1/128 as quiet as the driver—very quiet. These traditional TLs attenuate the opening very effectively. They do not support and augment the driver. This confronts a TL myth. Lighter stuffing alone does little to improve bass response of the system.

As one other example of this, see *Fig. 8* of a traditional TL using the Peerless 2732, which is critically damped. At 200Hz, opening output is −26dB, or 1/400 driver output. Also notice how flat the impedance curve is for this traditional TL. Unfortunately, there is little low frequency support even though fΘ = f_S = 34.

STUFFING

Attenuation of the pipe depends on 1) stuffing density, 2) material, and 3) pipe length—not very profound! Tight packing means more fibers are encountered by the resonant sound waves. Longer pipes mean more fibers are encountered. Fibers of the material have their own unique diameter. Fiberglass is much finer than polyester or AcoustaStuf, has more fibers per unit volume, and is much more effective at suppressing pipe output.

In the first draft of this article, I presumed there was no standard density of stuffing. In his landmark article[1], George Augspurger provided recommended stuffing amounts appropriate for special TL geometries "but not for simple, straight pipes."

TABLE 1

Using the Jordan JX92S, pipe resonance may be set at any frequency. This table shows cabinet size and stuffing for three resonances and two materials. Results for these values are compared in *Figs. 9* and *11*, *Figs. 10* and *12*.

JORDAN JX92S FΘ VARIATIONS	LENGTH	DENSITY #/FT^3	CROSS-SECTION	OUNCES OF MATERIAL
FIBERGLASS STUFFING				
45Hz (f_S)	60 in	0.57	32 in^2	10.2 oz
63Hz (1.4f_S)	41 in	0.68	41 in^2	10.7 oz
90Hz (2f_S)	28 in	0.78	53 in^2	10.8 oz
POLYESTER STUFFING				
45Hz (f_S)	70 in	1.28	27 in^2	23 oz
63Hz (1.4f_S)	49 in	1.63	35 in^2	26 oz
90Hz (2f_S)	34 in	2.01	45 in^2	28 oz

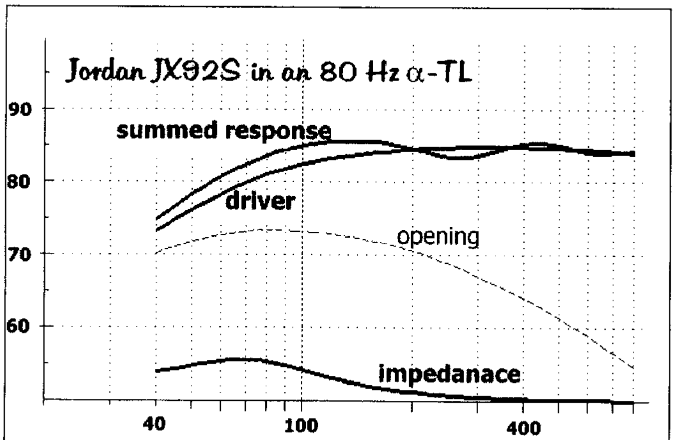


FIGURE 6: Response and impedance curves of the Jordan JX92S in an α-TL. This pipe is designed at 80Hz. Notice the broad flat impedance curve centered at about 70Hz. The sound produced by the driver is the bold line. As you follow it from midrange down to low frequencies, the slope is −6dB per octave. This indicates critical damping. Critically damped systems have excellent transient response. This is described as "clean" or "tight" sound. See the text for a brief discussion of the "summed response" curve. B-2215-6

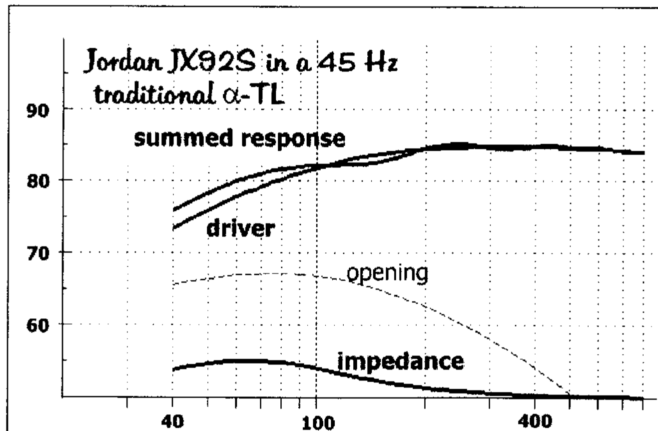


FIGURE 7: Traditional α-TL response. The pipe is constructed so pipe resonance is the same as the JX92S resonance 45Hz and stuffed with fiberglass. Compared to *Fig. 6*, the impedance curve has a similar shape but is centered at 64Hz. Driver response is identical. However, the longer pipe with lighter stuffing has less opening output than the 80Hz pipe in *Fig. 6*. In the past, it was assumed a longer pipe produces more bass. In fact, longer pipes are quieter at low frequency than short pipes. B-2215-7

As I reworked this piece, I looked at the right amount of stuffing for a given straight pipe frequency. It does not matter what driver f_S, Q_{TS}, or V_{AS} is. It does not matter how wide or slim the pipe is. The density of stuffing depends only upon fΘ. When determining the right density, I looked for about a 1.0dB dip at the 3Θ resonance and less than 0.5 lift beyond 3Θ. As I re-read his article, I realized Augspurger used this same standard.

Voice-coil drivers show more variation than this. When cabinet output meets this standard, the α-TL cabinet offers less coloration than the driver itself. That is quite a bold statement. My point is the driver is rarely uniformly flat through midrange. α-TL cabinets show less variation than the driver itself, but this is not the first time this claim has been made.

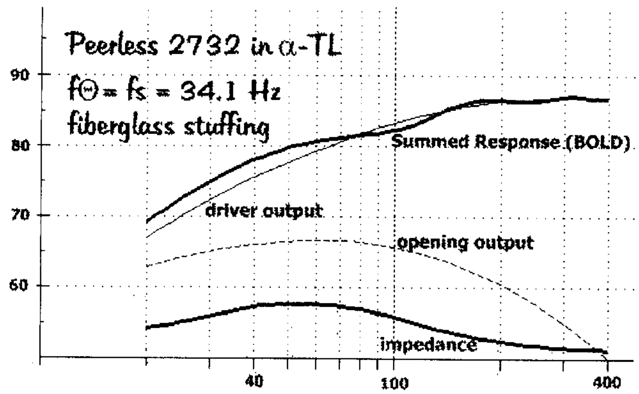


FIGURE 8: Traditional α-TL using the Peerless 2732. This graph is another example of how quiet long pipes are. The pipe frequency is the same as driver resonance, which is 34Hz. Summed response quiets noticeably below 125Hz. The shelving of response between 50 and 110 is largely due to the 3Θ resonance. When 3Θ resonance is better controlled, the shelf would be smoothed out. (Thanks to Peerless, who provided these drivers for an earlier, failed project.)

B-2215-8

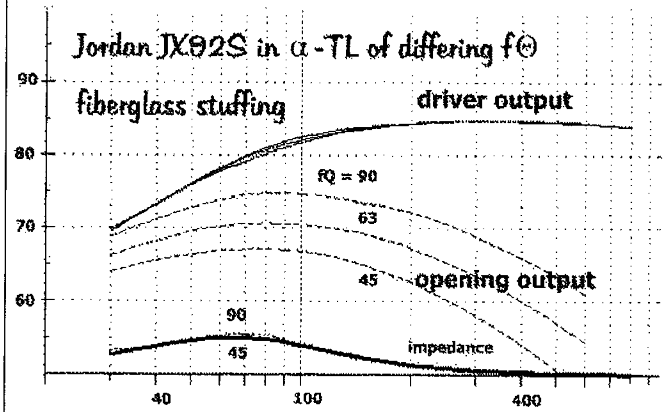


FIGURE 9: α-TL summed pipe responses—fiberglass. The fine lines on this graph are the combined output of the driver and opening seen in *Fig. 11*. This sums the amplitude and phase of the sounds and assumes the driver and opening are the same distance from the ear. The flattest response comes from the 63Hz pipe. High and low spots in the summed curves are due to phase differences between the driver and opening.

B-2215-9

"Listening tests proved that the [TL] cabinet had a 'cleaner' sound than the bass reflex type, the effect of the line being very noticeable in its lack of coloration on speech. Transient response was definitely better on the line speaker, the sound being more 'tight' and natural.

"The final subjective tests were very good. The sound quality is effortless

CONSTRUCTION

The first part of this Jordan JX92S project involves cutting the sides. To keep this project simple, I built a square cross-section. Start with four boards 31⅞″ long (*Photo 1*). MDF is the best to work with. I used ¾″ material for most of my projects because it doesn't split as easily and provides enough surface for adhesive. The inner dimension of the Jordan JX92S project is 7″ square. I cut the boards a little wider than 7¾″. This photo shows the driver opening layout.

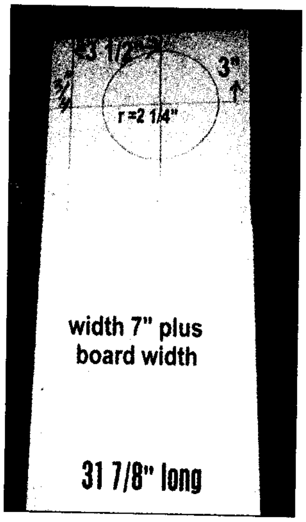


PHOTO 1: All sides of this project are the same. Since the material is ¾″ thick, the side boards are just over 7¾″. The driver needs an opening of radius 2¼″.

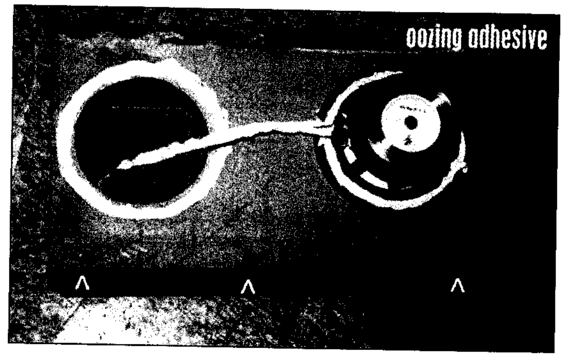


PHOTO 4: Assembled sides are held together with construction adhesive and temporary screws. The adhesive fills in gaps. The screws are removed the next day.

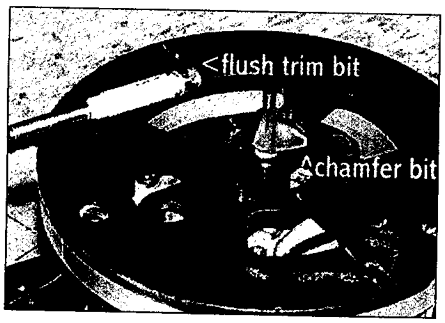


PHOTO 2: The chamfering bit used to widen the inside of the opening. Resting on the router is the flush trim bit used after assembly.

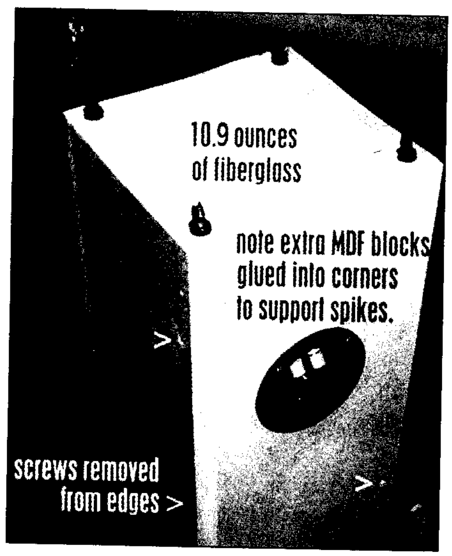


PHOTO 5: Bottom of the assembled cabinet. Extra blocks are added at the corners to receive the spikes. The round black object is the speaker wire d-cup.

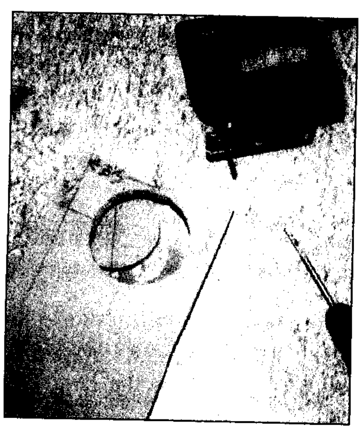


PHOTO 3: The face board with opening cut out.

PHOTO 6: The finished α-TL featuring Jordan's JX92S. Since I had wallpaper available, which matches the living room walls, I tried a different "finish."

Before assembling the sides, I cut the driver opening. It is 4⅛″ diameter. I don't have a nice router jig, so I cut the opening freehand. I used a plastic lid from a coffee can as my compass, which was very stable and made a perfect circle. I cut the hole using my saber saw, but I didn't get a perfect circle (*Photo 2*). If the driver doesn't fit, you can cut a little more from the hole. Often, I simply tilt the jig saw a little and just knock off the rim until it fits.

To me, the most important cabinet detail for smaller drivers is chamfering the rear of the hole. Chamfer is a 45° bevel cut. This is critical if you use thick material, which can obstruct airflow between the hole and basket, thus altering all the TSPs. Also, sound ricochets off a square-cut hole wall producing awful reflections back onto the cone.

The chamfering bit (*Photo 3*) allows free airflow from the rear of the driver and fewer reflection problems. Resting on the router is an edge trim bit (about $18). It is used later to square off and straighten the cabinet edges. A carbide edge trim bit will last for a few projects.

The sides are butt-joined and held temporarily with drywall screws. I pre-drilled the face but not the side and applied a continuous bead of Liquid Nails construction adhesive to one board. When I drove the screw straight into the material, I noticed some splitting of the side. I needed to reset some screws so I drove them on an angle without a pilot hole. This produced much less splitting, so I plan to use this angling technique in the future.

I used the Liquid Nails to glue four ¾″ × ¾″ × 2½″ blocks at the bottom inside corners. I ran some Latex caulk around the driver and the opening (*Photo 4*) and pressed the driver firmly into the caulk so it oozed out the front and rear. I installed four drywall screws along each edge. I was careful so I didn't over tighten them and strip the MDF, and let the assembly cure overnight.

The next day I removed the screws. With a utility knife I trimmed away the cured adhesive and caulk (*Photo 5*). Because I cut the MDF a little wider than needed, I trimmed the long MDF edges with the bit shown in *Photo 2*. The edges were straight and sharp.

At the end near the driver, I lined the inside of the cabinet with fiberglass ceiling tile, which was very effective at reducing midrange and treble reflections. I installed 10.6 oz of fiberglass throughout the cabinet. I cut the top MDF a little big, not quite 8 in^2, attaching it with Liquid Nails and pressing it into place. I didn't bother with screws. Later, I trimmed this with the router just as I did on the long edges. I installed four spikes at the bottom corners to keep the cabinet off the ground. These spikes were essential to detailed imaging.

I used a different cabinet covering on the project (*Photo 6*), having some wallpaper left over from our living room. My first attempt with this pre-pasted paper did not work. To wallpaper an MDF cabinet, first seal the wood with wallpaper primer (also called sizing). Apply wallpaper adhesive to the paper and the cabinet. Clay adhesive is the best. Place the paper centered on the front and wrap around both sides.

I pre-cut the driver hole in the wallpaper and I think that was a good idea. Wipe out air bubbles with a soft rag or brush. Apply pieces to the sides and wrap to the back. Trim the rear, top, and bottom with a razor-sharp tool. Lastly, apply the top piece and trim. Wallpaper is very forgiving and covers minor imperfections such as unfilled screw holes.

and natural. At first hearing the bass sounds deficient but extended tests show that this is not so, it is merely that one has been conditioned to hear resonant bass."[2]

I must caution that every driver has its own properties. Some are better than others in an α-TL. If you notice some irregularity in the midrange, simply install a little more stuffing. You can remove a bit of stuffing to see whether you can get a little more low end. α-TL construction is still an art. This α-TL design system gives you a very good head start on your project.

You are encouraged to vary the amount of stuffing until you attain the sound quality you prefer. Heavier stuffing brings the system closer to the Q_B = 0.5 acoustic suspension. Packing lighter than my recommended density allows more reinforcement and cancellation, producing uneven response.

The curves in *Figs. 9* and *10* are the sum of phase and amplitude of the driver and opening. The sum ignores floor lift, the 2–3dB additional amplitude, because the opening is at the floor. The model assumes driver and opening are equidistant from the ear. However, the driver is often placed near ear level while the opening is farther away at floor level. Room reflections and ceiling height are ignored in the graphs.

For these reasons, I do not fully accept summed response above 120Hz. The only way to tell whether your combination of stuffing material, density, length, and driver pleases you is to build an α-TL and listen to one in your room. Give the system some time and add stuffing to suit your taste.

FΘ—PIPE FREQUENCY

TL myth assumes you can lower system response by building a longer pipe; pushing fΘ lower must extend bass performance. This myth started 65 years ago when Voigt set "length just under one quarter of the lowest frequency at which efficient working is desired." He does not relate quarter-wave pipe frequency to driver resonance. Instead, he related it to whatever frequency "is desired."

Speaker builders have assumed just building a longer pipe will extend response. In fact, building a lower fΘ pipe just quiets it. Longer TLs perform much worse than shorter TLs. The lower limit for pipe frequency should be fΘ equals f_S. I recommend going no lower, any longer.

Shorter pipes produce +2 to +4dB additional bass through low frequency rolloff. This lift continues to near two times fΘ. Shorter α-TL achieves results similar to Augspurger's special geometries. As he comments on his geometries, he observes, "The efficiency matches that of an equivalent closed-box system; however, pipe output contributes 2-3dB in the low frequency range.... the net result is a corresponding increase in maximum output."

Augspurger also says, ". . . In contrast to a basic cylindrical pipe, at least four alternative geometries allow lighter damping, which results in higher efficiency." In fact, straight pipes can perform nearly as well as his geometries. The secret is higher fΘ and tighter stuffing.

Let's consider different pipe frequencies and their performance. I will use frequencies fΘ = f_S, $1.4f_S$, and $2f_S$ for contrast. Using the Jordan JX92S, the three pipe frequencies are 45, 63, and 90Hz. *Table 1* contains the cabinet dimensions using fiberglass and polyester. Fiberglass results are in *Figs. 11* and *9*; polyester results are in *Figs. 12* and *10*.

In *Figs. 11* and *12*, driver response is

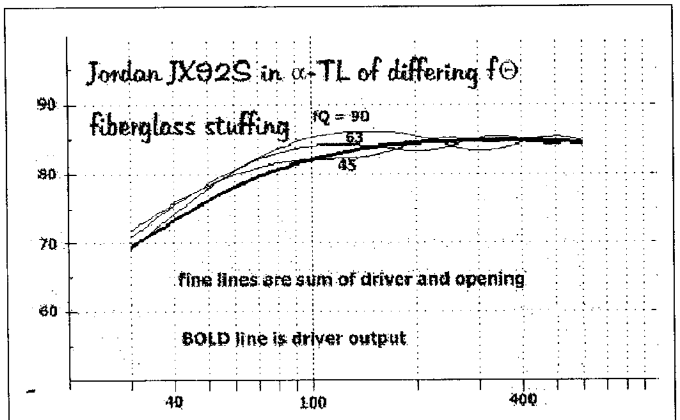


FIGURE 10: α-TL summed pipe responses—polyester. The fine lines on this graph are the combined output of the driver and opening seen in Fig. 12. This sums the amplitude and phase of the sounds and assumes the driver and opening are the same distance from the ear. These summed responses are very similar to the fiberglass results in *Fig. 9*. B-2215-10

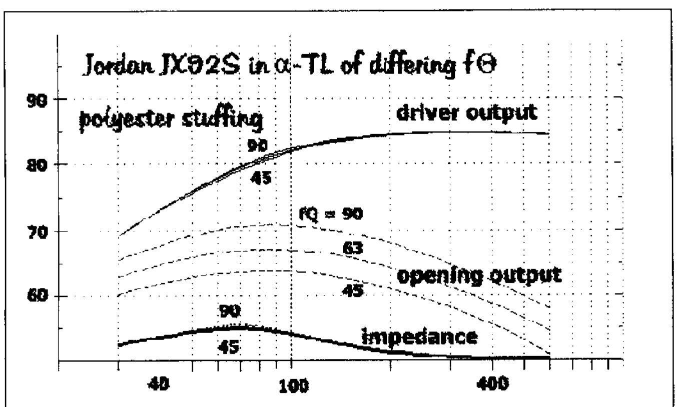


FIGURE 11: Comparison of three fiberglass stuffed α-TLs at different pipe resonances. Impedance is the same for all three pipes, driver output is virtually identical. The only difference is opening output. The longer lower pipes are clearly quieter. I recommend building no lower, any longer. B-2215-11

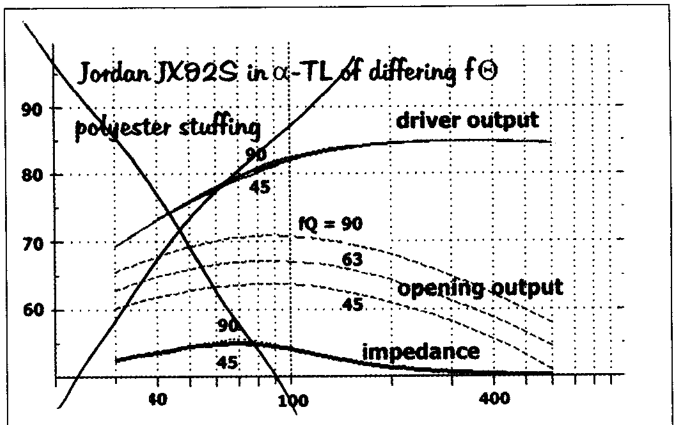


FIGURE 12: Comparison of three polyester stuffed α-TLs designed at different pipe resonances. Impedance is nearly the same for all three pipes; driver output is virtually identical. The significant difference is opening output, which needs to be quieter with polyester, cotton, and AcoustaStuf, so the summed response is appropriate (*Fig. 10*). B-2215-12

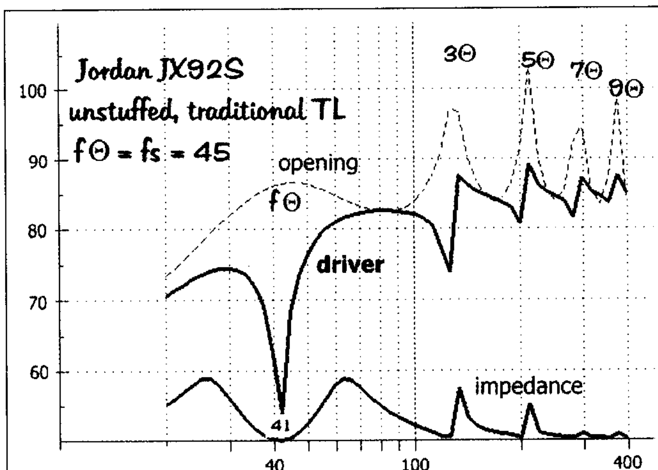


FIGURE 13: Unstuffed traditional α-TL response. The Jordan JX92S in an empty 45Hz pipe shows typical results. Augspurger's program makes numerous calculations and connects the points on the curves. The result is some clipping of the 3Θ and 7Θ harmonics. If this pipe was actually tested, the 3Θ and 7Θ peaks would be closer to the location of the labels. Notice the impedance anomalies at each harmonic. Also, opening resonance is at 45Hz but the driver is completely quiet, dead at 41Hz. B-2215-13

virtually the same—critically damped. Impedance curves are quite flat and practically the same. The only noticeable difference is opening output. The shortest pipe gets closest to driver output. However, there can be a lot of lift into midrange. I recommend choosing $f\Theta$ to be 1.2 to 1.6 times driver f_S.

Since length, density, and stuffing vary, cutoff is difficult to predict accurately. Cutoff is at least as good as the $Q_B = 0.5$ AS and may be as much as one-half octave lower, especially if $f\Theta$ is 1.2 to 1.6 times f_S. These pipes also avoid excessive midrange lift. Not bad considering the cabinet is smaller than a traditional TL.

IMPEDANCE

Pipe frequency is the primary reason the impedance curve flattens. There is a down side. Unstuffed TLs do not resonate at only $f\Theta$. They have acoustic and electric harmonics at odd multiples of $f\Theta$ at 3Θ, 5Θ, 7Θ, and so on.

Figure 13 shows these ugly peaks for an un-stuffed traditional 45Hz pipe using the JX92S. These are unbearable and must be suppressed. The only solution is stuffing, which is vital to deaden acoustic and electric irregularities produced by pipe harmonics.

The basic impedance curve for the JX92S on a large flat board is curve A in *Fig. 14.* This curve is centered at 45Hz, so we say $f_S = 45$. The broadness of the curve determines Q_{TS}, which is 0.40 for this driver.

Next, look at curve C, which is very irregular. It is the curve of the JX92S in an unstuffed traditional TL of $f\Theta = f_S = 45$. I set the cross-section based on my α-TL model. But this curve is more regular than it seems.

One important detail to notice is the first two peaks. If you consider the first two peaks alone, the curve looks like an exquisitely tuned bass reflex design. Amplitude is the same for these two peaks. An improperly tuned pipe exhibits unbalanced peaks.

The next important observation is the location of the peaks at 27 and 64Hz. These are important because $f_S = 45$ is very near the (geometric) center frequency of these two points; that is, $\sqrt{(27 \times 64)} = 41$. Unstuffed α-TLs always display this centering. The center frequency is normally about 10% lower than f_S.

The third peak is near 135, the next near 225, another near 315, and again near 405. These impedance peaks represent the 3Θ, 5Θ, 7Θ, and 9Θ pipe harmonics. As these resonances quiet at higher frequencies, the impedance peaks flatten. Actual harmonics are normally just below the predicted harmonics.

Finally, curve B is for the traditional stuffed α-TL. Notice the broad smooth curve. Although the α-TL is tuned to 45Hz, the impedance peak is not at $f\Theta = f_S = 45$. Stuffing deadens the first peak. Stuffing also deadens the pipe harmonics. The only remaining peak is at 64Hz, the same as the second unstuffed peak. Because the graph is on a logarithmic scale, this peak is only about 40% of the driver on a board.

So, it is pipe frequency that damps driver resonance; then stuffing damps pipe resonances. Proper pipe length and stuffing produce a flat impedance curve, phase unity, excellent transient response, and quick, uniform group delay. As $f\Theta$ moves away from f_S, cross-section adjusts so Q_{TS} is nearly neutralized in all α-TLs.

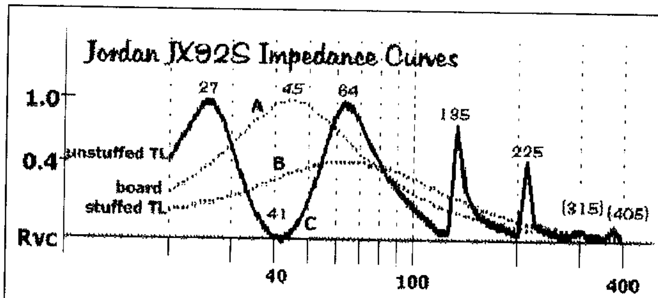


FIGURE 14: Comparison of unstuffed and stuffed traditional α-TLs. Line A is the impedance of the JX92S on a flat board. Line B shows the driver in a stuffed traditional α-TL. Line C is the wild impedance of an unstuffed pipe. Stuffing deadens all but one of the unstuffed peaks. The only remaining peak is located at the second unstuffed peak at 64Hz. Because the graph is on a logarithmic scale, this peak is only about 40% of the driver on a board. *Figure 14* holds the key to improving the α-TL. Low frequency response can be extended when the first and second peaks are developed and the third peak is subdued.

B-2215-14

αLPHA . . .

Those of you interested in engineering loudspeakers may have noticed a loudspeaker mystery unveiled here. Speaker builders are accustomed to α associated to acoustic suspension cabinet volume. In all quarter-wave systems, α is length dependent. More accurately, it is dependent upon the $f\Theta{:}f_S Q_{TS}$ ratio. The α-ratio was the ultimate mystery in TSP-based TL design.

Properly designed quarter-wave systems neutralize the driver resonant peak defined by f_S and Q_{TS}. α-TLs compensate or flatten the driver's electrical resonance peak. When you look at the α formula, note what happens when $f\Theta$ is set equal to f_S. Then $\alpha = \sqrt{(1 + (f_S/(f_S Q_{TS})))}$ or $\sqrt{(1 + (1/Q_{TS}))}$. α is related to the inverse of Q_{TS}. This explains the flattened impedance curve at driver resonance.

To get the flattest possible impedance curve, simply set $f\Theta = f_S/Q_{TS}$. This does not ensure extended low frequency; it only produces the flattest impedance. To get both the best response and impedance, select a driver whose Q_{TS} is between 0.5 and 1.0. Still, many people prefer the sound of low Q_{TS} drivers (below 0.4) in their TLs. This design works for all speakers no matter what Q_{TS} the driver has.

This article and design is subject to full copyright and patent protection. There is no restriction, of course, on private individuals making an α-TL for their own pleasure. These are the (proprietary) mathematical equations for the curves on *Figs. 2* and *4*, *Figs. 3* and *5*. These equations are reliable for pipe $f\Theta$ up to 120Hz. Beyond that, other factors influence results.

$L_f = 3816(f\Theta^{-1.09})$
$D_f = 0.0000002\ f\Theta^3 - 0.00009f\Theta^2 + 0.014f\Theta + 0.11$
$Z_f = 0.00000008f\Theta^3 - 0.00002f\Theta^2 + 0.0023f\Theta + 0.25$
$L_p = 4014(f\Theta^{-1.06})$
$D_p = 0.000003f\Theta^3 - 0.0007\ f\Theta^2 + 0.068f\Theta - 0.64$
$Z_p = 0.00000005f\Theta^3 - 0.000009f\Theta^2 + 0.0008f\Theta + 0.25$

. . . AND ΩMEGA

Mr. Augspurger provided the technical review of this article. I deeply appreciate his interest and support. He comments, "Four things I learned from reading the revised manuscript: (a) A simple quarter-wave damped pipe is as easy to build as a closed box, but can provide certain performance advantages. (b) With straight pipe geometry, enclosure volume may not be all that important . . . it doesn't make much difference whether the pipe is 8 in^2 or 10 in^2. (c) The quarter-wave pipe frequency does not have to match the speaker's free-air resonance. For best performance, it should not. (d) To get more bass, make the pipe fatter, not longer. I agree with all four assertions." He also agrees with my assertion that there is a specific stuffing density dependent upon pipe $f\Theta$ and material only.

Impedance curves can be manipulated by cabinet modifications. The second peak is moved near f_S and the third peak is deadened by the cabinet and not the stuffing. Simple modifications to α-TL cabinet design and stuffing lead to a different TSP-based design—the Ω-quarter wave reflex. ❖

ACKNOWLEDGMENTS

I am deeply indebted to G. L. Augspurger, who generously provided his software. Using it has allowed great progress in pursuing my hobby. The graphs in this article are produced by his program.

For more on quarter-wave design, see the best QW site on the planet at http://www.t-linespeakers.org/index.html. Dave Dlugos runs the site and has been very supportive of my design ideas. This article will be posted there after publication.

Martin J. King has been very encouraging as we corresponded about stuffing, TLs, TQWTs, and exolinear design. Visit his informative site at http://www.quarter-wave.com

REFERENCES

1. G. L. Augspurger, "Transmission Lines Update, Part 3: Pipe Geometry and Optimized Alignments," *SB* 4/00.

2. Dr. A. R. Bailey, "A Non-resonant Loudspeaker Enclosure Design," *Wireless World*, October 1965.

3. Benjamin Olney, "The Acoustic Labyrinth," *Electronics*, April 1937.

4. A. R. Bailey, "The Transmission-line Loudspeaker Enclosure," *Wireless World*, May 1972.