OPTIMIZING TRANSMISSION LINE LENGTHS

BY LARRY D. SHARP

In recent years, many articles have appeared in *SB* concerning transmission line designs. While most have been informative, only a few have mentioned the obvious relationship between stuffing density and line length. A lack of mathematical equations defining TL characteristics has probably kept many from attempting this type of speaker design.

A certain amount of math is involved, but don't let the equations scare you. Work them through, and you'll see where I'm going. When you're finished, I think you will understand TLs better.

THE MATH. Many builders calculate transmission line length using the following formula:[1]

$$\tfrac{1}{4}\lambda = \frac{1{,}130 \text{ ft./sec.}}{f_s \text{ (Hz)}} / 4$$

The length this method determines is correct for an undamped line. When the line is filled with a damping fiber, like wool or Acousta-Stuf®, it ceases to be an acoustical labyrinth and becomes a low-pass filter. This requires an equation modification. We must find the speed of sound through fiber.

The speed of sound through air at 0°C is 1,087 feet per second. To find the speed of sound at any temperature, use the formula below:[2]

$$c = \frac{1{,}087 \times \sqrt{273 + t°C}}{16.52}$$

Since 72°F = 22.3°C, you can see that the speed of sound at 72°F is 1,130 feet per second.

Bradbury's equation for the speed of sound through a fibrous material like wool or Acousta-Stuf follows:[3]

$$c' = \frac{c}{\sqrt{1 + (P_s/P)}}$$

where c' is the speed of sound through fiber, c is the speed of sound through air at 72°F (1,130 ft./sec.), P_s is the density of the stuffing material (0.5 lb./ft.³), and P is the density of air at 72°F (0.0745 lb./ft.³).

In the *Loudspeaker Design Cookbook*,[3] Vance Dickason lists the density of air as 1.18 kg./cubic meter (0.0736 lb./ft.³), which is correct for 76°F. However, I am attempting to standardize all values at 72°F for the convenience of using the 1,130 ft./sec. speed of sound.

Bradbury's equation using a stuffing density of 0.5 lb./ft.³ of fiber provides the following results:

$$c' = \frac{1{,}130}{\sqrt{1 + (0.5 / 0.0745)}}$$

$$= \frac{1{,}130}{\sqrt{7.71}} = \frac{1{,}130}{2.77} = 408 \text{ ft./sec.}$$

Now try 0.75 lb./ft.³:

$$c' = \frac{1{,}130}{\sqrt{1 + (0.75 / 0.0745)}}$$

$$= \frac{1{,}130}{\sqrt{11.1}} = \frac{1{,}130}{3.33} = 339 \text{ ft./sec.}$$

And 1 lb./ft.³ is:

$$c' = \frac{1.130}{\sqrt{1 + (1 / 0.0745)}}$$

$$= \frac{1{,}130}{\sqrt{14.4}} = \frac{1{,}130}{3.80} = 298 \text{ ft./sec.}$$

Now, instead of 1,130 ft./sec., replace *XXX* in the formula below with speeds of 408, 339, and 298 for quarter wavelength lines:

$$\frac{XXX \text{ ft./sec.}}{f_s \text{ (Hz)}} / 4 = L'$$

This lets you calculate line length at various cutoff frequencies. *Table 1* and *Fig. 1* indicate the length of transmission lines at frequencies from 20–50Hz and stuffing densities of 0.5, 0.75, and 1 pound per cubic foot of enclosure volume.

DESIGNING YOUR TL. Now that you've done the math and see the results, you may question those numbers. After all, can you really expect a 50" long line to go down to 25Hz? Using a woofer with a low f_s, I don't see why this figure can't be met. If you don't trust the equations, add 25% to your TL; it won't hurt anything.

The other considerations you should look at are woofer Q_{TS} and cross-sectional area of line. After selecting a woofer, consult *Table 1* for an appropriate line length. Use a minimum cross-

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TABLE 1

QUARTER WAVELENGTH TRANSMISSION LINE LENGTHS USING BRADBURY'S EQUATION

Freq. (Hz)	0.5 lb./ft.^{3} 408 ft./sec.		0.75 lb./ft.^{3} 339 ft./sec.		1 lb./ft.^{3} 298 ft./sec.	
20	5.10	61.2	4.24	50.9	3.72	44.6
25	4.08	48.9	3.39	40.7	2.98	35.8
30	3.40	40.8	2.82	33.8	2.48	29.8
35	2.91	34.9	2.42	29.1	2.12	25.4
40	2.55	30.6	2.12	25.4	1.86	22.3
45	2.26	27.1	1.88	22.6	1.65	19.8
50	2.04	24.5	1.69	20.3	1.49	17.9

sectional area (CS1) behind the woofer at least 25% greater than the effective cone radiation area (S_D). Most 8″ woofers have an S_D of about $33.3in^2$, so a minimum of $42in^2$ would be good.

John Cockroft[4] recommends increasing the cross-sectional area of a TL for stuffing densities above 0.5 lb./ft³, so to use the 0.75 lb./ft³ or the 1 lb./ft³ density lengths from *Table 1*, you probably should increase the minimum cross-sectional area by 40–60% greater than S_D, respectively.

John also addresses the issue of driver Q_{TS}. He believes a shorter line should use a woofer with a higher Q_{TS}. Lines longer than 41″ can use a Q_{TS} of 0.4 or less, while lines 25–40″ long should use a woofer Q_{TS} of 0.4–0.6, and for lines shorter than 24″, a Q_{TS} of 0.6–0.75 should work well.

In several issues of *SB*, readers have commented on the equations that Mr. Cockroft developed for "The Unline." On page 83 of *SB* 3/90, he made a statement we all should read. He simply says, "Consider the article a road sign: it points out the direction, but it doesn't walk the road for you."

I agree with his statement. Don't let the fear that you may not know enough about transmission lines stop you from proceeding with what will probably turn out to be the most satisfying speaker project you ever attempt. Sit down with a pad of quadrille graph paper, and using the tables and equations that have appeared in these articles, make a scale drawing of the ideas that come into your head. Then, cut the wood and build your TL design. You will probably be amazed at how good your transmission line speaker system sounds.

WHETHER TO TAPER. Some articles have recommended maintaining a constant cross-sectional area along the entire length of a transmission line.[1,5] While this works well, I must point out that lines with parallel wall surfaces will invariably cause standing waves and resonances to occur somewhere along the length of the line at various frequencies.

Several articles have recommended tapering the line,[6–8] and I believe this is the ideal approach. Tapering a TL eliminates the possibility of major resonances and standing waves, which slightly improves the efficiency of your TL and reduces the enclosure's overall size. In fact, the TL design shown in A.R. Bailey's original article[9] was a tapered line.

Taper the line to no less than 50–60% of S_D at the terminus area. You can taper a TL continuously by using angled baffles so only the side walls of the box are parallel, or you can taper in progressively smaller steps as Craig Cushing did with his compact TL subwoofer.[8]

FIBER'S ACOUSTIC PROPERTIES. A damping material inside a speaker enclosure absorbs midrange reflections that would otherwise bounce around inside the box and cause secondary emission from the driver cone. Without damping material, a speaker will be loud and colored in the midrange. In a transmission line, the damping fiber acts as a low-pass filter that eliminates all frequencies but the deepest bass. The woofer's output in the lower octaves is reinforced by the output at the terminus.

Most audiophiles agree that wool outperforms polyester as a damping material, and those who have tried Acousta-Stuf swear this is far superior to wool. But what makes one fiber sound better than another? The answer lies in basic physics.

Sound consists of a complex series of waves composed of compression and rarefaction of air molecules caused by the vibration of the speaker cone. *[Among other things.—Ed.]* The surface area of a damping material greatly determines what the material's absorption coefficient will be. A fiber with more

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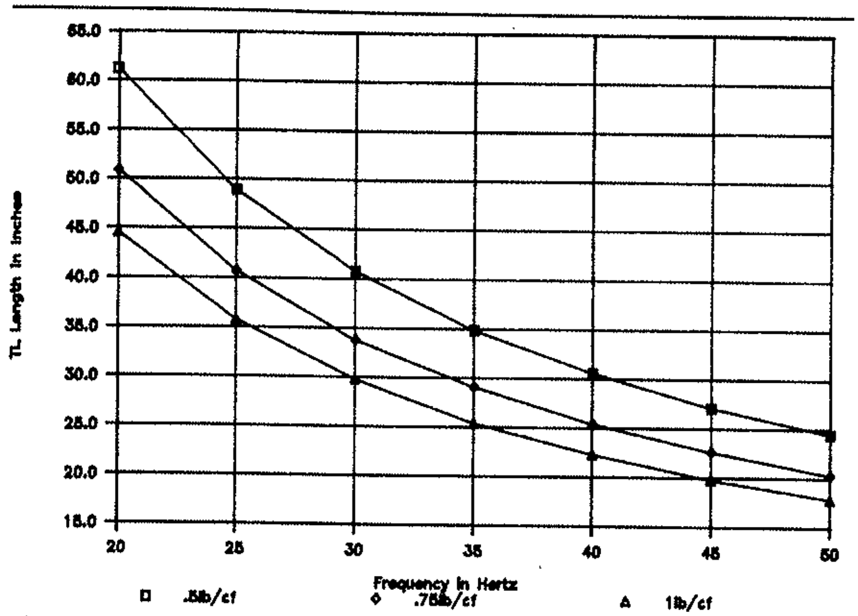

FIGURE 1: Transmission line length using 0.5, 0.75, and 1 lb./ft³

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surface area will break up and disperse a speaker's rear wave better than a fiber with less surface area.

Although you would need a microscope to see the shape of a fiber cross-sectionally, sound is easily affected by that shape. What you can see is the length of a strand of fiber. Polyester is a round, straight fiber—useful, but not great. Wool has cross-sectional ridges and a natural wave along its length. This gives wool more overall surface area than polyester, explaining why it sounds better. Acousta-Stuf is tri-lobal in shape and multi-directionally crimped. It has several times the surface area of wool.

CONCLUSIONS. Almost anyone can design a great sounding transmission line speaker system using the information presented in *SB*, *TAA*, *The Loudspeaker Design Cookbook*, and many other books available through Old Colony Sound Lab. Good luck with your TL design.