THE UNLINE:
DESIGNING SHORTER TRANSMISSION LINES

BY JOHN COCKROFT

In the years since Dr. Bailey's straightforward presentation, the transmission line loudspeaker enclosure has become an object of myth and fancy. Useful lines have been produced by some which are among the finest music reproducing systems yet devised. Others' attempts have ended up more useful as doghouses.

The original concept's rather large enclosure, optimally designed for a large listening room, is capable of awesome performance. I think the principle of the TL is excellent and the benefits of the nonresonant performance should not be limited to such an occasionally ideal environment.

Large TLs have extended low-frequency performance well into the nether regions of the threshold of human hearing. Equally important, they do so in such a smooth and natural manner, avoiding most problems designers experience with other types of enclosures. These side benefits of transmission lines have held my interest over the past several years.

As vented and sealed systems are designed in a myriad of sizes and parameters for a multitude of uses, why shouldn't the TL have the freedom to live a multifaceted existence for our listening pleasure?

To this end I have empirically designed over a dozen lines intended for use in small listening rooms. In principle, most performed quite well. Generally, I encountered the usual troubles that crop up when designing any type speaker system, such as matching speakers, balance and so on. I believe transmission lines can be used in many applications and have the potential to be extremely useful.

I recently took a retrospective look at my more successful TL systems and formed some general relationships. After considering and evaluating their empirical qualities, I developed an arbitrary "standard" transmission line enclosure that relates very closely to several of my systems. By using my concocted "standard" TL and others as points along a line, I came up with some equations that describe my speakers rather accurately and allow for a continuum of other enclosures between and beyond the ones I have constructed.

A CONTINUUM. The "standard" speaker I chose for the examples is reasonably close to Bailey's original. I could have used Bailey's exact line as the standard (and so can you), but it doesn't describe my speaker designs quite as well and that is the purpose of this little project.

The standard system I chose has a length of 72"; is stuffed with polyester fiberfill at a density of 0.5 lb./ft.^{3}; the minimum cross section equals the cone area of the woofer; and speaker unit Q_{ts} is 0.4. I never built this enclosure, of course. I use it here merely as a model on which to base other systems.

My procedure presents equations that predict line length, stuffing density, minimum cross-sectional area and speaker Q_{ts}, for enclosures with lengths shorter than the model system. You may design an enclosure starting with line length, or if you prefer, on the basis of speaker Q_{ts}.

First, I'll consider developing enclosures choosing a line length shorter than the model's. Once the length is settled the question of stuffing density comes up. It is solved by Equation 1:

$$d_1 = d_s \times \frac{1}{(LL_1/LL_s)^{1/2}}$$

where

d_1 = the desired new density for the shorter line
LL_1 = The desired shorter line length
LL_s = The "standard" line length
d_s = The "standard" density of 0.5lb./ft.^{3}.

After the density of the stuffing is determined, the minimum line cross section is considered in Equation 2:

$$Cs_1 = (d_1/d_s)Cs_s \times Ca$$

where,

Cs_1 = the desired minimum cross section;
Cs_s = The "standard" minimum cross section, in this case 1 times the cone area;
Ca = the area of the woofer cone. The cone diameter is usually measured from the center of the surround to the center of the surround.

Finally, the Q_{ts} of the woofer is calculated in Equation 3:

$$Q_{t1} = Q_{ts}(d_1/d_s)^{1/2}$$

where,

Q_{t1} = the desired speaker Q_{ts};
Q_{ts} = the "standard" speaker Q_{ts} of 0.4.

As you can see from the equations, as the line shortens, the stuffing density increases. To compensate for this, the minimum cross section also increases to give the speaker a better opportunity to "breathe" in the denser environment. The increased density tends to overdamp the speaker, so a higher Q_{ts} is required.

In my previous article ("The Shortline," *SB* 1/88, p. 18) I mentioned shorter lines might begin to function as a hybrid design between the classic line and the

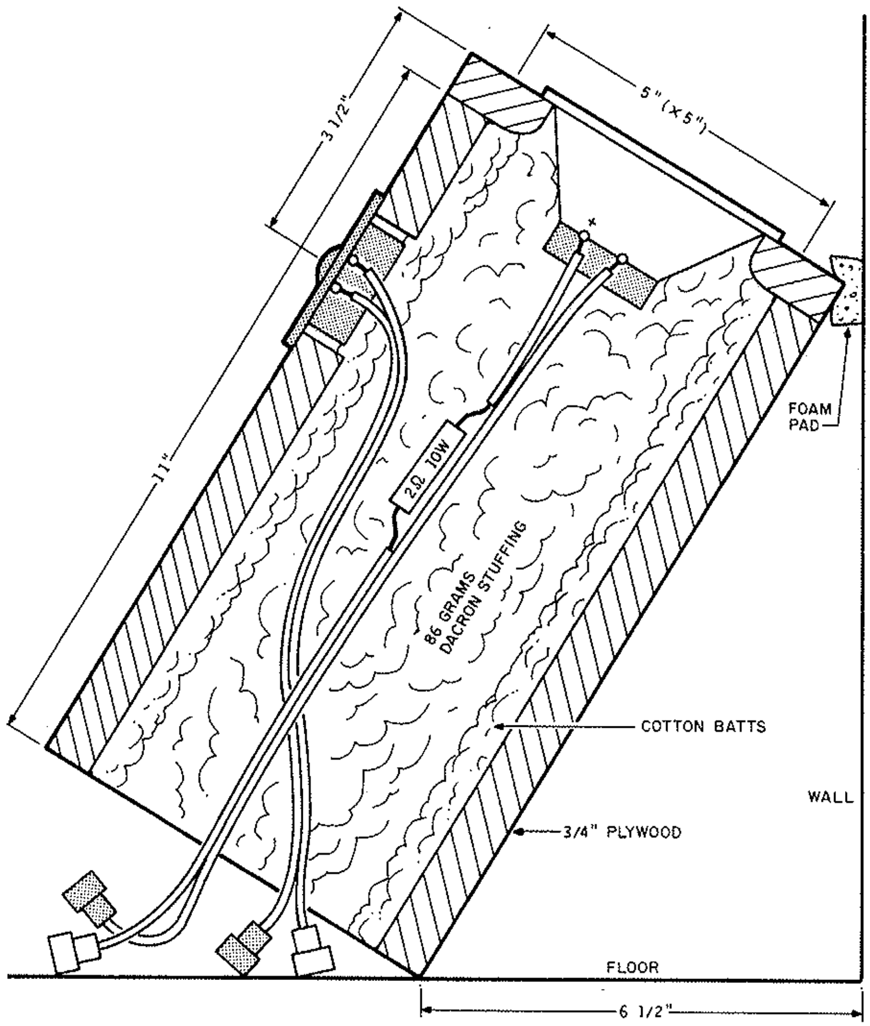

FIGURE 1: Diagram of the Unline showing the tweeter properly mounted. The original was biamped using a Marchand XM-1 fourth-order crossover at 3.5kHz.

aperiodic, pressure-relief type of enclosure, or as a "bottomless box." The sound remains very much "transmission line" in its general characteristics. The resonant frequencies remain low when compared to the aperiodic types.

OCTALINE FORMULAS. For an example, let's examine my Octaline speaker from *SB* 3/87, using the above equations. It is just about 36" long. Using Equation 1:

$$d_1 = 0.5 \frac{1}{(36/72)^{1/2}} = .7071 \text{ lb./ft.}^3$$

with Equation 2:

$$Cs_1 = (.7071/.5)1 = 1.414 \times (\text{cone area of } 8.9 \text{ in.}^2) = 12.6 \text{ in.}^2$$

Now Q_{ts}:

$$Q_{t1} = .4(.7071/.5)^{1/2} = .475$$

I constructed the Octaline a couple of years before I evolved these equations; I used a minimum cross section of 12.2 in.^{2}, and a Q_{ts} of about 0.505. Working empirically, the Octaline is within 6.3% of Q_{ts} and 3.2% of the minimum cross section of my "standard" line. Or, perhaps, my "standard" line is within those percentages of the Octaline. At the time I conceived the Octaline I wasn't aware of the role Q_{ts} might play in TL design.

To determine the parameters of a line for a speaker unit with a given Q_{ts}, use the following equations; begin by calculating the stuffing density (Equation 4).

$$d_1 = (Q_{t1}/Q_{ts})^2$$

Proceed with the cross section by using Equation 2. Finally determine the line length. (Equation 5):

$$LL_1 = LL_s \times \frac{1}{(d_1/d_s)^2}$$

As an example of the above, say you had a speaker with a Q_{ts} of 0.43. Then:

$$\text{stuffing density} = 0.5(0.43/0.4)^2 = 0.578 \text{ lb./ft.}^3$$

and:

$$\text{min. cross section} = (.578/.5) = 1.16 \times Ca$$

and:

$$\text{line length} = 72 \times \frac{1}{(.578/.5)^2} = 53.9''$$

Aside from having the correct Q_{ts}, to be successfully used with these equations a speaker should have a low F_{sa}. I haven't been able to work this parameter into my model, but I believe the lower the F_{sa}, the better. Using a speaker with an F_{sa} in the 30Hz area sounds much better than a speaker with an F_{sa} around 40Hz, and I'm sure those approaching 20Hz are even better.

Of course, these differences will only be noticed when music of ultra low frequency content is heard. For most music, speakers with 40Hz resonance will be quite adequate, particularly if Q_{ts} is at least .4 or higher. Lower Q_{ts} figures result in excessive roll-off of important musical content. Even with Q_{ts} .5, Q_{ts} will be down 6dB. Q_{ts} .3 will be 3dB down at 121Hz. It has been my experience that TL enclosures don't raise Q_{ts} greatly, as for instance a sealed box does.

If you plan to raise the Q_{ts} of a given speaker, I recommend you add mass to the driver cone, rather than using series resistance. In both cases you will lose efficiency, but with more mass you will lower F_{sa}, which is a much better bargain than a mere efficiency loss.

A speaker with a long voice coil overhang probably responds better when adding mass, since the loss of control with the higher Q_{ts} increases the tendency to overshoot, and the long coil gives more leeway for linear signals. Adding mass may make an infrasonic filter necessary, but I think one should be used in any case.

ACID TEST. Now, finally, let's look at the Unline. I built it because I wanted to give my equations a real test, to make sure they work. A small enclosure, that I had used on occasion as a transmission line loaded midrange, was 5" by 5" by 11," with a hole for a 4" speaker on top; the bottom was open. (What I'm calling

Continued on page 32

PHOTO 1: The Unline in all its unglory. The wad of cotton on the enclosure front keeps the tweeter leads from vibrating. Note the 2Ω series resistor used to raise Q_{ts}.

the bottom was actually the back when I used it as a midrange.)

I first thought I may be crazy to consider using this enclosure, a thought you may share, along with many others. Later, curiosity overcame my self-deprecation and I worked out the equations for the little box. The stuffing density came to 1.279 lb./ft.^{3}, hardly anything described by Dr. Bailey. The minimum cross section, at 22.8 in.^{2}, was feasible at least, as my enclosure's cross section is 25 in.^{2}. Q_{ts} came to 0.6398 and now the whole project looked like a loser and a waste of my time. I didn't have a 4" speaker with a Q_{ts} that high.

After a lot of stalling, I decided to proceed. It would be an acid test for the equations. I modified a Radio Shack 40-1022[1] which yielded a calculated Q_{ts} of 0.66, using 2Ω series resistance and 10 grams of ⅛" solid lead wire around the dustcap. 1.7Ω would have come to 0.638, but I didn't have the necessary values. Using series resistance is going against my own advice, but I couldn't see wasting a woofer on my hare-brained project.

I estimated the net internal volume at 0.149 ft.^{3} and used 86 grams (2.9 oz.) of polyester fiberfill. In addition, I lined the walls with a layer of surgical cotton, as it comes off the roll, which I spot-glued in place.

I connected 14-gauge wire to the woofer and terminated the ends in banana jacks. The wires merely extended out the bottom of the enclosure. As this was a quick-and-dirty breadboard type project, partly due to lack of faith in it and partly due to my natural laziness, I merely taped the Radio Shack 40-1376 tweeter to the enclosure (*Photo 1*).

I leaned the Unline against a wall, with the bottom rear edge 6 1/2" from the base. (I figured it needed all the rest it could get if it was going to do what I expected of it.) I biamplified the Unline through a Marchand XM-1 fourth-order crossover using a crossover frequency of about 3.5kHz.

CONCLUSIONS. As it turns out, the darned little thing works, and very well indeed. It sounds very much like my other lines, which isn't so surprising, since they use the same components. The sound is clean and open and very natural. On my Michael Murray organ CDs (Telarc), I am sure some fundamentals are missing, but not noticeably, or in any significantly disappointing way. It sounds "right."

Of course, the small driver, dense stuffing and 2Ω series resistor means it isn't as efficient as my other lines. The overall maximum SPL isn't as great either, but in my small apartment room of 1400 ft.^{3} it provides more volume than I want. I measured a single impedance peak of 22.6Ω at 34Hz (free air resonance was about 39Hz). I am quite pleased with the Unline's performance, which vindicates my equations.

As a further check, I have constructed 5, 8, and 10" driver versions of the Unline. All perform well. Should you be tempted to experiment a bit, I would be happy to know your results. For those interested, I have devised *Table 1*, listing various lines as a function of Q_{ts}, ranging from the "standard" to approximately the Unline. To arrive at values between those given, just interpolate, or work out the equations on any calculator with an 1/x and a square root key.

You can use this method with your favorite transmission line enclosure. For instance, if your "standard" model is a 10-foot line with a 0.5 lb./ft.^{3} stuffing density, a minimum cross section of 1.1 times the cone area and a Q_{ts} of 0.35, then a 4-foot line would require: density, 0.79; minimum cross section, 1.739 × cone area; and Q_{ts}, 0.44. I used a 0.5 stuffing density as it seems popular, but it could be 0.4, 0.55 or whatever you prefer. (I doubt if 0.4 would be a viable working density.)

A word about adding mass to loudspeaker cones: If the mass is increased by a factor of 1.5, Q_{ts} would be increased by $1.5^{1/2}$ and the resonant frequency is reduced by $1/1.5^{1/2}$. Of course all of this lowers the efficiency of the speaker; it drops to $1/1.5^2$, or about 6.3dB.

Thus, if you have a speaker with a cone mass of 20g, a Q_{ts} of 0.35, an F_{sa} of 40Hz and an efficiency of 90dB/W/M, you could add 10 grams to the cone to arrive at a speaker with a Q_{ts} of about 0.429, F_{sa} about 32.7Hz and an efficiency of about 83.7dB/W/M. I find the best

Continued on page 36

TABLE I

Transmission lines based upon shorter variations of an arbitrary "standard" transmission line with a length of 72," a stuffing density of .5 lb./ft.^{3} of polyester pillow stuffing, a minimum crossection of 1x the speaker cone area and a speaker Q_{ts} of .4.

Q_{ts}	d_1	LL_1	Cs_1
.40	.500	72.0	1.00
.41	.525	65.3	1.05
.42	.551	59.3	1.10
.43	.578	53.9	1.16
.44	.605	49.2	1.21
.45	.633	44.9	1.27
.46	.661	41.2	1.32
.47	.690	37.8	1.38
.48	.720	34.7	1.44
.49	.750	32.0	1.50
.50	.781	29.5	1.56
.51	.813	27.2	1.63
.52	.845	25.2	1.69
.53	.878	23.3	1.76
.54	.911	21.7	1.82
.55	.945	20.2	1.89
.56	.980	18.7	1.96
.57	1.015	17.5	2.03
.58	1.051	16.3	2.10
.59	1.088	15.2	2.18
.60	1.125	14.2	2.25
.61	1.163	13.3	2.33
.62	1.201	12.5	2.40
.63	1.240	11.7	2.48
.64	1.280	11.0	2.56

d_1 = stuffing density
LL_1 = line length
Cs_1 = minimum crossection factor

1. Radio Shack's current 4-inch woofer version is the 40-1022A, which may not give the same results in this application. See Mr. Cockroft's reply to Mr. Lewellen in this issue's *Mailbox* section, for details.

UNLINE

Continued from page 32

way to add mass is to glue a ring of lead or solid core solder, around the cone's dustcap junction. Make the ring curve equal to the dust cap's circumference and cut into 4 segments; it will lay flatter and fit into the junction better. I usually use white glue, which so far has held well, even on polypropylene. You may prefer RTV silicone rubber adhesive. If the cone has a viscous coating I don't know what works best.

I hope this article brings a glimmer of renewed interest to transmission line theory, and particularly smaller systems. There is no reason why those who lack the space for a classic line should be deprived of naturalness in their sound systems.