Transmission Line Loudspeakers
Part I: Theory

NEARLY ALL LOUDSPEAKER enclosures used for low frequency reproduction attempt to solve three problems: (1) isolating the loudspeaker's front radiation from the rear radiation to prevent the low bass from being wiped out; (2) controlling the woofer's rise in response and impedance at the resonant frequency; and (3) either losing the rear radiation completely, preferably in a way that will not be detrimental to the sound, or somehow using it to reinforce or dampen the woofer's bass response at specific frequencies. The acoustic suspension (or infinite baffle) and bass reflex enclosures are popular examples of solutions to these problems.

My dissatisfaction with these "conventional" enclosures and search for a superior alternative began several years ago. Bass reflex enclosures are, by definition, "resonant" enclosures; even the best designs are incapable of delivering flat, natural bass, free of peaks and other colorations around the region where bass reinforcement from the port takes place. The best acoustic suspension designs do not suffer from the resonant peaks present in bass reflex designs; however, I have yet to hear an acoustic suspension design completely free of "boxy" colorations caused by internal reflections. Large infinite-baffle enclosures provide no means of controlling cone motion at resonance, so one must use woofers with relatively stiff suspensions, and consequently higher than desirable resonant frequencies.

My interest in transmission line loudspeaker design began many years ago when I heard the "tower" version of the E.S.S. AMT-1 loudspeaker. This was E.S.S.'s only transmission line loudspeaker, and was the first loudspeaker I had heard that achieved acceptable low bass performance without boxy coloration or boomy bass. Unfortunately, E.S.S. ceased producting transmission line woofer systems when they discontinued this model shifting their emphasis to acoustic suspension and, more recently, passive radiator designs.

Even today, only a few commercial manufacturers are marketing transmission line loudspeakers, the most notable being Fried Products and I.M.F. (Both were founded by the same Irving M. Fried, although Mr. Fried is no longer connected with the latter company.) The transmission line loudspeaker simply hasn't enjoyed the kind of commercial success it deserves. Among the reasons are: (1) its relatively complex internal construction compared with "box" enclosures, which adds substantially to manufacturing costs; and (2) the relatively large enclosure needed for a given woofer diameter, when compared with "box" speakers using the same similar woofers.

Fortunately, these difficulties matter little to the home constructor who has moderate electronic and woodworking skills. The difficulty has normally been the lack of available sources on theory and practical models to work from. In the course of my research I found that many of the articles previously written on transmission line loudspeaker design were incomplete, inaccurate, or both. Among the more misleading comments in published articles are: "T.L. systems are designed basically by trial and error";[1] and, "If your T.L. design doesn't work, use the enclosure as a dog house and build a box speaker"![2]

Even worse, many of these articles contain no workable construction plans of proven designs. This leaves the constructor with little to work from, especially compared with the vast number of theory articles and construction plans available for box-type loudspeakers.

This paper's purpose is two-fold. In Part 1 I shall outline the theory of transmission line loudspeaker design, providing sufficient data for ambitious constructors to base their own designs on, while in Part 2 I'll provide plans for constructing three full range systems using T.L. woofers. These designs are not theoretical models: they are working models built and improved by me and successfully duplicated by many of my friends and colleagues.

THE THEORY

The transmission line loudspeaker is a refined descendant of the acoustic labyrinth invented in the 1930's by Stromberg-Carlson (see *Fig.1*). The labyrinth consisted of a pipe into which the woofer's rear radiation was loaded, where length was one-quarter wavelength (λ) of the woofer's free-air resonance. If the woofer's free-air resonance was 50Hz, the line would be 5.65 feet long (1130 ÷ 50 = 22.6 ÷ 4 = 5.65). The pipe was normally folded

FIG. 1

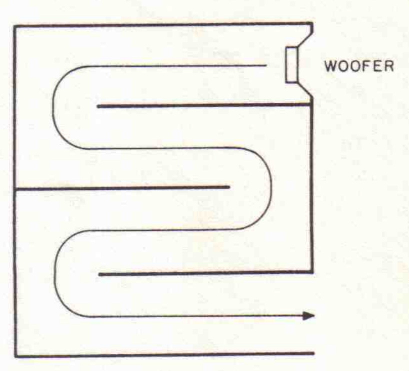
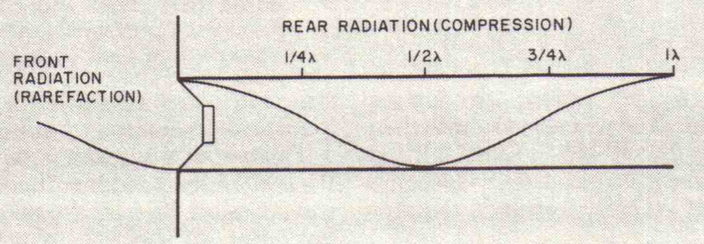


Fig. 1. Typical Acoustic Labyrinth Enclosure.

as in *Fig. 1*, to conserve space, and its maze-like appearance led to the name "labyrinth."

The $\frac{1}{4}\lambda$ size was chosen for two reasons: (1) to dampen excessive woofer output at resonance; and (2) to reinforce the octave above resonance. A look at *Fig. 2* will clarify this. It shows a woofer loaded into a pipe that is a full λ long at its resonant frequency (whatever it happens to be). The woofer is reproducing a sine wave (which I have drawn in) at this frequency. As the illustration shows, the front and rear radiation are 180° out of phase. (In this case, the woofer has moved backward, producing a rarefaction in front and a compression in the rear.)

FIG. 2



Phase Relationship of Rear Radiation to Front Radiation at Resonance:

At 1λ—180°out—No Good
At ¾λ—90° out—O.K. but the line is too long to be practical
At ½λ—in phase—No Good
*At ¼λ—90° out—***Correct Length**

Fig. 2. Phase relationship of front radiation to rear radiation for labyrinths of various lengths.

The phase relationship between the front radiation and the output of the pipe will determine whether cancellation or reinforcement takes place. Considering the first requirement, damping of the excessive output at resonance, turn again to *Fig. 2*. If the pipe is one λ of the resonant frequency, the pipe's output is 180° out of phase with the woofer's front radiation, causing total cancellation at this frequency. Obviously this is undesirable. At $\frac{3}{4}\lambda$, the output is 90° out of phase with front radiation. This is what we are looking for since the pipe's output will cause partial (not complete) cancellation of the output at resonance. Unfortunately, a pipe $\frac{3}{4}\lambda$ long would be unmanageably large; so we must find another length.

At $\frac{1}{2}\lambda$, the pipe's output is in phase; again, not good. At $\frac{1}{4}\lambda$, the pipe's output is again 90° out of phase (270° actually, but the effect is the same), and again we have partial cancellation of the output from the front of the woofer. This, therefore, is the length the labyrinth should be. At one octave above resonance, our labyrinth is now $\frac{1}{2}\lambda$ long. The pipe's output is in phase with the front radiation at this frequency, causing a reinforcement in this region. The pipe is usually lined with fiberglass to dampen internal reflections.

Although a step in the right direction, the acoustic labyrinth has several inherent weaknesses. First, it provides no adequate means of controlling the woofer's excessive cone motion at resonance. The pipe's output does cause partial acoustic cancellation in the listening area, but the woofer excursions can still be excessive, causing the driver to operate in its non-linear region at higher playback levels. The result of this non-linear operation is, of course, excessive distortion at all frequencies in the woofer's operating range. We can control this by using woofers with relatively stiff suspensions, but the result is poor deep-bass response due to high resonant frequencies for these types of woofer.

Secondly, the reinforcement at the octave above resonance is usually excessive, resulting in boom-box characteristics at this frequency. (This is similar to bass reflex action.) The result of all this is that a labyrinth will have either excessively high distortion at high levels due to poor woofer control, or poor deep-bass response. The excessive output at the octave above resonance may please some "West Coast" speaker fans, but it is not accurate. Old-fashioned labyrinths are *not* non-resonant designs.

The modern transmission line loudspeaker is theoretically non-resonant, and in the real world we can for all practical purposes achieve this theoretical ideal. The transmission line bears a superficial resemblance to the acoustic labyrinth, but they are quite different in operation. The purpose of a transmission line design is to completely lose the woofer's rear radiation in the pipe (henceforth referred to as the "line"). An ideal transmission line has no acoustic output from the end of the line ("line exit"). Such a line would be infinite length; since this is an obvious impossibility, the designer must select an appropriate finite length, which will normally be $\frac{1}{4}\lambda$ on the driver's resonance.

Since total absorption of the rear wave is the design goal, the line must be filled, not lined, with a suitable damping material. Long-fiber wool has proven to be best for this purpose.[3,4]

The line is loosely filled with the wool, at the rate of half a pound per cubic foot of line volume. The wool's purpose is two-fold. Of course it must absorb the rear radiation of the loudspeaker so no sound will emerge from the line exit, but it also has another interesting characteristic: it acts as an acoustic low-pass filter. This is extremely important, for controlling woofer cone motion (and impedance) at resonance. At higher frequencies, above two or three times resonance, the wool absorbs all rear radiation. At these frequencies, the movement of air inside the line is confined to a small area behind the woofer, i.e., the woofer "sees" a very short line. As the woofer operates at lower frequencies, movement of air in the line occupies a much larger portion of the line length. At the woofer's resonant frequency, the woofer "sees" the entire length of the line. This increased amount of air adds mass to the woofer cone, restricting excessive motion at resonance.

Note that at very low frequencies there will be a small amount of output from the line exit; but its amplitude at this point is so low that, unlike reflex action, it has virtually no effect on the woofer's front radiation. For all practical purposes, the rear radiation has been lost in the wool-filled line. Several builders have asked me what would result if the line exit were closed off. If one did this, the line would act more like an acoustic suspension system at very low frequencies. One of the reasons for a T.L. system's non-resonant characteristics is the complete freedom from internal pressure at low frequencies, eliminating the "bass in a box" character found in acoustic suspension systems.

As a serious audio constructor, you may wish to design your own T.L. system to suit your particular needs. Observe the following guidelines:

1. The line length should be $\frac{1}{4}\lambda$ (wavelength) of the woofer's free-air resonance. If this frequency makes the line impractically long, you can use $\frac{1}{4}\lambda$ of a pre-determined (higher) cut-off frequency. If the line is a full $\frac{1}{4}\lambda$ of the woofer's resonance, you may expect flat bass down to the woofer's free-air resonant frequency; it will usually be around 3dB down at this point. Since woofer resonance is not raised in a full $\frac{1}{4}\lambda$ line, a good 10″ woofer will provide flat low bass which acoustic suspension systems normally can't equal with 12″ or 15″ drivers.

2. The line's cross-sectional area

should be greater than the woofer cone's rear area. You may taper the line to conserve space, but I recommend that the line's cross-sectional area remain at least equal to the woofer cone area at all points.

3. Line the parallel surfaces immediately behind the woofer with carpet felt or fiberglass (1" thick or so) to prevent reflections back to the woofer cone.

4. Woofers should have butyl rubber or P.V.C. surrounds. Give preference to Bextrene or other non-paper cone materials. Drivers by Audax, KEF, and Dalesford are excellent. Philips paper cone woofers are very good, but their performance does not equal that of the Audax Bextrenes. Foam surrounds are not as good.

5. Make the enclosure of ¾" particle board, Titebond glue, and screws. Extensive internal bracing is unnecessary, due to the absence of internal pressure.

6. Install 45° angle pieces at corners near the woofer; they are unnecessary in the last half of the line.

7. Long-fiber wool is the preferred damping material (one half pound per cubic foot). Dacron-polyester is cheaper, but its performance unfortunately matches its cost. Fiberglass is out of the question, since it is highly reactive, rather than moderately resistive, at low frequencies: it acts more like a "no-pass filter" than a low-

Following these guidelines will produce a woofer system free of resonant or boxy characteristics, with true low bass fundamentals unmasked by upper bass boom. If upon first hearing you find that a well-designed T.L. system is bass deficient, maybe you need a trip back to the concert hall. Many listeners are used to overly fat upper bass in reproduced sound; some even prefer it. Live music doesn't sound like this, however. A transmission line system will reproduce what has been recorded on the disc or tape, no more and no less.

REFERENCES

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