This distinguished author's research on pipe configuration and stuffing material in transmission lines was the topic of a recent paper at AES.

Part 1

Transmission Lines Updated

By G. L. Augspurger

Every now and then I receive inquiries from amateur loudspeaker builders who seek reliable guidelines for transmission-line design. Although any kind of waveguide can legitimately be called a transmission line, most experimenters are interested in loudspeakers coupled to damped, nonresonant pipes. If everything works out just right, such a system can be dramatically neutral in quality in contrast to a comparable vented box or even a stuffed closed box.

About a year ago I began to compile a brief transmission-line bibliography. But after going through my own library and checking various technical journals, it became apparent that most existing literature consists of strongly voiced opinions. Actual test results are rare and often contradictory.

TESTING PIPES

So I decided to build and test a few damped pipes with different loudspeakers and stuffing materials. This seemingly simple exercise gradually grew into a full-blown research project, the goals of which were to develop a computer analog capable of modeling transmission-line systems, to validate the model by testing a variety of designs, and to develop basic performance relationships similar to the Thiele/Small analysis of vented boxes. I presented my findings at the 107th convention of the Audio Engineering Society in September 1999.

For the readers of *Speaker Builder*, however, I wish to go more deeply into the practical aspects of the study and to elaborate upon two areas I only touched on in the AES paper. First, that the behavior of stuffing materials is not what we have been led to believe, and second, that the effects of pipe geometry (not just length) are both unexpected and important.

The familiar symbols I use (*Table 1*) are mostly the same as those used for vented-box analysis. I have added f_P as a shortcut label based on the physical length of the air path, such as "a 100Hz pipe." The pipe's actual fundamental resonance f_0 is affected by a number of additional factors, including end correction, pipe geometry, and stuffing material.

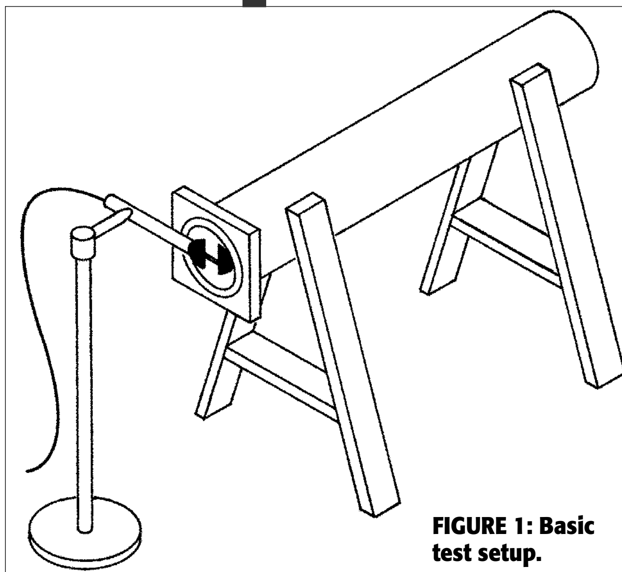

FIGURE 1: Basic test setup.

TEST METHODS

The simplest transmission line is a straight pipe with a loudspeaker on one end. I used 3″-diameter fiber tubes to make pipes 2′, 3′, and 5′ long. I also made a 6′ pipe from 4″-diameter PVC tubing and built several pipes with rectangular cross sections.

Figure 1 shows my basic test setup. I set the test pipe horizontally on a trestle, about 40″ above the floor, and connected a calibrated Bruel & Kjaer 4134 microphone to my TEF20 analyzer. I ran sweeps from 20Hz–1kHz with a frequency resolution of 10Hz, giving accurate readings down to about 25Hz, and also ran impedance curves using the voltage-divider method. The TEF system stores all measurements as sets of complex data points, preserving both amplitude and phase.

I made frequency-response tests using nearfield microphone placement. This technique[1] allows you to measure loudspeaker and pipe outputs separately, but there is a certain amount of crosstalk. Most of the unwanted sound travels directly through air, some comes from scattered room reflections, and some is transmitted as vibrations in the pipe walls.

By blocking the end of the pipe, I was able to measure leakage from the loudspeaker at the other end. Crosstalk in the 2′ pipe was about –25dB. It was down more than 30dB in the 5′ and 6′ pipes. If

TABLE 1
SYMBOLS USED

f_3	–3dB corner frequency of low-frequency rolloff
f_P	nominal quarter-wave pipe resonance frequency
f_0	actual pipe fundamental-resonance frequency
f_S	speaker resonance frequency
f_L	frequency of lower impedance peak
f_H	frequency of first upper impedance peak
Q_{TS}	total Q of speaker
V_{AS}	volume of air having compliance equivalent to speaker cone suspension
V_P	internal volume of pipe, including coupling chamber
V_C	internal volume of coupling chamber

pipe output is 20dB below cone output, then its contribution to combined system output is less than 1dB, so even in short pipes you can disregard the effects of crosstalk.

Although I was not aware of it at the time, my test procedures were almost the same as those used by Letts in 1975.[2] To the extent that measurements overlap, our results agree closely.

With accurate measurements of speaker output and pipe output, total system response is then equivalent to the complex sum of the two, and does not need to be measured separately. However, when a microphone is located very close to a small sound source, a movement of only 1 or 2mm can shift the level of measured response by more than 1dB. Such an error in relative level has little effect on combined response, but it corrupts damping calculations and subsequent computer modeling.

MINIMIZING ERRORS

To minimize such errors, I first made sure that cone areas closely matched pipe areas so that no scaling was needed. Then, for each measurement I carefully aligned the microphone with the edge of the pipe or the edge of the loudspeaker frame. Finally, I verified that cone and pipe data could indeed be summed by also making several system-response measurements with the microphone equidistant from speaker and pipe, at one apex of an equilateral triangle.

So far, so good, but nothing ever goes exactly according to plan. Since damped transmission lines are lossy systems, I naively assumed that small air leaks would not be a problem. Well, a tiny hole to bring the wire out isn't a problem, but a speaker-mounting panel that doesn't seat properly or a joint in the pipe that isn't caulked can dramatically alter system response. Curiously, leaks seem to affect stuffed pipes more than empty ones.

Then I ran into a really sneaky effect. Small speakers typically have relatively large magnets. If such a speaker is mounted on a pipe or a thick baffle board, its backwave must travel through a short, constricted passage between the cutout and the magnet. At low frequencies, the air in the passage effectively adds mass to the cone. With my little test speaker mounted on a 3″-diameter pipe, f_S dropped from 175Hz to 135Hz, and Q_{TS} increased from 0.54 to 0.65.

Another gremlin involved defective test leads. Commercial molded test leads often have crimped connections

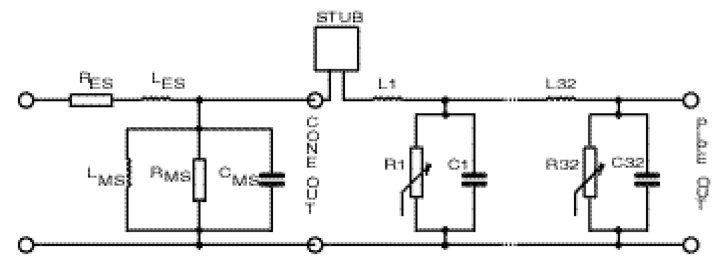

FIGURE 2: Transmission-line analog circuit.

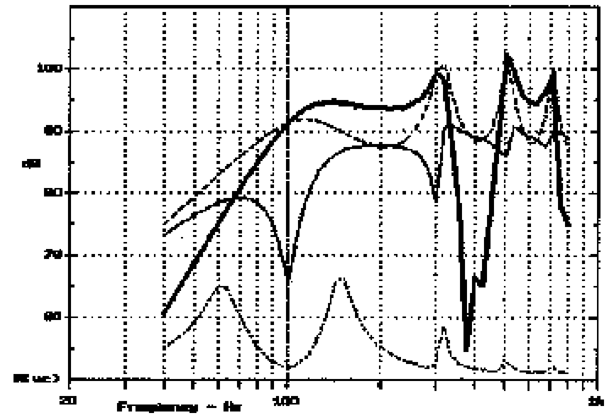

FIGURE 3: Response of loudspeaker on undamped straight pipe. Impedance (bottom), cone output, pipe output, and system response (bold).

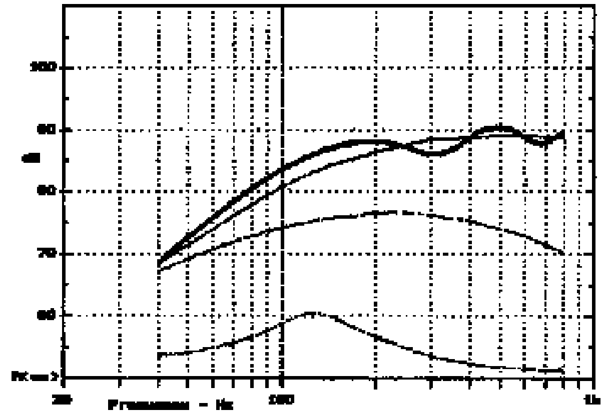

FIGURE 4B: Response of loudspeaker on straight pipe with moderate damping. Impedance, cone output, pipe output, and system response (bold).

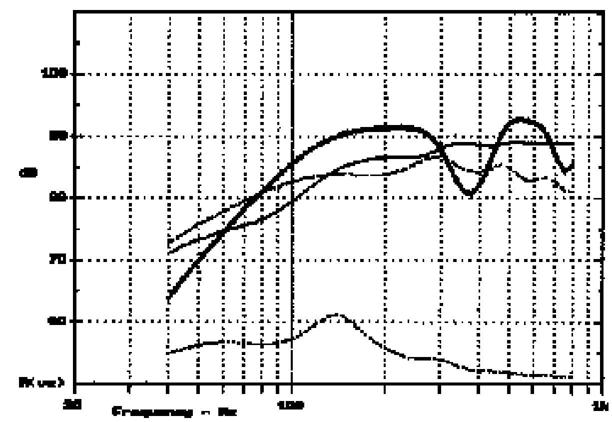

FIGURE 4A: Response of loudspeaker on straight pipe with light damping. Impedance, cone output, pipe output, and system response (bold).

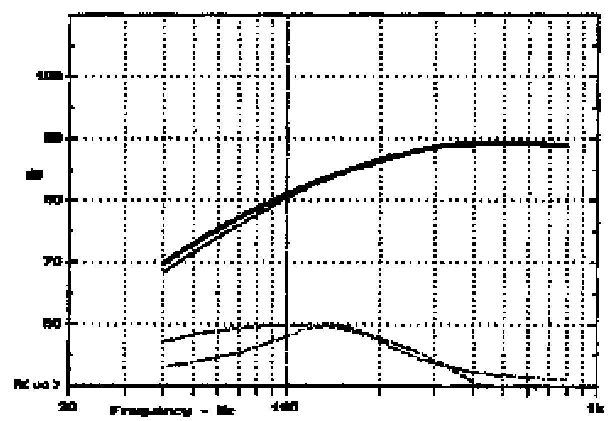

FIGURE 4C: Response of loudspeaker on straight pipe with heavy damping. Impedance, cone output, pipe output, and system response (bold).

under that nice vinyl jacket. Eventually corrosion sets in, and you now have a few diodes and a few ohms of series resistance as part of your test hookup. If the patch cord connects a 50Ω generator to a 5kΩ input, it works just fine, but if it connects a power amplifier to a 4Ω loudspeaker, the measurements are worthless.

COMPUTER SIMULATIONS

One goal of this project was to develop a computer analog to predict the behavior of various kinds of damped pipes driven by various speakers. Undamped pipes and horns are well understood. Relatively simple methods for modeling arbitrary horn shapes have also been described.[3,4]

I elected to work up a computer version of Locanthi's horn analog[5] and modify it for transmission-line modeling (*Fig. 2*). This circuit makes it easy to investigate arbitrary pipe shapes, and you can include damping as any combination of parallel and series resistance. Moreover, there is a certain elegance in using an electrical transmission line to model an acoustical transmission line. Those interested in a more detailed explanation of the computer model can obtain a preprint of my AES paper.[6]

As with other transmission-line models, the hangup is the stuffing. But at the start of this study, the computer program was required only to mimic known performance with one loudspeaker and then to calculate what would happen when using a different loudspeaker. In this regard, its predictions have proven to be remarkably accurate. Most of the gremlins described in the previous section were discovered because test results did not match computer curves.

After I had accumulated several dozen sets of test results, I was able to derive empirical models for different kinds and densities of damping materials and include them in the computer analog. I am still tinkering with these, but results agree closely with measured performance for a variety of pipe sizes and shapes.

LOUDSPEAKER AND PIPE BEHAVIOR

What happens when you put a loudspeaker on one end of a pipe and then gradually add stuffing? *Figures 3* and *4* show a typical example of what I actually measured. These are computer plots, but they are derived from measurements on a 3′ pipe. To make the curves easier to read, the physical length of the pipe is scaled down so that its quarter-wave resonance is exactly 100Hz.

According to some transmission-line theorists, the loudspeaker's cone resonance should match pipe resonance. The speaker I used for this example has a cone resonance of 100Hz. Q_{TS} is 0.46 and V_{AS} is 0.11ft^3.

What about speaker diameter and pipe diameter? Thiele/Small analysis should have taught us that cone diameter is not directly related to anything.

The precept is just as true for pipes as it is for boxes. Instead of the familiar V_{AS}/V_B, I will use the ratio of pipe volume V_P to V_{AS}. In this example, pipe volume is about $0.22ft^3$, so V_P/V_{AS} equals 2.

An undamped cylinder closed at one end resonates at odd multiples of its fundamental frequency. That the speaker cone is heavily loaded at these frequencies, just as in a vented box, is clearly shown in *Fig. 3*. The light solid line represents cone output, the dashed line is pipe output, and the heavy solid line is combined system response.

The cone is acoustically clamped at 100, 300, and 500Hz. Pipe output peaks slightly above these frequencies. The two are alternately in and out of phase at 200, 400, and 600Hz. Below 100Hz, pipe output is effectively out of phase with cone output, and combined response rolls off at 24dB per octave.

VOICE-COIL IMPEDANCE

The dotted line at the bottom of *Fig. 3* shows voice-coil impedance relative to DC resistance. 20dB indicates a 10:1 change, 6dB indicates a 2:1 change and so on. Why is impedance plotted logarithmically? Because that's the way it is supposed to be plotted. This way, impedance curves of different speakers can be compared directly, no matter what their individual voice-coil resistances. If you plot "real" numbers on a linear scale, you can only compare tests run with that particular speaker.

The impedance curve of this undamped pipe is obviously similar to that of a matched, vented box. A minimum at 100Hz is flanked by two peaks: f_L at about 64Hz, and f_H at 150Hz. Additional peaks at higher frequencies will disappear as you add damping.

Before looking at what stuffing actually does, consider what it is supposed to do. Benjamin Olney, the inventor of what we have come to call the transmission line, definitely expected pipe output to reinforce cone output at low frequencies.[7] He was intrigued by the fact that an undamped pipe acts as a pure delay line at its halfwave frequency. (Note that cone and pipe outputs are equal at 200Hz, and their combined output is 6dB greater.) Therefore, Olney argued that damping should be minimal in the halfwave region, but soak up unwanted upper resonances.

For this to happen, you need some kind of magic lowpass stuffing that goes from negligible damping to more than 18dB of attenuation in less than an octave. Unfortunately, real-world materials require several octaves to make the transition. Even a wisp of damping material largely squashes the pipe's fundamental resonance. It is true that bends or folds will supply additional attenuation, but only at relatively high frequencies.

BLANKET EFFECT

Figure 4a shows what happens when the test pipe is loosely filled with polyester blanket at a density of 0.5 lb/ft^3. This is a typical packing density for transmission lines, but in a short pipe it is less than optimal. Cone and pipe outputs still show the effects of resonances, and pipe attenuation above 200Hz is minimal. However, the 100Hz fundamental resonance has all but disappeared. The lower impedance peak no longer exists, and f_H has become a gentle bump. Note that cone and pipe outputs are additive down to about 85Hz, and that the low-frequency slope is now 18dB per octave.

When you increase stuffing density to 1.5 lb/ft^3, the result is a well-behaved transmission line. *Figure 4b* indicates nonresonant response with a 2dB sag at 300Hz and gentle rolloff below 200Hz.

Below 100Hz the slope is about 12dB per octave. Although pipe output is well below cone output, the two are additive over a range of more than two octaves. The only identifiable "resonance" in the impedance curve is f_H.

Additional stuffing (more than 2 lb/ft^3) gives the performance of *Fig. 4c*. This is a purist's transmission line, in which pipe radiation is negligible. Going beyond this point is self-defeating, since additional damping simply reduces cone movement at low frequencies.

These three figures are the foundation for understanding transmission-line performance. They are typical of long pipes and short pipes, big speakers and little speakers. Although appropriate stuffing densities vary, almost any fibrous material will exhibit the behavior shown. You can use these curves to develop some initial observations about transmission-line performance:

1. The system response of 4b would be flatter if the speaker's sensitivity above 300Hz were decreased by 2dB. Also, since the system behaves somewhat like a closed box, it seems reasonable that f_S should be lower than f_P. Finally, to reduce passband ripple, you might increase damping just a bit. After experimenting with adjustments of individual parameters, I came up with the response of *Fig. 5*. Now, f_3 matches f_P, and f_S is an octave lower.
2. In *Fig. 5*, pipe output and cone output add constructively down to 40Hz or so. It follows that it should be possible to set f_3 as much as an octave below f_P by adjusting loudspeaker parameters with no change in stuffing density. *Figure 6* shows how a nominal 109Hz pipe can be "tuned" to 65Hz. Efficiency goes down as well, just as you would expect from analogous closed box alignments. For a given f_3, there is some advantage in choosing a shorter, fatter pipe, because passband ripple shows up at higher frequencies where it is easier to control.
3. For a different cutoff frequency derived from either of these curves, you must scale pipe length and f_S accordingly. The relationships described previously still stand. In this case, what does not scale is stuffing density. Since the air path of a 50Hz pipe is twice as long as that of a 100Hz pipe, I expected a given density to yield equivalent results. Not so. The longer pipe requires lighter stuffing, and the relationship is not a simple one.

SIMPLE TRANSMISSION-LINE ALIGNMENTS

Table 2 summarizes the loudspeaker/pipe relationships of *Figs. 5* and *6*, which you can use as multipurpose alignments. To achieve the classic, slightly bass-shy alignment of *Fig. 4b*, simply reduce Q_{TS} by half, thus raising midrange sensitivity by 3dB. To simulate an infinite pipe, increase stuffing density by about 50% and assume that f_3 will go up about 25%.

Well and good, but what is the stuffing density for these alignments? For a 100Hz pipe, you can realize the performance shown with 1.75 lb polyester blanket or Acousta-Stuf. For a 50Hz pipe, the corresponding density is 1.0 lb/ft^3. Other materials require different densities. There is no direct correlation between pipe length and stuffing density.

These examples are only two of hundreds of possible alignments, but they

TABLE 2
LOUDSPEAKER/PIPE RELATIONSHIPS

FIGURE	F_3/F_P	F_S/F_P	V_{AS}/V_P	Q_{TS}
5	1.0	0.50	2.0	0.46
6	0.6	0.33	1.0	0.36

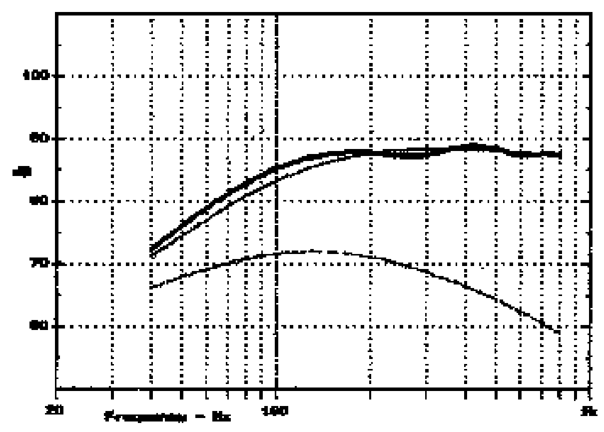

FIGURE 5: Response of straight pipe with improved alignment. Cone output, pipe output, and system response (bold).

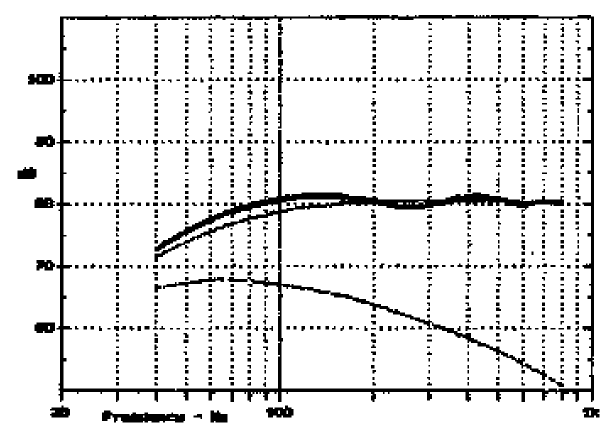

FIGURE 6: Response of straight pipe with alternate alignment. Cone output, pipe output, and system response (bold).

are typical of what you can do with a basic transmission line. Efficiency is 2–5dB less than a comparable closed box, no matter which low-frequency rolloff you prefer. Fortunately, as I will show in Part 3, it is possible to improve the situation by building something other than a simple straight pipe.

DIRECTIONAL EFFECTS

To conclude Part 1, I wish to point out a peculiarity of transmission-line response measurements. I stated that the complex sum of cone output and pipe output yields system response. This is understood to be on-axis system response. That is, the microphone is equidistant from the loudspeaker and the mouth of the pipe. If the pipe is folded so the two sound sources are close together, then it is also equivalent to acoustic power response.

But if pipe output is appreciable and the two sources are even a fraction of a wavelength apart (an inevitable by-product of a straight pipe), then some interesting directional effects are generated, and power response no longer tracks on-axis response. In a typical listening room, the perceived low-frequency response is dominated by reflected sound energy. Therefore, a folded transmission line may indeed sound different than an otherwise identical straight pipe, because its power response and directivity are different. To the best of my knowledge, Geoffrey Letts is the only researcher who has commented on this.[2]

REFERENCES

1. D. B. Keele, Jr., "Low Frequency Loudspeaker Assessment by Nearfield Sound-Pressure Measurement," JAES, Vol. 22, April 1974.

2. Geoffrey Letts, "A Study of Transmission Line Loudspeaker Systems," Honors Thesis, The University of Sydney, School of Electrical Engineering, 1975.

3. K. R. Holland, F. J. Fahy, and C. L. Morfey, "Prediction and Measurement of the One-Parameter Behavior of Horns," JAES., Vol. 39, May, 1991.

4. Dan Mapes-Riordan, "Horn Modeling with Conical and Cylindrical Transmission-Line Elements," JAES, Vol. 41, June, 1993.

5. Bart N. Locanthi, "Application of Electric Circuit Analogies to Loudspeaker Design Problems," JAES, Vol. 19, October, 1971.

6. G. L. Augspurger, "Loudspeakers on Damped Pipes—Part One: Modeling and Testing; and Part Two: Behavior," Preprint 5011 (F-1), Audio Engineering Society, 60 East 42 Street, New York, NY 10165-2250.

7. Benjamin Olney, "A Method of Eliminating Cavity Resonance, Extending Low Frequency Response and Increasing Acoustic Damping in Cabinet Type Loudspeakers," *Journal of the Acoustical Society of America*, Vol. 8, October, 1936.