Loudspeakers on Damped Pipes*

G. L. AUGSPURGER, *AES Fellow*

Perception Inc., Los Angeles, CA 90039, USA

First Locanthi's horn analog is shown to be well suited for modeling transmission-line loudspeaker systems. The circuit can accommodate arbitrary flare shapes and allows damping to be included as any combination of series and parallel losses. Four empirical parameters are then developed to simulate the effects of lining or stuffing. Finally three optimized transmission-line geometries are presented, which can be described in terms of generalized alignments using familiar Thiele–Small parameters. Using one of these new alignments, a transmission line can match the frequency response and efficiency of a comparable closed box, but with reduced cone excursion.

0 INTRODUCTION

The Acoustic Labyrinth loudspeaker enclosure was patented by Olney in 1936 and analyzed in a paper published the same year [1]. Olney proposed to correct the defects of simple open-back loudspeaker cabinets by taking a different approach altogether: ". . . the major problem was taken to be the elimination of cavity resonance, and the course pursued was the direct but drastic one of abolishing the troublesome cavity." The loudspeaker was to be mounted at one end of a folded tube lined with a material whose absorption coefficient increased with frequency. In theory this would provide useful summation of front and rear radiation at low frequencies while attenuating higher order resonances.

Versions of the labyrinth were produced by Stromberg-Carlson and others as late as 1950. Interest in the design as a high-quality loudspeaker enclosure was revived by Bailey in 1965, who used fibrous stuffing instead of absorptive lining [2]. It remains a favorite of loudspeaker experimenters and audio enthusiasts. To its devotees, the damped transmission line delivers a neutral, uncolored performance that cannot be matched by vented or closed boxes.

The length and shape of the pipe, the density and kind of material used for damping, and the optimum loudspeaker characteristics have been debated for more than 30 years. However, objective information is rare and is confined mostly to the frequency response measurements of a few successful designs. The goals of this project 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.

1 SYMBOLS USED

- f_3 = −3-dB corner frequency of low-frequency rolloff
- f_P = nominal quarter-wave pipe resonance frequency
- f_0 = actual pipe fundamental resonance frequency
- f_S = loudspeaker resonance frequency
- f_L = frequency of lower impedance peak
- f_H = frequency of first upper impedance peak
- Bl = loudspeaker force factor, N/A
- Q_{MS} = Q of loudspeaker mechanical system
- Q_{TS} = total Q of loudspeaker
- R_{ES} = dc resistance of voice coil
- R_{MS} = resistive component of loudspeaker mechanical system
- L_{ES} = inductance of voice coil
- L_{MS} = inductive component of loudspeaker mechanical system
- C_{MS} = capacitive component of loudspeaker mechanical system
- V_{AS} = volume of air having compliance equivalent to loudspeaker cone suspension
- V_P = internal volume of pipe (including coupling chamber)
- ρ = density of air, = 1.2 kg/m^3
- c = velocity of sound, = 344 m/s.

These are familiar symbols, in most cases identical to those used for vented-box analysis. The symbol f_P is

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a reference frequency based on the physical length of the air path, such as "a nominal 100-Hz 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.

2 BASIC ANALOG CIRCUIT MODEL

A damped pipe can be analyzed as a horn with losses. At least three earlier papers describe one-dimensional horn analogs capable of modeling arbitrary flare shapes. In one study [3] the flare is approximated as a series of exponential sections. In another, conical sections are used [4]. A third approach, originated by Locanthi, predates the others and was originally built as an analog transmission-line model using real inductors and capacitors [5].

Locanthi's analog includes the familiar mobility model of the loudspeaker itself, followed by an LC ladder in which series inductors represent air compliance and shunt capacitors represent mass. Each LC section is equivalent to a cylindrical element of specified diameter and length. If the lengths of individual elements are very small in relation to wavelength, then the analog is surprisingly accurate.

Fig. 1 shows the circuit as modified to model transmission-line loudspeaker systems. The model uses 32 sections so that arbitrary flares can be entered element by element in a fairly short time, yet there are enough sections to handle a reasonable bandwidth. The usable upper frequency limit for a 32-element transmission line is roughly 800 divided by its length in meters.

Three modifications were made to Locanthi's circuit. First, shunt resistances were added to model damping losses. These are shown as variable resistors because damping may be frequency dependent. Series resistances could be included to represent leakage losses, but their effect is negligible.

Second, since the loudspeaker may not be mounted at the end of the pipe but at some intermediate location, an optional 16-element closed stub was inserted at the pipe throat.

Third, a transformer between the loudspeaker and the horn throat has been omitted. The transformer was there to explicitly match the throat area to a larger or smaller driver cone area. Its effect can be duplicated by scaling the circuit values for either the horn or the loudspeaker. If there is a coupling chamber between the cone and the pipe throat, it can be represented by an additional series inductor. In practice, the coupling chamber compliance is simply included in the value of L_1.

The easiest way to calculate loudspeaker circuit values is first to divide R_{ES} and L_{ES} by $(Bl)^2$. Then C_{MS} in farads is numerically equal to the moving mass in kilograms, and L_{MS} can be derived from f_S. With this information plus Q_{MS}, the value of R_{MS} can be found.

Calculating transmission-line values is not much more complicated. Let

s_d = driver cone area, m^2
S_0 = throat area, m^2
S_n = section area, m^2
K_s = S_n/S_0
x = section length, m.

Then,

$$L_n = \frac{K_s x}{\rho c^2 S_0}$$

$$C_n = \frac{\rho S_0 x}{K_s}.$$

If necessary, these values can then be impedance scaled to the ratio $(S_0/S_d)^2$. Detailed information about the derivation of the analog and the calculation of acoustic loads can be found in Locanthi [5].

Following Thiele–Small loudspeaker system analysis we assume that radiation loading is negligible in the (bass) frequency range of interest. In this range, however, acoustic loads for cone and pipe radiation can be accurately included as simple RC shunts if desired [6].

As with a vented-box analog, the net system output is equivalent to the complex sum (including phase reversal) of cone output and pipe output. In most practical transmission-line systems any effects of mutual coupling between the two are small enough to be ignored. The effects of pipe bends and folds are also ignored. In a typical transmission line, they can be expected to occur above the frequency range of useful pipe output.

The ability of this circuit to model a fairly compli-

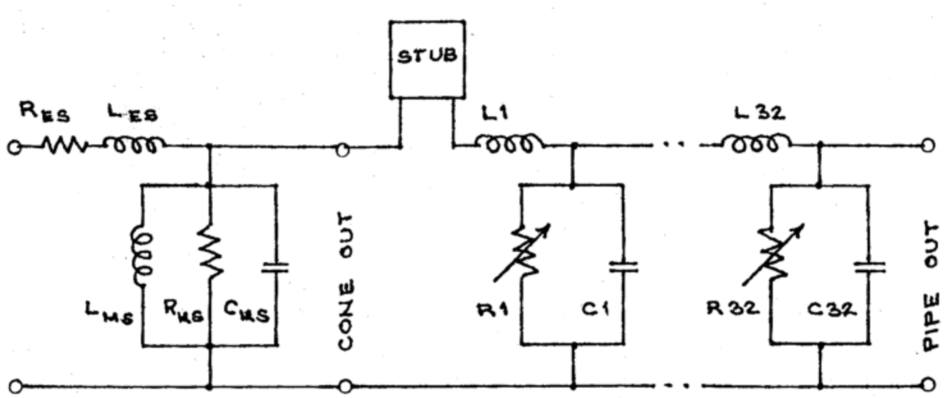


Fig. 1. Tranmission-line analog circuit.

cated, undamped transmission line is impressive. One of the test systems consists of a small loudspeaker mounted 0.14 m from the end of a 0.71-m tapered pipe. The measured cone output and pipe output are graphed in Fig. 2(a), and the corresponding analog circuit curves in Fig. 2(b).

Locanthi's horn analog has not received much attention, presumably because it is more complicated and less accurate than alternative computer models. However, a simple *RLC* ladder is easy to set up with any circuit modeling program and calculations are very fast. Moreover, using an electrical transmission line to model an acoustical transmission line seems particularly appropriate.

3 TEST PROCEDURE

The simplest transmission line is a straight pipe with a loudspeaker on one end. To check the accuracy of the analog and to study the behavior of damping materials, a number of these were built and tested. Four were cylindrical pipes varying in length from 0.6 to 1.8 m. The fifth was a reversible rectangular pipe with two slanted sides: a parabolic horn. Additional variants were built as the project went along.

To make response measurements, a given pipe was set horizontally on a trestle about 1 m above the floor. A calibrated Bruel & Kjaer 4134 microphone was connected to a TEF20 analyzer. Sweeps were run from 20 Hz to 1 kHz with a frequency resolution of 10 Hz, giving accurate readings down to about 25 Hz. Impedance curves were also run. Each test was saved to disk. The TEF system stores all measurements as sets of complex data points, preserving both magnitude and phase.

Frequency response measurements were made using near-field microphone placement [7] so that loudspeaker and pipe outputs could be measured separately with negligible flanking effects. By blocking the end of the pipe it was possible to measure leakage from the loudspeaker at the other end. Crosstalk in the 0.6-m pipe was about −25 dB. It was down more than 30 dB in the longer pipes.

Postprocessing allows the system response to be calculated as the complex sum of loudspeaker and pipe outputs. However, when a microphone is located very

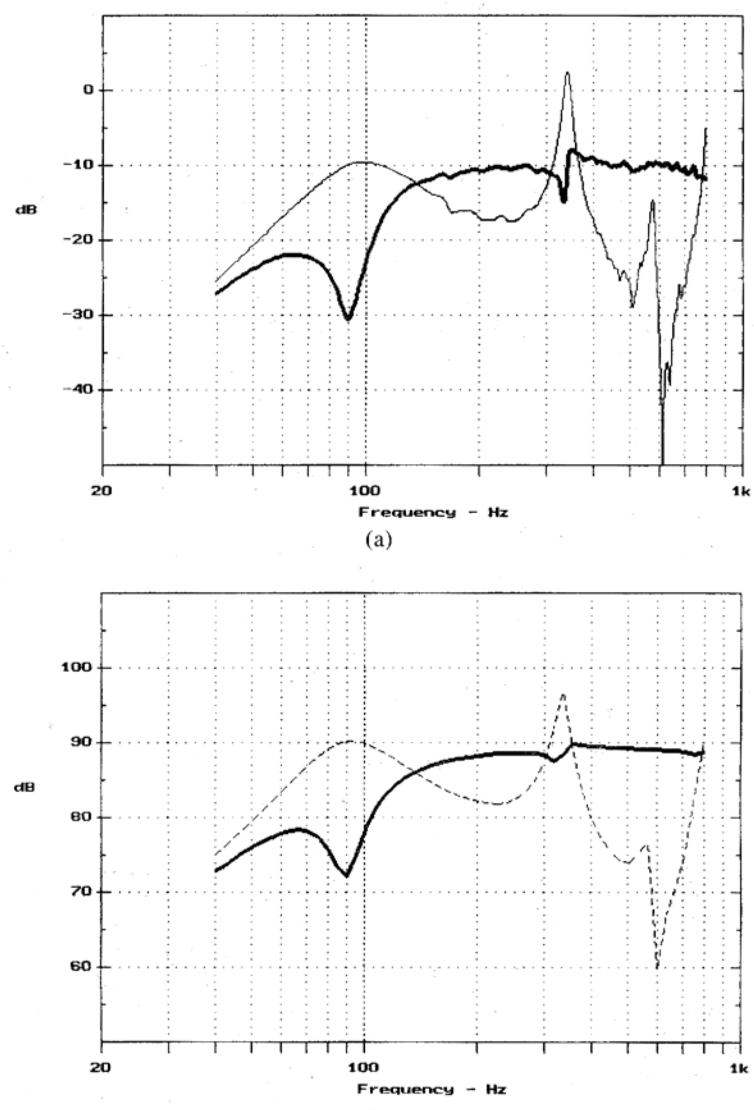


Fig. 2. (a) Measured response of undamped test system. (b) Response of analog circuit model. Cone output (bold) and pipe output.

near a small sound source, a movement of only 1 or 2 mm can shift the measured sound level by more than 1 dB. A number of preliminary runs were made to be sure that the test setup delivered repeatable results. To verify that the cone and pipe data could indeed be summed, several response measurements were made with the microphone equidistant from both loudspeaker and pipe, at one apex of an equilateral triangle.

It was later learned that this test setup closely parallels that of Letts' 1975 study [8]. To the extent that the tests overlap, results are in close agreement.

4 BEHAVIOR OF DAMPING MATERIALS

The available technical literature includes a great deal of information about the acoustical performance of absorptive materials. However, Bradbury's 1976 paper [9] is one of the few relating directly to transmission-line design. His study postulates that fibers are set in motion as sound waves pass through the line. Aerodynamic drag analysis is then used to predict resistive and reactive effects from fiber size, mass, and packing density. The concept was later expanded by Leach and applied to closed-box loudspeaker systems [10].

In the 1980s Bullock developed a transmission-line computer simulation based on Bradbury's model, but comparisons with measured performance proved to be ". . . not satisfactory" [11]. The conclusions put forth in Bradbury's paper are also at odds with some of the test results to be described here. One reason may be that his formula for computing the drag coefficient was admittedly tentative. Also, it is not certain that fiber motion is really that important. For example, Hersh and Walker [12] reported excellent predictions of measured behavior, yet their analysis makes the simplifying assumption that fibers are stationary.

For practical loudspeaker system design, our concern is not with the composition of the damping material but rather its actual performance. Moreover, we are only interested in the low-frequency response of a limited range of pipe lengths. On that basis, tests were made with various kinds of lining and stuffing.

Most of the tests used varying densities of four stuffing materials:

1) Ordinary fiberglass thermal blanket. This is readily available with paper backing, which can be removed.

2) Polyester fiber stuffing, "Poly Fluff," a product of Western Synthetic Fiber Inc., Carson, CA.

3) Microfiber stuffing, Celanese "Microfill."

4) "Acousta-Stuf." This is a Nylon polyamide fiber sold for use in loudspeaker enclosures. It is available from Mahogany Sound, Box 9044, Mobile, AL 36691-0044.

These materials are easy to buy, easy to use, and perform well for this application. Numerous other substances were tested, including cotton puffs, steel wool, packing pellets, and plastic foam.

It seems prudent to focus on inert, nonorganic materials. However, long-fiber wool was chosen by Bailey as the ideal stuffing for transmission lines, and his preference was supported by Bradbury. Unfortunately bulk wool is not easy to find in the United States, so fluffy wool yarn was tested instead. It displayed no unusual properties, performing roughly the same as Acousta-Stuf, which is advertised as a superior substitute for wool. A similar comparison was observed between cotton puffs and microfiber.

Microfiber is light and fluffy. Acousta-Stuf is ropy and fairly heavy. For roughly equivalent damping, the packing densities of these two materials must differ by a factor of 2 or more. When this is taken into account, the behavior of all four materials is similar.

Even so, there are some differences in attenuation characteristics. For example, at higher packing densities fiberglass displays a somewhat sharper knee and more rapid high-frequency attenuation than the other materials. On the other hand, it seems to be more prone to unexpected response irregularities at low densities.

Fig. 3 compares the measured pipe output of a test system stuffed with 8 g/L of fiberglass and 16 g/L of Acousta-Stuf. The Acousta-Stuf curve is nicely rounded. In comparison, the fiberglass has a sag around

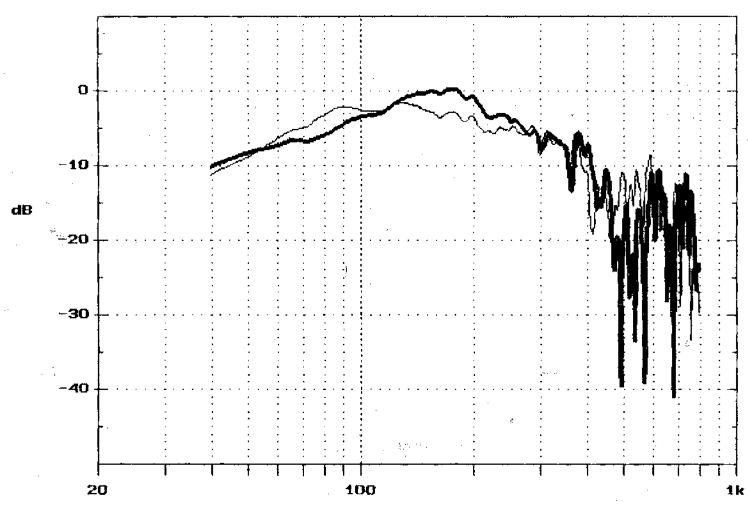


Fig. 3. Pipe output. 8-g fiberglass (bold) and 16-g Acousta-Stuf.

80 Hz, and a broad bump centered at 180 Hz. The remaining peaks and dips are characteristic of the test setup.

This is a typical example. The pipe output is always a little lumpy, and different materials have their own characteristic signatures. In transmission-line systems, if the pipe output is appreciable, then these small differences may be audible.

Most transmission-line literature recommends some optimum stuffing density regardless of pipe length. Common sense suggests that a 100-Hz short pipe should have the same stuffing density as a 50-Hz pipe twice as long. In reality, test results clearly demonstrate that the shorter pipe requires greater packing density for equivalent performance. Moreover, this is apparent from an examination of the analog circuit.

Consider a single transmission-line section. The values of L and C are proportional to the section length x. If the length of the pipe is doubled without changing its cross-sectional area, then L and C must also double. Viewing the section as a low-pass filter, its cutoff frequency has shifted down one octave with no change in impedance. Therefore, since R remains constant but x has doubled, damping per unit length must be halved.

A few tests were run using lining instead of stuffing. However, it became obvious that in pipes of small diameter, even highly absorptive lining cannot provide enough midfrequency attenuation to control passband ripple. Moreover, predicting the performance of lining involves the cross-sectional area and perimeter as well as the length, adding unwanted complications to a basic computer model.

5 MODELING DAMPING MATERIALS

The resistive component of damping is represented by shunt resistance. A frequency-related resistance is required even though fixed losses produce greater attenuation at higher frequencies. Fig. 4 shows analog circuit pipe output with fixed relative damping ranging from 0 to 10. The 1-m pipe is driven by a constant-velocity piston and terminated in its characteristic impedance. Typical absorptive materials exhibit somewhat steeper slopes, and a reactive component is also present.

It is well established that sound wave propagation through tangled fibers is slower than in free air, and is roughly proportional to some power of frequency. In a lightly damped pipe this shows up as a lowering of the nominal quarter-wave resonance frequency plus a smaller shift of the upper harmonics. In a nonresonant transmission-line system, however, damping has a much greater effect on low-frequency performance than propagation velocity. If velocity is set at a fixed value determined by passband ripple frequencies, then any remaining errors mostly affect the response below cutoff.

Four empirical parameters seem to be sufficient to model typical stuffing materials:

1) Fixed losses
2) Variable losses, corner frequency
3) Variable losses, slope
4) Relative sound speed.

The first three are used to calculate the values of shunt resistors at each frequency to be plotted. The last simply sets a scaling factor for capacitance values.

It can be argued that these are unscientific twiddle factors, but they enable the analog circuit described to deliver good approximations of transmission-line behavior. As an example, Fig. 5 shows the system of Fig. 2(b) with the addition of moderate damping. In this case, measured response curves have been omitted because they essentially duplicate the analog response.

6 BASIC SYSTEM BEHAVIOR

With no stuffing, a pipe resonates at odd multiples of its fundamental quarter-wave resonance. The loudspeaker cone is heavily loaded at these frequencies so that loudspeaker output is attenuated and pipe output is accentuated. To complicate the picture, the two are alternately in and out of phase at even multiples of the fundamental, resulting in a highly irregular system response.

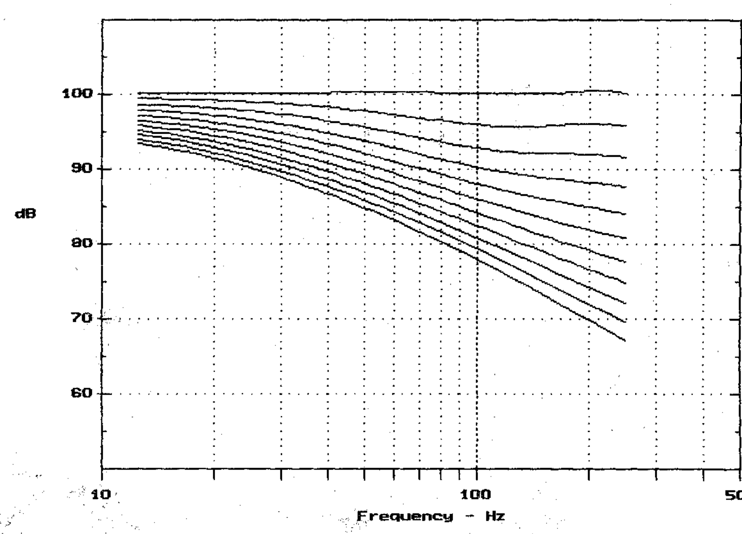


Fig. 4. Terminated pipe output for fixed damping. Relative damping from 0 (top) to 10.

This is clearly shown in Fig. 6, which is the analog response of a small automotive loudspeaker on a 0.78-m pipe. This is nominally a 109-Hz pipe, but it actually resonates at 100 Hz, which is also the loudspeaker's cone resonance. The light solid line represents cone output, the dashed line is pipe output, and the heavy solid line is the combined system response. Note that the upper resonances and antiresonances fall at exact 100-Hz intervals.

The dotted line at the bottom shows voice-coil impedance relative to dc resistance, plotted logarithmically. The impedance curve of this undamped transmission line is obviously similar to that of a vented box. The impedance minimum at 100 Hz is flanked by two peaks at about 64 Hz and 150 Hz. Additional peaks at higher frequencies will disappear as damping is added.

Fig. 7 illustrates what happens when the pipe is stuffed with light, medium, and heavy damping. Like Fig. 6, these are computer analog response curves, but they are all confirmed by actual test data.

When a small amount of damping is introduced, cone and pipe outputs still show resonances, and pipe attenuation is minimal [Fig. 7(a)]. The cone output suggests that quarter-wave loading has moved down to about 80 Hz. However, the fundamental resonance has all but disappeared from the impedance curve. The lower impedance peak no longer exists, and f_H has become a gentle bump. The cone and pipe outputs are additive down to about 85 Hz, and the low-frequency slope is reduced from 24 dB to about 18 dB per octave.

Moderate stuffing density, as shown in Fig. 7(b), results in a well-behaved transmission-line system with a sag of perhaps 2 dB around 300 Hz and gentle rolloff below 150 Hz. Below 100 Hz the slope is about 12 dB per octave. Although pipe output is well below cone output, the two are additive over more than two octaves. The only identifiable resonance in the impedance curve is f_H. The system is starting to behave very much like a closed box.

Still more stuffing results in a purist's transmission line, which effectively swallows up back radiation through the passband, as in Fig. 7(c). Going beyond this point is self-defeating since the output of the loudspeaker cone is progressively reduced by excessive damping.

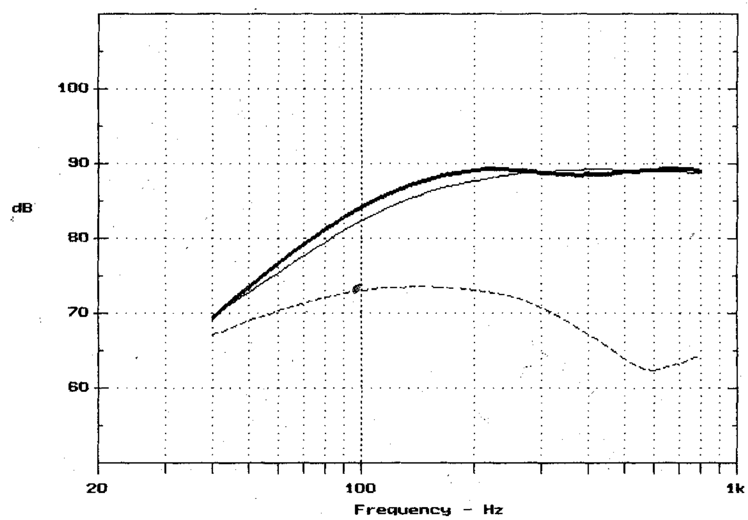


Fig. 5. System of Fig. 2(b) with medium-density stuffing.

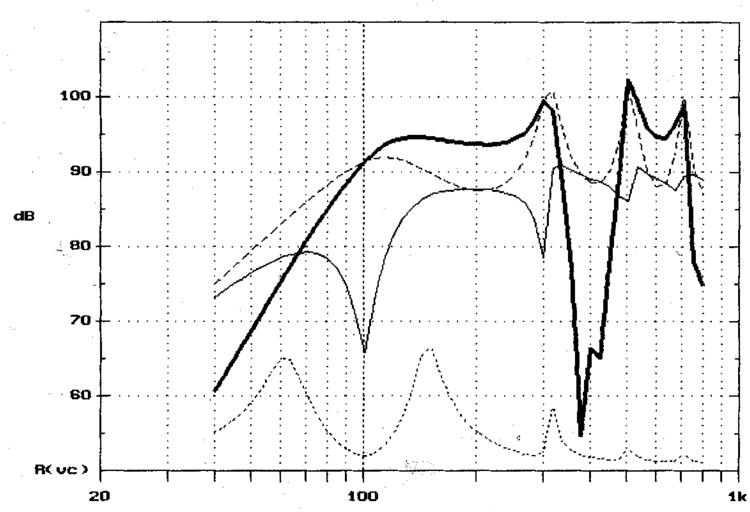


Fig. 6. Response of loudspeaker on undamped straight pipe. Impedance (bottom), cone output, pipe output, and system response (bold).

7 TRANSMISSION-LINE DESIGN FUNDAMENTALS

For highest possible efficiency with minimal passband ripple, it is apparent that damping should be negligible up through the second harmonic yet provide more than 20 dB of attenuation at the fourth harmonic. None of the materials tested even comes close. Rather than searching for a new kind of damping material, it seems more reasonable to look at the behavior of Fig. 7(b) and

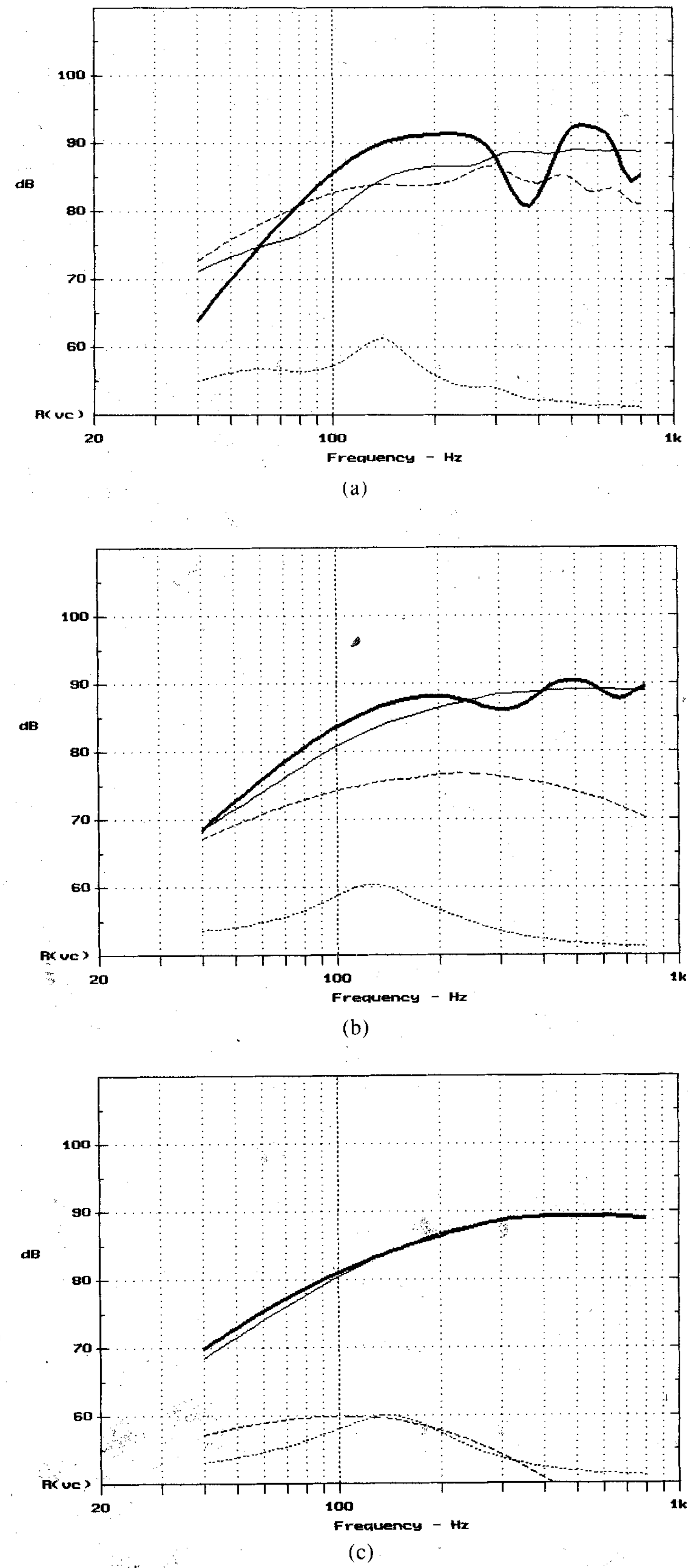


Fig. 7. Response of loudspeaker on straight pipe. (a) Light damping. (b) Moderate damping. (c) Heavy damping. Impedance, cone output, pipe output, and system response (bold).

see what changes might be made to flatten the response.

First Q_{TS} could be increased to lessen midrange sensitivity and thus level the response above 150 Hz. Also, as in a closed-box system, it appears that f_S should be substantially lower than f_3. Finally, to keep passband ripple within ±1 dB, the stuffing density must be increased slightly.

With some trial-and-error tweaking of the loudspeaker parameters, the response of Fig. 8(a) was achieved. Now f_3 matches f_P while f_S is an octave lower. Q_{TS} is about 0.5 and the pipe volume is one-half V_{AS}. Apart from selecting the right stuffing density, this is sufficient information to duplicate the response curve for any desired low-frequency cutoff. Notice that the pipe diameter is determined by the pipe length and V_P. The cone diameter per se is not a factor in low-frequency enclosure design, as Small proved more than 25 years ago [13].

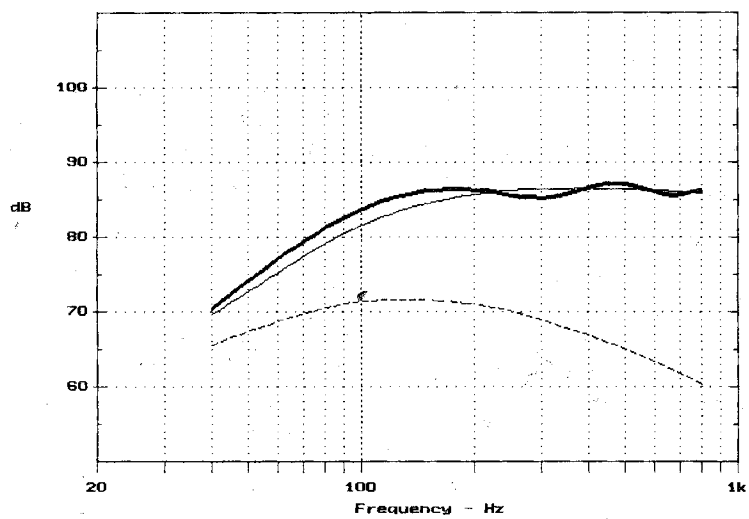
In Fig. 8(a) the pipe output and cone output add constructively down to 40 Hz or lower. Therefore it might be possible to set f_3 as much as an octave below f_P by specifying the proper loudspeaker parameters, with no change in stuffing density. With the benefit of hindsight, this is a logical assumption. It is confirmed by computer modeling and test results. Fig. 8(b) shows how a nominal 109-Hz pipe can be "tuned" to 65 Hz. Efficiency goes down as well, just as one would expect from Thiele–Small analysis of box-type systems.

Some experimenters have reported a miraculous extension of the low-frequency response by using high-density stuffing in very short pipes. This is wishful thinking. In the real world, as the packing density is increased beyond its optimum value the system behaves more and more like an overdamped infinite pipe. For maximum efficiency it appears that f_3/f_P should be between 0.7 and 1.4.

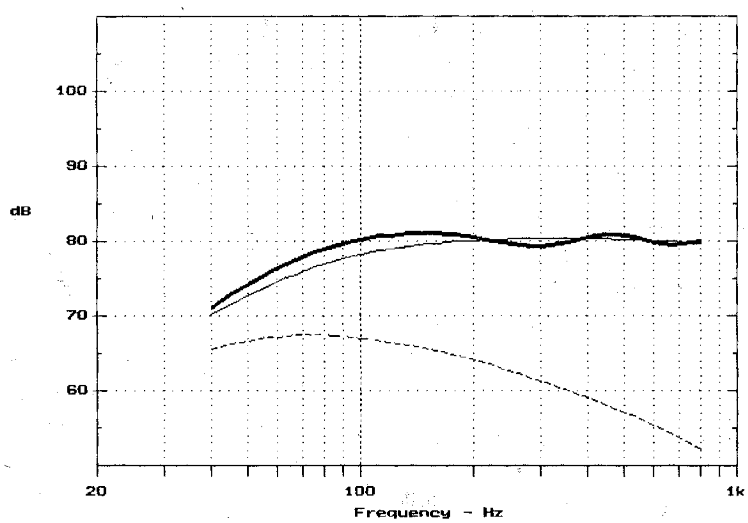
The following simple alignment table summarizes the Thiele–Small relationships of Fig. 8:

	$\frac{f_3}{f_P}$	$\frac{f_S}{f_P}$	$\frac{V_{AS}}{V_P}$	Q_{TS}
Fig. 8(a)	1.0	0.50	2.0	0.46
Fig. 8(b)	0.6	0.33	1.0	0.36

For a nominal 100-Hz pipe the alignments shown can be realized with 32-g/L polyester stuffing. However,



(a)



(b)

Fig. 8. (a) Response of straight pipe with improved alignment. (b) Response of extended low-frequency alignment. Cone output, pipe output, and system response (bold).

they can also serve as multipurpose alignments. The classic low-frequency rolloff of Fig. 7(b) can be approximated by halving Q_{TS}. To simulate an infinite pipe, the stuffing density should be increased by about 50%.

These examples show what can be done with traditional transmission-line design, but they are lossy. Efficiency is 2–5 dB less than for a comparable closed box. Fortunately the situation can be improved by considering something other than a simple straight pipe.

8 ALTERNATE GEOMETRIES

The computer analog made it easy to experiment with all sorts of geometrical modifications, including tuned stubs, abrupt discontinuities, tapered pipes, coupling chambers, and tricks with damping placement. Promising designs were built and tested. Five of these managed to deliver greater efficiency without sacrificing the traditional transmission-line performance. Fig. 9 shows these variant geometries:

- Tapering the pipe (reverse flare) lowers the fundamental resonance frequency without affecting the upper harmonics. The frequency range of constructive pipe output is broadened [Fig. 9(a)].
- Constricting the pipe exit (a vented pipe) has a similar effect [Fig. 9(b)].
- A coupling chamber lowers the fundamental resonance and increases the high-frequency attenuation of damping materials [Fig. 9(c)].
- An abrupt change in pipe diameter at one-third its length produces a reflection that offsets cancellation in the troublesome fourth-harmonic region [Fig. 9(d)].
- Mounting the loudspeaker at one-fifth the length of the pipe is even more effective in attenuating the pipe output near the fourth harmonic [Fig. 9(e)].

Of these, the tapered pipe, coupling chamber, and offset loudspeaker were chosen for additional analysis.

8.1 Tapered Pipe

Tapered tranmission lines go back to Bailey's design [2]. The reasoning seems to be that since energy decreases along the length of the pipe, space can be saved without making any difference in performance. In fact, tapering makes a big difference.

Tapering an undamped pipe can lower f_0 by more than one-third octave. Upper harmonics are almost unchanged. In a transmission-line loudspeaker system f_3 shifts down, giving a useful extension of the low-frequency bandwidth.

An area reduction between 1:3 and 1:4 seems to work best. If the pipe throat is too large, cross modes can be a problem. If the mouth is too small, excessive air turbulence may result. The taper can be linear or conic, or approximated by cylindrical sections. These variants influence the pipe output, but not enough to appreciably affect the overall system response. Fig. 10 shows the performance of an optimized system, normalized to a low-frequency cutoff of 100 Hz.

8.2 Pipe with Coupling Chamber

Coupling chambers have also been used in many transmission lines. The idea seems to have evolved empirically. Technical explanations range from better impedance matching to suppression of pipe resonances. The latter is close to the truth.

The loudspeaker cone is coupled to the pipe throat by the springiness of the air in the chamber. At mid and high frequencies the throat impedance is largely resistive, and the resulting low-pass action adds another 6 dB per octave of high-frequency rolloff. This can easily be seen by comparing Figs. 10 and 11. Both systems are 9-L nominal 125-Hz pipes stuffed with the same packing density. The coupling chamber is also stuffed. In Fig. 11 the coupling chamber accounts for 3 L and a slimmer pipe contains the remaining 6 L.

The system response of Fig. 11 closely matches that of Fig. 10. Above 200 Hz, however, the pipe output rolls off more rapidly and passband ripple is reduced even though the ripple frequencies have moved down. Also, in the 100-Hz region the cone excursion is slightly less.

For the system to function as modeled there must be a clear demarcation between pipe and coupling chamber. On the other hand, if the chamber is too large, then we have restored the cavity that the transmission line was supposed to eliminate. A good compromise is to make the chamber volume one-third of the total volume.

8.3 Offset Loudspeaker

Quarter-wave stubs are sometimes used in duct silencers to suppress specific frequencies. In a damped transmission line the effect is more akin to a shelving filter. Fig. 12 shows how this geometry can be used to

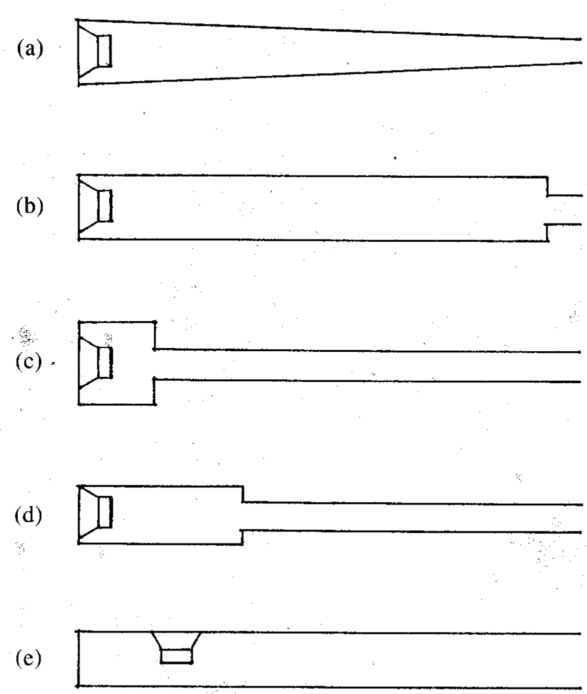


Fig. 9. Alternate pipe geometries. (a) Tapered. (b) Vented. (c) Chamber. (d) Stepped. (e) Offset loudspeaker.

achieve performance at least as good as in the previous examples. A straight pipe is used with the loudspeaker located at one-fifth the length of the pipe.

This system has the same volume, the same stuffing density, and the same low-frequency cutoff as the previous two examples. However, f_3 is now higher than f_P. A longer, thinner pipe is required for comparable performance.

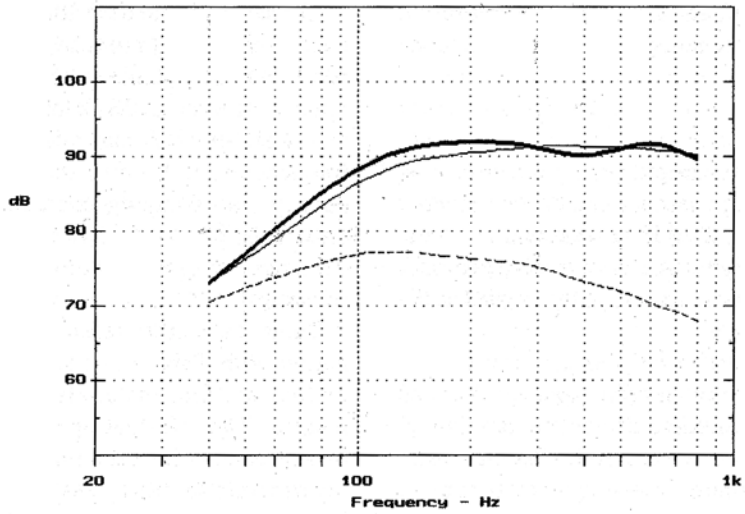


Fig. 10. Tapered pipe transmission-line response. Cone output, pipe output, and system response (bold).

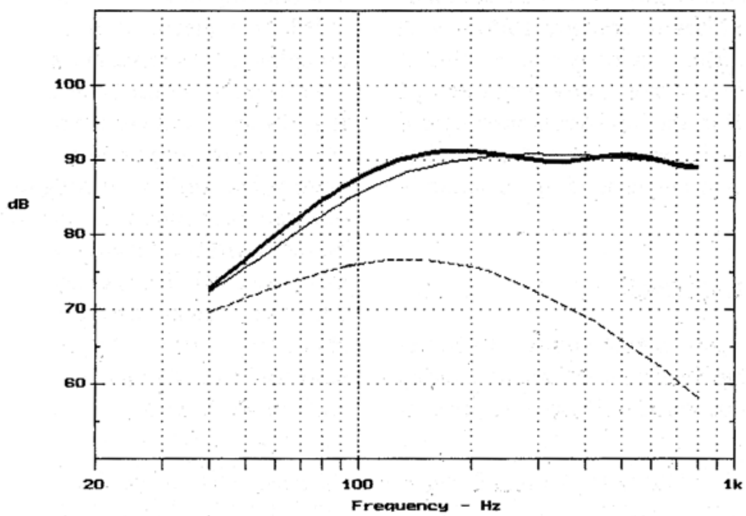


Fig. 11. Coupling chamber transmission-line response. Cone output, pipe output, and system response (bold).

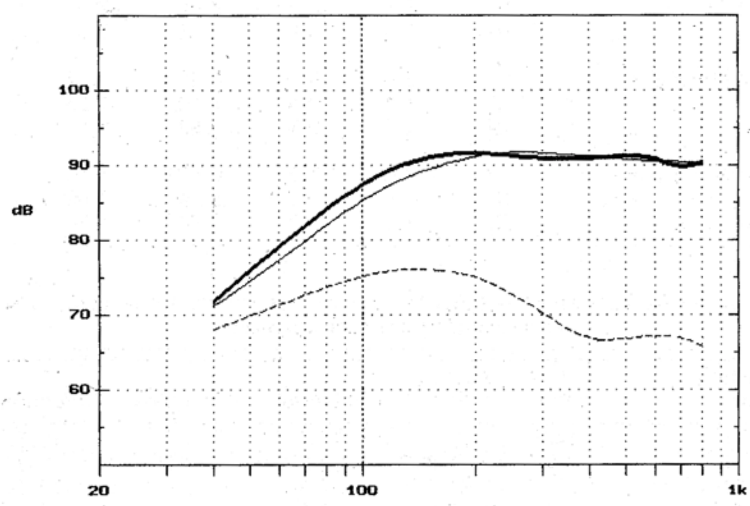


Fig. 12. Offset loudspeaker transmission-line response. Cone output, pipe output, and system response (bold).

8.4 Alignment Table

Alignments based on the Thiele–Small parameters are listed in Table 1 for all three systems. Three sets of values for each design offer a reasonable spread of loudspeaker choices. In reality, all three alternates represent the same loudspeaker mechanism with different cone suspension compliances.

8.5 Combinations

It is possible to combine various pipe geometries. As a case in point, a coupling chamber can drive a tapered pipe. Although it has been used in at least two commercial transmission-line designs, this combination provides no reduction in pipe volume and slightly degrades the low-frequency performance.

Other combinations are similarly disappointing. For example, a tapered pipe with an offset loudspeaker can be made to squeeze out another decibel of efficiency, but at the cost of greater cone excursion. The net result is a decrease in the maximum low-frequency output.

8.6 General Comments

The optimized transmission lines described are characterized by second-order low-frequency rolloff with minimal passband ripple. The efficiency can match that of an equivalent closed-box system, however the pipe output contributes 2–3 dB in the low-frequency region. Since loudspeakers are displacement limited at low frequencies, the net result is a corresponding increase in maximum output.

9 STUFFING SPECIFICATIONS

In theory, separate system alignments would be required for different stuffing materials, different packing densities, and different pipe lengths. However, the general trend for all materials is an increase in sound attenuation with an increase in frequency. As previously noted, if appropriate packing densities are chosen for the four materials studied, then their damping characteristics are similar over a moderate range of frequencies.

There is little concern about the pipe output at frequencies well below f_3 because this region is out of the passband. For acceptable passband ripple, the pipe output must be at least 15 dB below the cone output at frequencies well above f_3 and will continue to drop at higher frequencies. It follows that for a specified cutoff frequency, the damping characteristics must be matched only over a range of two octaves or less. However, densities for pipes of various lengths must be specified separately.

Table 2 is a cross reference chart to be used in combination with Table 1. It shows the equivalent densities of four stuffing materials over a range of useful pipe lengths. The information is derived from several sets of measurements for each material and should be reasonably accurate for fiberglass, Acousta-Stuf, and polyester. Fewer tests were made with microfiber and a fair amount of interpolation is included. Also, tests made with very low packing densities show appreciable variations.

Which material is best? Each material has its own damping characteristics, and even with close matching the differences may be audible. On this basis the choice is arbitrary, but there are other factors to consider. Probably the most important is consistency.

Polyester pillow stuffing seems to be fairly generic, but there is no guarantee that a batch from another manufacturer will be the same as Poly Fluff. Fiberglass thermal blanket delivers consistent performance at packing densities greater than 15 g/L. Its unpacked density is about 10 g/L (0.6 lb/ft^3), and its physical properties are held to close tolerances. On the debit side, it is nasty stuff to work with.

Table 1. Optimized alignments for three practical systems.

Design		f_3/f_S	f_3/f_P	f_S/f_P	V_{AS}/V_P	Q_{TS}
Tapered	I	2.0	0.8	0.40	3.10	0.36
(nom. 4:1)	II	1.6	0.8	0.50	2.00	0.46
	III	1.3	0.8	0.63	1.20	0.58
Coupling chamber	I	2.0	0.8	0.40	2.14	0.31
	II	1.6	0.8	0.50	1.35	0.39
	III	1.3	0.8	0.63	0.84	0.50
Offset loudspeaker	I	2.0	1.2	0.60	3.10	0.36
	II	1.6	1.2	0.74	2.00	0.46
	III	1.3	1.2	0.94	1.20	0.58

Table 2. Packing densities (g/L) for various pipe lengths for tapered, offset, and coupling chamber alignments.

Length (m)	f_P (Hz)	Acousta-Stuf	Polyester	Fiberglass	Microfiber
0.61	140	27.0	29.0	14.5	10.5
0.91	94	21.0	22.5	11.0	9.0
1.22	71	16.0	17.5	9.5	7.5
1.83	48	12.0	13.5	—	5.5
2.44	36	8.0	10.5	—	4.3

Acousta-Stuf is more expensive than fiberglass or polyester but its characteristics are closely specified. As delivered, it is lumpy and must be thoroughly teased, especially for low packing densities. Otherwise, it is easy to use and delivers predictable results.

Microfiber is very light and fluffy. Once packed to the desired density it seems to stay in place, but loose wisps will drift around for days. If the brand name Celanese Microfill is used, then its acoustical properties should be as predictable as those of fiberglass or Acousta-Stuf.

All of these materials can be tricky to use in long, large pipes requiring low packing densities. Partitioning a fat pipe into two or more thin pipes will help keep the stuffing in place and make the structure more rigid. Using thick lining instead of stuffing is another alternative, but is outside the scope of this study.

10 DIRECTIONAL EFFECTS

Letts [8] seems to be the only researcher to have noticed the unusual directional properties of transmission lines.

If the dimensions of a sound radiator are very small in comparison with the wavelength, then it is assumed to behave like a point source. Its coverage pattern is omnidirectional, constrained only by large adjacent surfaces. A small sealed or vented loudspeaker system is essentially omnidirectional at frequencies below 200 Hz or so.

In contrast, a loudspeaker on a lightly damped straight pipe is a unidirectional gradient source at low frequencies. Its coverage pattern is the same as that of a cardioid microphone. If the pipe output is less than the cone output, the directional effects are less pronounced but still in evidence. The pipe output must be at least 15 dB below the cone output for the directivity to be determined by the loudspeaker alone.

All of the system response curves in this paper are on-axis curves, that is, they represent a response at some point equidistant from the loudspeaker and the pipe mouth. If the pipe output is appreciable, then the off-axis response and the total power response may both be quite different from the on-axis curve. Such differences are minimized if the loudspeaker and the pipe mouth are very close together.

Since the low-frequency tonal balance heard in a typical listening room is dominated by generally reflected sound, it follows that a loudspeaker on a straight pipe may indeed sound different than one on an otherwise identical folded pipe.

11 CONCLUSION

This study has attempted to demystify the nonresonant transmission-line design pioneered by Bailey: a loudspeaker is mounted on a pipe stuffed with tangled fibrous material of uniform density, providing sufficient damping to control the passband ripple yet allow useful reinforcement of the cone output at low frequencies.

With a few small modifications, Locanthi's horn analog was shown to be an excellent tool for modeling transmission-line loudspeaker systems. However, to derive usable parameters for real-world damping material it was necessary to test a number of pipes with different materials of varying densities.

Based on test results, four empirical parameters were found sufficient to approximate the performance of damped transmission lines. Three of these define a frequency-dependent resistive component. Surprisingly, the relative propagation velocity can then be set to a constant value even though, in reality, it is also frequency dependent.

For a pipe of given length, different materials require different packing densities to achieve desired damping. Once this is done, the passband performance is essentially the same for any of the materials tested.

The pipe length establishes a usable range of cutoff frequencies, typically a one-octave band centered at f_P. Within that range, f_3 is controlled by the loudspeaker parameters in relation to pipe length and volume. Damping remains unchanged.

In contrast to a basic cylindrical pipe, at least four other geometries allow lighter damping, which results in higher efficiency. Systems can be scaled to any cutoff frequency and any practical efficiency by using simple alignment tables. Optimized alignments were developed for three alternate geometries. Allowing for ± 1-dB passband ripple, these new alignments approximate the response of an equal-volume closed box, but with reduced cone excursion and correspondingly greater maximum low-frequency output.

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THE AUTHOR

George L. Augspurger received the B.A. degree from Arizona State University at Tempe, the M.A. degree from UCLA, and has done additional postgraduate work at Northwestern University.

After working in sound contracting and television broadcasting, he joined James B. Lansing Sound, Inc., in 1958, where he served as a technical service manager and, later, as manager of the company's newly formed Professional Products Department. In 1968 he was appointed Technical Director. In 1970 he left JBL to devote full time to Perception Inc., a consulting group specializing in architectural acoustics and audio system design.

Mr. Augspurger is a member of the Audio Engineering Society, the Acoustical Society of America, and the United States Institute of Theatre Technology.