How to improve transmission-line efficiency with a configuration other than a simple straight pipe.

Part 3: Pipe Geometry and Optimized Alignments

Transmission Lines Updated

By G. L. Augspurger

After I was satisfied that my computer analog could match real-world test results, I used it to experiment with all sorts of modifications to the basic stuffed pipe. Five of these seemed to deliver greater efficiency without sacrificing traditional transmission-line performance. *Figure 13* shows these designs:

1. Tapering the pipe lowers the fundamental resonance with almost no effect on upper harmonics; it also broadens the frequency range of constructive pipe output.
2. A constricted exit effectively increases air mass, which again lowers the fundamental resonance with less effect on upper harmonics.
3. A coupling chamber between the driver and the pipe throat not only lowers the fundamental resonance, but also serves to increase the pipe's high-frequency attenuation.
4. A sudden reduction in cross-sectional area at ⅓ of the total pipe length produces a secondary reflection that tends to cancel the first-passband response dip.
5. Mounting the driver at ⅕ the length of the pipe is even more effective in reducing the first-passband dip.

I decided that the tapered pipe, coupling chamber, and offset speaker showed the most promise, so I subjected these to additional computer analysis. I built and tested at least one example of each.

Tapered Pipe

A pipe of gradually decreasing cross section (reverse flare) is a common transmission-line variant. It may have been borrowed from experiments with undamped pipes in the 1950s. The theory usually given is that since internal energy gradually decreases from loudspeaker to exit, you can make the pipe correspondingly smaller with no change in performance.

In fact, there is a dramatic change. The fundamental resonance moves down in frequency, while the upper harmonics are almost unchanged. As a result, pipe output reinforces cone output over a broader frequency range, and less damping is required for given passband ripple. (According to some loudspeaker advertisements, the nonparallel sides of a tapered pipe should "eliminate standing waves." However, this is true neither in listening rooms nor loudspeaker enclosures.)

A reduction in area between 1:3 and 1:4 seems to work best. If the exit is too small, then excessive air turbulence may result. The taper can be linear, or conic, or approximated by straight sections. These variations slightly affect pipe output, but not enough to change overall system response. Stuffing density should be the same from one end to the other.

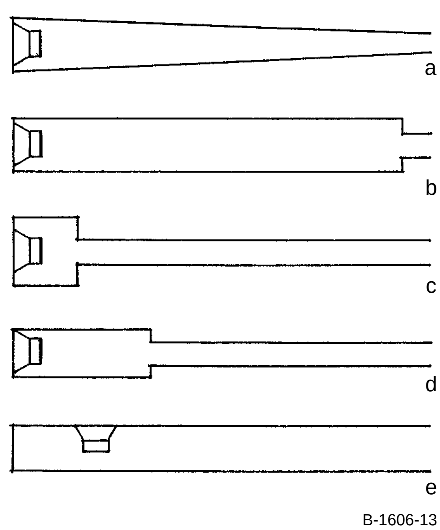

FIGURE 13: Alternate pipe geometries (top to bottom): tapered, vented, chamber, stepped, offset speaker.

Figure 14 shows the performance of a 4:1 tapered line normalized to a low-frequency cutoff of 100Hz. This scaling makes it easy to visualize what would happen with any other cutoff frequency. For example, if you wish to design a 40Hz system, then multiply everything by 0.4; response will be down 10dB at about 24Hz, and the first passband dip will be centered at 160Hz. In this particular alignment, the cutoff frequency f_3 is 0.8 times f_P.

Pipe with Coupling Chamber

Many successful transmission-line designs have also used coupling chambers. Technical explanations range from better impedance matching to suppression of pipe resonances. However, what really happens is not hard to understand. At mid and high frequencies the acoustic impedance of a damped pipe is resistive. Since the speaker cone is coupled to the pipe by the chamber's air springiness, the resulting R/C lowpass filter adds another 6dB per octave of high-frequency rolloff. You can clearly see this in *Fig. 15*.

Again, less damping is required to control passband ripple. However, for the system to work as described, there must be a clear demarcation between pipe and chamber, and the chamber must be boxy in shape. If the chamber is too small, then it is more like a stepped pipe. If you use a large chamber, then you have restored the resonant cavity that the transmission line was supposed to eliminate. A safe rule is to make chamber volume ⅓ of the total volume, as in *Fig. 15*.

You might think that any damping material in the chamber would interfere with its role as pure acoustic capacitance. However, computer simulations and actual measurements confirm that the pipe and chamber should both be stuffed. Low-frequency performance is not affected one way or the other, but mid-range response is smoother when the chamber is damped.

Offset Speaker

In Voigt's original corner horn, the back of the driver was loaded by a flared pipe driven at ⅓ its length. He did this to suppress the resonance at three times the fundamental frequency. The idea was picked up by Ralph West in a 1949 corner-speaker design for the Decca Record Company. West pointedly contrasted his cut-down horn against a damped pipe: "The very wide-open end damps the system by turning energy into sound. This is better than merely wasting the energy with layers of felt."[12]

With a properly matched loudspeaker, the Decca enclosure is able to deliver smooth bass response up to about four times its fundamental resonance. As with all undamped pipes, however, mid-band response is a series of abrupt peaks and dips.

The reason for this digression is that you can also improve the performance of a damped pipe by mounting the driver some distance away from the closed end. In this case, you should center the driver at ⅕ the length of the pipe to smooth out the first-passband dip. Unlike the other systems described, f_3 is set about 20% higher than f_p for flattest low-frequency response.

Figure 16 shows the response of such a transmission line. The system has the same pipe volume, the same stuffing density, and the same cutoff frequency as *Figs. 14* and *15*, but the pipe is longer and thinner.

Combinations

It is possible to combine various pipe geometries, but any additional benefits range from slight to nonexistent. For example, adding a coupling chamber to an offset speaker largely negates the value of either one used alone.

The combination of a coupling chamber and tapered pipe has often been used in successful transmission-line designs, but a straight pipe is more efficient. In this case, the taper gives no reduction in pipe volume and actually degrades low-frequency performance.

You can taper a pipe driven by an offset driver, with perhaps a tiny extension of low-frequency bandwidth, but this is accompanied by greater cone excursion. The net result is a decrease in maximum low-frequency output.

To summarize, all three geometries I've described are capable of comparable performance and can be specified by simple system alignments. Hybrids are not recommended.

OPTIMIZED ALIGNMENTS

You can scale the performance graphed in *Figs. 14*, *15*, and *16* to any desired frequency and any reasonable efficiency by establishing appropriate relationships be-

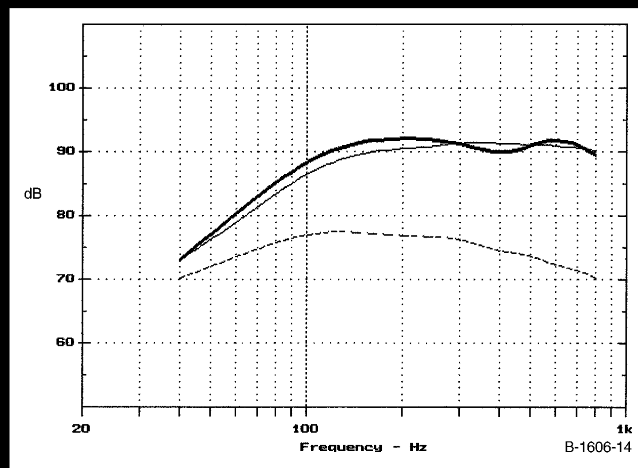

FIGURE 14: Tapered pipe optimized alignment response: cone output, pipe output, and system response (bold).

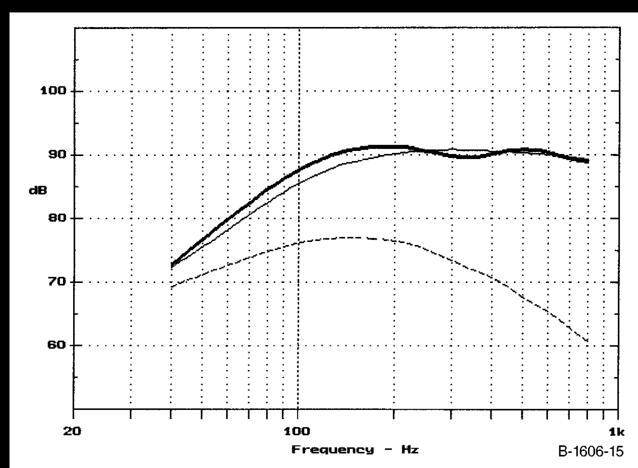

FIGURE 15: Coupling chamber optimized alignment response: cone output, pipe output, and system response (bold).

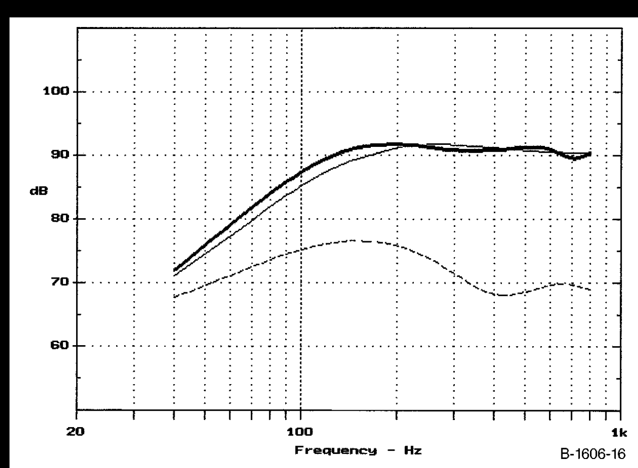

FIGURE 16: Offset speaker optimized alignment response: cone output, pipe output, and system response (bold).

TABLE 1
PACKING DENSITY IN LB/FT³ VS PIPE LENGTH FOR TAPERED, OFFSET, AND COUPLING-CHAMBER ALIGNMENTS.

LENGTH INCHES	F_P HZ	ACOUSTA-STUF	POLYESTER	FIBERGLASS	MICROFIBER
24	140	1.70	1.8	0.90	0.65
36	94	1.30	1.40	0.70	0.55
48	71	1.00	1.10	0.60	0.45
72	48	0.75	0.85	-	0.35
96	36	0.50	0.65	-	0.27

tween pipe geometry, stuffing characteristics, and driver parameters. This is shown in *Tables 1* and *2*.

Table 1 is a cross-reference of stuffing densities versus pipe length. It is appropriate for all three geometries presented here, but not for simple, straight pipes. The values listed are derived from several sets of measurements for each material. I have a high degree of confidence in the listings for fiberglass, Acousta-Stuf®, and polyester. I made fewer tests with microfiber, and a fair amount of interpolation is included. Also, tests made with low packing densities show appreciable deviations from the norm.

Table 2 sets forth relationships between driver parameters and pipe geometry. I have shown three sets of values for each design to provide a practical spread of driver choices. In reality, all three alternatives describe the same speaker mechanism with different cone-suspension compliances.

First, look at the optimized alignments referenced as a, b, and c. I have restricted Q_{TS} to values less than 0.6 and, as a result, f_3 is always higher than f_S. Note also that f_3 is set at $0.8f_P$ for the tapered pipe and coupling chamber,

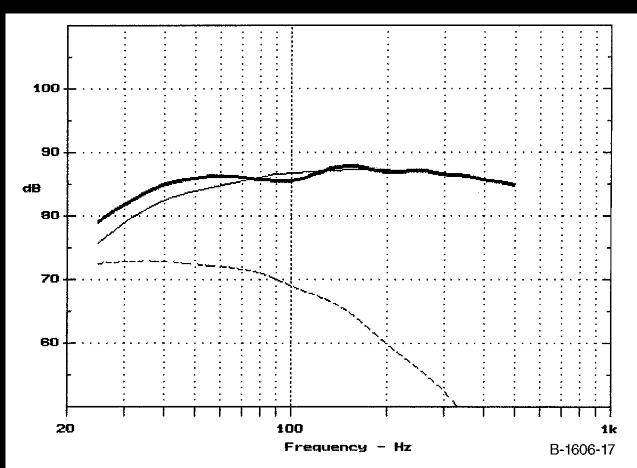

FIGURE 17: Bailey's 1972 transmission-line simulation: cone output, pipe output, and system response (bold).

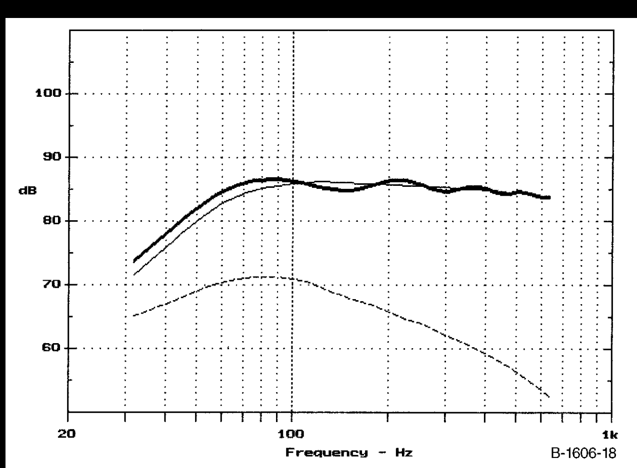

FIGURE 18: High-Q woofer on 43Hz tapered pipe: cone output, pipe output, and system response (bold).

and at $1.2f_P$ for the offset speaker. There is nothing magic about these numbers, but they make efficient use of pipe volume without requiring unrealistic driver parameters. Even so, it is a little discouraging to see that f_3 is 30% higher than f_S at best, and this ratio requires Q_{TS} to be at least 0.5.

In many cases you might be willing to increase pipe volume in exchange for a lower cutoff frequency. This is what I have done in the corresponding "extended" alignments referenced as d, e, and f. For the tapered pipe and offset driver, I simply doubled pipe volume and then adjusted Q_{TS} until I achieved the desired response. However, the coupling-chamber alignments did not respond well to this technique. For these, I repeated the values for Q_{TS} and then adjusted other relationships as needed.

For a given driver, the extended alignments push f_3 down by about ⅙ octave for the coupling chamber, and by more than ⅓ octave for the tapered and offset designs. For both sets of alignments, packing density can vary by –15% with only a small change in system response. The tapered line is slightly less sensitive to changes in damping than the other two designs. When in doubt, a little too much stuffing is better than too little.

GENERAL COMMENTS

The optimized alignments listed above are characterized by second-order low-frequency rolloff, with nominal –1dB passband ripple. The efficiency matches that of an equivalent closed-box system; however, pipe output contributes 2–3dB in the low-frequency range. Since loudspeakers are displacement-limited at low frequencies, the net result is a corresponding increase in maximum output.

As a point of interest, it is possible to design a transmission-line system in which f_S, f_P, and f_3 are all equal. Bailey's 1972 design (*Fig. 17*) is inefficient, but delivers very good performance.

(His design was available in kit form and was tested by Letts as part of his thesis project.[13] Using this information, the frequency response graphed in *Fig. 17* is a best-fit computer simulation. Q_{TS} is 0.6, and V_{AS} is about $2ft^3$; f_S, f_P, and f_3 are all 35Hz.

The 8¢ folded line consisted of three sections approximating a 2.3:1 taper. V_P was close to $3.3ft^3$. The line was stuffed with long-fiber acetate at a density of 1 lb/ft^3, which seems to be roughly equivalent to Acousta-Stuf at 0.5-lb density.)

By using a driver with Q_{TS} greater than 0.707, it is also possible to extend low-frequency response below f_3, as in *Fig. 18*. This automotive woofer has a 63Hz free-air resonance; Q_{TS} = 0.95, and $V_{AS} = 0.4ft^3$.

PRACTICAL EXAMPLE

As a practical test, I decided to design a transmission-line enclosure for the Vifa P17WJ. This popular driver is intended for use in vented boxes, but is also a favorite with transmission-line builders. Its cone resonance is listed as 37Hz, Q_{TS} = 0.35, $V_{AS} = 1.23ft^3$, and its rated sensitivity is 88dB (1W/1m).

Looking first at the optimized alignments and doing a little rough interpolation, it appears that f_3 must be at least 67Hz. The latter figure is achieved with a coupling-chamber design having a total volume of about $0.7ft^3$.

I had hoped for something nearer to 55Hz, which suggests that one of the extended alignments would be a better choice. Tapered alignment (e) is close enough to use without interpolation. Using this, f_3 works out to be 59Hz, with

TABLE 2
ALIGNMENTS FOR SIX PRACTICAL SYSTEMS

Design		f_3/f_S	f_3/f_P	f_S/f_P	V_{AS}/V_P	Q_{TS}
Optimized System Alignments						
Tapered	a)	2.0	0.8	0.40	3.10	0.36
(Nom. 4:1)	b)	1.6	0.8	0.50	2.00	0.46
	c)	1.3	0.8	0.63	1.20	0.58
Coupling	a)	2.0	0.8	0.40	2.14	0.31
Chamber	b)	1.6	0.8	0.50	1.35	0.39
	c)	1.3	0.8	0.63	0.84	0.50
Offset	a)	2.0	1.2	0.60	3.10	0.36
Speaker	b)	1.6	1.2	0.74	2.00	0.46
	c)	1.3	1.2	0.94	1.20	0.58
Extended System Alignments						
Design		f_3/f_S	f_3/f_P	f_S/f_P	V_{AS}/V_P	Q_{TS}
Tapered	d)	2.0	0.8	0.40	1.50	0.25
(Nom. 4:1)	e)	1.6	0.8	0.50	1.00	0.33
	f)	1.3	0.8	0.63	0.60	0.41
Coupling	d)	1.75	0.7	0.40	1.10	0.31
Chamber	e)	1.40	0.7	0.50	0.68	0.39
	f)	1.10	0.7	0.63	0.42	0.50
Offset	d)	2.0	1.2	0.60	1.50	0.25
Speaker	e)	1.6	1.2	0.74	1.00	0.33
	f)	1.3	1.2	0.94	0.60	0.41

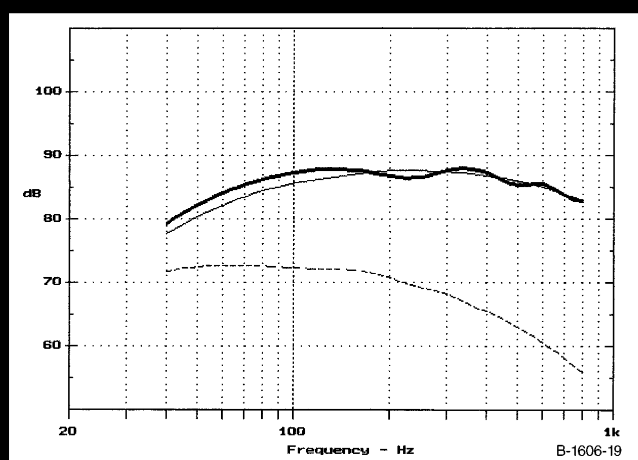

FIGURE 19: Vifa P17WJ on 74Hz tapered pipe: cone output, pipe output, and system response (bold).

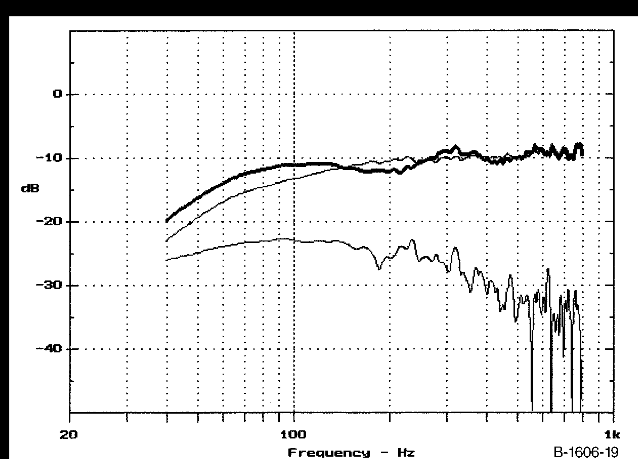

FIGURE 20: Vifa P17WJ on tapered test pipe: cone output, pipe output, and system response (bold).

V_P = 1.23ft^3, and f_P = 74Hz. These figures seem reasonable. *Figure 19* shows the predicted response with 0.5 lb of Acousta-Stuf.

At this point, I was ready to construct and test the system, but Murphy's Law intervened. The cone resonance of my recently acquired P17WJ was closer to 50Hz than 37Hz. Even after a strenuous break-in period, f_S settled in at 48Hz.

This is not an unusual situation. To keep the Sales Department happy, a new loudspeaker prototype was built with a very floppy suspension and correspondingly low cone resonance. Once in production however, it became obvious that it needed a stiffer centering spider to keep the voice coil from rubbing and the cone from bottoming out. The infinite-baffle response is about the same, and the buyer is really getting a more rugged loudspeaker, right?

What the higher resonance implied was that Q_{TS} was actually about 0.4, and V_{AS} had decreased to 0.75ft^3. If I had built a vented box for the P17WJ, I would have been very upset, but transmission lines are much more forgiving. In this case, the best-fit tapered alignment simply moved from (e) to (f). Pipe dimensions and passband performance were the same.

Figure 19 is a computer curve, but you can compare it directly with the measured response of *Fig. 20*. Below 500Hz, the system-response curves track within 0.5dB. The correspondence is even more impressive when I confess that I did not build the pipe described. Instead, I used one of my existing test pipes: f_P was 68Hz instead of 74Hz, V_P was 1.0 instead of 1.23ft^3, and the taper was only 2.5:1.

SUMMARY

I restricted this project to a particular class of drivers on damped pipes, stuffed with tangled, fibrous material of uniform density. The damping is sufficient to control passband ripple, yet it allows useful reinforcement of cone output at low frequencies.

- With practical damping materials, the result is a nonresonant system, not a tuned pipe.
- For a pipe of given length, different materials require different packing densities to achieve desired damping. Once this is done, system performance is essentially the same for any of the materials tested.
- 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 driver parameters in relation to pipe length and volume. Damping remains unchanged.
- Systems can be scaled to any cutoff frequency and any practical efficiency by using simple alignment tables.
- In contrast to a basic cylindrical pipe, at least four alternate geometries allow lighter damping, which results in higher efficiency.
- Allowing for −1dB passband ripple, optimized alignments approximate the response of an equal-volume closed box, but with reduced cone excursion.

REFERENCES

12. Ralph West, "The Decca Corner Speaker," *Five Speakers*, Miles Henslow Year Books Ltd., London, (1964?).

13. Geoffrey Letts, "A Study of Transmission Line Loudspeaker Systems," honors thesis, The University of Sydney–School of Electrical Engineering, (1975).