Material selection and density are critical considerations when stuffing a pipe.

Part 2

Transmission Lines Updated

Stuffing Characteristics

By G. L. Augspurger

A VERY BRIEF HISTORY OF STUFFED PIPES

In the early 1900s lightly stuffed pipes were used as nonresonant sound conduits or absorbers. For example, Olson's ribbon microphone terminated the rear surface of the ribbon in a tube damped with tufts of felt.

Benjamin Olney's Acoustical Labyrinth, patented in 1936, appears to be the first application of damped pipes to loudspeaker design. "A tube filled with absorbing material of gradually increasing density was first considered, but it soon became evident that such a device...would be difficult and expensive to construct."[8]

Olney decided it would be more practical to use absorptive lining instead of stuffing. His analysis suggested that both diaphragm motion and pipe radiation would be small at the quarter-wave frequency. He expected that at an octave higher, absorption in the tube would still be relatively low, so pipe radiation would reinforce cone radiation.

"If the absorbing material be properly chosen and a sufficient quantity employed," he wrote, "the higher-order resonances and antiresonances of the tube will be suppressed, and the driving point impedance at the higher frequencies will be determined largely by the absorption in the tube." Olney was also aware that in a pipe with losses, the speed of sound is less than in free air. He speculated that the wave front would gradually become curved as it traveled through his labyrinth.

He then built such a device and made exhaustive measurements that confirmed that pipe radiation substantially reinforced cone radiation around 70Hz, and then rolled off rapidly at higher frequencies.

LABYRINTH OR BOX

In fact, what Olney built, measured, and patented was not what he described as an acoustical labyrinth. It probably functioned more like a damped vented box. (No one seems to have noticed this.) However, later versions built by Stromberg-Carlson definitely were lightly damped pipes. By then the inventor recommended that the pipe's quarter-wave resonance should match the speaker's cone resonance for linear response down to f_P.

In 1965 A.R. Bailey described his experiments with "nonresonant" stuffed pipes.[9] He tested pipes stuffed with fiberglass and with long-fiber wool and decided that wool was clearly superior. He reported that wool at a density of 0.5lb/ft^3 closely matched the characteristic impedance of air above 100Hz, yet provided a high rate of sound attenuation. More surprisingly, near 30Hz the speed of sound through a wool-stuffed pipe was slowed by about 50%. For pipe radiation to reinforce cone radiation in the 30Hz region, he was able to reduce pipe length from 30′ to 15′.

A little more than ten years later, a paper appeared by L.J.S. Bradbury[10] that attempted to provide a scientific basis for Bailey's findings. Bradbury postulated that aerodynamic drag would set fibers in motion at low frequencies, effectively adding mass and slowing the speed of sound through a stuffed pipe. He developed an elaborate theoretical analysis that allowed acoustical behavior to be predicted from a knowledge of fiber diameter, mass, and packing density.

Using Bradbury's equations, Robert Bullock developed a computer program to design transmission-line loudspeaker systems, but the results were less than satisfactory. One reason may be that Bradbury's formula for computing the drag coefficient was admittedly tentative. Another is that some of his underlying assumptions may be incorrect.

MATS AND BLANKETS

In 1980 Hersh and Walker published a thorough analysis of the acoustic behavior of Kevlar® mats and blankets.[11] Their findings should be applicable to any similar fibrous material. Citing previous work, the authors emphasized the importance of fiber orientation in relation to the direction of the sound wave as well as interaction between fibers in determining the drag coefficient. Like Bradbury and others, Hersh and Walker measured a dramatic reduction in sound speed at low frequencies. However, their theoretical model assumes that the fibers are stationary.

An enormous amount of work has been published regarding the acoustic behavior of fiberglass and similar fibrous materials. Books have been written on the subject. However, like Hersh and Walker's paper, much of this material relates to duct silencers, engine mufflers, or aerospace design, and is not readily available to loudspeaker designers. As far as I can tell, there is sufficient evidence to support the following general statements:

- If the thickness of the material is greater than a fraction of a wavelength, then attenuation increases with increasing frequency.
- Wave propagation through fibrous packing slows at lower and lower frequencies. This effect is associated

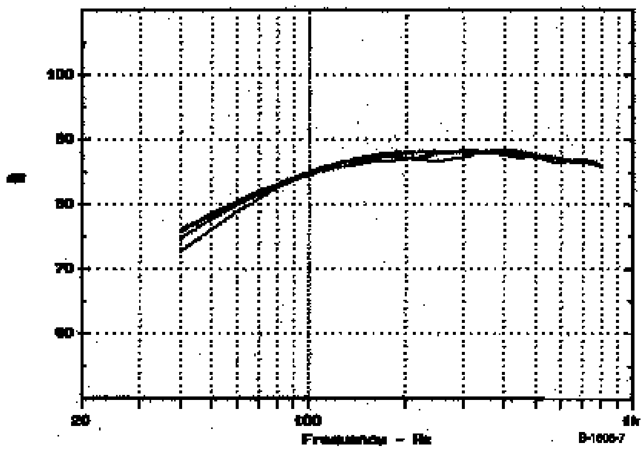

FIGURE 7: Response of 100Hz pipe with varying sound speed. Relative speed: 0.80, 0.63, 0.50, and 0.40.

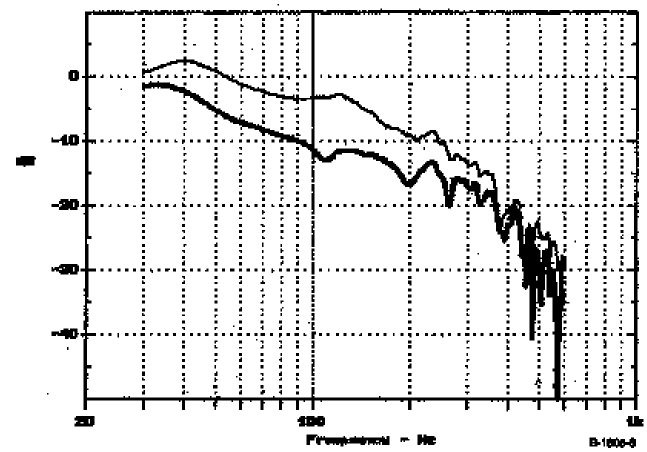

FIGURE 8: Comparative pipe transfer functions.

with a reactive (mass) component of acoustic impedance.

- Air expansion and contraction are at least partially isothermal, but this factor is small in relation to other effects.
- Any motion of fibers can be ignored when you are modeling basic acoustical behavior.
- Orientation of fibers is important. A random tangle may behave differently than a mat woven from the same material.

SLOW SOUND — SOME CAUTIONARY COMMENTS

Bailey's experiments suggest that you can cut the size of a transmission line in half by loosely stuffing it with wool. Bradbury seemed to accept the idea. It seems almost too good to be true, and it is.

Yes, the effective length of a short stuffed pipe is equivalent to a longer empty pipe at low frequencies, but a change in acoustic impedance is involved. More important, propagation speed and damping are tied together. A "slow" pipe is a damped pipe, and damping is the more important factor. Moreover, even if you speculate that wool does slow wave propagation to half the speed in fiberglass for the same damping (which it does not), the net result is not what Bailey reported.

My computer simulation allows damping and sound speed to be specified independently. *Figure 7* shows what happens when damping is constant but relative sound speed is varied over the range from 0.8 to 0.4. There is some change in low-frequency response, but it becomes significant only about an octave below f_3, which remains stubbornly fixed at 100Hz. In terms of transmission-line response, trying to measure and specify sound speed is both uncertain and unnecessary. It seems that, for the past 30 years, we have all been chasing the wrong rabbit.

To get a clearer picture of what the stuffed pipe is doing, the loudspeaker's amplitude and phase response must be eliminated. Instead of summing loudspeaker and pipe outputs, you can use complex division to derive the pipe transfer function—pipe output in relation to cone output. Now you have a way to compare various kinds of stuffing on various pipes regardless of the loudspeakers used for individual tests.

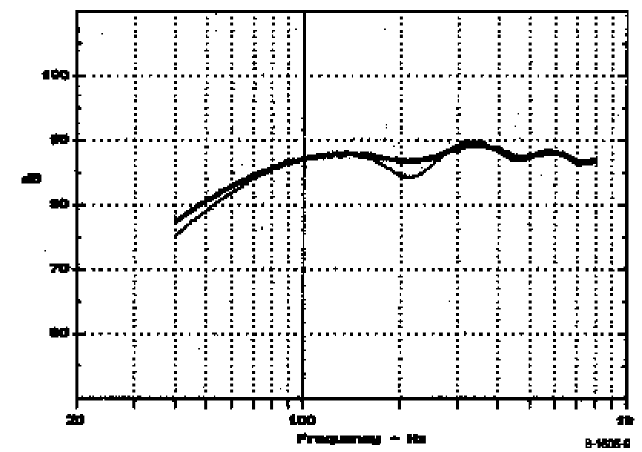

FIGURE 9: System response: flared versus tapered (bold).

A good example is illustrated in *Fig. 8*. The two curves are unsmoothed pipe transfer functions derived from actual measurements. The upper curve appears to be a lightly damped pipe. Pipe output exceeds cone output around 40Hz, then levels out at 60Hz, and finally rolls off fairly rapidly above 150Hz.

The lower curve obviously shows more damping at low frequencies. With a little smoothing, it might represent a 40Hz, 6dB per octave low-pass filter. In the 100Hz octave band, it provides about 6dB greater attenuation than the upper curve.

The two transfer functions also differ in their group–delay characteristics. The actual plots are ragged, but their general shapes can be described. The lower curve has a group–delay maximum of about 10.5ms at 40Hz, followed by a broad S-curve reaching 6.0ms at 125Hz and then gradually averaging out to 4.0ms above 250Hz. The upper curve generally has a similar shape, but peaks at about 8.0ms, with a secondary bump of about 5.0ms before joining the lower curve at 250Hz. At 40Hz and 125Hz the "speed of sound" is about 20% different between the upper and lower curves.

Now, the interesting thing is that the two sets of measurements were made on the same 4′ pipe with the same speaker and the same stuffing! However, this pipe has slanted sides. Its area is $21in^2$ at one end and $49in^2$ at the other. The upper curve was run with the speaker on the small end (flared pipe) and the lower curve with the speaker on the large end (tapered pipe).

The difference in system response is shown in *Fig. 9*. It is obvious that pipe geometry is just as important as length and damping in establishing transmission–line performance.

PRACTICAL DAMPING MATERIALS

The preceding example makes it clear that theoretical analysis of damping materials may not be the best approach to

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understanding transmission line loudspeaker systems. One purpose of this project was to develop empirical guidelines based on actual measurements. After all, it really doesn't matter what the damping material is if you can predict what it will do.

So I proceeded to run response curves on pipes stuffed with a variety of materials ranging from steel wool to plastic packing pellets. The selection was rapidly narrowed to four well behaved, easily obtained materials:

1. Ordinary fiberglass thermal blanket. This is usually sold with paper backing, which you can remove.
2. Polyester fiber stuffing. I used Poly Fluff, a product of Western Synthetic Fiber Inc., Carson, CA.
3. Microfiber stuffing — Celanese "Microfill."
4. "Acousta-Stuf" — nylon polyamide fiber available from Mahogany Sound, Box 9044, Mobile, AL 36691-0044.

For practical reasons, you should avoid organic materials. However, Bailey preferred long-fiber wool, and present-day experimenters continue to follow his advice. Bulk wool is not easy to find in the US, so I tested fluffy wool yarn instead. It displayed no unusual properties, behaving roughly the same as Acousta-Stuf. Similarly, cotton puffs are roughly equivalent to microfiber.

Microfiber is light and fluffy. Acousta-Stuf is ropy and fairly heavy. For equivalent damping over a given range of frequencies, the packing density of Acousta-Stuf must be at least twice that of microfiber. Once this is taken into account, all four materials behave very much the same.

The reason for this happy state of affairs is that, for any given system alignment, precise damping characteristics are important only over a bandwidth of about two octaves. In a practical transmission-line system, useful summation of pipe output and cone output extends from perhaps an octave below f_3 to an octave above. At higher frequencies, pipe output continues to decrease, but the exact rate of rolloff is not critical. Similarly, at frequencies well below cutoff, you can disregard any minor differences in response.

DENSITY DIFFERENCES

For comparable results, a short pipe requires greater packing density than a long one. This seems to contradict common sense, but test results demonstrate it is true. It follows that system alignments must include absolute pipe length as a design factor.

If stuffing makes a short pipe behave somewhat like a longer pipe, can its effective length be further increased by increasing stuffing density? Yes and no. *Figure 10* compares transfer functions of 1.0 lb density Acousta-Stuf in a 6′ pipe with 3.0 lb density of the same material in a 2′ pipe. These are computer curves, but they accurately model test results below 300Hz or so. Over a wide frequency range, the two curves differ by no more than 1dB.

However, although effective sound speed is slower in the shorter pipe, it is not slow enough to make up for the difference in path length. In a practical transmission-line design, the cutoff frequency probably will lie between 0.7 and 1.4 times f_p. Within that range, adjustment of system response can be accomplished by changing loudspeaker parameters, not stuffing.

In practice, the optimum packing density for a given material is determined by acceptable passband ripple. Once this is done, overall system response is almost the same for all four materials. Even with best-fit matching, however, there are some differences in performance. At higher packing densities, fiberglass has greater high-frequency versus low-frequency attenuation than the other materials. On the other hand, at low densities it seems to be more prone to unexpected glitches in response.

Figure 11 shows measured pipe transfer curves of ½ lb fiberglass and 1 lb Acousta-Stuf. Up to 400Hz or so, the response of Acousta-Stuf rolls off fairly smoothly. In contrast, the fiberglass curve has a sag around 75Hz and a broad bump centered near 200Hz.

This is a typical example. In contrast to the computer model, pipe output is always lumpy, and different materials have their own characteristic acoustic signatures. In the range where pipe output contributes to system output, these differences may be audible.

STUFFING SPECIFICATIONS

For pipes of various lengths, it is possible to draw up a set of charts showing equivalent packing densities for the four materials tested. It turns out that a single table is adequate for general-purpose alignments, because short pipes always require high damping and long pipes require relatively light damping. Such a table is included in Part 3 of this report.

A few general rules of thumb may be useful. For most purposes, you can consider Acousta-Stuf and Poly-Fluff as pound-for-pound equivalents. In contrast, the packing density of fiberglass blanket must be half that of Poly-Fluff. The density of microfiber should be about a third that of Poly-Fluff, but the actual ratio is not constant.

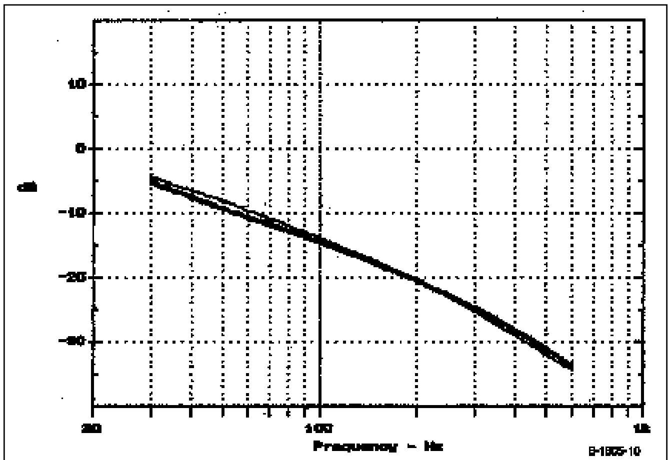

FIGURE 10: Acousta-Stuf transfer functions: 1.0 lb-density in 6′ pipe versus 3.0 lb-density in 2′ pipe.

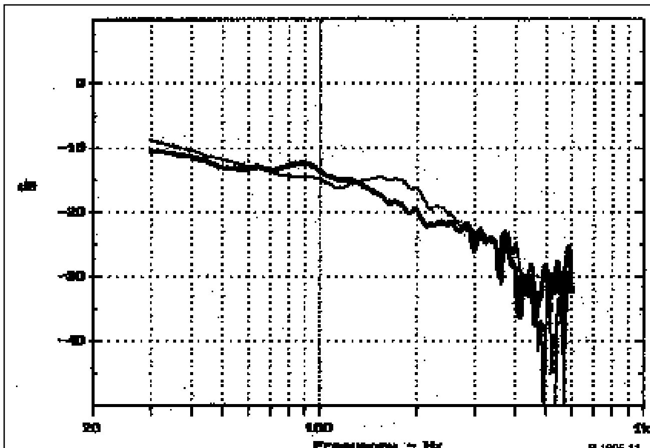

FIGURE 11: 6′ pipe transfer functions: 1.0 lb-density Acousta-Stuf versus 0.5 lb-density fiberglass blanket.

Which material is best? Each one shows deviations from ideal damping characteristics, and even with close-matching, these deviations may be audible. However, there are other factors to consider, such as consistency, availability, and ease of handling.

Ordinary fiberglass thermal blanket from three different sources seems to deliver consistent performance at packing densities of 1.0 lb or greater. Its unpacked density is about 0.6 lb/ft^3. However, it is nasty stuff to work with and seems more likely to shed fibers than Acousta-Stuf or polyester.

Polyester pillow stuffing seems to be fairly generic, but I don't know whether a batch from another manufacturer would match the performance that I measured using Poly Fluff. Over a useful range of packing densities, this is the easiest material to work with.

Acousta-Stuf is more expensive than the other materials, but its characteristics are closely specified. As delivered, it is ropy and must be thoroughly teased, especially at low packing densities. Otherwise, it is easy to use and does not shed.

Microfiber is like thistledown. Once compressed to the desired density it seems to stay in place. However, loose wisps drift around for days. If you use the brand name Celanese "Microfill," then its acoustical qualities should match my test results.

Any of these materials may be tricky to use in a large pipe requiring low packing density. Partitioning a fat pipe into two or more thin ones will help keep the stuffing in place and at the same time make the structure more rigid.

STUFFING VARIATIONS

Is there any practical way to increase pipe output in the frequency range of constructive summation while maintaining a steep rolloff at higher frequencies? You might follow Olney's example and use absorptive lining instead of stuffing. Consider a duct silencer. It contains very thick lining with a constricted air space in the middle. This arrangement provides minimal steady-state loss with high absorption above 100Hz or so.

I made a few test runs using thick lining, but it became obvious that in pipes of moderate size there simply isn't enough room to get the desired midrange attenuation. Moreover, in contrast to stuffing, it is almost impossible to develop general design guidelines. For these reasons, I decided to restrict this study to stuffed pipes. Some experimenters have combined lining and stuffing, but I don't see why the combination should be any more effective than the proper density of stuffing alone.

Graduated stuffing density is another favorite of experimenters. Some recommend higher packing density toward the pipe exit. Others insist that density should decrease from loudspeaker to exit.

It has long been known that a damped pipe can provide constant resistive loading over a wide frequency range if damping is light at the throat and steadily increases toward the exit. You can do this

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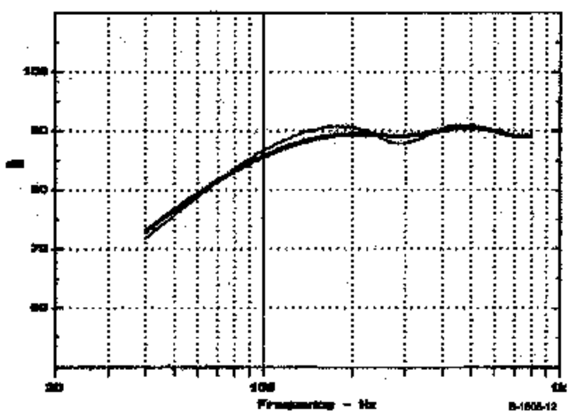

FIGURE 12: Overdamped pipe response: fully stuffed (bold) versus 0.8 length stuffed.

by varying stuffing density or by using a wedge of high-density fiberglass in place of stuffing. The latter configuration is often called a "terminated tube." It simulates the acoustic load of an infinite exponential horn and is used to test high-frequency drivers.

Constant attenuation at all frequencies is exactly what you don't want in a transmission-line loudspeaker system. However, when I measured a pipe with a fiberglass wedge, its behavior was not what I expected – not really worse or better than homogeneous stuffing. It deserves further experimentation.

Another interesting variant is to stuff only the first 80% of pipe length and leave the exit region empty. Once everything is readjusted for acceptable passband ripple, there is no net improvement. However, the comparative performance graphed in *Fig. 12* suggests that this can be a useful technique for final tweaking after an experimental design has been built. Once you have assembled a folded transmission line, it is almost impossible to adjust overall packing density. However, it is easy to add or remove stuffing near the pipe exit.

Experimenting with damping location and density can yield usable variations in response, but I have found no magic low-pass filters. The most practical way to improve transmission-line performance is to change the shape of the pipe, and that is what I'll discuss in Part 3.