EXPERIMENTS WITH TAPERED PIPES

BY DAVID B. WEEMS

"If you run into trouble, use the line as a dog house and design either a closed box or reflex enclosure for your woofer![1]" For champions of transmission lines who are disturbed by those frivolous words,[2] here is a peace pipe. Or, to be more specific, a tapered pipe. Like the labyrinth, the tapered pipe makes use of quarter-wave loading. Unlike the labyrinth, the driver is placed some distance from the end of the pipe.

Tapered pipes were popular in Britain years ago, but except for a small amount of damping material behind the driver, they were bare-walled. In fact, the designer of one 1960s pipe enclosure said damping material in the pipe would spoil the performance.[3]

The stuffed tapered pipe is an alternative to those designs. Voigt was the first to use the "stopped" pipe, which is similar in action to an organ pipe. In 1949, Ralph West developed the Decca corner speaker. Both systems had relatively small drivers.

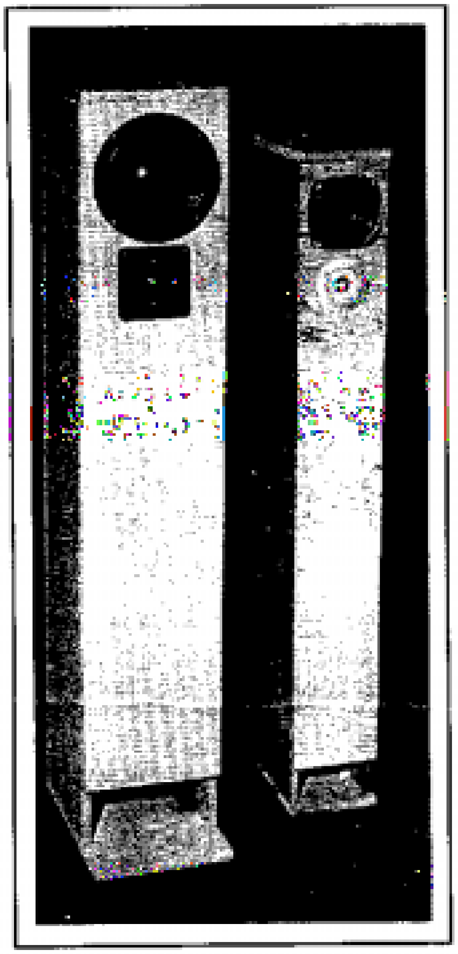

PHOTO 1: The tapered and damped pipe systems.

THEORY. The principle behind the pipe is shown in *Fig. 1*. The sketch in *Fig. 1a* shows relative pressure and velocity in a closed pipe at resonance. Pressure points occur at nodes, high velocity points at loops. If you mount a speaker at the closed end of the pipe (*Fig. 1b*), it will be loaded by the high pressure at that end, greatly increasing efficiency. Two problems hinder this arrangement. First, the pipe's fundamental frequency is so strongly favored, low frequency performance can sound like one-note bass. Another disadvantage is odd harmonics production. The first harmonic is the most serious, occurring at three times the fundamental's frequency (*Fig. 1c*). To correct it, place the driver at one-third the distance from the pipe's stopped end (*Fig. 1d*). At that point, the pressure will become somewhat lower than at the closed end, but still high enough to provide good loading at the fundamental. At the first harmonic frequency, the drive point occurs at a loop instead of a node, and output will be reduced.

Voigt[5] tapered the pipe to reduce the one-note effect and to spread the resonance over a band of frequencies (*Fig. 1e*). In later versions, the throat area was reduced to zero for smoother response and the driver installed at the midpoint of the line (*Fig. 1f*). More about that later.

The English builders of a generation ago designed their pipes for a single-cone 8" driver. Total cost of a driver and enclosure for one popular model was about £5, or at the rate of exchange in those days, about $14. The speaker fired upward at the rear wall so the highs dispersed around the room at a subdued level. In an attempt to restore the lost overtones, listeners applied treble boost. Some thought the arrangement's high frequency reproduction was inadequate. One asked, "Who put the blanket over the cymbals?" The problem of highs lost in the reflection process was compounded by the voice coil inductance in the single-cone speaker.

British builders almost always used ⅝" plywood to construct their pipes. Thick walls were unnecessary, they said, because their enclosures were stiffest at the point of greatest pressure. Some suggested using a slight degree of wall flexure because it would increase acoustic coupling near the fundamental frequency and damp air column resonances. Such statements, however, made pipe design seem more like magic or luck than science. Everyone seemed to agree on the necessity for tight joints. One author said a 1/16" gap in the driver mounting would reduce the output at 35Hz by a factor of four.[4]

About five years ago, after having ignored pipes because of their resemblance to the infamous "air coupler" of early US hi-fi days, I built a pipe for a dual cone 6" x 9" car driver featuring a 10 oz. magnet and foam suspension. The $7 speaker had an amazing bass re-

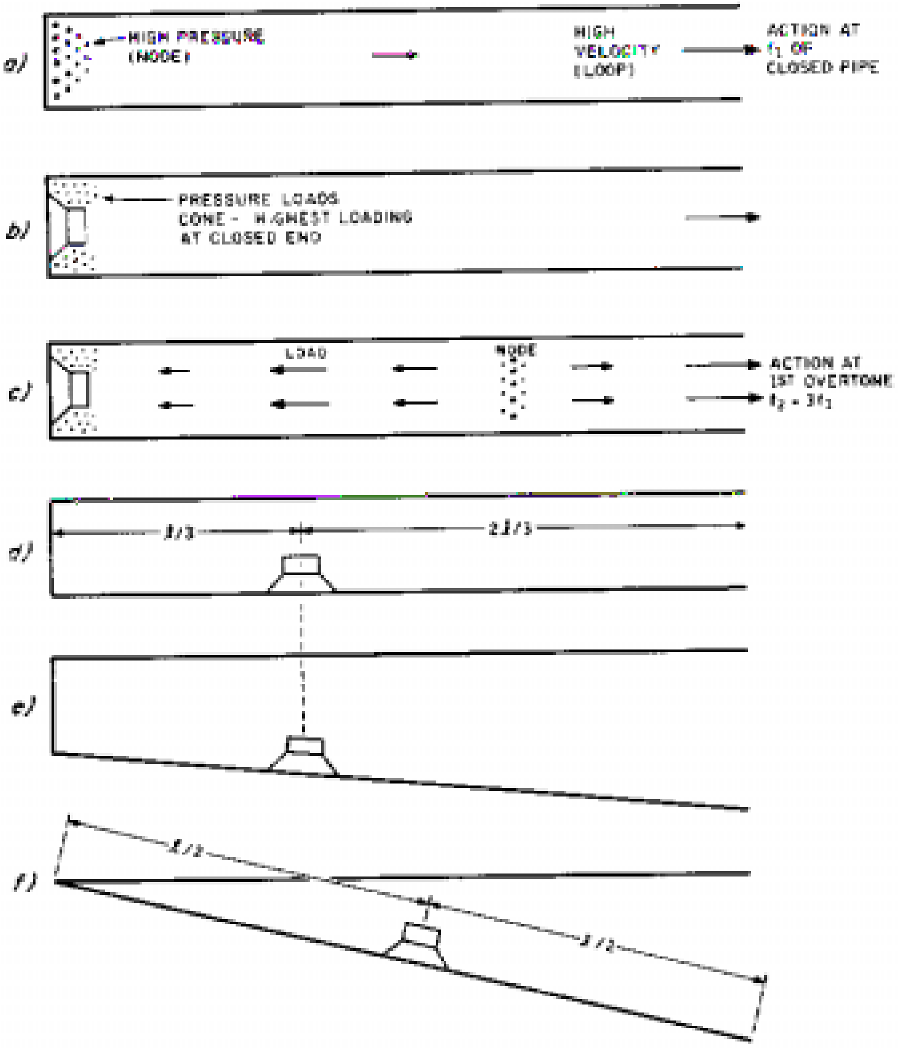

FIGURE 1: Various pipe systems. See text.

sponse in the pipe, but it also had some obvious peaks, the worst of which occurred at 95Hz and 220Hz. The 220Hz peak was probably caused by the second harmonic which arises at five times the pipe's fundamental frequency. A driver with a heavier magnet gave much smoother response in the 95Hz region, but showed no improvement in the higher resonance. I considered attacking the 220Hz problem with a Helmholtz resonator designed to absorb energy at that frequency, but other endeavors interrupted my plan.

Recently, while digging through abandoned projects in my shop, I discovered the old pipes and wondered how the principle would work with better drivers and with damping material in the line. To save time and material, I decided to make a miniature pipe for a 4" woofer, the Radio Shack #40-1022. I knew I could later apply my experience to larger systems, but first, I had to design the enclosure.

PIPE DESIGN. To design a tapered pipe system, you must choose appropriate dimensions for pipe length, throat and mouth area, and drive point. The fundamental frequency is almost totally set by one parameter—the total line length. The formula given for a labyrinth or pipe length is:

$$l = C/4f - 1.7r$$

where l is the length of pipe, C is the speed of sound in air, f is the pipe's fundamental frequency, and r is the pipe's radius or equivalent radius.

This formula, however, produces a longer than necessary pipe length. Opposing factors are at work here because tapering the pipe tends to raise the fundamental frequency, but folding and choking the mouth at the port lowers it. A bare pipe will usually perform as though it were about 30% longer than its measured length, and when you add damping material, it can seem even longer. As a rough estimate, expect the required length to be about 65% of the calculated length.

The pipe's cross-sectional area will vary from near zero to zero, to a maximum of about 2.5 times that of the driver's effective piston area. The pipe area should be about equal to the cone's area at the drive point, but ±20% is acceptable. The port area is typically equal to the cone area, or about 0.4 that of the maximum area.

Taper rate is one aspect of the tapered pipe that varies with driver size. A 4" woofer requires less than a third of the pipe area needed by a 9" driver. If a pipe for a 4" woofer was designed to have the same taper rate as that for the larger speaker, its total length would be 20". Even if it "acted" like a 30" pipe, the fundamental frequency would be about 100Hz. That is too high, even for a 4" woofer. You can neglect taper rate as a design factor for small drivers, but a low taper rate may demand more stuffing. If

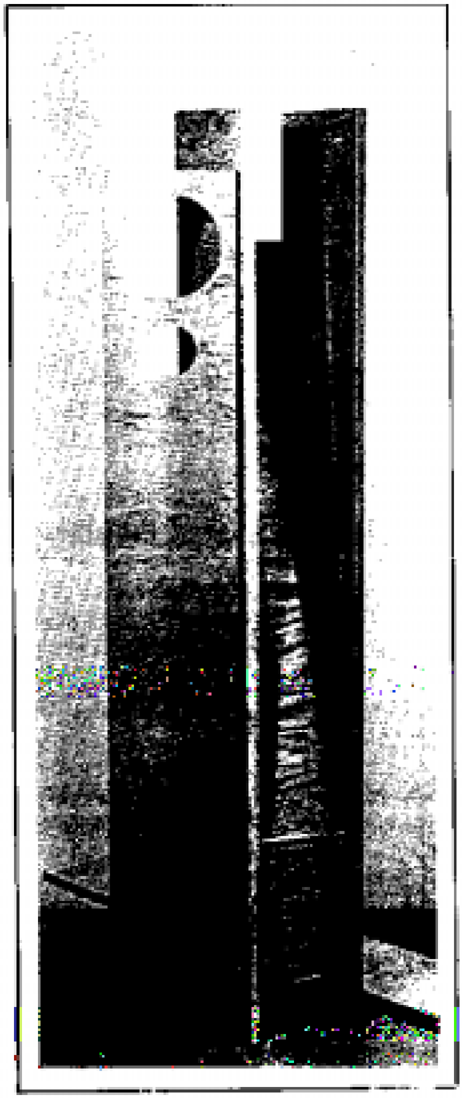

PHOTO 2: Internal construction of a tapered pipe.

you wish to experiment with bare pipes, use an 8" driver.

I made a quick guess at the proper length by setting the enclosure height at 3', which placed the drivers close to ear level. Unlike the British designs, I decided to mount the drivers in the conventional way, on the enclosure's front. To complement the Radio Shack woofer, I used a Radio Shack ¼" tweeter (#40-1376). The crossover for this simple system is nothing more than the high-pass capacitor that comes with the tweeter. An L-pad adjusted the tweeter level to match the woofer's rather inefficient level. Unlike conventional systems, however, I placed the tweeter below the woofer, a move which made more of an effect that I expected.

After drawing a rough design sketch, I noticed the drive point would be somewhat short of the mid-point from the throat to the mouth. You can only estimate the pipe length; the true acoustical length may be different from that estimate. The formula for optimum drive point distance from the throat is:

$$d = 1/(2 + \sqrt{A_t/A_m})$$

where d is the drive point distance from the throat, 1 is the pipe length, A_t is the throat's cross-sectional area, and A_m is the mouth's cross-sectional area.

The mouth is defined as the port area. The maximum area is that of the section just before the port. As you can see from the above formula, d can vary from one-third where the area of the throat is equal to that of the mouth, to one-half where the pipe tapers to zero throat area. Again, unless you use a straight pipe, you can only estimate the drive point's optimum location.

After doing some arithmetic, I found that by starting the throat at a point 6" above the mouth and using an initial area of 2"^{2} the pipe would approximate the formula for the drive point. The maximum area would be 24"^{2} which would be choked to 9.25"^{2} at the mouth (*Fig. 2*).

My final decision concerned the building material's type and thickness. For such a small pipe, ¼" plywood seemed adequate. But, because I had a supply of ½" material and because using ¼" plywood seemed like heresy, I opted for the thicker walls. If you wish to try a pipe system without damping material, try a thinner material.

Here is a quick summary of my construction methods, should you choose to follow them:

1. Cut out the parts and prepare to attach the partition to the sides with glue and nails.
2. To place the partition precisely, first set it in place on the inner surface of each side and mark an outline around it. Then, drill guide holes for nails down the center line of that outline.
3. After reversing the side, drive a nail into the partition through a hole at each end of the line of holes, just far enough to temporarily hold the partition.
4. Remove the side and spread glue on the matching surfaces. When you do the final nailing, the pre-nailed holes will ensure the parts don't slip out of place as you drive down the other nails.
5. After the glue sets, caulk the joints and install the front and back panels with silicone rubber sealer and nails. The sealer prevents air leaks on the joints you can't reach during internal caulking.
6. To make the top and bottom removable, install cleats inside the pipe to receive screws.
7. Gasket any removable parts with foam weather stripping or other sealer.

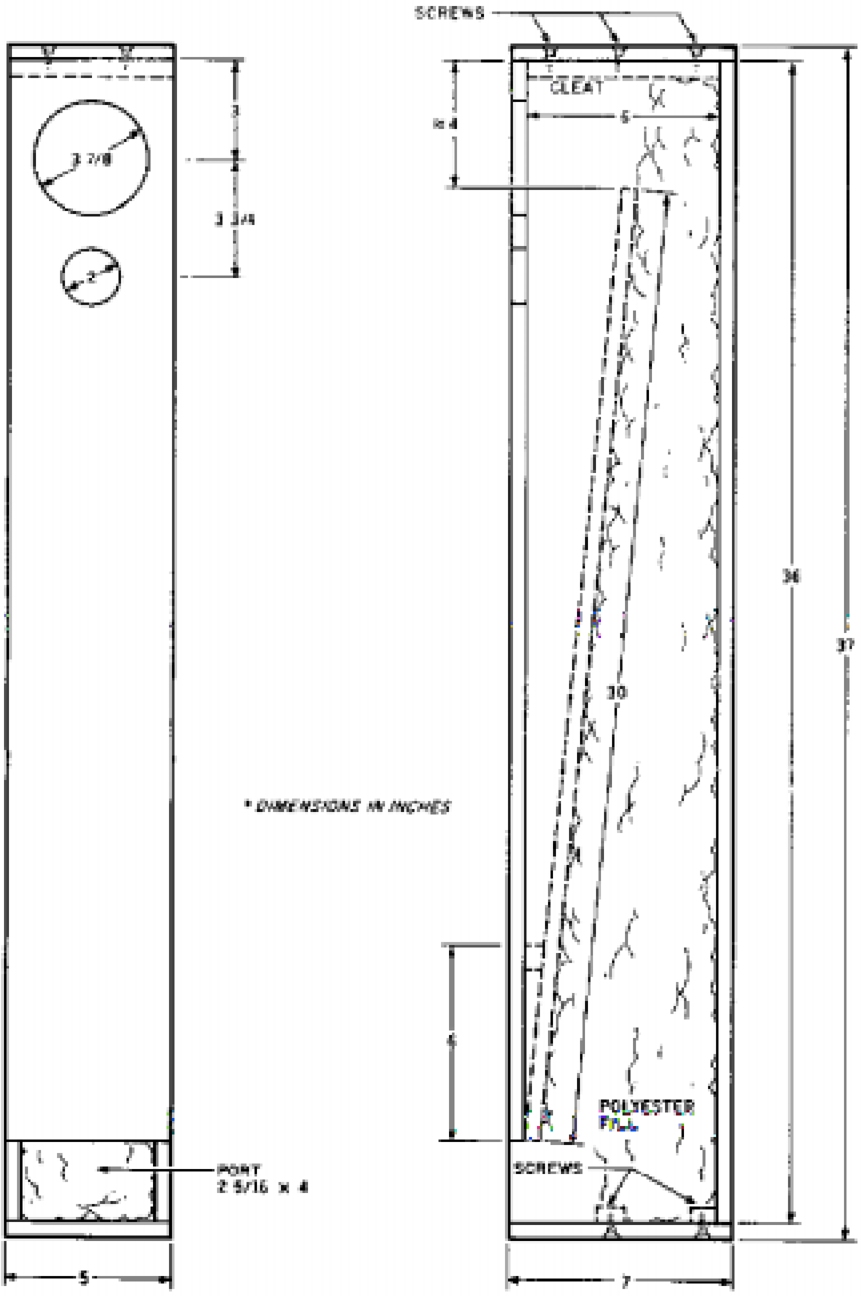

FIGURE 2: Dimensions of tapered pipe system for 4" woofer.

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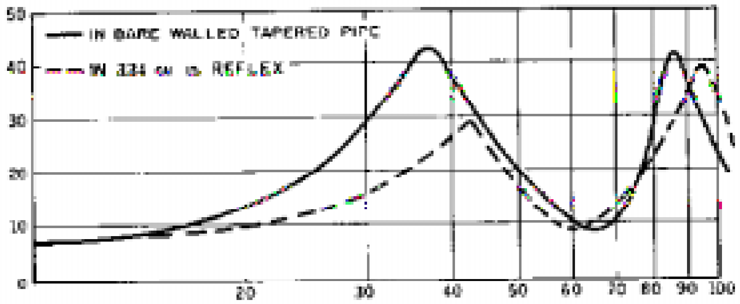

FIGURE 3: Impedance curves of 4" woofer in bare tapered pipe and in reflex.

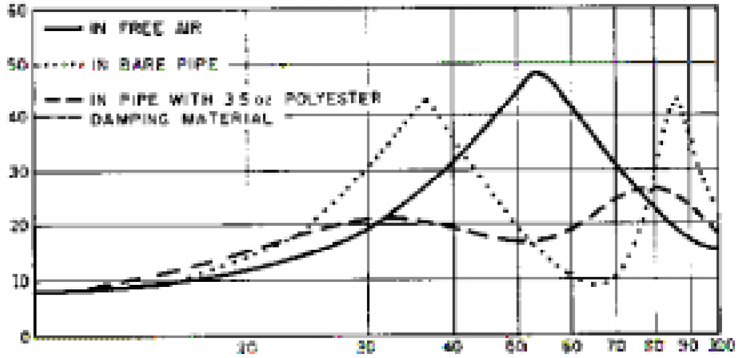

FIGURE 4: Impedance curves of 4" woofer in free air and in pipes.

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TEST RESULTS. In *Fig. 3*, the impedance curve of the 4" woofer in a bare pipe looks similar to the same model woofer in a reflex. As I discovered later, the woofers behaved significantly differently in some tests. Some writers call the impedance peaks in tapered pipes "resonances," but Baldock claims the term resonance isn't appropriate because a reactive component is present.[2] When I ran an oscilloscope test on bare pipes, the ellipse closed to a straight line at the peaks and valleys of the impedance curves. After I added damping material, the ellipses remained open. The lower peak was likely produced by cone loading from the air in the pipe, while the upper one was likely caused by enclosed air stiffness behind the cone.

If you analyze the curves for the woofer in free air and in the pipe, you'll see the lower peak in the pipe occurs at about 37.5Hz, whereas in free air, the single peak is at 53Hz or 1.41 times that of the pipe. This ratio tells you the air load mass in the pipe is approximately equal to the mass of the cone itself.

On listening tests, the bare pipe produced a hollow, ringing sound, particularly on male voices. When I conducted a rough frequency test, significant peaks and valleys occurred in the region below 500Hz. So, I lined the pipe area behind the woofer with a 1" layer of acoustical fiberglass on the sides, back, and under the top of the enclosure. I then noticed some improvement in the listening tests, and a considerable difference in the 200–500Hz frequency response test.

I added loose wads of polyester batting to the pipe, placing ¼ oz. in the throat, filling the space behind the woofer, and then gradually increasing the amount in the large section of the pipe. With each addition, I monitored the progress with impedance and listening tests.

You can stuff the pipe until the impedance curve shows a single peak, like that of a closed box speaker. The peak frequency, however, will be lower in the pipe than in a closed box. In my case, the single peak occurred at 60Hz. After stuffing and restuffing, I arrived at what seemed to be a good compromise between under and overstuffing: a total of 3½ oz. of batting. My pipe's internal volume is 0.5 ft^3, not including the volume occupied by drivers, partitions and cleats. Therefore, the rate of fill is probably about 8 oz. per cubic foot. The impedance curve for that condition is shown in *Fig. 4*.

After the final stuffing, I compared the pipe speaker performance with drivers of the same model in a closed box and a reflex enclosure. The closed box was clearly superior to the other two in one respect. With a total volume of only 140 in^3, it occupied the least amount of room space. The reflex had a volume of 334 in^3 and was tuned to 60Hz.

I then conducted nearfield microphone tests, which showed the three systems performed similarly in the 80–100Hz range. Listening trials, however, told me a different story about bass range perception. The closed box speaker was clearly more limited in low frequency response. (Nearfield technique doesn't register the output of ports removed some distance from the woofer.)

When listeners compared the reflex with the pipe, most initially thought the reflex had a bit more bass than the pipe. After longer and more careful listening, however, their conviction waned because the pipe speaker performed better on the lowest frequencies. Frequen-

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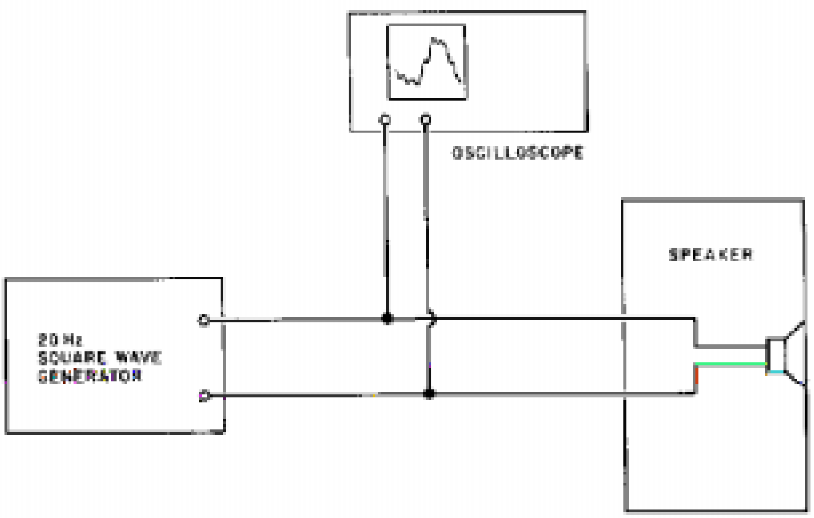

FIGURE 5: Test setup to measure hangover.

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cy response tests confirmed this conclusion. The reflex had slightly more output in the 70–100Hz range, while the pipe was clearly superior below 60Hz.

An interesting way to compare speaker performance is to feed a 20Hz square wave to the speakers and observe the patterns produced on an oscilloscope. This simple test setup is shown in *Fig. 5*.

The pattern will alter according to the resonance frequency of your speaker and its degree of damping. The lower the resonance frequency, the fewer the number of oscillations that will show on the trace. The oscillations' amplitude, however, will also vary. I used this method to test four identical woofer models: one in free air, then again in free air with a blob of modeling clay (whose mass was equal to the cone's mass) stuck to the cone; and three other woofers in the three types of enclosures I mentioned earlier.

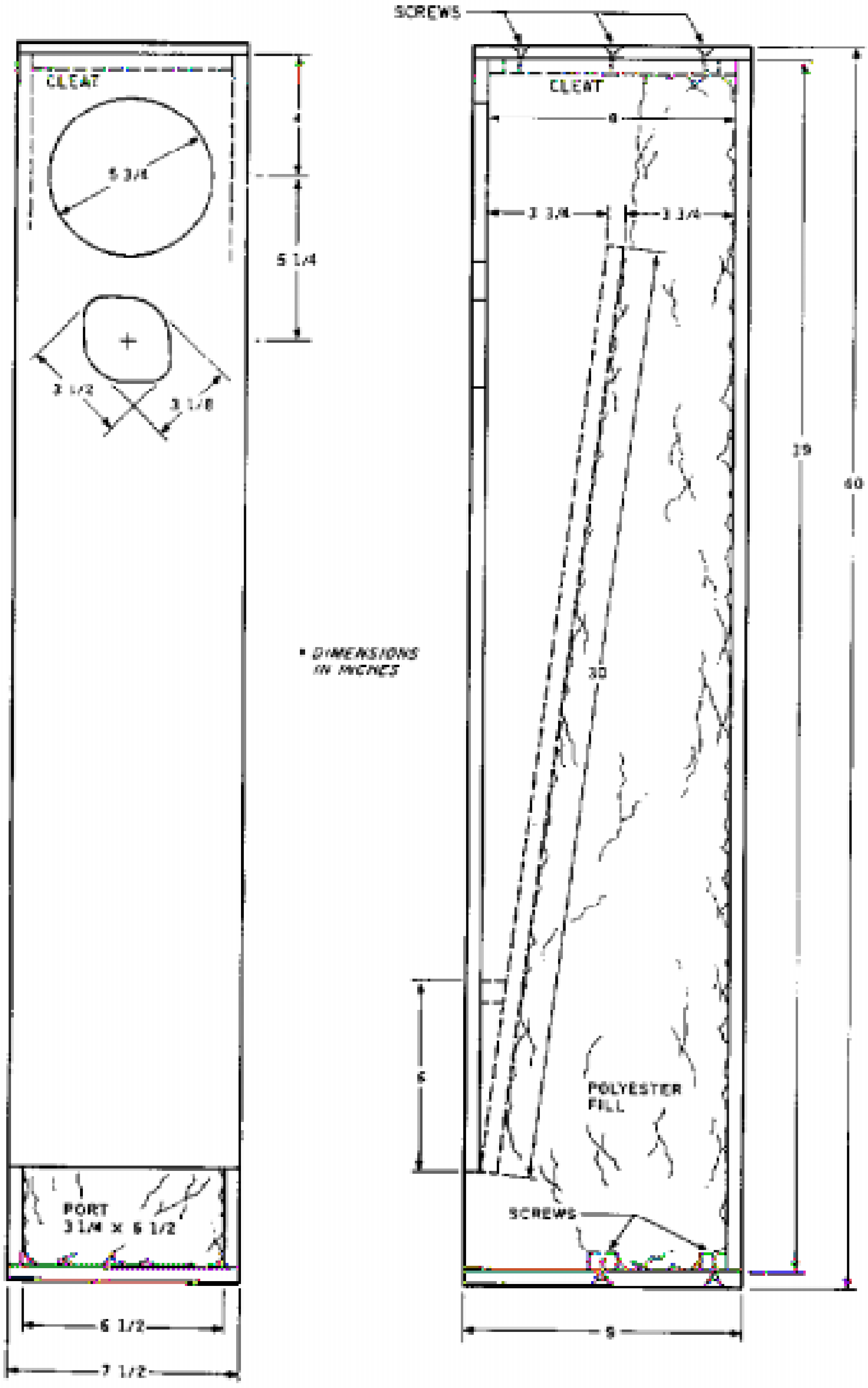

FIGURE 6: Dimensions of tapered pipe for 6½" woofer.

Before you examine my various pattern photographs, be aware my oscilloscope exhibits considerable droop when it is fed a 20Hz square wave. That droop may be caused by a too small coupling capacitor, but whatever the reason, it is constant. If your instrument's controls are unchanged during the tests of various speakers, consider the comparisons valid.

The pattern in *Photos 3a* and *3b* indicate, as expected, the driver cone moves farther in free air than when installed in an enclosure. Little change occurred in the two free air tests, except for the lower resonance frequency in the one I conducted after I added mass to the cone. The trace for the closed box woofer (*Photo 4a*) shows decreasing oscillation amplitude, but the reflex's trace (*Photo 4b*) indicates little amplitude change. The pipe speaker (*Photo 4c*) shows a single pulse movement, about half a sine wave, then very little hangover. I took *Photo 4c* after I added damping material to the pipe, but the woofer in the bare pipe's trace was almost identical except for a small deflection at tail's end.

To test the woofers in the three kinds of enclosures, I fed each a 55Hz sine wave signal from an audio generator through a tone burst generator and an amplifier (*Photos 5a–5c*). In fairness to the reflex speaker, it had no more overshoot than the pipe speaker at frequencies above 80Hz, and only slightly more at 70Hz. The pipe speaker was at least equal to the others at all frequencies, except at 180Hz where it showed a bit more hangover.

After reviewing the experiments with the 4" woofer, I decided the tapered pipe system deserved further testing with a larger woofer. With that in mind, I began to work on a pipe designed around the Peerless TP165F.

SECOND DESIGN. Peerless lists the TP165F's effective piston area at 12.45×10^{-3} square meters, or about 20 in^2. I made the internal dimensions 6½" x 8", putting the pipe's theoretical maximum area at 52 in^2. By using ½" material, the minimum outside dimensions are 7½" x 9." Because pipes are so compact, they occupy very little floor space and yet do not require stands. On most floor surfaces, however, you may wish to enlarge the bottom board to add stability to the tower. Extend the board beyond the enclosure's front to counter gravity's pull on the front-mounted drivers.

For easy pipe construction, place the tweeter below the woofer, as shown in *Photo 1*. Ironically, a tall enclosure, with the tweeter at ear level, should have the

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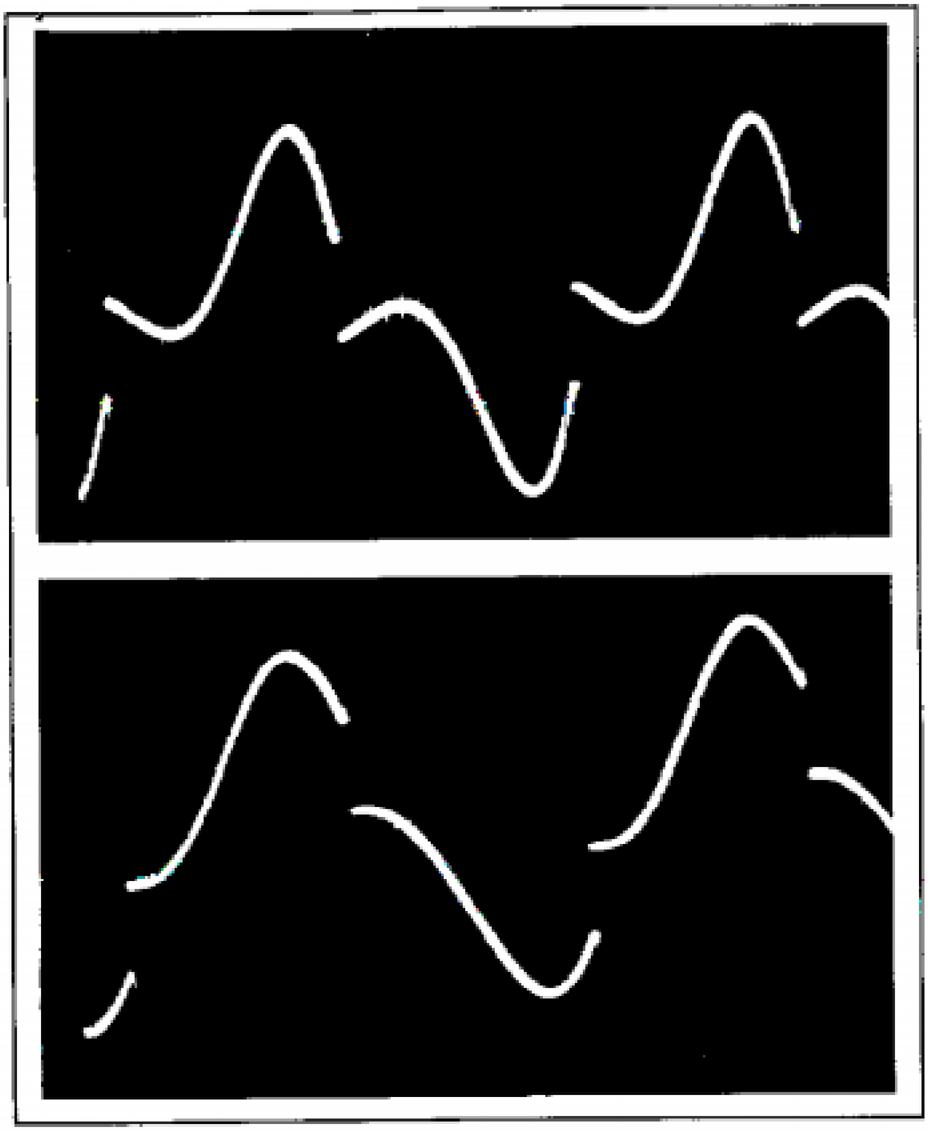

PHOTO 3: Square wave test on a 4" woofer in free air (a), and with mass added to cone (b).

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tweeter above the woofer. When I planned my design, I overlooked one effect of placing the tweeter below the woofer. Although, as you will see, I later solved the problem to my satisfaction, consider placing the tweeter outside the pipe, on top of the tower. This decision will depend on your personal preferences as you weigh performance against appearance and construction ease.

I increased the larger pipe's length in an attempt to extend the bass range. Except for loading the driver to a lower frequency, however, I doubt whether it made much improvement. Again, I had to do some arithmetic to estimate the optimum drive point. My figures indicated I should begin the throat about 6" above the mouth, with an initial area of slightly under 5 in.^{2} You can do this by gluing a ¾" strip across the front of the partition, at the point where it will make contact with the rear of the front panel.

I ran the usual tests with various amounts of damping material and settled on a lighter optimum packing density than I had used on the smaller pipe. The final amount was a square foot of 1" fiberglass on the surfaces behind the woofer, an ounce of polyester batting in the throat, and 5 oz. in the remainder of the pipe. Although the density was lower than for the smaller pipe, the impedance curve was similar (*Fig. 7*).

The larger system's bass performance was promising from the start, but something about the sound wasn't right. At first, I was tempted to blame the tweeter, a German-made MBM25S I obtained from McGee Radio, but later tests proved me wrong. As it turned out, I had several problems, some of which involved the crossover network.

EVOLUTION OF A CROSSOVER. My first crossover network choice was a second-order APC (all-pass crossover) described by Bullock.[5] My enclosure design had placed the woofer-tweeter center-to-center distance at 5¼", so I planned to put the crossover frequency below the point where that distance was equal to a wavelength, or under 2.6kHz. With that in mind, I chose a crossover frequency of 2.2kHz.

At first, the system sounded loud—an ominous symptom. The problem turned out to be a rise in output between 800Hz–1.8kHz, so I made a filter to smooth the woofer's response in that range. The filter transformed the sound, helping the speaker to wear well in long listening sessions. But one abnormality remained: the vertical response was not uniform when I stood in the sound field and then sat down. Even people who liked the anomaly mentioned it. "It sounds sweeter when you sit down," one person remarked.

When I checked the frequency response at various elevations, I found a null in the 2.6kHz region at ear level while listening from across the room. I realized that when I placed the tweeter below the woofer, it tipped the axis upward (*Fig. 8*). At standing ear level, the null was replaced by a smooth response. Surely, the crossover network was in-

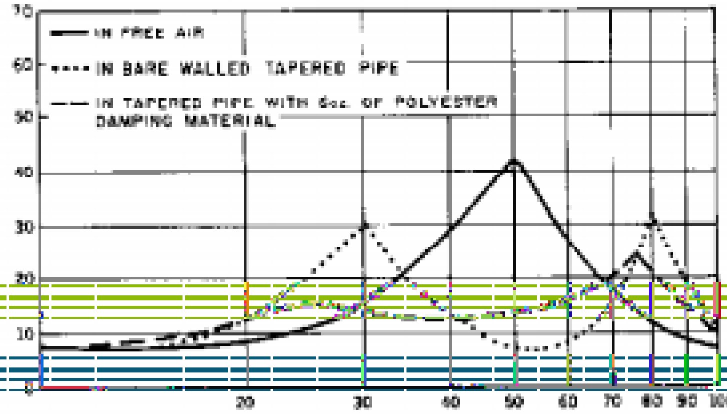

FIGURE 7: Impedance curves of 6½" woofer (Peerless TP165F) in free air and in tapered pipes.

volved, but the problem was caused by a combination of factors that made the woofer's realized rolloff rate different than that predicted by the second-order filter.

I measured each driver's response, substituting a resistor in the crossover network for the muted driver. In the 2–3kHz band, the woofer's and tweeter's output were equal.

I had several solutions to choose from. An obvious one was to use a higher order crossover. Having already made up a set of crossover networks, I tried to salvage them with notch filters, tuned to 3kHz, in the woofer circuit. The first filter, made with a 0.25mH coil and an 11μF capacitor, did not provide enough cut. So, I made up another set, using 1mH coils and 3μF capacitors. They solved the problem, but I wondered whether a simpler method could give me an acceptable performance.

Throughout the tests, I tried nearly every option, including reversed driver polarities. Finally, a single, larger-than-normal inductance in the woofer circuit offered promise. So, I reduced the crossover frequency to 2kHz and made up a third-order filter for the tweeter. When you consider the woofer's impedance with the Zobel in its circuit is about 6Ω, the calculated value for a single inductance is about 0.48mH. Instead of deriving the value from calculations, I set up the speaker outdoors on a quiet day and ran microphone tests with various values of inductance. The one that produced the flattest curve turned out to be 1mH, more than twice the indicated value. This, however, is not a rare conclusion.

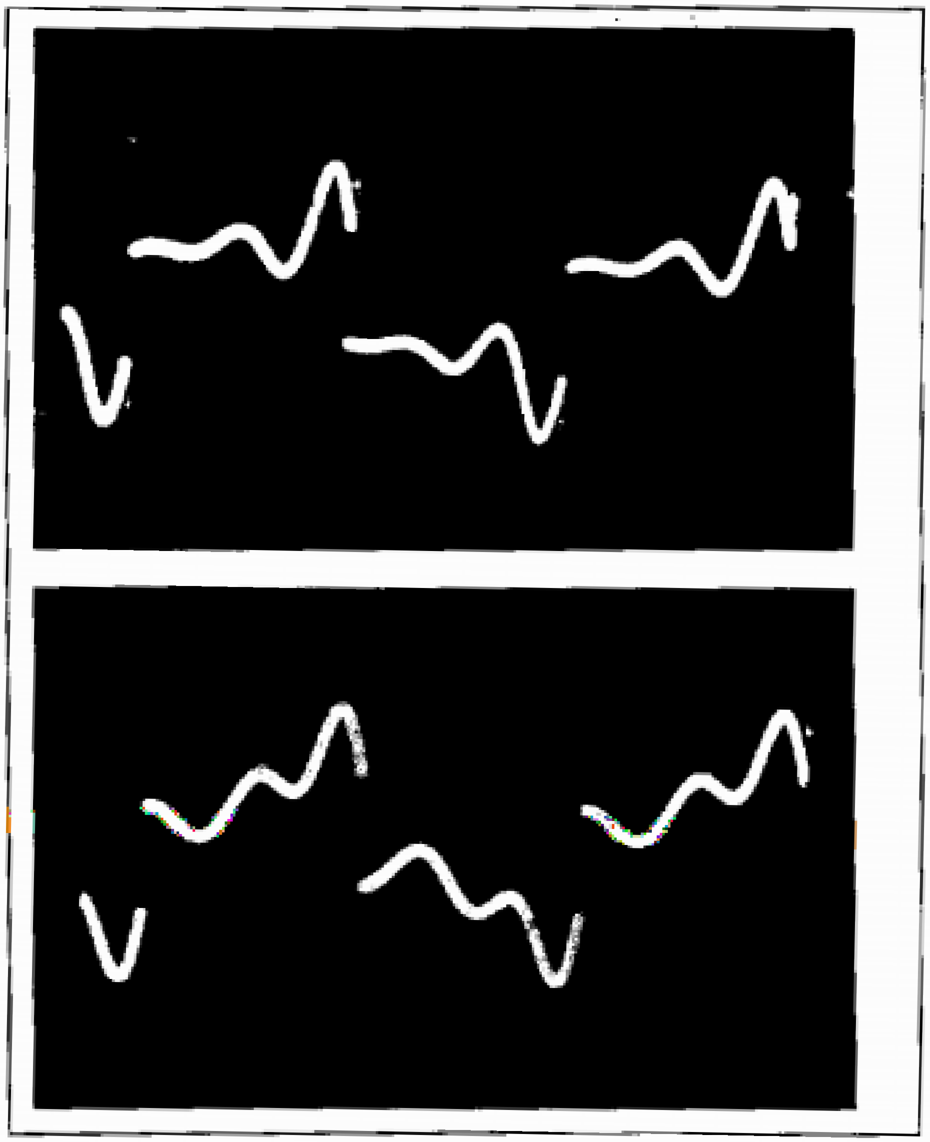

PHOTO 4: Square wave test on 4" woofer in closed box (a), in reflex (b), and in tapered pipe (c).

RESONANT PEAK FILTERS. The MBM25S gave a good performance, but I found it had one peculiar trait. Even with a third-order network, a considerable output from the tweeter occurred at 1.1kHz—its resonance frequency. The obvious fix seemed to be a resonant peak filter.

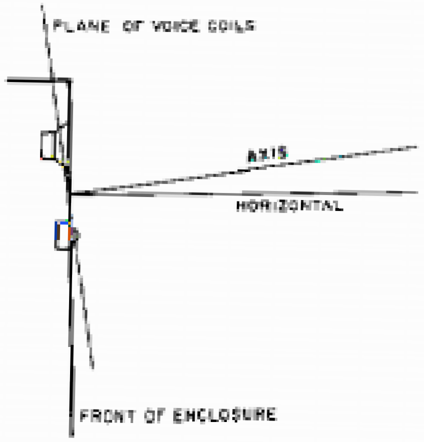

FIGURE 8: When the tweeter is installed below the woofer, as shown in the plans, the axis tips upward.

The *Loudspeaker Design Cookbook*[7] (LDC) lists the following formula for resonant peak filters:

$C = 1/15.2\,f$
$L = 1/39.48\,f^2C$
R = approximate rated driver impedance.

Filters produced by this formula are effective in removing the peak, but they can also effect a lower than desired impedance in the octave above resonance. In those cases, you need a higher Q. A formula that usually works well is:

$$C = 1/50f$$

You can compute the other values from the *LDC* formulas. If possible, choose the final values by experimenting. I used the formula above to make up the RPFs (resonant peak filters) suggested in the crossover diagram (*Fig. 9a*). You will need a different RPF (*Fig. 9b*) for the MCD25M, the more expensive titanium tweeter made by the MBM25S's German manufacturer. For either tweeter model, the combined impedance of the RPF, L-pad and tweeter is about 6Ω, so the same crossover values will work on both.

While the wiring diagram shows reversed polarities for the drivers, putting the drivers in phase will make for a slightly more uniform response at crossover. Unfortunately, it also raises the level a bit at 1.8kHz. Going back to the reversed condition will shift the boost upward on the axis, leaving a slight dip at crossover at ear level when you're listening while sitting. Unlike the earlier problem, however, the dip is too shallow to be noticed by most listeners. Another solution is to move the tweeter to a position on top of the enclosure. A small baffle here should give you improved horizontal distribution.

The tapered pipe, with its low cost and construction ease, should be a contender in the enclosure race. It does require a bit more tinkering with damping material than a simple box, but challenge is part of the game.

The damped pipe has several advantages over the bare pipe, including one that might not be obvious. In 1963, Alan Lovell, news editor of the British magazine *The Tape Recorder*, heard unusual noises coming from one of his tapered pipe enclosures. After analyzing the sound, he found his cat had crawled into the pipe and was stuck. He called and called, the cat howled and howled, but it didn't move. Mr. Lovell had to take his enclosure apart to get the cat out. Another builder reported the first time his cat saw a tapered pipe, it went right into it.

As a result of these incidents, warnings were issued for builders to place screens over their pipes' ports. So, if you run into trouble, don't expect to use the discarded pipe as a cat residence. But, if you know anyone who has a pet snake...

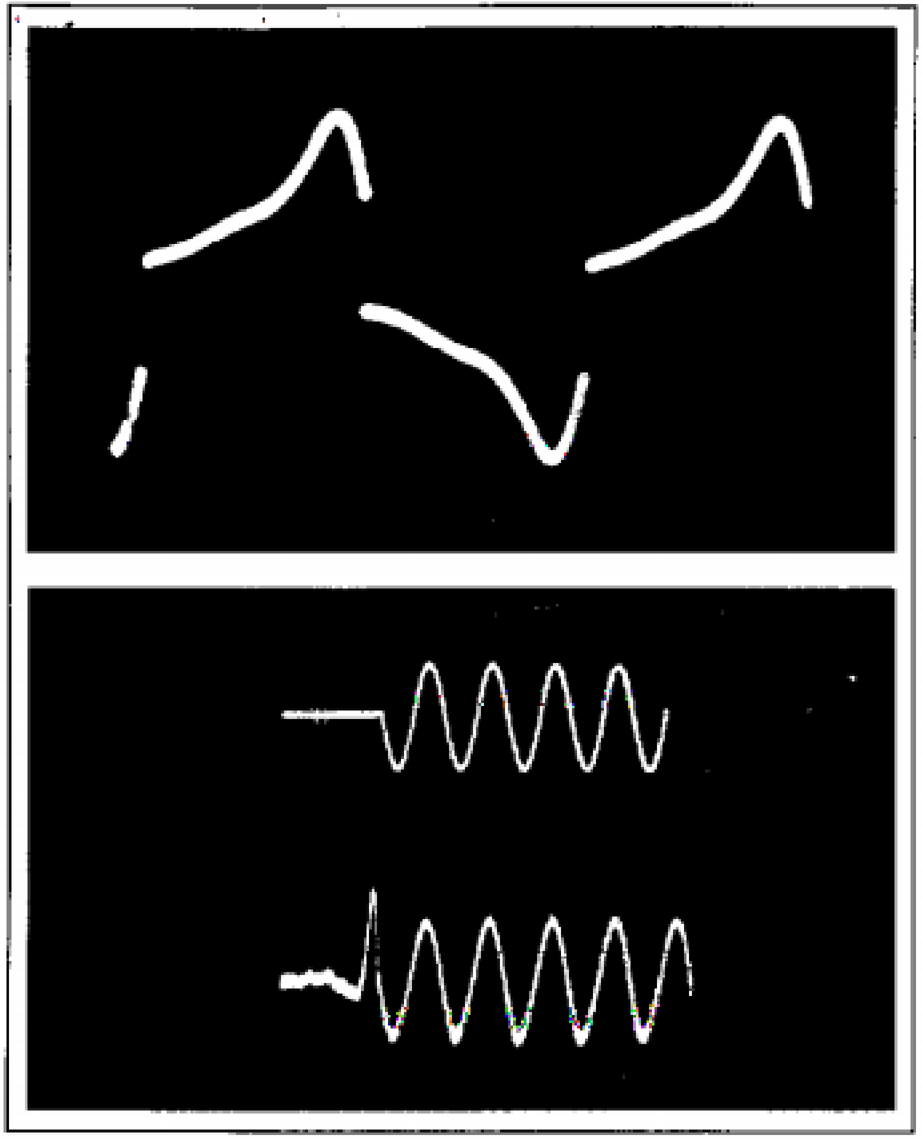

PHOTO 5: Tone burst test on 4" woofer in closed box (a), in reflex (b), and in tapered pipe (c).

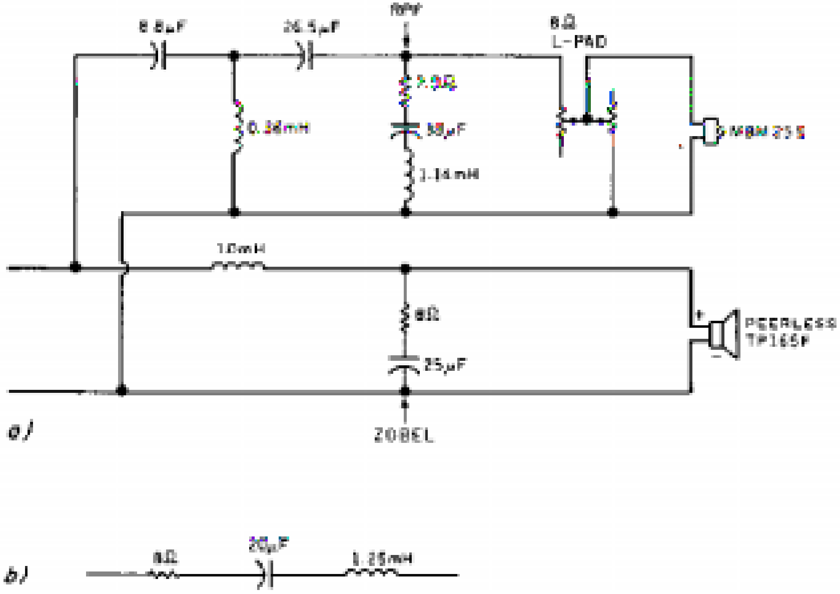

FIGURE 9: Crossover network for Peerless TP165F woofer and MBM25S tweeter [crossover frequency 2kHz] (a), and the RPF you should use with an MCD25M titanium tweeter (b).

ABOUT THE AUTHOR

David B. Weems began experimenting with speakers in the 1950s and has published speaker projects in many periodicals including Popular Mechanics. *He is the author of* How to Design, Build & Test Complete Speaker Systems *(Tab Books #1064, out of print) and* Designing, Building & Testing Your Own Speaker System, *2nd Ed. (Tab Books #1964).*

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