Back

Omega Quarterwave Reflex

Louder, flatter, lower! Knowing driver fs, Qts, and Vas, reading some graphs, and doing some simple algebra allows you to design the right omega quarterwave reflex pipe for any driver.

By Rick Schultz

Alpha transmission line and omega quarterwave reflex are unique and separate from prior quarterwave approaches because you are able to design a very good quarterwave system based solely upon Thiele-Small parameters (TSPs). Omega quarterwave reflex (ΩQR) is a new type of pipe made by a few simple modifications to alpha transmission line (αTL) design. It delivers about one octave deeper bass response and flatter mid-bass performance. The size of the omega quarterwave reflex pipe remains very reasonable.

Figure 1 compares the response and impedance of the two pipes using the same driver I used in "Alpha Transmission Lines" (*aX* August 2003), the Jordan JX92S. Notice the flattening between 80 and 400Hz. Low-end performance change is powerful. The flat response continues into the upper 30s. The impedance curve of the ΩQR is smooth but not as smooth as the αTL.

"Omega quarterwave reflex" is a new term. Its design falls between alpha transmission line and bass reflex systems, showing evidence of both systems. I choose this term to recognize the two most apparent and critical characteristics of ΩQR pipes: length and aperture. Length defines quarterwave resonance. Reduced aperture size provides the reflex for more power.

In my alpha transmission line article, I list specific transmission line properties. The first three are:

* Driver attached to the closed end of the pipe
* Open end of the pipe is completely open
* Internal stuffing fills the entire length

Both αTL and ΩQR pipes have straight parallel sides. This keeps construction simple. Adjustments you can make to transform a transmission line into a quarterwave reflex are:

* Stuff two-thirds of the pipe
* Move the driver down the side of the pipe
* Reduce the aperture area

Aperture output brings about flatter and deeper response. **Figure 2** compares the opening output of the αTL and the aperture output of the ΩQR; arrows mark the changes. ΩQR pipe adjustments suppress midrange output 4dB

FIGURE 1: Response and impedance comparison.

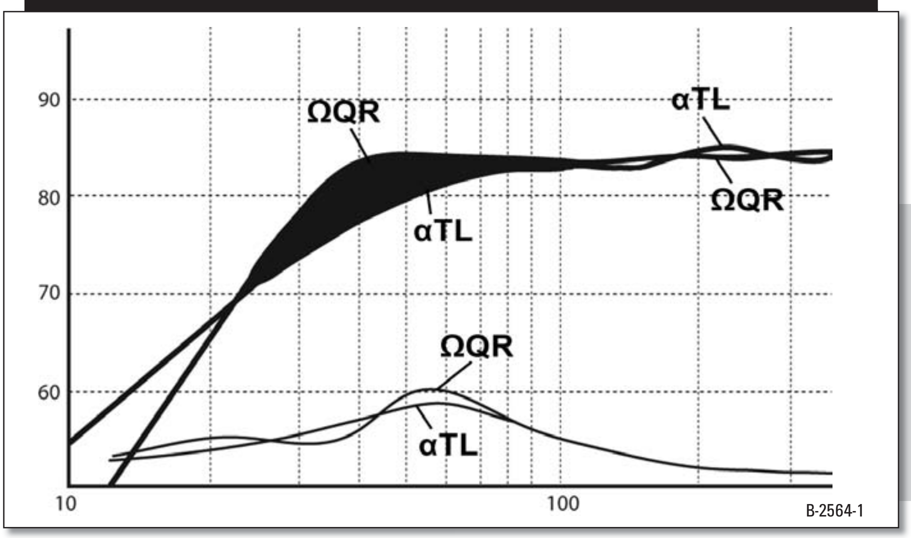
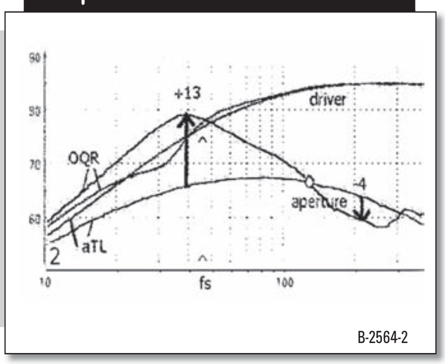


FIGURE 2: Driver and aperture response.



between 180 and 280Hz. Another arrow marks the 13dB improvement at 37Hz. The αTL opening energy is broader and higher than driver fs; the ΩQR aperture energy is narrower and lower than fs.

OMEGA QUARTERWAVE BASICS

Omega quarterwave reflex systems are resonant pipes closed at one end and open at the other. An unstuffed pipe's fundamental resonates at the speed of sound divided by [four times length], written c/4l. Unstuffed pipes suffer from the problem of pipe harmonics (**Fig. 3**).

All unstuffed quarterwave pipes sound dreadful! In addition to the fundamental fΘ, which I want, unstuffed pipes have many other peaks in response. They occur at odd multiples of the fundamental, written nc/4l, where n is an odd number: 3*fΘ, 5*fΘ, 7*fΘ, and so on. I identify these harmonics as 3Θ, 5Θ, 7Θ, and so on.

Figure 3 demonstrates the response of the JX92S in an unstuffed TL. The upper line in **Fig. 3** marks opening output. The tall peak near 140Hz is the 3Ω harmonic.

Notice how this pipe harmonic affects the rest of the performance. The driver has a narrow null in response also near 140Hz. This appears as the sharp downward dip in the driver response line directly below the peak in the opening line. "Null" means a dramatic quieting of sound. The driver barely moves and makes little sound of its own at a null. The electrical signal to the voice coil produces sound mainly through the opening at a null.

The bottom of the graph shows impedance. Notice the impedance spike at the 3Θ harmonic frequency. Every subsequent pipe harmonic displays the same effects on driver and impedance.

STUFFING ADJUSTMENT

Many adjustments have been tried to tame the wild and harsh harmonics of a quarterwave pipe. For a pipe to work properly, the 3Θ harmonic must be reduced so it is at least 18dB below driver output. If 3Θ is quieted to this level, higher harmonics at 5Θ, 7Θ, and beyond are usually quieted.

Recall that an αTL pipe uses stuffing along the entire length to approach this -18dB target. Unfortunately, over-stuff-

FIGURE 3: Unstuffed quarterwave pipe.

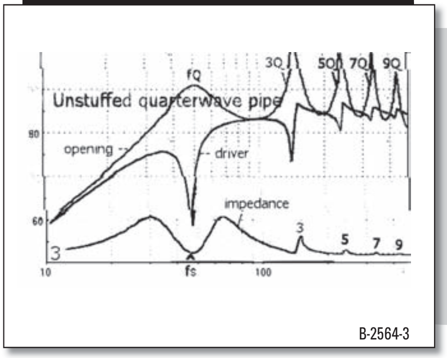
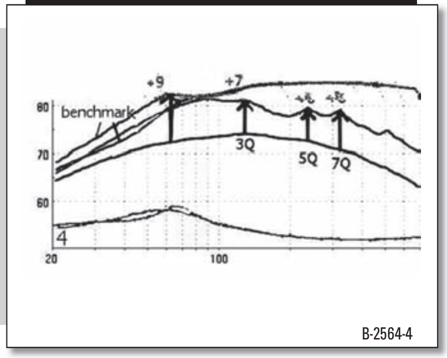


FIGURE 4: Pipe stuffed two-thirds length.



ing quiets the fundamental. Most transmission line builders add or remove stuffing by ear until they reach an acceptable balance between a helpful fundamental and quiet harmonics.

Stuffing near the opening inhibits air movement and quiets the fundamental (fΘ). Clearing stuffing away from the opening allows considerable air movement at the open end of an omega quarterwave reflex.

Stuffing only two-thirds of the pipe leaves the open end clear, allowing air to move freely about the opening. **Figure 4** compares a pipe stuffed two-thirds its length to a pipe stuffed the entire length. Opening output from the two-thirds stuffed pipe operates louder but unevenly compared to the fully stuffed pipe.

Focusing on the two-thirds stuffed pipe, the fundamental near 60Hz improves noticeably by a very useful +9dB. Unfortunately, harmonics increase awkwardly. Peaks average +7dB compared to the pipe stuffed the entire length. This two-thirds stuffing adjustment has its benefits and drawbacks.

The first significant pipe adjustment—stuffing two-thirds of the pipe—improves low frequency efficiency. This two-thirds stuffed pipe will be the benchmark, the point of reference going forward (see Benchmark sidebar). Successive adjustments extend low end response and smooth the high-side ripples.

DRIVER ADJUSTMENT

For decades, builders have placed the driver at the closed end of a straight quarterwave pipe. Eventually, they moved the driver down the side of the pipe. Many suggest moving the driver down the pipe one-third of the length. A few suggest moving the driver only one-fifth the distance. Still others determine placement by trial-and-error.

In **Fig. 6**, the upper opening line depicts the benchmark pipe output. The second, lower opening line shows the same pipe with the driver moved to one-third of length.

This driver adjustment flattens driver response between 70 and 200Hz. Driver performance dips 1 or 2dB at the low end below 60Hz. In this under-stuffed pipe, moving the driver down one-third the length quieted the 3Θ harmonic 9dB. Unfortunately, the 5Θ peak remains strong. The fundamental also dips only 1 or 2dB. Setting the driver at one-third is worthwhile but there are minor drawbacks.

Wondering what might happen by setting the driver at a point where it does not interact with harmonics, I set the driver at the “golden ratio” point; that is 0.618. I set the driver 1.0-0.62 or 0.38 length from the closed end. See **Fig. 3** for the results.

The results are actually worse than at one-third. The 3Θ harmonic quiets only 7dB. The 5Q harmonic is not quieted in the least. Higher harmonics are barely affected. Low-frequency response remains the same as in **Fig. 6**. This is heading in the wrong direction.

What about another spot? I set the driver at one-fifth length to suppress the 5Θ harmonic. I expected that the pesky 3Θ wave would still be there, wouldn’t it? See **Fig. 7** for results.

There is no low-end loss near 60Hz. The 5Θ harmonic quiets -12dB compared to the benchmark. Higher harmonics are never worse than the benchmark. This looks good. As a bonus, even the 3Θ harmonic quiets -3dB. One-fifth placement shows some promise.

Both one-third and one-fifth placements have advantages. We’ll reconsider driver placement when all adjustments come together at the end of this article.

LOAD ADJUSTMENT

My goals are to get as much useful low frequency air movement as possible from the open end plus the flattest possible frequency response from the system. So far, the two-thirds stuffing adjustment produces a system fundamental near 60Hz. The low end does not change much whether the driver is at one-third or at one-fifth length.

The wide-open, unstuffed end of the “under-stuffed” benchmark system does not play low enough. Since driver fs of the Jordan JX92s is 45Hz, I hope to go lower than 60Hz, which would be a significant improvement over αTL design.

The last adjustment “loads” the pipe. By reducing the size of the opening, the driver does more work moving air back and forth through the opening. As the pipe opening becomes smaller, it increases the load on the driver, as

FIGURE 5: Driver at one-third length.

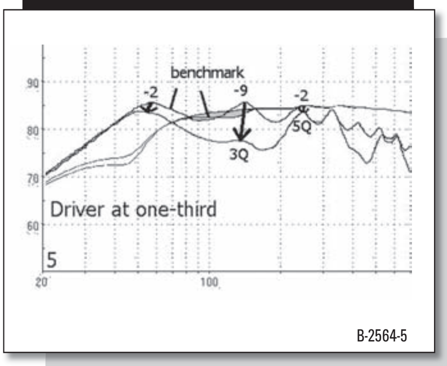


FIGURE 7: Driver at one-fifth length.

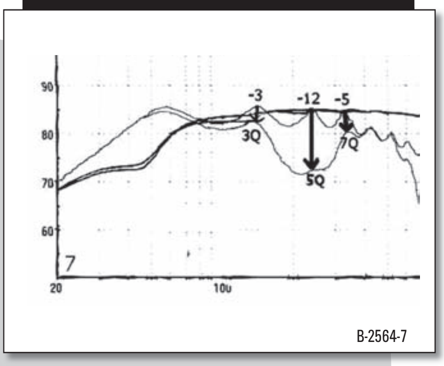


FIGURE 6: Driver at golden ratio.

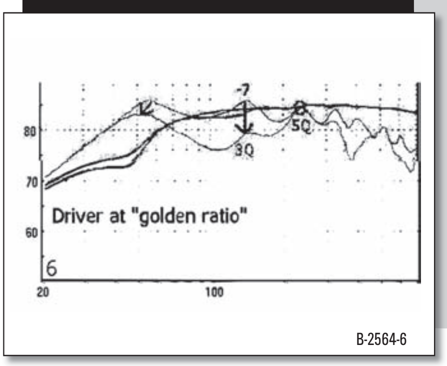
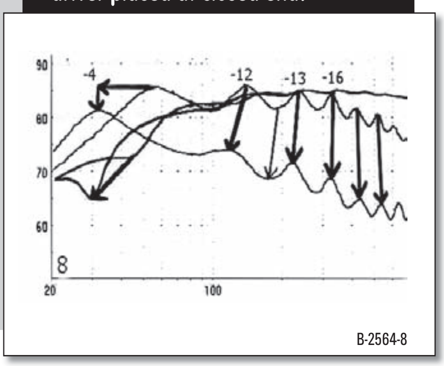


FIGURE 8: Aperture loaded pipe with driver placed at closed end.



though the air at the aperture has more mass.

Setting aperture at a fraction of cross-section area changes performance in a powerful way. From experience, I know the opening needs to be reduced considerably to have the desired effect. Using one-tenth seemed a reasonable start.

Figure 8 compares the benchmark to an aperture-loaded system. Both pipes have the same 40 in² cross-section. Keeping the driver at the closed end in both pipes exposes the effect of aperture-loading alone. The effect is dramatic.

The pipes differ only by size of the aperture, which shrinks to one-tenth cross-section. The opening of the benchmark is 40 in², while the aperture-loaded pipe has a 4.0 in² aperture.

BENCHMARK

It is important to have a point of reference when considering pipe adjustments. The benchmark pipe for this article is a straight pipe with the driver at the closed end. The benchmark pipe and all adjusted pipes have the same length and cross-section. They are stuffed just two-thirds of pipe length.

The benchmark and adjusted pipes are under-stuffed to demonstrate the effects of pipe adjustments. The benchmark and adjusted pipes use just 0.25#/ft³ of AcoustaStuf.

The benchmark is by no means the best pipe. It is simply a reference used to understand the effects of pipe adjustments. The benchmark's performance appears in **Figs. 4** through **10**.

Benchmark Pipe

- under-stuffed (0.25#/ft³ AcoustaStuf)
- driver at closed end
- two-thirds of pipe stuffed
- open-end fully open
- 3Θ harmonic near 140Hz; 5Θ near 210Hz
- driven by the Jordan JX92s

Comparing frequency responses and impedance curves to this benchmark offers evidence of an adjustment's value. ■

Three very positive changes occur with restricted aperture as seen in **Fig. 8**. First, the fundamental shifts lower, from 58 to 32, almost a one-octave shift! The pipe resonates lower, even though the length is not changed. Pipe loading lowers the fundamental (fΘ).

This is a significant distinction between αTL and ΩQR. In an αTL, recall the driver makes use of length alone. In an ΩQR, your driver takes advantage of both length and aperture to form this new resonance at 32Hz.

Second, harmonics are significantly damped. 3Θ is down 14dB, or 1⁄25 as loud. All remaining harmonics are down even more. This quieting is even more dramatic than moving the driver down the side of the pipe. Shrinking the aperture substantially quiets the awkward harmonics.

As a final bonus, the driver efficiency improves. Notice the driver curve shows more low-end performance. There is a trade-off. It takes considerable energy to produce the 32Hz response. The 58Hz peak of the wide-open pipe becomes shifted but also quieted by 4dB at 32Hz. This may appear to be a problem, but overall frequency response of the system actually flattens with aperture loading. Mass-loading has a dramatic effect on the fundamental frequency but only a slight effect on harmonic frequencies.

PIPE SIZE

For ΩQR design step 4 (see section entitled "Let's Build One"), I simplify the math for finding cross-section (Sx) compared to "Alpha Transmission Lines" (*aX* August '01) at step 9. I do this because cross-section is the least important pipe characteristic.

I treat Z from "Alpha Transmission Line" as a constant and include it in the denominator of step 4. I further simplify the calculation by changing the √(1+fs*Qts) from αTL to just √(fs*Qts) in ΩQR. These two simplifications do not compromise ΩQR performance.

The beneficial adjustments evaluated so far are stuffing two-thirds of the pipe, setting the driver at one-third or one-fifth, and reducing aperture to one-tenth of cross-section.

The last feature to discuss is length, which is simply read from **Table 1**. I modeled many pipe lengths keeping stuffing, aperture ratio, and driver placement the same. Mr. Augspurger's software allowed me to find the best length using a number of drivers. Once I determined the best length, I compared them to driver TSPs and found a clear relationship between length and fs divided by Qts (fs/Qts).

ALL TOGETHER

To summarize each adjustment's benefits:

* Stuffing two-thirds makes low end response louder.
* Driver placement quiets harmonics for flatter midrange response.
* Loading the aperture shifts the low end response lower plus quiets har-

FIGURE 9: All adjustments with driver at one-third (under-stuffed).

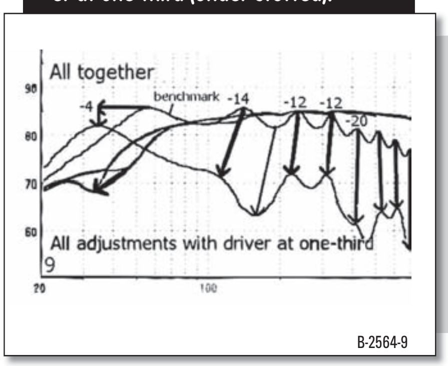


FIGURE 10: All adjustments with driver at one-fifth (under-stuffed).

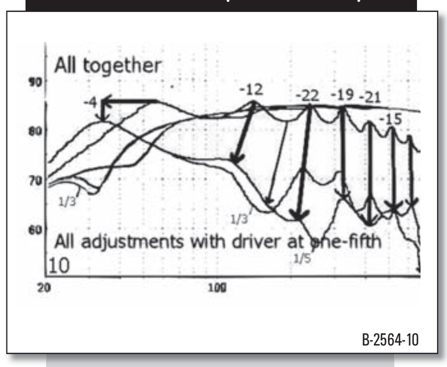


FIGURE 11: Fully adjusted pipe with recommended stuffing.

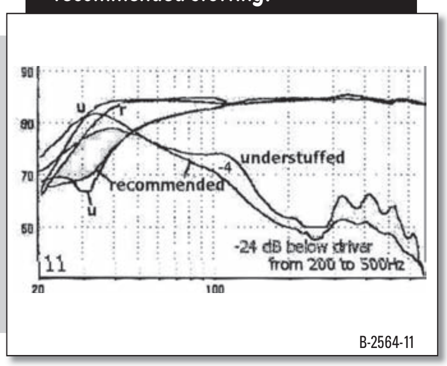


TABLE 1: Diverse drivers and their ΩQR pipe characteristics using AcoustaStuf. These drivers represent many sizes, manufacturers, and a wide range of TSPs. They are sorted by Qts. Pipe characteristics are calculated using AcoustaStuf. These pipe adjustments are used to generate Figures QR1 through QR11. The small circle on each frequency response indicates driver fs.

Make	Model	Figure	Qts	Vas	fs	length	driver	stuff to	Sx	Sa	density	amount
				in^3	Hz	in	in	in	in^2	in^2	$\#/ft^3$	oz
A-L	515E	QR1	0.22	35800	25	65	14	43	700	70	0.8	17
Audax	HM100C0	QR2	0.26	350	65	28	6	19	31	3.1	1.3	0.4
Vifa	P21WO	QR3	0.33	5190	33	72	15	48	190	19	0.7	4.3
Adire	Tumult	QR4	0.36	9760	19	117	25	78	160	16	0.5	6.9
Jordan	JX92s	A	0.40	930	45	65	14	43	59	6	0.8	21
Audax	HM170Z0	QR5	0.40	2740	40	72	15	48	150	15	0.7	3.6
Peerless	CSX176H	QR6	0.43	1690	38	80	17	53	87	8.7	0.7	2.3
JBL	LE8T	QR7	0.46	2140	45	73	15	49	150	15	0.7	3.2
Madisound	10208	QR8	0.54	8840	24	132	28	88	250	25	0.5	11
Morel	MW166	QR9	0.64	720	48	91	19	60	64	6.4	0.6	17
Fostex	FW800N	QR10	0.68	195000	18	185	39	123	4100	410	0.4	23
selenium	8PW3	QR11	0.81	1740	72	79	17	53	320	32	0.7	22

monics.

Figure 9 shows the results of all adjustments: two-thirds stuffed, aperture reduced to 4.0 in^2, driver at one-third, and proper length. Driver response is a little smoother between 50 and 150Hz. The 3Θ harmonic shows only 2dB quieting compared to the aperture-loaded pipe in **Fig. 8**.

Figure 10 shows the driver moved to just one-fifth. The performance is striking. The 3Θ harmonic is at the same level as the system in **Fig. 8**. The real benefit is above 3Θ. The 5Θ harmonic quiets 9dB more than **Fig. 8** while the rest of the harmonics continue to drop off. 5Θ and 7Θ harmonics are so quiet compared to the driver (-22dB or 1/160 and -19dB or 1/80, respectively) that their interaction with driver sound becomes inaudible.

Keep in mind that the benchmark and comparison pipes in **Figs. 3** through **10** are lightly stuffed with AcoustaStuf. This last pipe could use some more stuffing. **Figure 11** compares the understuffed ΩQR from **Fig. 10** to the same pipe with the recommended stuffing amount.

Stuffing this pipe to 0.75#/ft^3 produces four more decibels of harmonic quieting. At 140Hz aperture response is -18dB (1/64) compared to the driver. One goal is to quiet the 3Θ harmonic by 18dB. This pipe is exactly where it needs to be.

Higher harmonics are about -24dB (1/256) compared to the driver, noticeably better than the goal. Pipe harmonics are very quiet and peaks are smoothed over.

ΩQR can get low extension from fullrangers or subwoofers. αTL may be the better design for midrange and widerange drivers. αTL remains worthwhile when you desire smooth impedance and little extra mid-range presence.

LET'S BUILD ONE

Follow these steps to design an omega quarterwave reflex for your driver.

1. If you use polyester or AcoustaStuf stuffing, refer to **Fig. 12**. With fiberglass stuffing, use **Fig. 13**.
2. Divide driver fs by Qts and read the upper curve for your material from **Fig. 12** or **13**. This is your pipe length.
3. For the same fs/Qts, read the lower curve in **Fig. 12** or **13** for your material. This is your driver placement. Place the center of the driver at this point.

FIGURE 12: Omega Quarterwave Reflex design graph using polyester or AcoustaStuf.

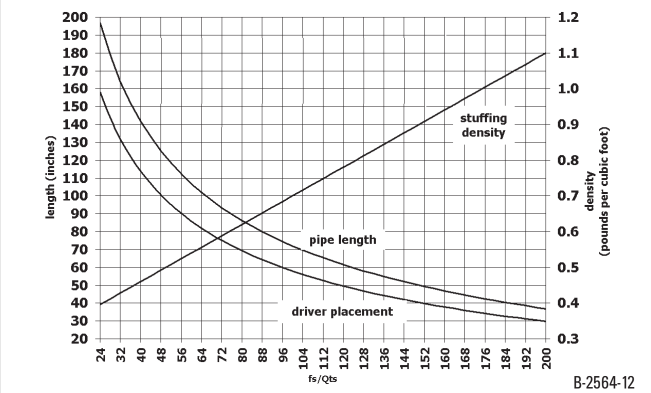


FIGURE 13: Omega Quarterwave Reflex design graph using fiberglass.

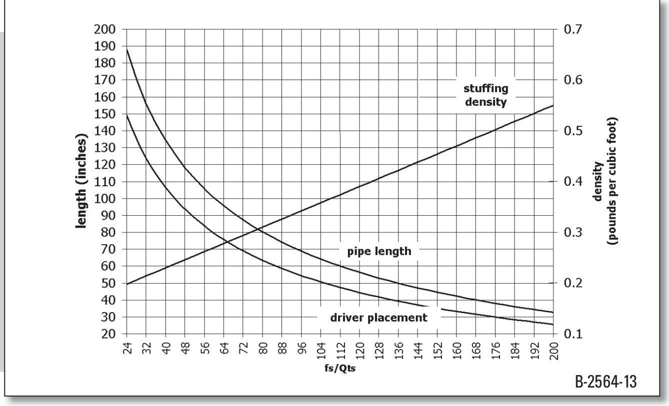
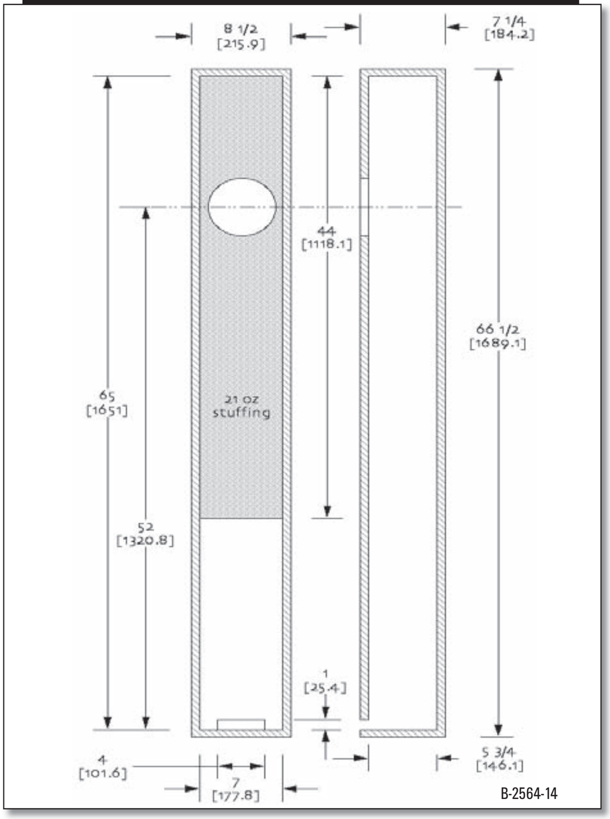


FIGURE 14: Schematic diagram of the Omega Quarterwave Reflex with Jordan JX92S.



4. a. Poly, AS: Pipe cross-section area (Sx) equals fs*Vas*sqrt(fs*Qts)/4500.

b. Fiberglass: Pipe cross-section area (Sx) equals fs*Vas*sqrt(fs*Qts)/3500.

c. Vas must be in cubic inches.

5. Aperture is always one-tenth cross-section area. Sa = 0.10*Sx.

6. Using fs/Qts again, read stuffing density line for your material on **Fig. 12** or **13**.

7. Amount of material needed equals 0.67*length*cross-section*density.

8. One last detail: stuff only two thirds of the pipe from the closed end.

These steps determine cross-section, aperture, length, driver placement, and stuffing. **Figure 14**, the schematic of the omega quarterwave reflex, shows where everything is located in and on the pipe.

I will, for consistency, use the same Jordan JX92S used in "Alpha Transmission Lines" as my example here. The JX92S TSPs: fs is 45, Qts is 0.40, and Vas is 15.3 liters, or 932 in^3. Since writing "Alpha Transmission Line," I was contacted by Larry Sharp of Mahogany Sound, who offered some of his AcoustaStuf product that I will use for this pipe.

1. I am using AcoustaStuf stuffing and **Fig. 12**.
2. Driver fs/Qts is 45/0.40=112. From the upper curve at 112 in **Fig. 12**, pipe length is 65″.
3. For the same fs/Qts, the reading from the lower curve at 112 in **Fig. 12** is 52″. This is the location of the center of the driver.
4. AS: Pipe cross-section area (Sx) equals 45*932*√(45*0.40)/4500=40 in^2.
5. Aperture is always one-tenth Sx. Sa = 0.10*40=4.0 in^2.
6. Reading the stuffing line at 112 on **Fig. 12**, stuffing density is between 0.7 and 0.8 pounds per ft^3.

Beyond ΩQR

The intent of this article is to demonstrate a simple design. Here are some additional adjustments you may wish to try.

First, a special note concerning D'Appolito and other dual driver arrangements. If you plan to use a dual driver setup in an Omega Quarterwave Reflex, you can take advantage of both drivers' locations. Keep driver spacing as recommended by the designer. Set your properly spaced pair of woofers as close to the one-third and one-fifth points as you reasonably can. This placement should have the combined benefits seen in **Figs. 5** and **7**.

Next, George Augspurger reviewed an early version of this article. He brought to my attention his concern about the relatively small apertures of some pipes. This is a valid concern. There could be "chuffing," which is the sound of turbulent air rushing through a small aperture.

Speaker building is always an art. You are encouraged to vary your aperture to experience the results. Mr. Augspurger suggests two alternatives that should reduce chuffing. You may simply enlarge the aperture. Start by expanding the aperture by about 25%. You can continue to enlarge the aperture until the chuffing stops. The sacrifice may be slightly decreased low frequency extension.

The other option is adding a short duct—probably about 1/10 pipe length and a little larger than the recommended aperture area Sa. Adding a duct is not discussed in the main text, because it adds complexity to the structure. My focus has been simplicity.

I am not aware of any program that models a lengthwise slot or triangular aperture. Some builders suggest that a lengthwise slot breaks up the harmonics and reduces the peaks. Some recommend an aperture wider at the end of the pipe that draws to a point.

My impression is that the slot should be no more than one-sixth length. A triangular aperture may work up to one-sixth length, but to be safe, you may want to keep them to one-tenth length before trying a taller slot or triangle. I suggest starting with Sa as described in this article and enlarging if needed.

Finally, throughout αTL and ΩQR I have relied on fluffy stuffing to control harmonics. The combined pipe adjustments in **Fig. 10** are fairly good on their own. I hope lining alone and not stuffing the ΩQR will produce good results. An effective and easy lining is fiberglass acoustical ceiling tile. One manufacturer says their 1″ thick ceiling tile reduces reflected sound over 95%. I suspect lining a pipe with this material will sufficiently quiet harmonics and may actually improve the fundamental slightly.

I have not tried these variations (yet) and leave it to the most bold among you! ■

7. Amount of material needed equals 0.67*65*40/1728*0.75=1.3 pounds, or 21 oz.
8. From the closed end, stuff 44″ of the pipe using 21 oz. of AcoustaStuf. The open end of the pipe is clear of stuffing.

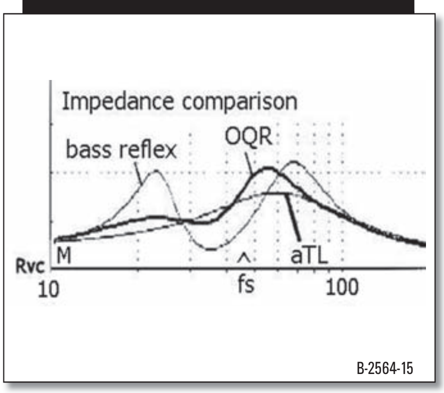
Figure 14 includes measurements for this JX92s omega quarterwave reflex pipe.

Pipe adjustments described here are not new or original ("Rhinos," *Speaker Builder* 5/99). Others have advocated shorter or aperture-loaded or partially stuffed pipes before now. ΩQR harnesses to all the most useful pipe adjustments into one reliable design system. ΩQR design significantly improves pipe making because pipe dimensions arise exclusively from driver TSPs. ΩQR design is more reliable than rules of thumb.

Some ΩQR adjustments need to be followed carefully, while others are more forgiving. Adjustments from most rigid to most flexible are: driver placement, length, Sa:Sx ratio, stuffing amount, and cross-section. As you design your pipe, you may need to compromise. My advice is to get driver placement, Sa:Sx ratio, and length within 10%; and stuffing amount and cross-section within 25%.

Figure 15 compares αTL, bass reflex, and ΩQR impedance curves. ΩQR impedance seems to be a blend of the other two. ΩQR impedance runs in between the αTL and bass reflex. The ΩQR curve looks like an average of the two. ΩQR impedance is smoother than the bass reflex but more dynamic than the αTL. *aX*

FIGURE 15: Impedance comparison of bass reflex, transmission line, and quarterwave reflex.



This article and design is subject to full copyright and patent protection. The combination of shorter pipe length, aperture loading associated with TSPs and "pulse" impedance curve (**Fig. 15**) are unique ΩQR properties subject to full intellectual property protection. Private individuals may, of course, make an ΩQR for their own pleasure. The (proprietary) mathematical equations for the lines in **Figs. 12** and **13**:

Poly length = (1200/√(fs/Qts))-48, inches
Poly driver = length*0.21, inches
Poly density = (.004*fs/Qts)+0.3, pounds per ft^3
fgl length = (1170/√(fs/Qts))-50, inches
fgl driver = length*0.21, inches
fgl density = (.002*fs/Qts)+0.15, pounds per ft^3

Alpha transmission line is elegant in its simplicity. Omega quarterwave reflex is striking in its power. Both are simple to build. I investigated and evaluated many claims before settling on the pipe adjustments used for omega quarterwave reflex design. Moving from alpha to omega has taken some consideration outside the lines. ■

ACKNOWLEDGMENTS

Again, I am deeply indebted to G. L. Augspurger. His program produced the figures in this article. Martin G. King remains a leader in the advancement of quarterwave theory and application. Ed Dell has been very kind and patient with an amateur writer like me.

Thanks to my wife Sandy for the past 26 years together.

You can find additional information on this article at **www.audioXpress.com/magsdirx/ax/addenda/index.htm**

REFERENCE

1. *Great Sound Stereo Speakers Manual with Projects*, David B. Weems, MacGraw-Hill (c) 1990, ISBN 0-8306-9274-6