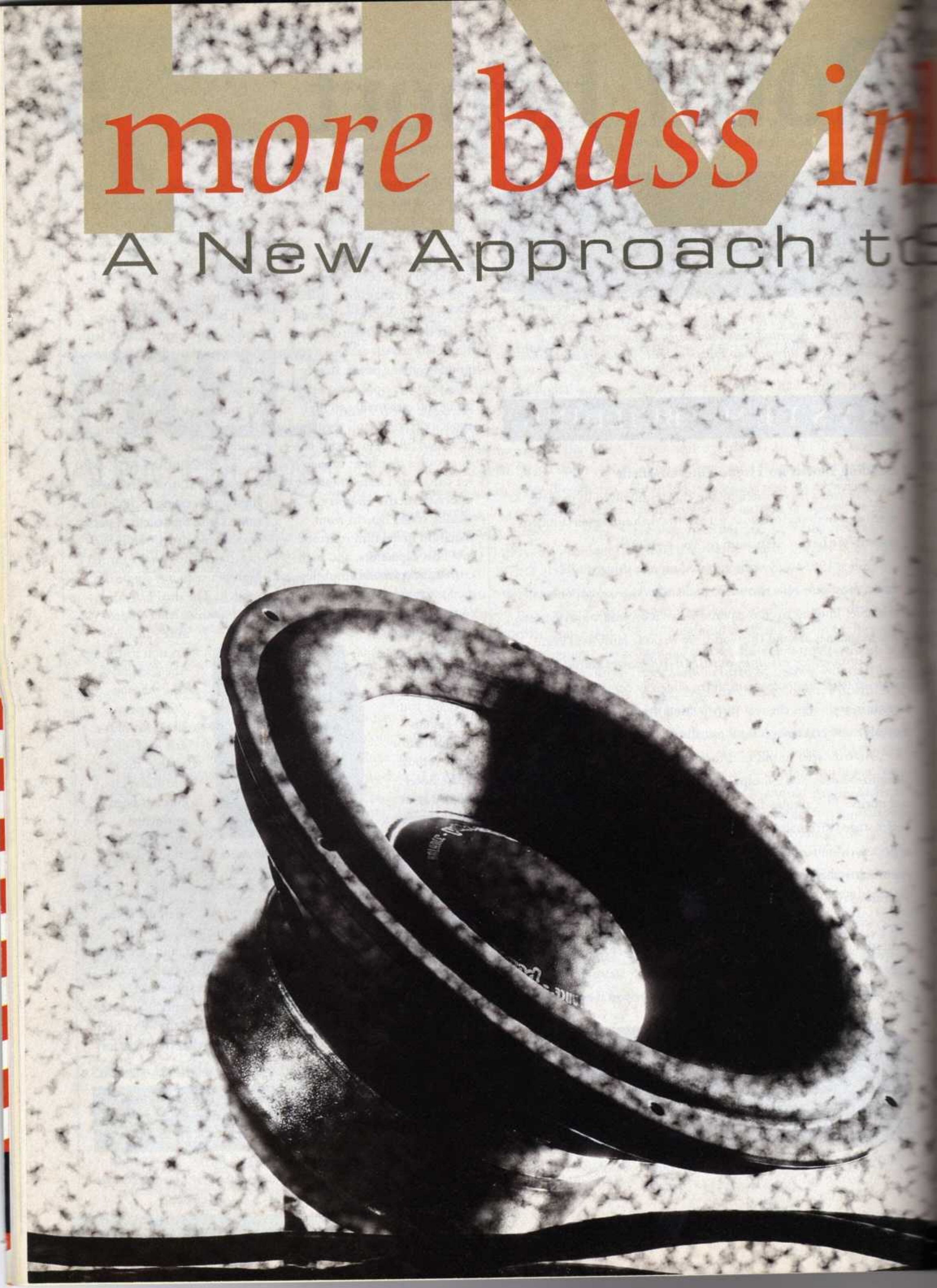
more bass in

A New Approach to



less space
Subwoofer Design

by Matthew Polk

The growing popularity of home theater and high-performance car systems has made achievement of high sound pressure levels at very low frequencies far more important than in the past. Otherwise normal people who previously were satisfied with a modest pair of stereo speakers now find themselves wanting plaster-cracking bass capability to go along with their big-screen TV and surround system. The good news is that computer modeling techniques, advanced materials, and more accurate and practical methods of measurement have facilitated dramatic improvements in the design of woofer and subwoofer systems. But with the need to accommodate six or seven loudspeakers in a room for home theater, the perennial question of speaker size versus performance has become more vexing than ever.

In the past, traditional woofer designs worked very well for most home applications. Serious practical limitations are encountered in attempting to reproduce the lowest frequencies at very high levels, however. Our efforts at Polk Audio to solve these problems have yielded a subwoofer design technique that, we believe, overcomes many of these previous limitations. It enables us to produce powerful subwoofer systems that are also quite compact.

> HVCD *enables the creation of powerful subwoofer systems that are also quite compact.*

These gains are achieved by redefining the mathematical tuning ratios for bandpass woofers to exploit very high-mass drivers having unusually powerful motor systems. This technique is combined with a new port configuration that enables efficient reproduction of deep bass at high levels while minimizing turbulence and noise.

At an Audio Engineering Society convention many years ago, the late Harry Olson concluded his description of the accidental invention of the cardioid directional microphone by observing, "If you're not moving, you can't stumble over anything." For me, the same sort of accident occurred while preparing a presentation on (appropriately) subwoofer design techniques for very deep bass reproduction. In the process, I stumbled on the idea that more compact bandpass woofers with more extended low-frequency response and greater dynamic range could be constructed if we were willing to consider driver design parameters well outside normally accepted limits.

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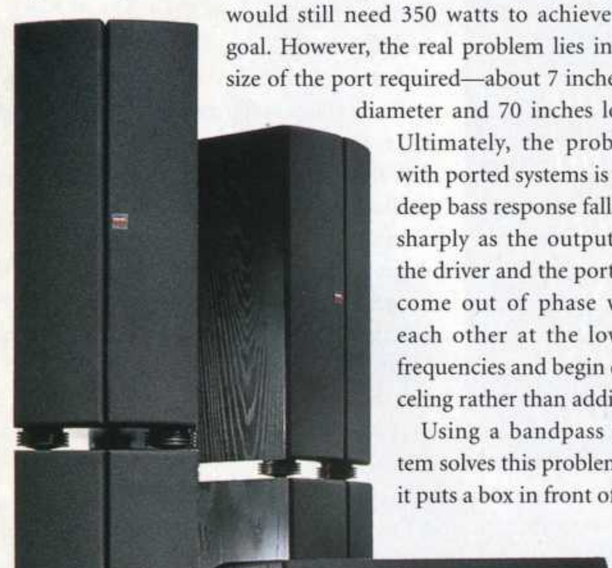
photo by Bill Kouirinis

During the presentation, I discussed the three major types of woofer designs: sealed, ported, and single-vented bandpass. The idea was to show that of the three, the bandpass enclosure had the best relationship of size to performance. As I worked on my notes, however, I realized that in the very low bass range, below 40 Hz, none of these approaches held a clear-cut advantage.

If you ask about producing lots of deep bass, most people assume that it takes a big woofer in a very big box. The question is, how big? Let's say the goal is to reproduce 110 dB SPL at 25 Hz, which is very loud and very deep (though still wimpy by car audio standards). That would require a 15-inch woofer in an 8-cubic-foot sealed cabinet, with about a 200-watt amplifier. But what do you do if 8 cubic feet is too big (about the size of an under-the-counter refrigerator)? Figure 1 shows the relationship of cabinet size to frequency response for various sealed cabinets. To give an idea of the performance sacrificed for a smaller cabinet, the 1.5-cubic-foot cabinet with 9 dB less output at 25 Hz would need an amplifier capable of producing more than 1,600 watts! Even the 4-cubic-foot system would require more than 400 watts.

It is possible to increase the output slightly by using a ported system. As seen in Fig. 2, with the correct 15-inch driver and an appropriate port, the output of the 4-cubic-foot cabinet can be increased significantly above 35 Hz but only slightly at 25 Hz. And this system would still need 350 watts to achieve the goal. However, the real problem lies in the size of the port required—about 7 inches in diameter and 70 inches long! Ultimately, the problem with ported systems is that deep bass response falls off sharply as the outputs of the driver and the port become out of phase with each other at the lowest frequencies and begin canceling rather than adding.

Using a bandpass system solves this problem, as it puts a box in front of the woofer cone, essentially eliminating direct output from the driver. (The term "bandpass" comes from the fact that this arrangement creates a sharp high-frequency rolloff in addition to the normal low-end rolloff. Because the only output from the system is through the port, no cancellation occurs and deep bass response can, in theory, be extended.) Figure 2 also shows the performance of a 4-cubic-foot (total) bandpass system using a 15-inch driver. As you can see, rather than proving the bandpass design clearly superior to the sealed and ported ones, it demonstrates that none of these systems actually has much of an advantage in deep bass reproduction.



I had arrived at this same point very late the night before I was to give my subwoofer presentation. The conclusion felt somehow intuitively wrong, but it was too late and I was too tired to do anything about it. In a happy accident, however, I punched a wrong number into the computer program I was using to generate the system curves and hit the recalc key. The mistake I had made was to increase the moving mass of the driver in my computer model by a factor of ten, from 60 grams to 600 grams. Normally I would have expected this to make the system's efficiency so low that thousands of watts would still produce only a whisper. But before correcting the mistake, I noticed that although the response curve was somewhat erratic, the efficiency was amazingly good considering the extremely high mass. I also noticed that my computer model, which calculates cabinet volume while holding the in-system driver resonance constant, had produced values for the chamber sizes that were so small I was sure there had to be an error. Before falling asleep on my keyboard, I made a few changes to other parameters, trying to get some results that made sense. The calculated cabinet volumes were not a mistake. Neither was the calculated efficiency. I went to bed with the sense of anxious puzzlement that accompanies discovering something without understanding just what it is.

The driver parameters for an HVCD system are well outside those normally considered practical.

The next day, at the conclusion of my presentation, I suggested that it might be possible to substantially extend the deep bass response of a bandpass system without significantly increasing cabinet size or sacrificing too much efficiency. This could be done, I theorized, by using drivers having very high moving mass and very high Bl product. (Bl product is a measure of a driver's motor efficiency, based on the strength of the magnetic field in the voice-coil gap and the length of wire on the coil that is immersed in the field.) I reasoned that this would work only with a bandpass system because its overall efficiency is determined mostly by the acoustic mass of the port, whereas in a direct-radiating design it is determined largely by the moving mass of the driver.

SCALING, SCALING

Theory, of course, is one thing and reality sometimes quite another. I wondered why, if my theory were correct, no one else had taken this approach. The concept of bandpass woofers has been known for at least 50 years, and they are now very popular in subwoofer/satellite systems, where cabinet size versus performance is extremely important. Typically these woofers must blend with small satellites in the 140-Hz range and have flat response down only to about 50 Hz, with rapid rolloff below 40 Hz. I wondered why this design type, so popular for compact and efficient reproduction of mid-bass, wasn't used more often to reproduce deep bass. I wondered also if the reason was in some way related to what I had stumbled over late at night on my computer.

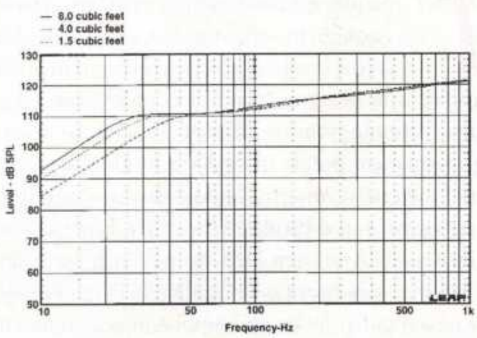


Fig. 1—Output versus frequency of a 15-inch woofer in sealed boxes having volumes of 1.5, 4.0, and 8.0 cubic feet, driven with 200 watts.

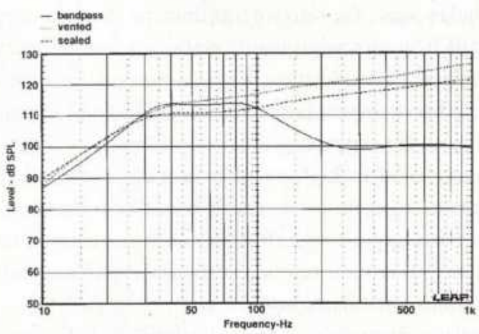


Fig. 2—Comparison of output versus frequency for 4.0-cubic-foot sealed, vented, and bandpass woofer systems, each driven with 200 watts.

One way computer models of loudspeaker performance are created is by representing the speaker's behavior in the form of an equivalent electrical circuit. Then standard techniques of analyzing electrical circuits can be used to predict the system's response quite accurately, particularly at low frequencies. The circuit-element values used in the analysis are calculated from the speaker system's actual mechanical, electrical, and acoustic parameters. Or, if the circuit values required to produce the desired performance are known, the parameters required to build the system can be calculated by the reverse process.

One standard technique for circuit analysis is to "scale" a network, up or down in frequency, to have the same characteristic response over a different frequency range. For example, a circuit representing a loudspeaker system whose response would be 3 dB down at 50 Hz could be scaled to find the circuit values for a system that would be 3 dB down at 25 Hz instead. The new circuit values could be used to calculate the parameters required to build the lower-frequency system. I decided to use this method to translate one of the successful "mid-bass" bandpass woofer designs into a new design having similar characteristics but covering a range centered one octave lower. This, I hoped, might shed some light on why bandpass designs were so rarely used for deep bass reproduction.

The results of this process are shown in Fig. 3 and Table I. The "mid-bass" design, using two 6.5-inch drivers wired in parallel, is 3 dB down at 48 Hz. The actual parameters for this system were used to calculate circuit values for an equivalent circuit that I then scaled down one octave. The new circuit values were then used to calculate parameters for a new system. As shown in the table, the new parameters could, in theory, be used to construct a subwoofer with two 8-inch drivers that would have a –3 dB point of 24 Hz. (Any size driver could be chosen, but a pair of 8-inch drivers would be the practical minimum for reproducing very low frequencies.) The new design is 6 dB less efficient than the original if the two designs are compared in the middle of their ranges, but it is 10 dB more efficient at 30 Hz. Overall efficiency, at 88 dB, is quite acceptable, and the new cabinet, less than 2 cubic feet in volume, is quite small for a woofer that efficiently reproduces frequencies near 20 Hz. Most interesting to me, however, was the fact that the 8-inch woofers called for have very high moving mass—more than 90 grams each—and a very high Bl product of 11.7 webers/meter. This result seemed to confirm my theory that it is possible to use heavy drivers with powerful motors to make relatively small subwoofers with extended deep-bass response.

These results also suggest why loudspeaker engineers had not considered designs of this type. It is a combination of driver parameters well outside those normally considered practical, a lack of

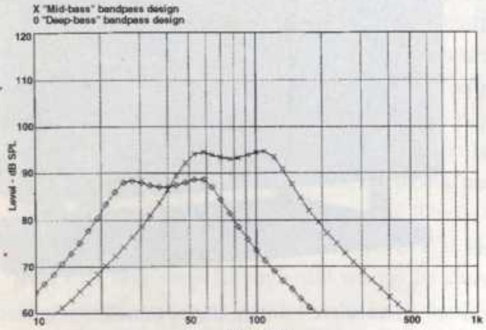


Fig. 3—Response of an actual "mid-bass" bandpass design (crosses) versus that of a theoretical design reaching one octave lower (diamonds). The mid-bass woofer system uses two 6.5-inch drivers, whereas the deep-bass variant uses two 8-inch drivers. The deep-bass design was derived by frequency-scaling of an equivalent electrical circuit representing the mid-bass system's characteristics. Design parameters are listed in Table I.

Table I—*Design parameters for the two bandpass woofer systems whose responses are shown in Fig. 3.*

	Mid-Bass Design	Deep-Bass Design
Woofers	Two, 6.5-inch	Two, 8-inch
Bl Product	6.4 webers/meter	11.7 webers/meter
Moving Mass (Per Driver)	15 grams	92 grams
Free-Air Resonance	45 Hz	18.6 Hz
Sealed-Chamber Volume	0.55 cubic foot	1.0 cubic foot
Vented-Chamber Volume	0.45 cubic foot	0.85 cubic foot
Total Cabinet Volume	1.0 cubic foot	1.85 cubic feet
Port Diameter	3.0 inches	4.5 inches
Port Length	5.0 inches	31.0 inches
Mid-Band Efficiency	93 dB	87 dB
Efficiency at 30 Hz	78 dB	88 dB
–3 dB Point	48 Hz	24 Hz

Table II—*HVCD bandpass-woofer tuning ratios.*

$$Qmc = \frac{Mmd \times fc}{kg \times sec^{-1}} \quad Qtc = \left(\frac{MAS}{CAT}\right)^{1/2} \times \frac{1}{R0} \quad Qtp = \left(\frac{MAP2}{CA2}\right)^{1/2} \times \frac{1}{R0}$$

Mmd	Moving mass of driver (kg)
fc	Resonant frequency of driver in sealed chamber (Hz)
MAS	Acoustic mass of driver (kg/meter^4)
CAT	Combined acoustic stiffness of driver suspension and air in sealed chamber (meter^5/newton)
R0	Acoustic resistance of voice coil (newton-seconds/meter^5)
MAP2	Acoustic mass of air in port (kg/meter^4)
CA2	Acoustic stiffness of air in vented chamber (meter^5/newton)

practical technology for fabricating such drivers, and the counterintuitive nature of such an approach that tends to point the efforts of loudspeaker engineers in other directions. For example, a typical 8-inch woofer would have about 20 grams of moving mass and a Bl product of less than 7.0. Drivers with characteristics like those of the 8-inch woofers discussed above are simply not available unless you have the facilities to make your own. Even then, the construction of such drivers presents technical and manufacturing problems that, as recently as just 10 years ago, could not have been overcome in any practical manner.

Fortunately, advances in materials and plastics molding have made it possible to produce heavier cones that are strong enough to withstand the considerable forces involved and rigid enough to avoid catastrophic cone breakup. In addition, improvements in adhesive technology have made it possible to create strong, permanent bonds using hard-to-glue cone and surround materials. Powerful motor structures continue to be expensive and difficult to construct, however, despite the availability of new high-strength magnet materials. The most significant development here has been in the use of computer design and simulation techniques to optimize the efficiency and linearity of powerful motor systems.

It makes sense for heavy drive units to produce deep bass, but it is somewhat counterintuitive that they can also increase bass efficiency. In sealed systems, for example, very heavy drivers are often used to extend low bass response at the expense of efficiency. (This technique is frequently used in high-performance car systems.) In this case, a larger motor assembly won't help because it will increase upper-range efficiency at the expense of reduced output around resonance and decreased low-bass output due to overdamping.

A reflex system gets additional output and efficiency from the port. But its efficiency is ultimately limited at very low frequencies through cancellation of the port output by out-of-phase direct sound from the driver cone. A heavy-cone driver would make things worse by increasing the low bass coming directly from the cone, which would then cancel more of the deep bass output from the port.

In a bandpass system the port is the only radiating element, and the efficiency is controlled mainly by the relationship of the port to the vented chamber. Because no cancellation occurs between port and driver, a very heavy driver with a large motor system can be tuned to give both greater deep bass extension and higher efficiency. In addition, unlike the motion of a driver diaphragm, the movement of air in a port is not mechanically limited. As a result, the system's maximum deep bass output can be much higher for any given driver size.

Having satisfied myself that I was on the right track, I still had the problem of finding a quantitative method to describe systems making use of these insights. Bandpass systems are among the most difficult to design because they have so many interdependent system parameters. Consequently, I felt that a simple quantitative design procedure would be the only way to determine the ultimate potential of this approach to bandpass woofer design. In seeking such a method, I was looking for a way of mathematically expressing what is different about these systems. It is not simply that the cones are heavy, that the Bl product is high, or that the bass response is very deep for the size of the cabinet. It is the relationship of all these things that separates the new systems from standard bandpass designs. After much trial and error, I found that their performance could be simply characterized by three new tuning ratios: Qmc, Qtc, and Qtp (see Table II).

Ratio Qmc reflects the relationship of the driver's mass to the stiffness of the air in the sealed chamber. It is similar to the mechanical Q used by Thiele and Small but omits the effect of mechanical losses and is normalized to 1 mechanical ohm. Ratio Qtc reflects the relationship of driver mass, cone area, DC resistance, and sealed-box volume. It is very similar to Thiele and Small's "total system" Q (Qt), but as with Qmc, it omits the effect of mechanical losses. Ratio Qtp is the same as Qtc except that the mass of the port and vented-box volume are used; it's sort of a loss-free total Q for the vented chamber. Although Qtc and Qtp are very useful in the design process, Qmc is the ratio that really describes these systems. You might think of it as a system compression ratio; systems with Qmc greater than 5.0 tend to have exceptional performance for their size.

Development of the mathematical description for this new type of woofer system required the construction of numerous prototypes to prove the principle. In the process, we developed a fairly concise method of designing systems using the ratios introduced above. What follows is a summary.

STEP-BY-STEP DESIGN

1. Select the driver's cone size, suspension compliance, mechanical losses, and voice-coil DC resistance. As usual, a larger driver gives greater maximum output but requires a larger cabinet. Suspension compliance (the inverse of stiffness) should be as high as possible to ensure that most of the stiffness in the system will come from the sealed air volume. A practical maximum value for the suspension compliance would be 1 millimeter per new-

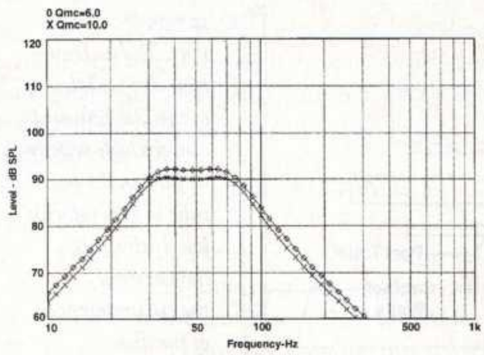


Fig. 4—Responses of alternative bandpass designs covering the same frequency range, one with a Qmc of 6.0 (diamonds), the other with a Qmc of 10.0 (crosses).

Table III—*Design parameters for HVCD subwoofers with Qmc values of 6.0 and 10.0. (Theoretical responses for these systems are shown in Fig. 4.)*

	Qmc = 6.0	Qmc = 10.0
Woofers	Two, 10-inch	Two, 10-inch
fc	48 Hz	48 Hz
fp	48 Hz	48 Hz
Qtc	1.0	1.0
Qtp	1.0	1.0
Qmc	6.0	10.0
Bl Product	13.1 webers/meter	16.5 webers/meter
Moving Mass (Per Driver)	62.5 grams	104 grams
Free-Air Resonance	26.8 Hz	21 Hz
Sealed-Chamber Volume	2.3 cubic feet	1.25 cubic feet
Vented-Chamber Volume	1.6 cubic feet	1.0 cubic foot
Total Cabinet Volume	3.9 cubic feet	2.25 cubic feet
Port Diameter	6.0 inches	6.0 inches
Port Length	16.35 inches	28.25 inches
Mid-Band Efficiency	92 dB	90 dB
Efficiency at 30 Hz	90 dB	89 dB
–3 dB Point	29 Hz	27 Hz

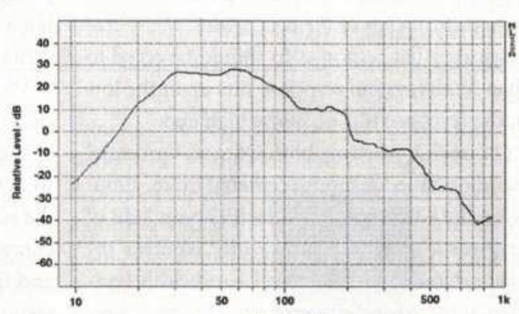


Fig. 5—Actual anechoic response of a subwoofer built to the parameters shown in Table III for Qmc = 10.0 (scale at left does not indicate actual efficiency). This is very close to the theoretical response for the same system, as shown in Fig. 4.

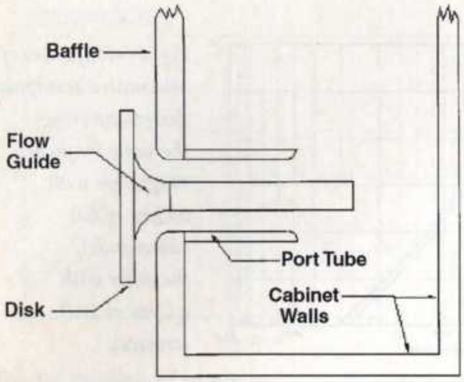


Fig. 6—Cross section of a Power Port. The widening from the middle of the disk outward converts high-velocity airflow in the port tube to low-velocity, low-turbulence flow around the circumference of the disk.

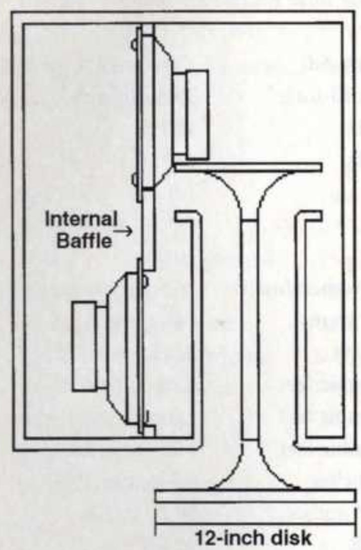


Fig. 7—Cross section of the HVCD subwoofer design that produced the response shown in Fig. 5.

ton, although the exact value is not particularly important. Mechanical losses also have very little effect on these systems as long as they are not too large. Use a value around 6.0 kilograms per second for calculation purposes and don't worry about it.

2. Choose fc, the resonant frequency of the driver in the sealed chamber. This will be roughly at the center of the bandpass response. The maximum bandwidth will be about 1.7 octaves between the 3-dB-down points.

3. Choose fp, the resonant frequency of the port against the vented chamber. For a symmetrical or flat response, fp should be equal to fc. When fp is lower than fc, the system response tilts up at the low end; when fp is higher, the response tilts up at the high end.

4. Choose values for Qtc and Qtp. Setting both Qtc and Qtp equal to 1.0 gives a slightly saddle-shaped response centered on fc, about 1.7 octaves wide (between the –3 dB points) and with about 1 dB of ripple. Increasing Qtc gives a narrower bandwidth, whereas increasing Qtp gives a wider bandwidth. Narrower bandwidth typically gives higher efficiency. Increasing either Qtc or Qtp gives a response with more ripple, while decreasing either reduces ripple. For example, making both Qtc and Qtp equal to 2.0 gives about a 1.6-octave bandwidth with more than 5 dB of ripple. With Qtc and Qtp both equal to 0.85, the bandwidth remains 1.6 octaves, but the ripple almost vanishes. The cabinet volume stays the same for all values of Qtc and Qtp as long as they remain equal to one another.

5. Choose Qmc. For any given response, larger values of Qmc mean smaller cabinets and lower efficiency. Large Qmc values also require heavy drivers with powerful motor structures. For systems whose response curves are centered around 60 Hz, Qmc values of about 6.0 produce quite compact systems with good efficiency.

6. Calculate remaining parameters. After the above decisions are made, chamber volumes, port size, Bl product, driver moving mass, and frequency response can be computed.

DESIGN EXAMPLE

I needed a pair of woofers that, together, would produce 120 dB SPL at 30 Hz. Normally this would require two 18-inch woofers in sealed cabinets of about 12 cubic feet each. Using the design principles outlined above, I believed that I could achieve the goal by using one 12-inch or two 10-inch drivers per cabinet. Knowing that the design would probably require very heavy woofers with a high Bl product, I decided to work with two 10-inch drivers per cabinet. That would enable me to distribute the mass between two drivers and to handle more power. Also, if 2-ohm voice coils were used, the drivers could be wired in series, thereby doubling the system's Bl product and achieving a 4-ohm total impedance. I chose a suspension compliance of 0.263 millimeter per newton, which is well within practical limits.

A relatively small **Power Port** *proved capable of better performance than a huge conventional port.*

We know that making both Qtc and Qtp equal to 1.0 yields smooth response together with a bandwidth of roughly 1.7 octaves to the –3 dB points and roughly 1.35 octaves to the 0-dB points. If we want flat response at 30 Hz, then the resonance of the driver in the sealed volume (fc), which represents the center of the response curve, should be about 0.675 octave above 30 Hz. By choosing fc and fp equal to 48 Hz, we should get a relatively flat, symmetrical response that is less than 3 dB down at 30 Hz. For Qmc, I chose a value of 6.0 for my first try.

The response for this system is predicted to be about 2.5 dB down at 30 Hz and to deliver 92 dB from 2.83 volts at 1 meter. Total cabinet volume is just under 4.0 cubic feet, net of space occupied by the drivers and the port. Unfortunately, this was too big for the application, so I decided to try a Qmc of 10.0 to see if the cabinet could be made smaller without losing too much efficiency. Figure 4 and Table III show the effect of increasing the value of Qmc.

With a Qmc of 10.0, the cabinet volume shrinks to about 2.25 cubic feet, net, and the efficiency is still around 90 dB. Response is only about 1 dB down at 30 Hz. If we apply 300 watts to each woofer, this would give almost 115 dB SPL per cabinet. The two together would give 121 dB SPL, thereby achieving the output goal. The drivers would need peak-to-peak excursion capability of about 0.5 inch to achieve this performance. That is fairly demanding for a 10-inch driver, but because this is a bandpass-type system, which naturally filters out harmonic distortion, low-distortion output can be achieved even if the driver excursion is not absolutely linear.

Because of the use of some volume damping, a system constructed according to this design ends up tuned a little lower than indicated by the model. Its measured anechoic response, shown in Fig. 5, was very close to the predicted response. Efficiency also was found to be very close to the predicted value. But testing the system's maximum output revealed a further practical problem. At high levels, huge amounts of noise were generated by the large volumes of air passing through the port. In fact, above about 110 dB SPL at 30 Hz, the noise and the energy loss were so great that they seemed to place an upper limit on how loud the woofers could play. In addition, the port for the prototype system was fairly large, 6 inches across and nearly 30 inches long. We actually tried an even larger port, 9 inches in diameter and 60 inches long! (The greater length was required to get the same acoustic loading with the larger diameter.) That produced much better results and higher maximum output but, obviously, was completely impractical.

A workable solution came in the form of a simple idea from one of our engineers. Noise is generated mainly where high-velocity air exits suddenly from the end of the port into the room. The problem occurs because the air slows too quickly at the exit and becomes turbulent. This causes both noise and loss of energy, which worsen, exponentially, as the airflow increases. The solution lies in finding a way to allow the fast-moving air in the port to slow down gradually as it emerges into the room. One method is to gradually enlarge the tube at its end, flaring it. In practice, however, this helps only if the flare is very, very large. Our solution accomplishes the same thing much more efficiently and compactly.

THE POWER PORT

In this case, a picture really is worth a thousand words. Figure 6 is a cross section of a new type of vent we call the Power Port. The idea is to direct the port tube's high-velocity airflow radially outward from the center of the disk toward the edge. This provides a constantly expanding cross-sectional area for the air to flow through, which reduces velocity as the air flows into the room. The result is that turbulence, noise, and energy loss are greatly reduced. It also eliminates the need to use a very wide port tube, meaning that the size of the entire thing can be dramatically reduced without sacrificing performance. In the design example, a Power Port using a 5½-inch diameter, 14-inch-long port with a 12-inch disk was capable of better performance than the huge 9 x 60-inch port discussed previously. Based on this new port geometry, two of these woofers were able to generate 120 dB SPL at 30 Hz in a 3,500-cubic-foot room with acceptably low distortion. In addition, the new port geometry yielded a 1.5-dB efficiency gain over the standard 6-inch-diameter port and significantly reduced power compression. Figure 7 shows a cross section of the prototype system.

Through luck and persistence, we have developed a design method and a port geometry that can be combined to produce bandpass woofers with exceptional deep-bass performance in cabinets of quite reasonable size. We call this technology High Velocity Compression Drive (HVCD), which comes from the high-velocity air in the port and the high compression from the large drivers in the small sealed chamber. I realize that the math can be daunting and some of the concepts confusing. However, if you would like more information or wish to build a system for yourself that uses these principles, contact Polk Audio. For a small fee to cover our costs, we will be happy to send you a computer program to make the calculations and a single-use license for the patents covering this technology. See "Build Your Own HVCD Subwoofer" for details. A

BUILD YOUR OWN HVCD SUBWOOFER

If you would like to build an HVCD subwoofer for your own use (or would simply like more detail on how the system works), Polk Audio will supply the basic resources necessary to get you started. Call 800/638-7276 and ask for Dave Lytwynec at extension 208 or Ken Swauger at extension 891. For a small fee to cover the company's costs, they will send you a MathCad or generic spreadsheet file that will do the necessary calculations, a single-use license for the technology, and information on where you can buy appropriate drivers and other components.