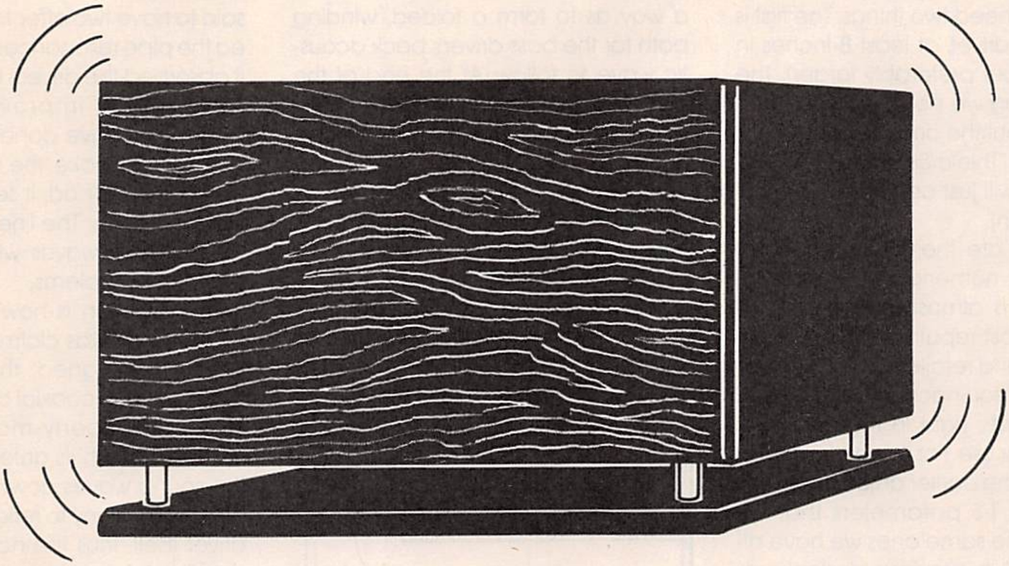
Design Your Own SUBWOOFERS



These computer programs can help you add the bass response you want to your existing speaker system.

BY WILLIAM R. HOFFMAN

When assembling a home theater, a lot of attention is paid to the video display device (most often a monitor or projection TV), but a sound system is as important, if not more so, in delivering the "theater" experience. Without the thundering bass that is an integral part of many of today's movies, especially action ones, watching those movies at home would be a lot like, well . . . watching ordinary TV.

So, then, how do we go about getting all that bass we want? Well, we can just run out and plunk down hundreds, or even thousands of our hard-earned dollars at our favorite audio emporium to buy some really big speaker systems. And then, when we get home, just set them up and start listening to our heart's content. With today's high-end, high-performance speaker systems, along with modern audio equipment and signal sources such as laserdiscs, we can hear it all, whether it be some prehistoric animal stomping around our living room, or the mighty growl of a giant pipe organ.

But what if we don't have all the money we need to get the speaker systems of our dreams? Can we build something to add the bass to our existing systems, and save a lot of money as well? The answer is yes—we can build a subwoofer! In this article, we will look at some of the more common designs used in commercial subwoofers, and then see what it takes to make our dream bass speaker come alive.

Some Basics For Bass. The five most common bass enclosure designs for a cone-and-magnet-type driver are: (1) the acoustic-suspension, or simple sealed cabinet; (2) the tuned-port or "bass-reflex" design; (3) the folded duct, or "transmission line;" (4) the double driver in a short connecting tunnel, called an "isobaric" system; and finally, (5) the multi-chamber "tuned-bandpass" cabinet.

Well then, just where do we start our design work? With one of today's personal computers, that's where. Using one of those machines, and the software programs we provide, anyone can do all the complex math required to design an effective subwoofer. And in the case of the bandpass-type system, the math can be very complex indeed!

Before we go further, let's review briefly some of the computer-based design work we've presented earlier. To begin with, a program to design the first enclosure type, a sealed acoustic-suspension system, was originally presented in "Design Your Own Loudspeakers," which appeared in the February 1994 issue of **Popular Electronics**. That was then followed with programs for crossover design and other functions ("Designing Loudspeaker Crossovers," **Popular Electronics,** July 1995). Finally, we added a program for creating a vented-box design, which is the second enclosure type mentioned above ("Design your own Bass-Reflex Speakers," **Popular Electronics,** April 1996). This time, we will present some design programs for the last three system types we just mentioned: the transmission-line, isobaric, and bandpass systems.

To create an effective subwoofer design, we need two things. The first is good bass driver, at least 8-inches in diameter (but preferably larger). The second thing we need is some information about the driver, which is contained in its "Thiele/Small parameters" (which we will just abbreviate as "T/S" from now on).

But what are the T/S parameters? They are a numerical specification that today is almost universally supplied by most reputable driver manufacturers and retailers. Even companies like Radio Shack offer them with their products, right in their catalog, ready for our use. For those of you who have read the earlier articles outlined above, the T/S parameters that we need are the same ones we have already used in previous design programs. They are: (f_O) the bass resonance frequency of the driver in free air, in Hz; (V_{AS}) the volume of air that has a stiffness equal to the driver's cone suspension, in cubic feet; and finally (Q_{TS}) the total "Q" value of the driver at its bass resonance, which is specified as a number usually between 0.3 and 0.5 (at least for those drivers useful to us here).

It's important to note that those specifications have not always been supplied by manufacturers. If, by chance, we happen to have some old bass drivers lying around without these T/S values, forget about using them with these designs. Just as with all our other design programs, we MUST have the T/S values—no exceptions! (Note: You cannot effectively estimate what those parameters might be just by examining a driver's construction. They could conceivably be determined via testing, but the equipment and techniques required are beyond the scope of this article, and the average hobbyist.)

So with that said, let's begin!

The Transmission-Line Design. The transmission-line system is one of those audiophile oddities that has been with us since the early 1970s in its present form, although in another, earlier form its history extends back to the 1940s. Shortly after the end of World War II, an American company, Sromberg-Carlson, began manufacturing a type of speaker enclosure called an "acoustic labyrinth." That design was simply a box, subdivided internally with many partitions in such a way as to form a folded, winding path for the bass driver's back acoustic wave to follow. At the end of the path was an opening, or port, leading out of the enclosure into the listening room.

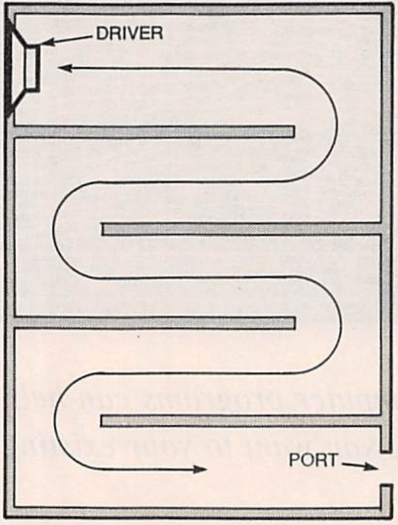


Fig. 1. This acoustic labyrinth, the forerunner of the transmission-line enclosure, was developed in the late 1940s.

Figure 1 shows an approximation of that early design. Note that it was really just a long folded tube, or pipe, and, in fact, it behaved just like one as well: It readily resonated like an organ pipe when ever its length equaled ¼ wavelength (or an odd multiple thereof) of any tone being reproduced by the enclosed driver. Needless to say, the speaker's response was anything but flat. Because of those resonance problems, and the complexity of construction and high cost, the system was soon abandoned.

The next development in the transmission-line speaker came along in 1972, when a British writer and engineer named A. R. Bailey published a design that was a variant on the labyrinth. It was similar to what Stromberg-Carlson had done, but the tunnel, or "line" as it was now called, was stuffed with fiberglass, wool, or something similar. In 1974, another British engineer, Arthur Radford, after some further development of the idea, apparently received the first patent on the basic design as it is known today.

The damping material both those men used in their design work was said to have two effects. First, it damped the pipe resonances, and, second, it absorbed the driver's back waves. In making that improvement, they claimed to have done just what was needed to make the system a success. Now we had, it seemed, a perfect enclosure: The line got rid of the driver's back waves without causing any other problems.

The question is how and why did that work? It was claimed that, when properly designed, the system behaved like the coaxial cable that connects a properly-matched radio transmitter with its antenna: It carried the sound waves down the line without allowing any to reflect back at the driver itself, thus the name "transmission line." A cutaway view of a transmission-line speaker is shown in Fig. 2.

But did it really work? Well, some thought that it did, while others saw additional problems with the design (reflections back and forth at each bend in the line, for instance). In 1976, Dr. L.J.S. Bradbury, a British aeronautical engineer published a study

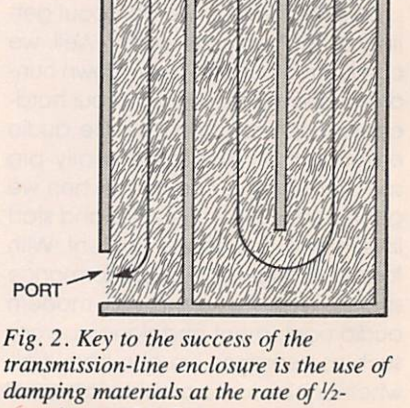


Fig. 2. Key to the success of the transmission-line enclosure is the use of damping materials at the rate of ½-pound-per-cubic-foot.

of the effects that damping material in a duct, or tube had. His study showed that it did two significant things. First, that the speed of a sound wave moving down the line was greatly reduced, and that the reduction was proportional to the density of the material used (see Fig. 3). And, second, that the stuffing tends to act like an excellent absorber at all but the very lowest bass frequencies. In other words, it acted like a low-pass filter of sorts (see Fig. 4). Both those effects were good news for TL-design fans, and are what make our design work here possible.

Listing 1 is a PC program written in generic BASIC and suitable for running under all current versions of GWBASIC or BASICA. Our program's file name is TLDES-1.BAS, and when run, will give us all the pertinent information for designing our TL bass speaker system. To load the program, just open your BASIC interpreter, and type the program listing in, line by line, exactly as it is printed. It's really very simple, as easy to do as typing a letter to someone. If you have never used BASIC before, try checking out a book from your local library on the subject. You will find that it is very easy to use once you get started.

Once we have loaded the program from Listing 1, and have started it running with the appropriate command-line prompt, the opening screen will ask us for two pieces of information about the bass driver we are using. The first is f_O, and the second is the driver's diameter (in inches).

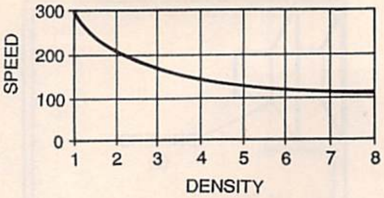


Fig. 3. This chart shows how the speed of sound through the transmission line is affected by increasing the amount of sound-absorbing material in the line.

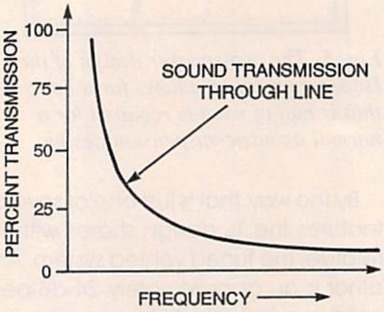


Fig. 4. Using sound absorbing materials in the transmission line also produces a low-pass-filter effect.

Once those are entered, the program will calculate and display on the screen five parameters of our design.

The first is "Line length," which is the physical length of our folded line, in feet, so that it will be acoustically ¼-wavelength long at the bass-resonance frequency of the driver. The length displayed is based on the assumption that the folded line will be uniformly filled with a damping material such as Fiberglas (or a similar material) at a density of ½-pound-per-cubic-foot and is based on a formula from Bradbury's work, mentioned above.

The next parameter displayed is "Line Cross-Sectional Area," which is the minimum area allowed for our line, and is equal to the driver's cone area. We can make that area somewhat larger if we wish without changing the performance of our system, though there is no particular advantage in doing that, but it must not be smaller. Making it smaller might cause excessive turbulence in the air flow, or cause other non-linear effects.

The third parameter is the "Vent Area," or the area of the port at the line's open end. Again, that is the same as the surface area of the driver, and can remain that size regardless of what cross-sectional area we choose for the line itself.

Fourth is the "Approximate Box Volume" in cubic feet, which is simply the line's length multiplied by the cross-sectional area. That will give us some idea of the size of our speaker cabinet, but not the exact size because it does not take into account the thickness of any of the wood. Obviously, if we make our line cross-sectional area larger than originally specified, then we will have to recalculate the new box size ourselves.

The final parameter is "Weight Of The Damping Material," which is simply the calculated volume of the line multiplied by the weight of the stuffing material figured at ½-pound-per-cubic-foot. Again, if we change the area of the line, we will have to recalculate the amount of material needed.

LISTING 1

```
100 PRINT:PRINT:PRINT:PRINT:PRINT
110 PRINT"                DESIGNING A TRANSMISSION LINE "
115 PRINT:PRINT
120 PRINT"                     LOUDSPEAKER SYSTEM"
125 PRINT:PRINT
130 PRINT"                            by"
135 PRINT:PRINT
140 PRINT"                       William R. Hoffman"
145 PRINT:PRINT:PRINT
150 PRINT"         The free air bass resonance frequency of the driver"
155 INPUT"         (Fo), in Hz. is =";FO
160 PRINT
165 INPUT"         The diameter, in inches, of the bass driver is=";D
200 LET A=(1130/FO)/4
210 LET F=1+(5.000000E-01/7.400000E-02)
215 LET F=SQR(F)
220 LET F=1130/F
230 LET B=(F/FO)/4
240 LET XS=(D/2)^2*3.145900
250 LET XF=XS/144
260 LET BV=XF*B
270 LET WS=BV*5.000000E-01
```

```
290 CLS:PRINT:PRINT:PRINT:PRINT:PRINT
300 PRINT"          For a bass driver"D"inches in diameter, with a free"
310 PRINT"          air resonance of"FO"Hz, and an enclosure packed with"
320 PRINT"          damping material at 1/2 lb. per cu. ft, the basic"
322 PRINT"          specifications for a transmission line enclosure are:"
325 PRINT
350 PRINT"               Line length ="B"feet."
355 PRINT
360 PRINT"               Line crossectional area ="XS"sq. in."
365 PRINT
370 PRINT"               Vent area ="XS"sq. in."
375 PRINT
380 PRINT"               Approximate box volume ="BV"cu. ft."
385 PRINT
390 PRINT"               Weight of damping material ="WS"lbs."
395 PRINT
400 PRINT"          Do you wish to try another set of specifications?"
410 INPUT"          (1=Yes, 2=No) and Enter=";X
420 IF X=1 THEN 145 ELSE 990
990 PRINT
995 PRINT"          Good listening!"
999 END
```

With the information just calculated for us, we can now sit down with a pencil, a piece of graph paper, and a ruler and design our TL system. Using Fig. 2 as a general guide, we next draw out a design with a folded line path anyway we might like it to be, say, to fit a particular enclosure shape we might have in mind. Our design doesn't have to be exactly like Fig. 2, but it should have the bass driver mounted near the top of the system's face, with the outlet port near the bottom. (That is a typical arrangement for the TL system, and seems to get good results from the design.)

Because the line will be folded many times along its length, to correctly calculate how long it is, all we need do is find the center-line distances along each section of the line, and add them together. That is very important, because at low frequencies, as Bradbury pointed out, the enclosure still transmits sound waves and acts like a tuned, resonant pipe. Because of that, our specifically determined line length will make the pipe's ¼-wave resonant frequency the same as our driver's bass resonance. And that will, in turn, produce a "node" (an area of increased pressure) right against the back of the driver, providing some necessary acoustic loading for best bass response. (Although our design here cannot actually provide the exact value of acoustic loading the driver might need, as the other systems we have designed have done, nonetheless, for our purposes everything should still work just fine.)

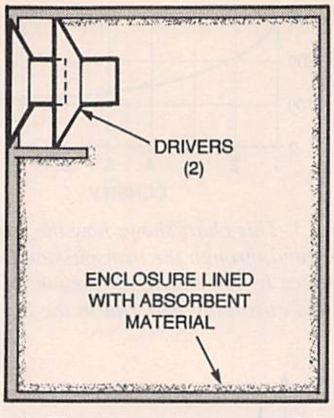


Fig. 5. The two-speaker design of the Isobaric enclosure allows for a box size that is half of what is required for a normal acoustic-suspension design.

By the way, that is just one of several features the TL design shares with its relative, the tuned vented system. Another is an approximately 24-dB-per-octave cutoff rate in its bass response below the system resonance frequency.

So what does a TL system sound like? And what will we get for our efforts in building such a complex enclosure? Those are good questions, and is where the arguments come in between audiophiles. Typically, a well-designed and -built TL system is prized for having a very smooth, clean, pure, and undistorted bass response. Audiophiles who like classical or jazz music really go for this design. But, on the other hand, if you like lots of bass "punch" or "sock" you might be happier with one of the other designs. Let's get to those next.

The Isobaric System. As you can see in the cutaway view in Fig. 5, the isobaric system uses two identical (this is important) bass drivers, wired in-phase and one behind the other, and mounted in a short tunnel. The tunnel should be just long enough to allow the magnet and frame of the front driver to clear the cone of the back one, even when the rear driver's cone is moving in-and-out its maximum distance while being driven by the amplifier. Beyond that, the rest of the enclosure is just like any other sealed, acoustic-suspension box, with one important exception: the volume required for the box behind the second driver is only half of what would be required for just one driver alone! We'll find out more about that in a minute.

The concept behind the isobaric system was first described in the 1950s by Dr. Harry F. Olson, then working at RCA. Included in his description was the curious halving of the required box volume. But it wasn't until the middle 1970s, when a company called Linn Products, of Glasgow, Scotland marketed a speaker called the "Isobarik," that the idea became a commercial reality. The system remains in limited commercial production today.

Now then, just how do we get the system to work with only half the enclosure volume normally needed? Do we just make our box too small, and live with the thick, muddy, boomy sound from the resulting high "Q" peak in the driver's bass output? Of course not, and here's why.

LISTING 2

```
9 PRINT:PRINT:PRINT:PRINT:PRINT
10 PRINT "        LOW FREQUENCY ISOBARIC (TWO DRIVER) ACOUSTIC"
11 PRINT:PRINT
12 PRINT "         SUSPENSION LOUDSPEAKER DESIGN PROGRAM"
13 PRINT:PRINT:PRINT
14 PRINT "                         By"
15 PRINT
16 PRINT "                  William R. Hoffman"
17 PRINT:PRINT
20 INPUT "              Proceed? (1=yes 2=no) and Enter ";P
22 PRINT:PRINT:PRINT:PRINT:
25 ON P GOTO 30, 990
30 INPUT "              Free air resonance of driver (Hz) =";B
35 PRINT
40 PRINT "              Air volume compliance equivalent of"
45 INPUT "              one driver (Vas) in cu. ft. =";C
46 PRINT
50 PRINT "              Free air total Q of driver at"
55 INPUT "              bass resonance (Qts) =";D
60 PRINT
65 PRINT "              What is desired completed system  Q "
70 INPUT "              at bass resonance (Qcab) =";E
75 PRINT:PRINT:
100 LET Z=(E/D)^2*(1.149999)-1
110 LET Y=B*E/D
120 LET X=(C*5.000000E-01)/Z
121 CLS:PRINT:PRINT:PRINT:PRINT:PRINT
122 PRINT"              For an 'Isobaric' (dual driver) enclosure design"
123 PRINT"              where the drivers have an fo of"B"Hz, a"
124 PRINT"              Vas of"C", and a Qts of"D", the specifications"
125 PRINT"              are as follows."
126 PRINT
130 PRINT"              For an in cabinet bass driver Q of"E":
135 PRINT
140 PRINT"                 The cabinet volume is ="X"cu. ft. which "
141 PRINT"                 does not include the volume occupied by "
142 PRINT"                 the two drivers and the space between them."
145 PRINT
150 PRINT"                 And the driver bass resonance frequency"
155 PRINT"                 will be ="Y"Hz"
172 PRINT
175 PRINT"              Would you like to try another driver?"
180 INPUT"              (1=yes 2=no) and Enter ";F
182 PRINT
185 ON F GOTO 30, 990
187 PRINT
990 PRINT"              Good listening!"
999 END
```

As we have learned from past discussions, the requirement for air loading on the cone of a bass driver is proportional to the mass of the cone (or sum of the masses of both cones, in this case) and the force generated by the "motor" (the magnet and voice coil), which in this case is also the sum of both magnets and both voice coils working together. So if one driver requires a 2-cubic-foot box to perform optimally, then two identical drivers connected together in the isobaric design, having effectively twice the cone mass, and twice the voice-coil force, but only the same cone area as one driver exposed to the air, can produce the same performance using only a 1-cubic-foot box. Mathematically, all we are doing is summing the cone masses and voice-coil motor strengths, and applying the same formulas Thiele and Small used to those summed values. Doing that, we always get a value for V_{AS} that is half that of one driver.

While the smaller enclosure size is nice, it is not the only advantage the isobaric system offers. Because we have two voice coils operating in phase together, we also have a system that can handle twice the power of a simple sealed box. Those two advantages—half the cabinet volume and twice the power—make this design principle really shine for a subwoofer.

The term "isobaric" comes from two words: "isothermal," which technically describes the sound-radiating conditions at low frequencies within the small volume of air in the tunnel between the drivers, and "baric," which refers to the idea that the front driver sees a constant pressure on the back of its cone because of the second driver—a theoretically ideal situation (or so the theory goes). Whether that second point is true, however, is a subject of real debate among audiophiles, some as adherents, and others as detractors. Debate aside, can we design a successful bass system with the isobaric principle? Of course, and here's how.

Listing 2 is our isobaric design program, ISBDES-1.BAS, and is again written in generic BASIC. It should be entered and run following the same procedures discussed for the first program. Once the opening screen appears, we are prompted for the same four basic pieces of information: f_O, V_{AS}, Q_{TS}, and the value of the completed system Q we want. For the first three of those, enter the T/S values of only one of the drivers—remember that we are assuming here we have a reasonably well-matched driver pair (most are, when of the same manufacturer and type).

As for the "completed system Q," we discussed that parameter when we first discussed sealed-box design in an earlier article, but for those of us new to the series, here is a short recap: Anytime we enclose the back of a driver in a small, sealed cabinet the resulting loading by the mass and compliance of the trapped air raises both the bass resonance frequency and the Q (degree of peaking) of the speaker at bass resonance. So, of course our value of completed system Q, (technically referred to as "Q_{CAB}, and that's how we will now refer to it) must be higher than that of the driver in free air. But then, just what should it be? Actually there is no one single value for it. What we actually have is a choice from a range of values, depending on how we like our bass to sound. Here are some guidelines for you to use when making your selection: For a bass response that is very clean, but maybe a little on the "lean" side, you want a Q_{CAB} of about 0.5 to 0.6. For a richer, but still very natural bass sound use a value of around 0.7. (That value is technically the best. For those into filter design, our system's bass response is of course, a high-pass function, and 0.7 is the coefficient value for a Butterworth filter that gives the fastest cutoff along with the least ripple and phase shift.)

Going on, in using Q_{CAB} values of 0.8 to 1.0 we need to be careful. With those, the bass can sound very rich and full, but if we are not careful in our placement of the speakers in our listening room, they can also end up giving us two types of problems related to room acoustics. The first is that the sound starts to become "thick and muddy," especially when the systems are placed in a corner, or almost anywhere in a small, cubical room. Second, room placement of the system can become quite critical in order to avoid getting exaggerated standing waves and other reflection problems. Systems with Q_{CAB} values of greater than 1.0 would have a distinct one-note-bass "boom-boom-boom" quality, regardless of where they are placed; while that might work for certain types of popular music, most people would find it very annoying to listen to for any length of time.

Once you have entered all the required information, the program then calculates the volume of the box behind the second driver, and the new value of the bass-resonance frequency. Below that resonance frequency the system's response will fall off at a rate of about 12-dB-per-octave, just like any sealed-cabinet design does.

Once we have our values, it is time to turn to the actual design. As before, all we need is a pencil, ruler, and some graph paper. To design the tunnel between the two drivers, use the ruler and measure the depth of one of the bass drivers, and then its front-cone depth. Deduct the second measurement from the first, then add about 1 to 2 inches to allow for cone travel to determine the spacing in our short tunnel. That done, we can then just follow the drawing in Fig. 5 to complete our cabinet design.

(Note: If you like, you can use the ENCDES-1.BAS program presented in my earlier article, "Designing your own Loudspeakers," **Popular Electronics** February 1994, to help design your box. Just enter the box volume into that program and it will calculate a suggested set of dimensions for the enclosure that will minimize standing waves and resonances.)

How is our system, once built, likely to sound? The answer is that the bass response will be pretty much set by the value of Q_{CAB} we choose, and therefore, as described above. But also, the relatively small cabinet and much higher power capacity will add to its appeal. In fact, the halving of the required cabinet size might allow us to use a bigger bass driver than originally planned and still get a manageable box size. And a bigger driver will get us even more bass power output.

The Dual-Chamber Tuned-Bandpass System. When we go shopping for a speaker system, what we often see as far as a subwoofer goes is just a simple box with a hole or port in one side. Not very impressive looking, but when we hear the mighty bass coming from such systems, we immediately know—that is the one for us!

What we are looking at is a "dual-chamber tuned-bandpass" subwoofer, and it is shown in a cutaway view in Fig. 6. In that illustration, the fact that the design has two chambers is obvious, and we can see that the active bass driver is mounted into one wall of the interior divider within the system. The divider also creates a sealed air volume behind the driver, while the driver's front faces into another chamber that is vented through a port into our listening room. By now, most of us would right away recognize that the vent and front-air volume create a resonant system, like any normal tuned-port or "bass-reflex" design, and that the rear chamber is just a standard acoustic-suspension sealed box. So what we have here is those two designs mated together.

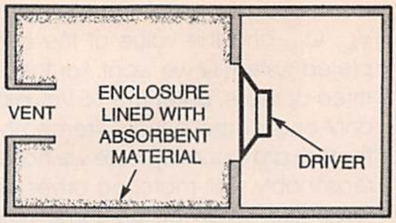


Fig. 6. Though complex to design, the dual-chamber, tuned-bandpass speaker can produce outstanding bass.

While mating the two designs obviously works well, the process of doing so can get very complicated. But with our next program, BPDES-1.BAS, shown in Listing 3, our personal computer will do all the hard math for us, making things very much easier.

But, first, a little background on the system. Although a patent was issued for a design called a "pass-band" speaker, a forerunner of the design shown here, in the 1950s, the world really did not become aware of it until 1979. That's when an engineer named Laurie Fincham, then with KEF loudspeakers in England, published a paper on his development of the design. Indeed, KEF still manufactures a line of loudspeakers using the design principles Fincham had worked out. Then, in 1989, another engineer, E. R. Geddes,

LISTING 3

```
100 PRINT:PRINT:PRINT:PRINT:PRINT
110 PRINT"          DESIGNING A DUAL CHAMBER BANDPASS "
115 PRINT
120 PRINT"                    SUBWOOFER SYSTEM"
125 PRINT:PRINT
130 PRINT"                           by"
135 PRINT
140 PRINT"                        William R. Hoffman"
190 PRINT:PRINT:PRINT
200 PRINT"          What is the free air bass resonance frequency of the"
210 INPUT"          driver (fo), in Hz. =";FS
215 PRINT
220 PRINT"          What is the drivers air volume compliance"
225 INPUT"          equivalent (Vas) value, in cu. ft. =";V
230 PRINT
235 INPUT"          What is the drivers total Q is free air (Qts) =";Q
240 PRINT
245 PRINT"          What is the desired low frequency cutoff"
250 INPUT"          of the system =";FL
255 IF FL>FS THEN 290 ELSE 260
260 PRINT
265 PRINT"          Your chosen value of cutoff requency is less than the"
266 PRINT"          free air resonance frequency of the driver, which is "
267 PRINT"          not permitted. Do you wish to try again with another"
268 INPUT"          value? (1=Yes, 2=No) and Enter";A
270 IF A=1 THEN 240 ELSE 990
290 PRINT
300 LET VF=(1.200000*Q)^2*V
310 LET A=FL/(FS/Q)
320 LET B=A+9.499999E-01
325 LET FH=B*(FS/Q)
330 PRINT"          For the system we are currently designing, the "
340 PRINT"          bandpass high and low frequency limits are going"
345 PRINT"          to be:"
350 PRINT
355 PRINT"               Low frequency cutoff ="FL"Hz.
360 PRINT
365 PRINT"               High frequency cutoff ="FH"Hz.
370 PRINT
375 PRINT"          Do you wish to continue with these values?"
380 INPUT"          (1-Yes, 2=No) and Enter =";B
385 IF B=1 THEN 400 ELSE 387
387 PRINT
390 PRINT"          Do you wish to try another value of low frequency"
395 INPUT"          cutoff? (1=Yes, 2=No) and Enter =";C
396 IF C=1 THEN 240 ELSE 990
400 PRINT
410 LET QT=A+3.700000E-01
420 LET VB=V/(((QT/Q)^2)-1)
430 LET FB=QT*(FS/Q)
440 PRINT
445 PRINT"          In order to calculate the length of the duct used to"
450 PRINT"          tune the front enclosure to the desired frequency, "
455 PRINT"          a value for its diameter must be selected. Enter any"
460 PRINT"          value of 1 in. to 6 inches that is convenient to use."
465 PRINT
470 INPUT"          Chosen duct diameter (in inches) =";D
475 PRINT
480 LET DA=(D/2)^2*3.145900
485 LET DL=((2691*DA)/(VB*(FB^2)))-(8.799999E-01*SQR(DA))
490 LET VT= VF+VB
500 PRINT"          For the chosen duct diameter of "D" inches, the "
510 PRINT"          required duct length is ="DL"inches.
520 PRINT
530 PRINT"          Is this value of duct length satisfactory?"
540 INPUT"          (1=Yes, 2=No) and Enter =";E
550 IF E=1 THEN 600 ELSE 560
560 PRINT
565 PRINT"          Do you wish to try another value for duct diameter?"
570 INPUT"          (1=Yes, 2=No) and Enter =";F
575 IF F=1 THEN 465 ELSE 990
600 CLS:PRINT:PRINT:PRINT:PRINT:PRINT
610 PRINT"          For a bass driver with a free air resonance of"FS"Hz,"
620 PRINT"          and a value of free air Q (Qts) of"Q", and an air"
630 PRINT"          volume compliance (Vas) of"V", the bandpass bass "
640 PRINT"          system has the following specifications:"
650 PRINT
660 PRINT"               Lower cutoff frequency ="FL"Hz.
670 PRINT
680 PRINT"               Upper cutoff frequency ="FH"Hz.
690 PRINT
700 PRINT"               Volume of front box ="VF"cu. ft."
710 PRINT
720 PRINT"               Volume of rear box ="VB"cu. ft."
730 PRINT
740 PRINT"               Total volume of both boxes ="VT"cu. ft.
750 PRINT
760 PRINT"               Front box tuning frequency ="FB"Hz.
770 PRINT
780 PRINT"               Tuning duct specifications:"
790 PRINT"                    Duct diameter ="D"inches."
800 PRINT"                    Duct length ="DL"inches."
990 PRINT
991 PRINT"          Do you wish to try another design?"
992 INPUT"          (1=Yes, 2=No) and Enter =";X
993 IF X=1 THEN 190 ELSE 995
995 PRINT
996 PRINT"          Good listening!"
999 END
```

published a technical paper that extended Fincham's work by creating a system with two, three, or even more vented chambers, both on the driver's front, and its back side. Also, Dr. Amar Bose, of the Bose Corporation here in the U.S., saw the use for those designs, and in 1985 took out a patent on the double-chamber, double-tuned system—which they jealously guard!

So why all the sudden activity in the last 10 years? Because despite the complexity of the design, it really works, and works well! Here's why:

Figure 7 shows the frequency response of a typical dual-chamber tuned-bandpass system. Note that this is indeed a true bandpass design, with our particular configuration having a cutoff slope of 24 dB-per-octave on either side of the pass band, just like a regular tuned, vented box. And note that no electrical crossover is actually required—a big advantage here since, for low frequency use, inductors and capacitors must be very big—and expensive! We get that bandpass response because the driver is entirely inside the enclosure, and the only sound comes out of the vent. Literally, the vent and the bass-resonance frequency of the driver shapes the entire response of the system, an important point to remember.

But, as we have said, such a system does become very complex to design. The bass cutoff frequency of the driver in the sealed portion of the cabinet must match the tuned frequency of the front, vented part. And the Q of the driver in the sealed box must be adjusted to match the Q of the vented front box to get the proper bandpass-response function. Further, because all those factors interact with each other, the bandpass system definitely is not a "cut and try" design.

So here is where the design program really helps us. By simply entering a driver's T/S values, and the bandpass low-frequency limit we want, the program designs our entire system for us. It calculates an exact set of values for both front and back air volumes, as well as the vent dimensions, and the bandpass-frequency limits, without our having to do any actual construction work. If our calculated design doesn't suit us in some way, we can then try other drivers with different T/S values until we find the combination that we want.

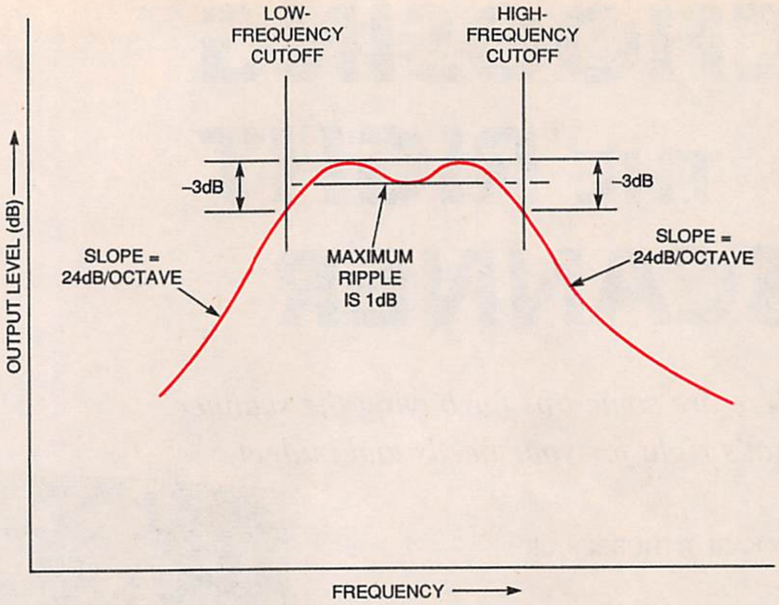


Fig. 7. Here's the frequency response of a typical dual-chamber, tuned-bandpass speaker.

Designing Our System. Just like the other systems, use a pencil, ruler, and graph paper to sketch out the final box design from the information supplied by the program. When designing the vent, use the largest diameter possible that will fit within the available space in the front box. That will help prevent "wind noises" due to turbulence in the air stream (which can be significant) through the vent. Remember, if the vent is so large that it occupies more than about 15% of the volume of the front enclosure, then adjust the box's dimensions accordingly so that its free volume stays at the value calculated by our program. Here, again, the ENCDES-1.BAS program can help us by getting our box dimensions for us.

It is a good idea, as Fig. 6 shows, to line the front chamber with a single layer of Fiberglas batting (not paper backed) or a similar absorbent material to reduce standing waves in the enclosure. However, never place any loose damping material in the front cabinet. Such material would tend to flop around inside the box, in time with the motion of the bass driver's cone, and, as Fincham observed, make odd "chuffing" noises and even upset the system's tuning; make sure all damping materials are securely attached to the chamber's walls.

Even with the bandpass action of our system, some kind of electrical low-pass filter (even a simple one like that designed by the XDES-1.BAS program in the article "Designing Loudspeaker Crossovers," which appeared in the July 1995 issue of **Popular Electronics**) should be used. If possible, limit the upper frequency range to about twice that of the vent's specified upper cutoff frequency. That is important because, even with its resonant tuning, it is still possible to get some direct sound output from the vent at higher frequencies.

Some Final Thoughts. The only other things to keep in mind about any of these designs is that, in building them, use the same, simple, common-sense procedures that everyone else does in building a speaker system. Use good, heavy ¾-inch material, like chipboard or, better yet, floor underlayment for the boxes. Glue, and screw or nail all joints together, reinforcing them as necessary. Make sure that there are no cracks or other unintended openings in the finished system. As necessary, even put some silicon sealer around the driver's rim for a tight seal.

Especially watch out for air leaks around where the wires for the driver enter the box at the speaker terminals. Also, use a good grade of wire, at least 18 gauge or better, for making all electrical connections. Finally, make sure that the speaker wire is stapled down to the box wall to prevent it from buzzing or rattling. ■