

12" Dual Voice Coil Servo Subwoofer System

Now you can build your own subwoofer system, featuring a dual voice-coil driver design. **By Daniel L. Ferguson**

My article in the November '03 issue of *audioXpress* ("A Servo Dual Voice Coil Subwoofer," p. 18) presented research I had done on a servo subwoofer which used a dual voice coil driver with one coil driven and the other used as a velocity sensor. The article explored the relationships between velocity, acceleration, and sound pressure level, and showed that the sensor voice coil output voltage could be representative of cone velocity if the crosstalk from the driven voice coil could be eliminated. While I achieved some degree of success with the concept, I was not ready to go forward with a construction project.

The main drawback with the design at that point was distortion at higher volume levels during large transients such as kick drums. Since then, I have continued to experiment to eliminate that problem and have progressed enough to proceed with building the first working model. This article gives the results of that effort and the details to allow you to construct a similar unit.

In the original version, the feedback signal contained two components—the derivatives of the sensor voice coil voltage and driven voice coil current—

which are the defining variables in the basic equation for the sensor voice coil acceleration transfer function. As it turns out, it is very difficult to match the phase relationships between these two to mimic the physical system. At this point, I must report that I have had only modest success after many hours of experimentation. I found that the system was very stable when either sensor voice coil voltage or driven voice coil current was used as feedback. When combined, system stability was significantly reduced.



PHOTO 1: Rear view of Dayton 12" DVC driver.

Therefore, I have set aside the driven coil current component—at least for the present—and have developed a servo system that uses only the sensor

ABOUT THE AUTHOR

Dan Ferguson has a BS and MS in mechanical engineering from Clemson University with a specialty in automatic controls. He is a long-time speaker builder and the author of three books on auto sound (the latest, *Car Stereo Speaker Projects Illustrated* is available from Old Colony Sound Lab) and several articles for *Speaker Builder/audioXpress*. He has been employed by Kimberly-Clark Corporation in various management positions for the past 22 years and is currently an operations consultant on a large MIS project. He and his wife have three grown children and five grandchildren, and reside in Appleton, Wis.

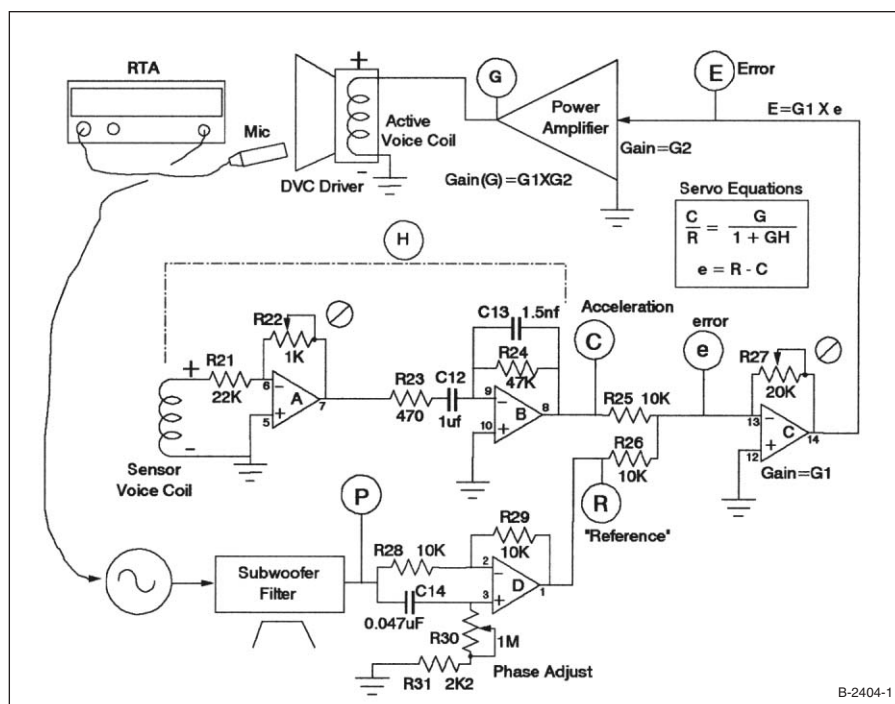


FIGURE 1: Servo circuit diagram.

voice coil voltage as feedback. While this is a theoretical compromise, it seems to work reasonably well. The reason for this is that the current-induced crosstalk from the driven voice coil appears to be minimal within the bottom decade. At very low frequencies, it is present, but only at low levels. While I intend to continue to experiment with the theoretical model, the more practical version presented in this article is still a significant improvement over open-loop subwoofers and appears to be very stable and reliable.

CONCEPT

Figure 1 shows the diagram of the simplified servo system. The sensor voice coil output voltage is scaled and inverted in op amp A and fed to an improved differentiator circuit driven by op amp B. The differentiator output at point C (the “controlled variable”) is representative of the driver cone acceleration within the 20 to 120Hz or so bandwidth. Collectively, the system consisting of the sensor voice coil and the differentiator make up the “sensor,” referred to in control terminology simply as “H.”

Since an unused op amp section was available on the quad chip used, I added an optional phase adjustment circuit driven by op amp D. Depending on the position of R30, the subwoofer’s phase can be offset from the input signal by approximately 0 to –180°. While this is somewhat of a “luxury” item, it has the potential for significantly im-

proving system integration with the main speakers. The phase shifter output at point R represents the “reference” which the servo attempts to reproduce.

Op amp C has a variable gain from 0 to 2 depending on the position of R27 and is adjusted to allow setting the power amplifier volume control at a convenient level. The summing junction of this inverting op amp is the sum of the sensor output (which has been inverted by op amp A) and the input signal. The sum of these two is the system error correction signal. The

job of the servo is to attempt to drive this to zero.

Overall system gain is the product of op amp C and the power amplifier gains and is referred to simply as “G.” Later on, you’ll see how these servo variables are applied in classical automatic control theory.

DRIVER SELECTION AND TESTING

The starting point was selecting the proper dual voice coil (DVC) driver. The ideal candidate should have low Qts, low free-air resonance frequency (Fs), low Vas, high excursion (Xmax), and

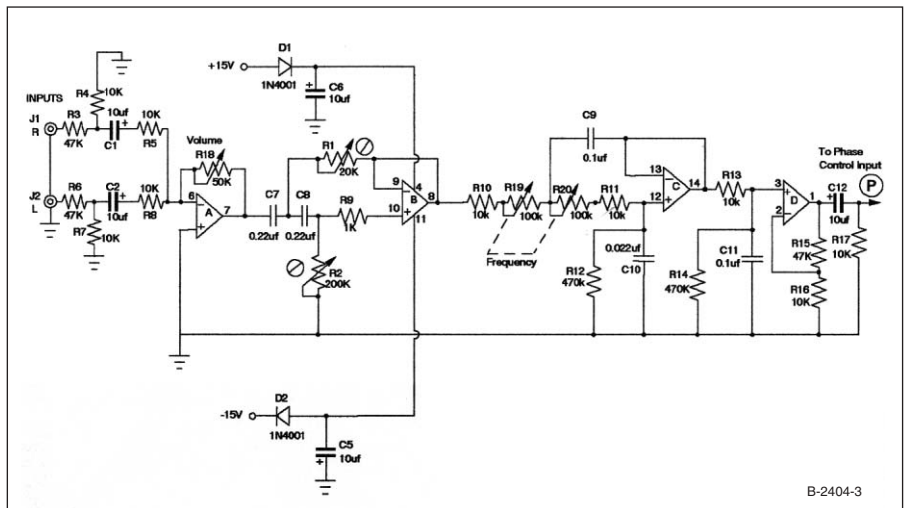


FIGURE 3: Servo subwoofer filter schematic.

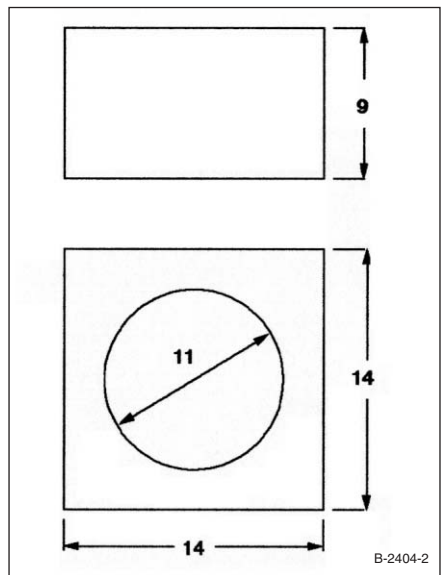


FIGURE 2: Subwoofer enclosure inside dimensions.

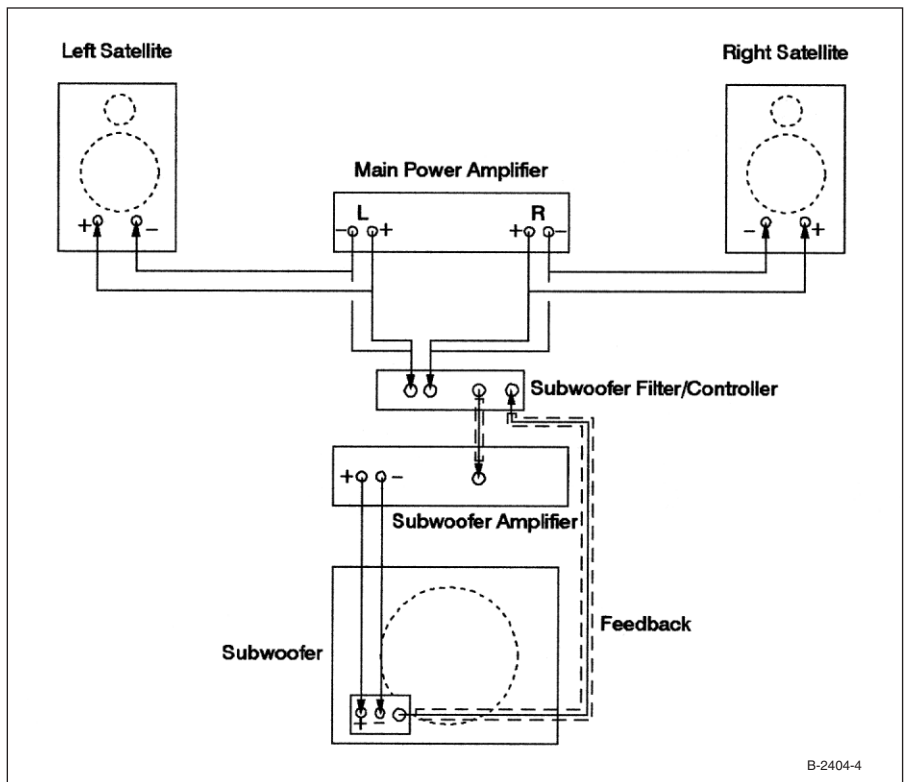


FIGURE 4: System wiring diagram.

good power handling. Last of all, it should be reasonably priced.

Taking all these factors into consideration, there are not many suitable drivers to choose from. The one I settled on is manufactured by Dayton and distributed as catalog number 295-185 by Parts Express, who graciously lent a sample unit for this article. The published specifications for this driver are as follows:

Power handling: 350W RMS/per coil, 600W total
 Voice coil diameter: 2"
 Voice coil inductance: 1.81mH
 Nominal impedance: 8Ω per coil/4Ω total
 DC resistance: 2.69Ω (both coils connected in parallel)
 Magnet weight: 112 oz.
 Fs: 21.7Hz
 SPL: 87.4dB 1W/1m, 90.4dB @ 2.83V/1m

(both coils connected in parallel)
 Vas: 4.25ft³
 Qms: 12.53
 Qes: 0.38
 Qts: 0.37
 Xmax: 15.1mm
 Net weight: 18 lb
 Catalog price: \$119.80

Collectively, these appear to be an excellent set of specifications. The ±15.1mm (0.59") excursion rating held prospects for a linear magnetic system operation at high sound pressure levels, which is crucial for a servo mechanism. All the other parameters are similarly favorable.

Photo 1 shows the bare driver. It's a brute with a stiff, heavy, treated paper cone reinforced by an equally stiff 6½" diameter domed "dust cover." The relatively thick foam surround is approximately an inch wide and appears consistent with the

driver's high-excursion rating. Connection terminals are heavy-duty spring types able to accommodate large diameter wire and are plated to resist corrosion. The magnet assembly is covered with a rubber boot and is free of

sharp edges. Altogether, the unit is impressive in appearance and heft.

After a couple of hours of break-in with a 3V 25Hz signal, I measured the Thiele/Small parameters and attained the following results:

Fs: 20.6Hz
 Re: 2.6Ω
 Qms: 9.96
 Qes: 0.38
 Qts (voice coils in parallel): 0.365
 Vas (added mass method): 3.50ft³
 Vas (closed box method): 3.47ft³

The critical parameter, Qts, was dead on. Having a somewhat lower Fs and Vas is usually an advantage. Lower Fs means lower cutoff frequency, while lower Vas translates to reduced box size for any given alignment. All parameter measurements were consistent and repeatable. Clearly, this was the most "linear" woofer I have experimented with to date.

With one voice coil driven, the measurements were essentially the same, except that Qts is now double what it was with both coils driven. And, of course, the DC resistance (Re) of a single voice coil is double that of two coils in parallel.

Fs: 20.7Hz
 Re: 5.2Ω
 Qms: 10.89
 Qes: 0.82
 Qts: 0.76
 Vas (added mass method): 3.50ft³
 Vas (closed box method): 3.47ft³

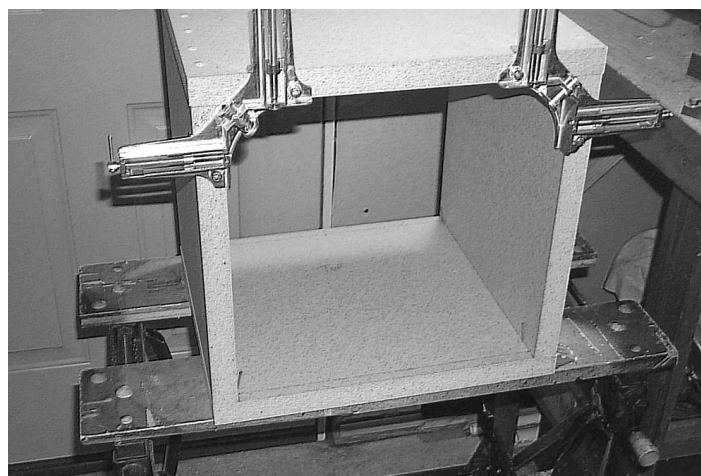


PHOTO 2: Subwoofer enclosure under construction.

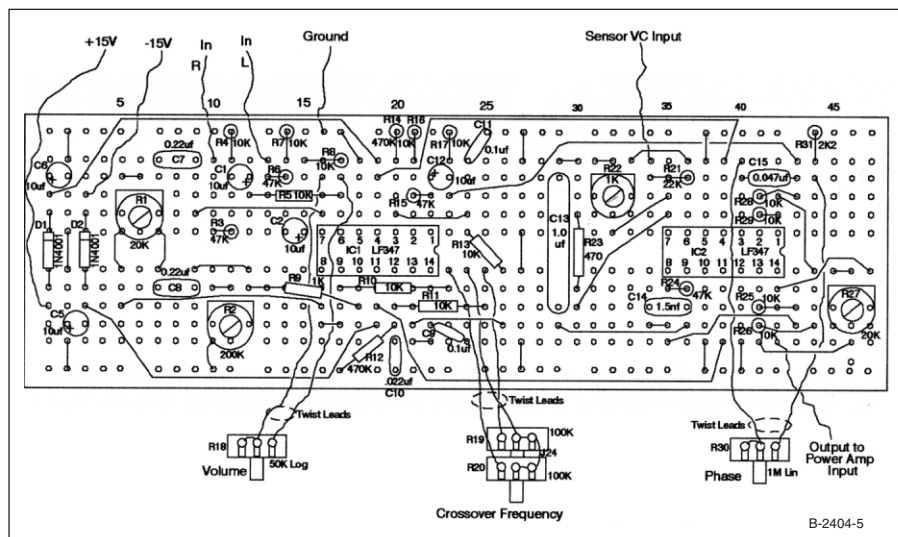


FIGURE 5: Subwoofer controller PC board layout.

ENCLOSURE CONSTRUCTION

In order to minimize any nonlinearities the enclosure might introduce into the servo loop, I decided to make the structure more rigid by constructing it out of 1½" thick counter top material. While this material is not readily available, I was able to find a local kitchen counter shop that not only could supply the material but was also willing to precision-cut the pieces to size for a nominal fee. As a result, I paid a total of \$27 for the initial six pieces for the trial 1½ft³ box, which is shown under construction in Photos 2 and 3.

The completed box is rigid, to say the least. Since the resistance of a material to flexure varies with the cube of the thickness, this box should be 3.4 times

stiffer than an equivalent box constructed from $\frac{3}{4}$ " thick material.

As has become my standard practice, I sized the pieces for a $\frac{1}{16}$ " overlap at each joint and glued and screwed the pieces together. I needed to buy a new flush cutting router bit to handle the thicker material. The one I chose is made by CMT (#806.630.11), which is able to trim off stock up to 2" thick like a lightsaber. I also used my router with a straight plunging bit to accurately cut

the driver mounting hole using a simple jig made from a piece of scrap bolted to the router's bottom plate and a nail for a center pivot. The accuracy of the hole diameter is dependent only on how accurately the center pivot nail is placed.

After testing and experimentation by adding blocks to reduce volume, I deter-

mined that one cubic foot would be adequate to achieve the target closed box Q of 1.5. I cut the box down and installed a new back. The result is shown in *Photo 4* with dimensions given in *Fig. 2*. As long as box volume is maintained,

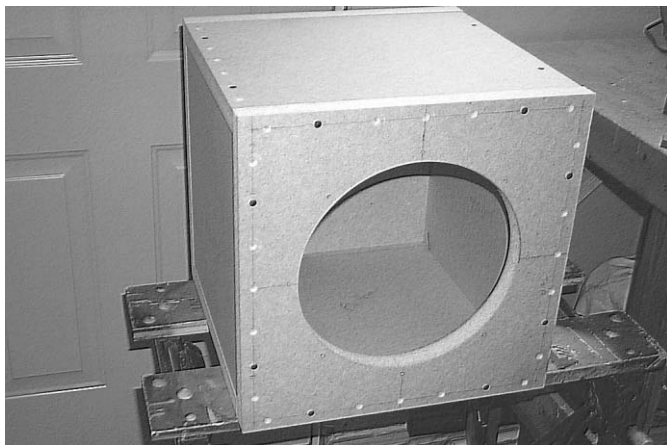


PHOTO 3: Subwoofer enclosure with front and rear panels.



PHOTO 4: Assembled subwoofer front view.

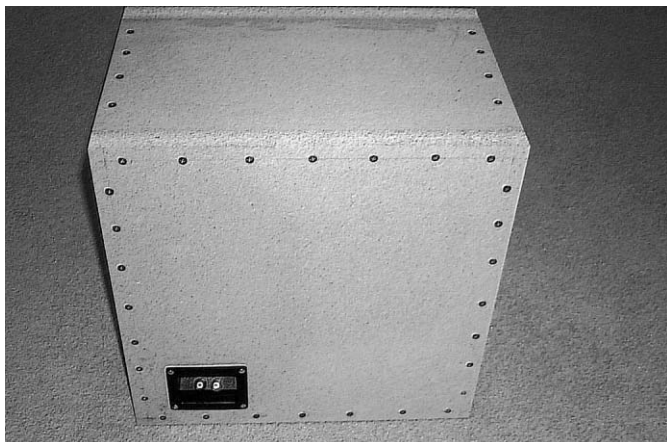


PHOTO 5: Assembled subwoofer rear view.

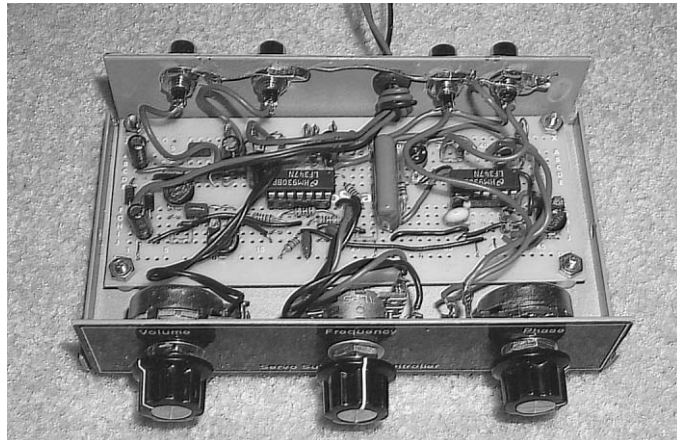


PHOTO 6: Assembled subwoofer filter/controller.



PHOTO 7: Subwoofer filter/controller front view.

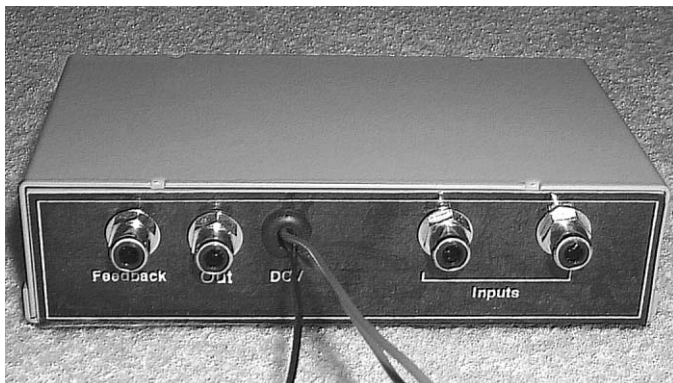
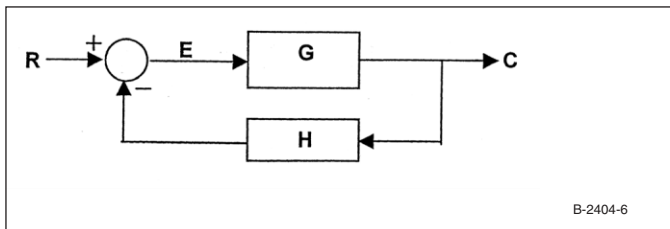


PHOTO 8: Subwoofer filter/controller rear view.



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FIGURE 6: Basic block diagram for a closed-loop system.

none of the dimensions are critical except for the driver mounting hole diameter. With the dimensions shown, there is plenty of room to install a grille frame if you desire one.

Photo 5 shows the terminal cup installed in the rear of the enclosure near a corner, which is the strongest point and shouldn't weaken the back as much as it would near the center. I also installed an RCA jack in the terminal cup to provide a convenient sensor voice coil connection.

CONTROLLER

To ensure repeatability of results, I decided to include all of the subwoofer control functions on one circuit board. All that's required for a complete servo is a regulated $\pm 15V$ power supply and an external amplifier. The subwoofer filter section schematic is shown in Fig. 3. You can possibly omit this portion of the circuitry if you have a suitable filter available with similar response characteristics.

For maximum flexibility, I designed this version of the filter with high-level inputs, which are connected to the

right and left satellite speaker terminals. Figure 4 shows the complete external wiring diagram.

Light-gauge speaker wire with an RCA plug on one end is the preferred interconnect for the controller inputs. Standard, shielded audio patch cords

connect the sensor voice coil to the feedback input terminals and send the controller's output to the power amplifier (Note: It may not even be necessary to use shielded cable for the feedback connection). Nothing fancy is required here. The tiny operating bandwidth and

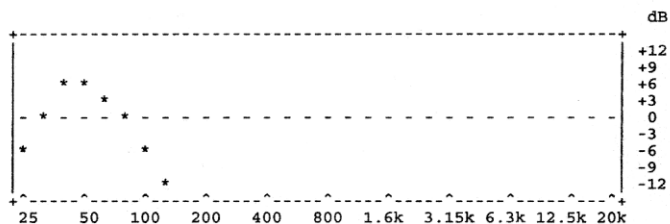


Fig. 7a

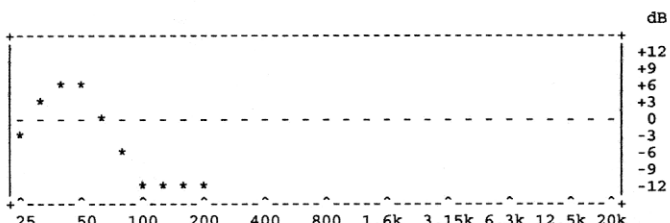


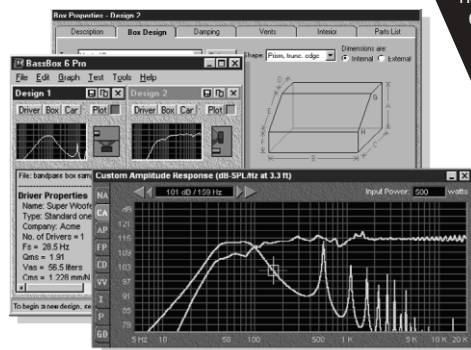
Fig. 7b

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FIGURE 7: Subwoofer loop response. 7a: close-miked response. 7b: accelerometer response.

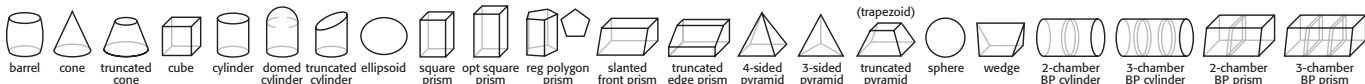
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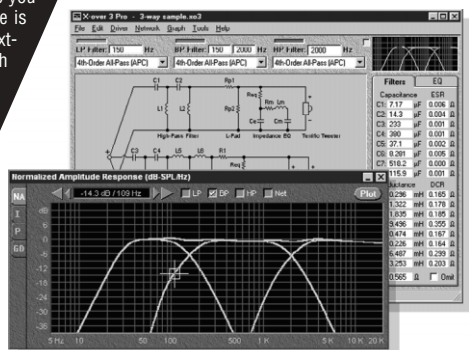
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ultra-low frequency range just doesn't justify it.

The controller circuit board is built on a standard prototyping board available from Radio Shack or a number of other suppliers. The layout is shown in *Fig. 5*. If you use the same cabinet I did, you will need to trim off approximately 1/4" from each end of the board and drill new mounting holes before getting started. The completed control unit is shown in *Photos 6, 7, and 8*. I made front and rear "faceplates" using Lotus Freelance and printing them on full-page label stock.

After that, I covered them with transparent shipping tape before cutting them out and placing them on the cabinet.

SOME BASIC SERVO THEORY

The basic block diagram for a closed-loop system is shown in *Fig. 6*.

The classic equation (expressed in Laplace transforms), which describes the closed-loop transfer function of a simple servo, is

$$\frac{C}{R} = \frac{G}{1 + GH}$$

This states that the controlled variable, C, varies with the reference variable, R, according to the ratio of the transfer function of the controller/amplifier, G, divided by 1 + the product of G and the transfer function of the feedback sensor, H.

Ideally, C/R would always equal 1 so the controlled variable would equal the reference. Since it's an imperfect world, the challenge for the servo designer is to come as close as possible to this ideal.

It can also be shown that the error-correction signal transfer function, E, can be described by

$$\frac{E}{R} = \frac{1}{1 + GH}$$

$$\text{where } E = R - HC$$

If you want the error to be small, GH must be much greater than zero. However, as you increase GH, you will eventually reach a point where the system becomes unstable.

Therefore, if H is too high, you will need to reduce the amplifier gain to maintain stability. This could reduce the forward gain so much that the speaker output is insufficient. Clearly, a balance must be reached so that the power amplifier gain setting is near midpoint for good signal-to-noise and adequate sensitivity.

After much experimentation, I settled on the following servo settings for the best combination of accuracy and stability. With the system operating in steady-state at 40Hz, I took the following measurements:

R27 set at its maximum of 17K

$G1 = R27/R25 = 17K/10K = 1.7$

$G2 = V_{out}/V_{in} = 0.97V/0.2V = 4.85$

Total $G = (G1 \times G2) = (1.7 \times 4.85) = 8.25$

With R22 set at = 333Ω

$H = 0.142V = 0.71R$

Therefore $GH = (8.25 \times 0.71) = 5.85$

Since GH is much greater than 1, the servo should have a positive effect on error reduction.

OPEN-LOOP SYSTEM RESPONSE

Prior to final testing, I lightly stuffed the enclosure with 14 oz of poly fiber fill, which reduced the closed box Q from 1.5 to 1.4 and closed box resonant frequency from 40.2Hz to 37.3Hz. Directionally, this should improve system

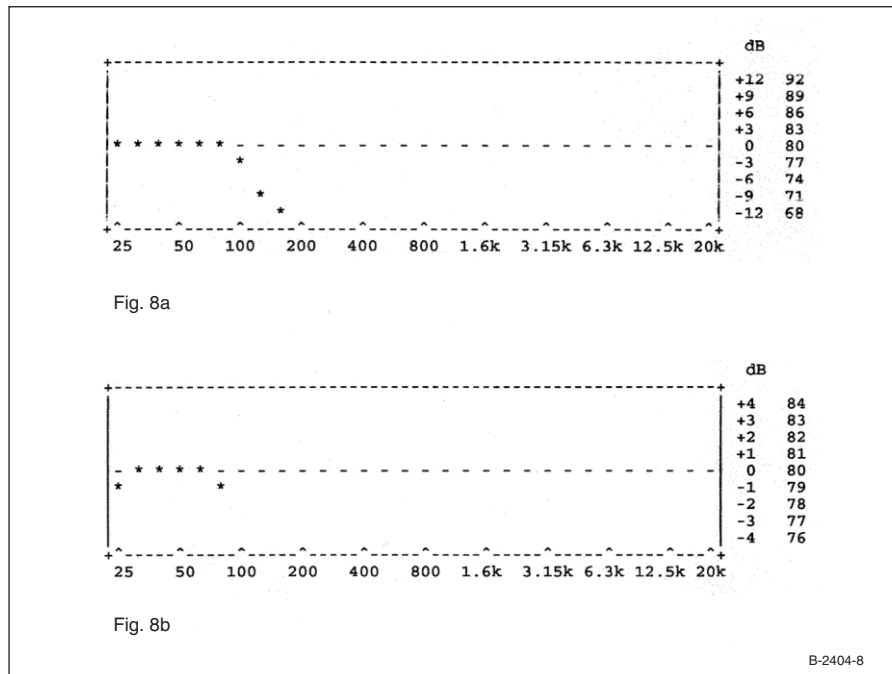


FIGURE 8: Subwoofer filter response. 8a: 3dB per division scale. 8b: 1dB per division scale.

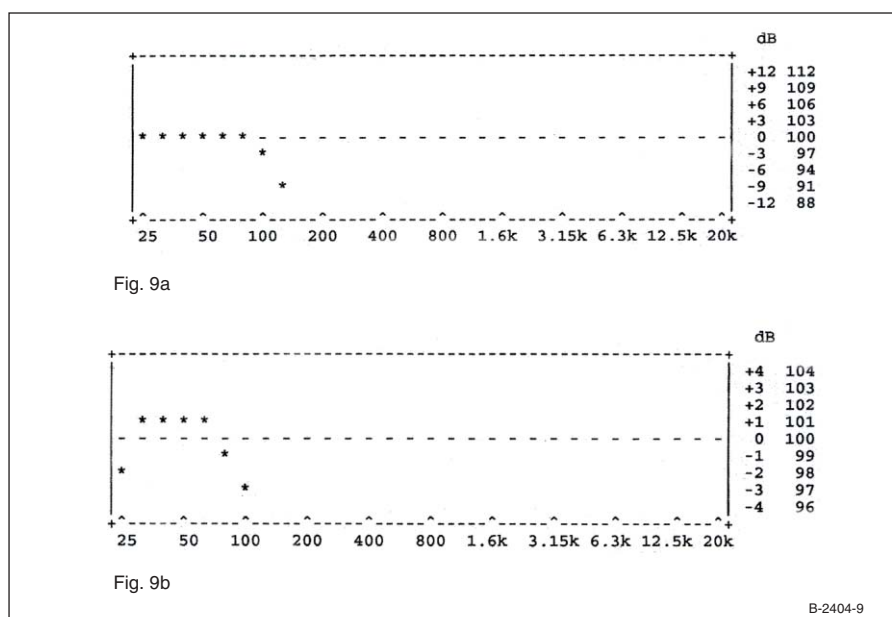


FIGURE 9: Subwoofer closed loop response. 9a: 3dB per division scale. 9b: 1dB per division scale.

performance since another basic servo design principle is to develop the best open-loop response possible before closing the loop.

Using the hookup shown in *Fig. 1*, I applied pink noise to the system and measured the response with my Audio Control SA3055 real-time analyzer. *Figure 7a* is the open-loop response measured with the RTA microphone. This is clearly the response of a grossly undersized box.

Figure 7b is output of the sensor voice coil after taking its derivative (point C in *Fig. 1*) under the same system conditions as previously stated. There are some differences between *Figs. 7a* and *7b* that are cause for concern. While the peak is at the right frequency, the slopes on either side are not the same as those measured with the mike. Although these differences appear to be genuine, the servo still performs well, as the following data shows.

CLOSED-LOOP RESPONSE

If the servo is working, the subwoofer will reproduce the response curve of the subwoofer filter.

With the subwoofer filter trimpot settings at $R1 = 17.2K$ (the maximum setting for the particular trimpot I used) and $R2 = 70K$, I applied pink noise to the filter inputs and obtained the response shown in *Fig. 8* from the filter output (point P in *Fig. 1*). *Figure 8a* is with the resolution set to 3dB per divi-

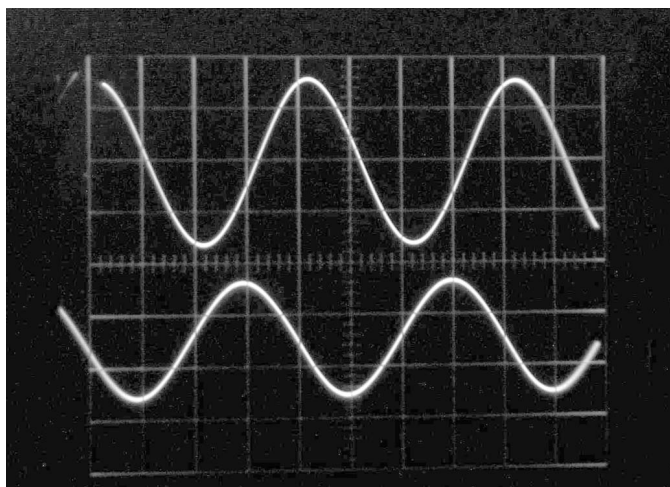


PHOTO 9: Subwoofer closed-loop waveform at 25Hz.

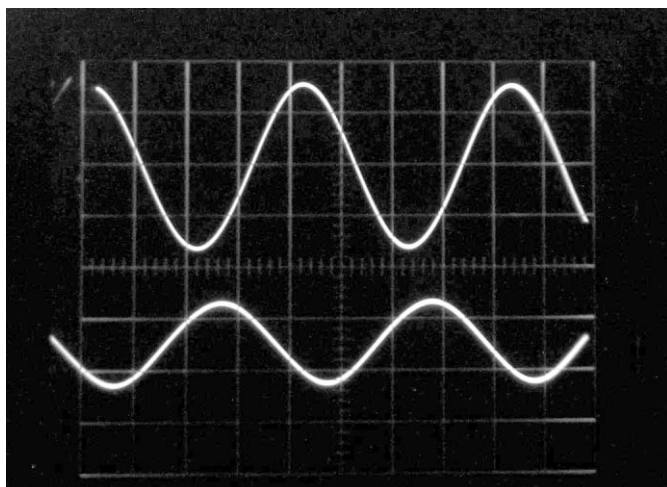
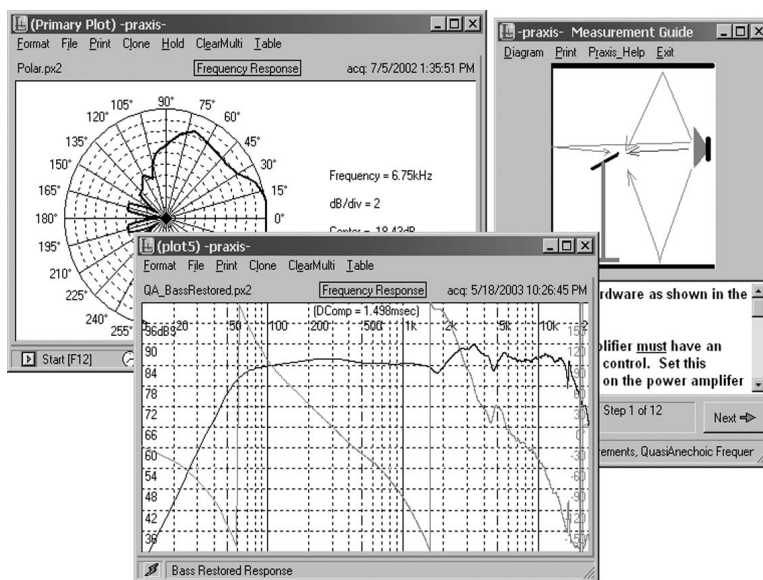


PHOTO 10: Subwoofer open-loop waveform at 25Hz.

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sion. *Figure 8b* is the same response curve with the resolution set to 1dB per division. Clearly, the curve is ruler flat within the passband and is a proper reference for the servo.

Next, I connected the complete servo without changing any settings and achieved the acoustic, close-miked response curve for the subwoofer shown in *Fig. 9*. *Figure 9a* is with the resolution set to 3dB per division. It is identical to the reference curve.

Figure 9b is the same curve with the resolution set to 1dB per division. It is very similar to the reference curve and is identical within the passband. The slopes on either end of the passband are, in fact, steeper than the filter and are consistent with the sensor coil's response noted previously. However, the difference is on the order of only 1dB, which should make it inaudible.

For this portion of the test, I judge the servo to be a success.

CLOSED-LOOP WAVEFORMS

Photo 9 shows the subwoofer sine waveform at 25Hz with the amplifier output set at about 2V AC. The upper trace is the input reference signal taken at Point R in *Fig. 1*, while the lower trace is the close-miked subwoofer output. The waveform appears to be sinusoidal and distortion-free.

For comparison, *Photo 10* is the same operating point with the feedback signal unplugged. While the amplitude is significantly lower, the waveform still appears to be sinusoidal. This is clearly credited to the quality of this driver. Higher frequencies within the subwoofer filter passband are considerably easier to reproduce.

Photo 11 is a sample at 30Hz. At this point, the amplitude is the same as the upper trace reference. *Photo 12* is the same operating point with the feedback unplugged. The amplitude has clearly fallen off.

Another test of the servo is its ability to track a complex waveform. *Photo 13*

shows the closed-loop subwoofer response to a 25Hz square wave. The upper track is the reference signal from the subwoofer filter; the lower track is the close-miked subwoofer response. After a square wave passes through the subwoofer filter, it's not too square any more.

Now, it's important to understand that this is *not* distortion. It is simply what happens when the higher-frequency components are filtered out of the square wave.

In any case, the irregular shape of this curve makes for a good gymnastic workout for the servo to try to track, and it does a fairly creditable job of doing so. *Photo 14* shows the identical condition with the feedback unplugged. There is some deterioration in both shape and amplitude.

HOW LOUD WILL IT PLAY?

I placed my RTA mike at a distance of 1m from the subwoofer at a height of 1m off the floor. At a power amplifier voltage

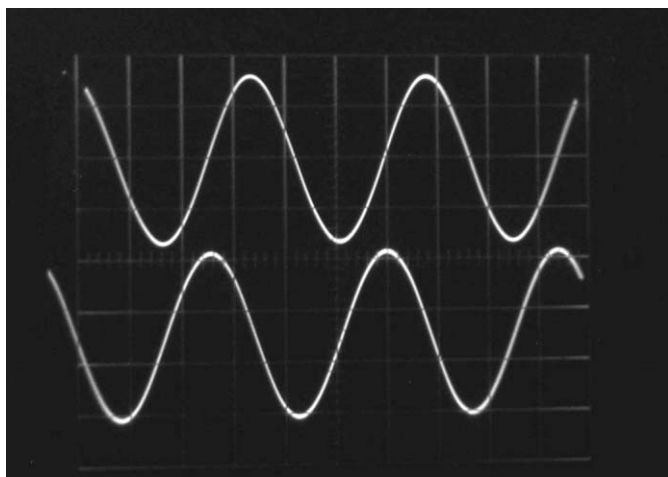


PHOTO 11: Subwoofer closed-loop waveform at 30Hz.

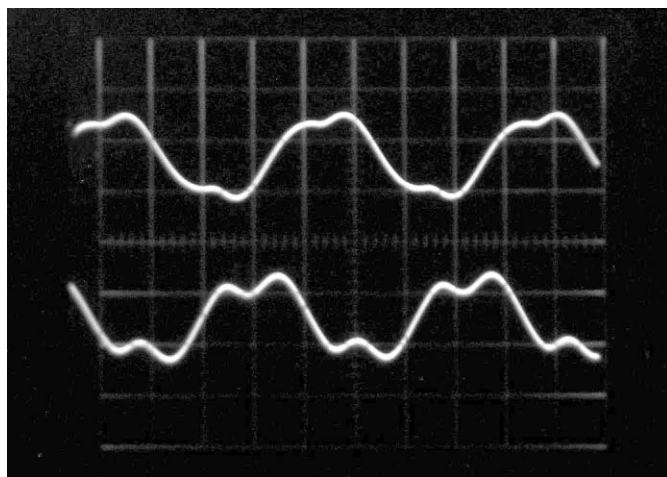


PHOTO 13: Subwoofer closed-loop waveform—25Hz square wave.

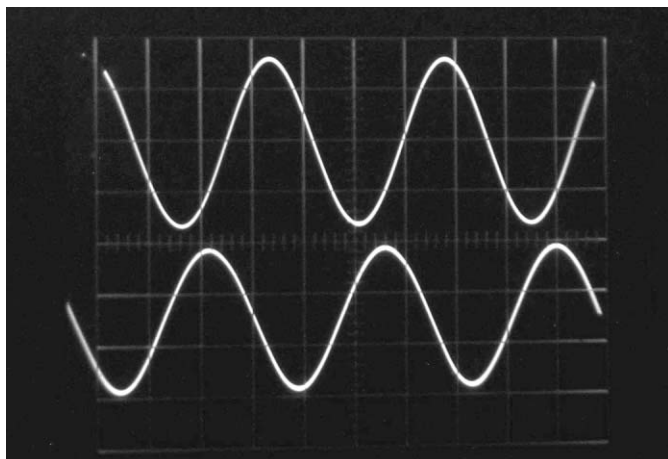


PHOTO 12: Subwoofer open-loop waveform at 30Hz.

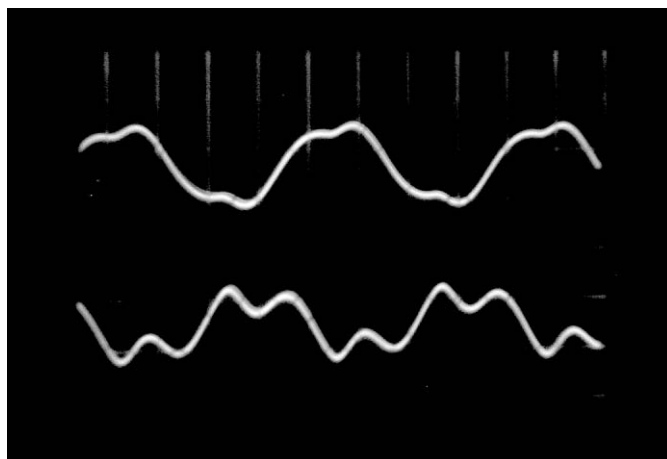


PHOTO 14: Subwoofer open-loop waveform—25Hz square wave.

of 22V RMS, the sub produced an output of 90dB at 30Hz before the waveform began to show signs of becoming triangular. At 35Hz, the sub would handle 25V RMS before visible distortion and the output reached 100dB.

HOW DOES IT SOUND?

There is only one word necessary to describe the sound of this sub—smooth. When low frequencies are reproduced without distortion, they become almost subliminal. In addition, the servo forces the sub to react faster to transients than an open-loop sub, so kick-drum impacts are immediate. It just

might be a good match for a pair of electrostats or magnaplanars. Since the cabinet is so compact, you could build one for each channel.

Before closing, a word about setting up the phase control for a seamless blend with the main speakers is in order. The easiest way I have found to optimize the phase control setting is to run a single tone through your entire system at the crossover frequency you are aiming for—preferably somewhere around 80Hz. Position yourself between the sub and the main speakers and adjust the sub volume until it appears to be equal to the main speakers. Then

sweep the phase control up and down until the tone is the loudest.

At this point, the sub is in phase with the mains. You can make this test more definitive with a sound-level meter.

CONCLUSION

My design goals for this project were to apply what I learned from the original experimentation and build an accurate, compact subwoofer with adequate output within the passband of 20 to 100Hz. In my opinion, it meets these goals. More importantly, this subwoofer makes beautiful music. So, while it's a little bit of a technical compromise, it's no slouch. I recommend it for a fun project. ♦

PARTS:

RESISTORS	VALUE	QTY	PART NO.	SUPPLIER
R4, R5, R7, R8, R10, R11, R13, R16, R17, R25, R26, R28, R29	10k	13	10.0KXBK-ND	Digi-Key
R9	1k	1	1.00KXBK-ND	Digi-Key
R12, R14	475k	2	475KXBK-ND	Digi-Key
R3, R6, R15	47.5k	3	47.5KXBK-ND	Digi-Key
R21	22.1k	1	22.1KXBK-ND	Digi-Key
R23	475	1	475KXBK-ND	Digi-Key
R31	2.21k	1	2.21KXBK-ND	Digi-Key
R1	20k Trimpot	2	3306P-1-203	Digi-Key
R2	200k Trimpot	1	3306P-1-204	Digi-Key
R27	1k Trimpot	1	3306P-1-102	Digi-Key
R18	10k Pot (Log)	1	271-1721	Radio Shack
R19, R20	100k Dual Pot	1	271-1732	Radio Shack
R29	1M Pot (Linear)	1	271-211	Radio Shack
DIODES				
D1, D2	1N4001	1	1N4001GI	Digi-Key
CAPACITORS				
C1, C2, C5, C6, C12	10μF/35V Electrolytic	5	493-1077-ND	Digi-Key
C7, C8	0.22μF/50V Metal Film	2	P4667	Digi-Key
C9, C11	0.1μF/50V Metal Film	2	P4525	Digi-Key
C10	0.022μF/50V Metal Film	1	P4517	Digi-Key
C12	1.0μF/50V Metal Film	1	P4675	Digi-Key
C13	1.5nF/100V Metal Film	1	495-1092-ND	Digi-Key
C14	0.047μF/100V Metal Film	1	495-1101-ND	Digi-Key
INTEGRATED CIRCUITS				
IC-1, 2	LF-347	2	LF347N	Digi-Key
HARDWARE				
Circuit Board		1	276-170	Radio Shack
Knobs	¾" Dia.	2	274-415	Radio Shack
Cabinet	5½ × 3 × 1¼	1	537-139-P	Mouser
RCA Jacks		4	161-1052	Mouser
Grommet	5/16" Dia.	1	534-731	Mouser
Nylon Spacers	¼" long	4	561-K4.25	Mouser
Screws	4-40 × ½"	4	H146	Digi-Key
Nuts	4-40	4	H216	Digi-Key
IC Socket	14 Pin	2	A24808-ND	Digi-Key
WIRE				
Red, Green, Black	22 gauge Stranded	1 pkg.	278-1224	Radio Shack
Bus Wire	24 gauge	1 spool	278-1341	Radio Shack

SUPPLIERS

Parts:

Parts Express

725 Pleasant Valley Dr.
Springboro, OH 45066-1158
1-800-338-0531
www.partsexpress.com

Mouser Electronics

958 N. Main
Mansfield, TX 76063-4827
1-800-346-6873
www.mouser.com

Digi-Key

701 Brooks Ave. South
Thief River Falls, MN 56701-0677
1-800-344-4539
www.digikey.com

Radio Shack

Local Store
1-800-THE-SHACK
www.radioshack.com

Lumber and building supplies:

Local countertop contractor
Local home improvement stores

PARTS LIST

MATERIALS:

1 sheet countertop material (30" × 8' × 1¼")
1 box 2" long course thread sheet rock screws
Rope caulk
3' twin lead speaker wire
Carpenter's glue

REFERENCES

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2. Dorf, Richard C., *Modern Control Systems*, Addison - Wesley Publishing Company, Inc., 1967.
3. Dickason, Vance, *The Loudspeaker Design Cookbook*, The Marshall Jones Co., third edition, 1987.
4. Jung, Walter G., *Audio IC Op-Amp Applications*, Howard W. Sams & Co., Inc., second edition, 1978.
5. Malvino, Albert Paul, *Electronic Principles Third Edition* - McGraw-Hill Book Company, 1984.