



A Servo Dual Voice Coil Subwoofer

Here's an application of the closed-loop concept to the subwoofer to produce accurate, low-cost bass.

By Daniel L. Ferguson

A great deal of effort has been put forth over the past half century to find the best way to reproduce clean, accurate bass. Many different solutions to the problem have been presented in publications such as the *Journal of the Audio Engineering Society* and *Speaker Builder*. With few exceptions, all of them are “open-loop” systems. They all depend on the electromechanical ingenuity of the loudspeaker designer and the physics of the enclosure design to, in effect, “predict” how the voice coil and diaphragm will react to an electrical input.

While some of these designs work better than others, all open-loop solutions have limitations in accuracy. Not many subwoofers are capable of reproducing the lowest octave at audible levels, and when they do, distortion levels of 5 to 10% are common.

The “opposite” of an open-loop system is a closed-loop one, in which the movement of the driver's diaphragm is measured and compared to the input signal, and the difference between the two becomes the error signal, that is used to “force” the diaphragm motion to conform more closely to the input. This is the concept of negative feedback that is used in a servomechanism, which Webster defines as “an automatic device for controlling large amounts of power by means of very small amounts of power and automatically correcting the performance of a mechanism.” The date of this definition is 1926, so the concept has been around for a while. Applied to the loudspeaker, the implications are that a closed-loop subwoofer should have deeper bass extension, lower distortion, and flatter fre-

quency response.

While the closed-loop woofer concept is not new, it's been slow to migrate to the commercial loudspeaker industry—undoubtedly due to its significantly higher cost and complexity. Examples of commercial servo subwoofers that come to mind are the hugely expensive Infinity Servostatic system of the 1970s and the modern Velodynes. Both of these use accelerometers attached to the driver cones to measure the cone motion. Other methods of directly or indirectly measuring cone motion have been tried, but none that I am aware of have been accepted on a wide basis.

BACKGROUND

The purpose of this article is to present some work I have done on developing an accurate and relatively low-cost method to close the loop on a subwoofer. This method uses a dual voice-coil driver in a closed box configuration, with one coil driven and the other coil used as a velocity sensor to provide

the feedback signal to the servo.

Figure 1 illustrates how the concept works. The signal is introduced into a summing junction, where it is compared to the measured acceleration signal produced by the undriven voice coil of a dual voice-coil woofer. The difference between these two becomes the error signal, which is fed to a power amplifier that drives the other voice coil. This concept only works for closed box systems, where the motion of the driver cone is the sole source of sound produced by the system.

This idea first occurred to me in 1984. I remember the year because I recall where I was working when I contacted one of the major loudspeaker manufacturers that produced dual voice-coil (DVC) woofers to ask about the feasibility. I had a nice conversation with a very

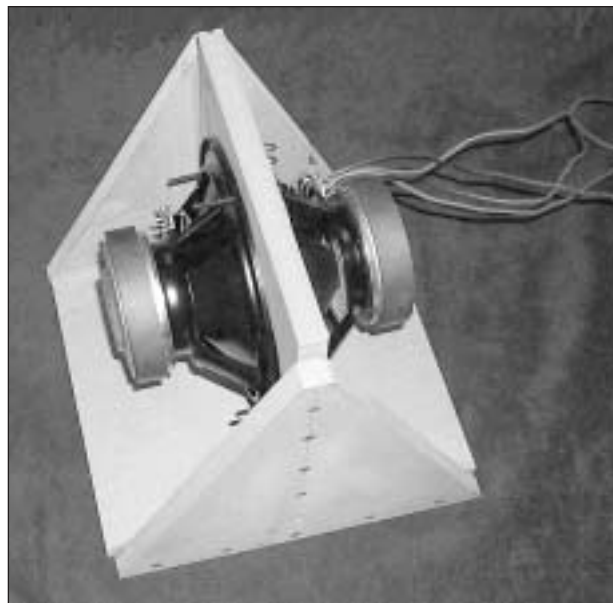


PHOTO 1: Setup to test velocity signal.

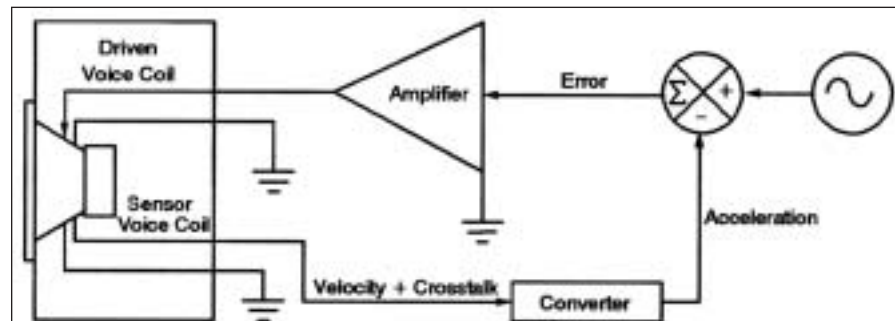


FIGURE 1: Servo woofer.

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obliging fellow who was an authority on loudspeaker design. When I asked about the possibility of using one of the coils as a velocity sensor, he replied that it wouldn't work because the sensor signal would be "nonlinear." Since mathematically nonlinear functions are the kiss of death in servo design, I reluctantly tucked the concept away in the back of my mind but never really forgot about it.

Recently, I decided to see whether I could find anything on the Internet concerning the use of a dual voice-coil speaker in a servo configuration (one coil driven and the other used as a sensor). I was thrilled to find a paper on the subject published in 2000 by the University of Michigan¹. I couldn't wait to download and read it.

The paper was written by four researchers at three major universities, so I was confident of the quality of the work. It answered the questions I had wondered about and filled in almost all of the missing gaps. However, I found one crucial area that I believed I could significantly improve upon.

The main points of the paper (from my perspective) were:

1. The sensor voice coil produces a voltage proportional to velocity that is a mathematically linear function!
2. Sound pressure level (SPL) is proportional to loudspeaker cone acceleration—not velocity. Therefore, the derivative of the velocity signal must be used as the feedback signal in a servo.
3. The sensor voice-coil voltage contains induced voltage (crosstalk) from the driven voice coil.
4. The induced voltage can be filtered out.

EXPLICATION OF POINTS

1. The principle that a conductor moving through a magnetic field produces a voltage proportional to velocity is one of Faraday's laws and is the basis for all generators. What was new information for me was that the loudspeaker voice-coil magnet system produces a linear voltage. In other words, the faster the voice coil moves, the higher the voltage. The term "linear" does not necessarily (or usually) mean a straight line; it means that the process can be modeled with linear

differential equations. This is crucial to the servo design.

2. I have always wondered whether SPL was proportional to velocity or acceleration. Reference 1 cites a 1959 Audio Engineering Society paper by J. F. Novak which states that SPL is proportional to acceleration for a speaker with a diameter less than one-third of its highest operating frequency wavelength. For a subwoofer, the passband is ideally 20 to about 100Hz. Therefore, the highest audible frequency it would probably produce is an octave or so above this (200Hz).

At 200Hz, the wavelength of sound is about 67.8". One third of this is 22.6", so the relationship should hold for woofers up to that diameter.

3. It should be obvious that two precision-wound coils in intimate contact with each other will exhibit plenty of mutually induced crosstalk.
4. The authors of reference one used a second-order filter to contour the sensor voice-coil velocity signal to make it more representative of the actual velocity. This is where I believe they arrived at a sub-optimal solution.

In their elegant mathematical model, the equation (after simplifying) that describes the voltage appearing at the sensor voice-coil terminals is:

$$V_s(t) = c(dx/dt) + M(di_1/dt)$$

where $V_s(t)$ = voltage across the sensor voice coil

c = forcing factor or back emf constant of the electromechanical system

dx/dt = velocity of the cone

M = mutual inductance of the two voice coils

di_1/dt = rate of change of current in the driven voice coil

From this equation, the crosstalk component in the sensor voice-coil voltage is produced solely by the rate of change of current in the driven voice coil. If it can somehow be removed, the sensor voice-coil voltage will accurately represent cone velocity. It would seem more straightforward, then, to use a current sensing circuit to directly measure the current in the driven voice coil and then simply subtract it from the voltage present at the sensor voice-coil terminals. When properly scaled, the sum of the current and sensor voice-coil signals should equal cone velocity, and the derivative of this signal should be representative of the driver's sound pressure level. Therefore, the main point of this article is to investigate whether or not this supposition is correct.

PUT TO THE TEST

Before proceeding with design of the servo, I needed to prove my theory. The first step in the process was to verify that the velocity signal is inherently clean and representative of cone velocity if no induced voltages from the driven coil were present. I accomplished this by bolting two 8" DVC drivers

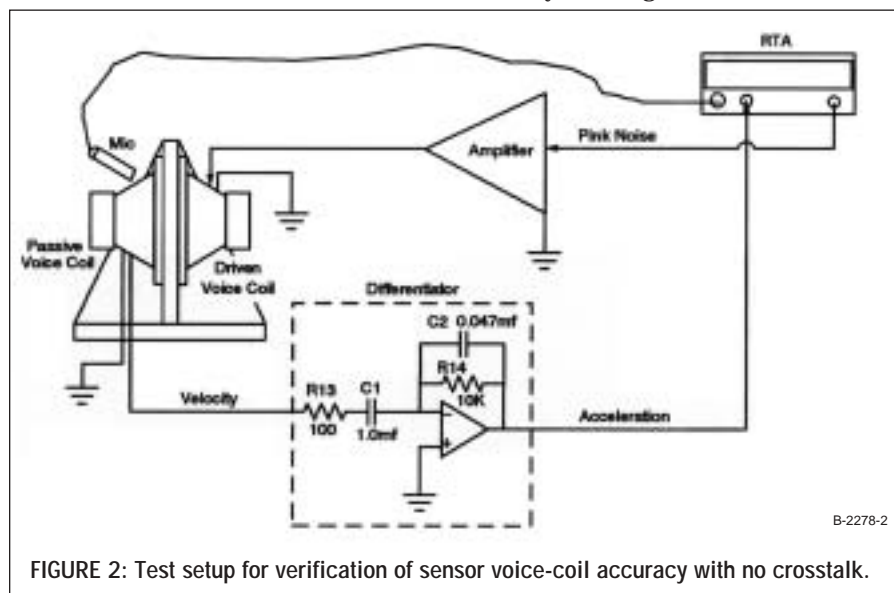


FIGURE 2: Test setup for verification of sensor voice-coil accuracy with no crosstalk.

(Peerless 831858) together face-to face as shown in *Photo 1*. One driver is driven with a signal generator and power amplifier while voltages are measured at one pair of voice-coil terminals on the passive driver.

The wiring diagram for the test rig is shown in *Fig. 2*. Since there are no electrical connections to the passive driver (it's driven by the air trapped between the two), there can be no mutually induced voltage. So whatever voltage is present is produced solely by the motion of the driver's voice coil moving through the magnetic field.

While I could accurately measure SPL with a real-time analyzer, SPL is proportional to acceleration—not velocity. With no way to measure the cone's velocity directly, I could only measure it indirectly after converting it to accel-

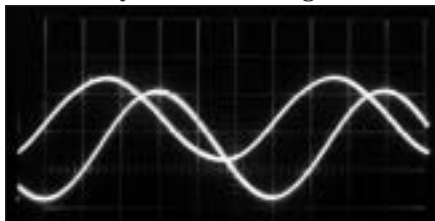


PHOTO 2: Voice-coil signal measurements.

eration. Running the passive driver's output signals through a derivative circuit (referred to as a differentiator) accomplished the analog conversion from velocity to acceleration (*Fig. 2*).

The first test looked at the raw voice-coil signal to see whether it was clean

and sinusoidal at all frequencies. The lower trace in *Photo 2* is a representative sample at 30Hz. The upper trace is the same signal after processing through the differentiator. Both appear to be free of anomalies. Since the derivative of $\sin(\omega t)$ is $\omega \cos(\omega t)$, the approxi-

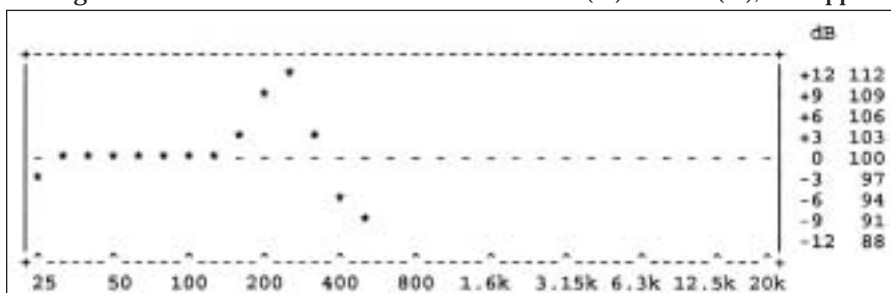


FIGURE 3A: Passive driver acoustic pink-noise response.

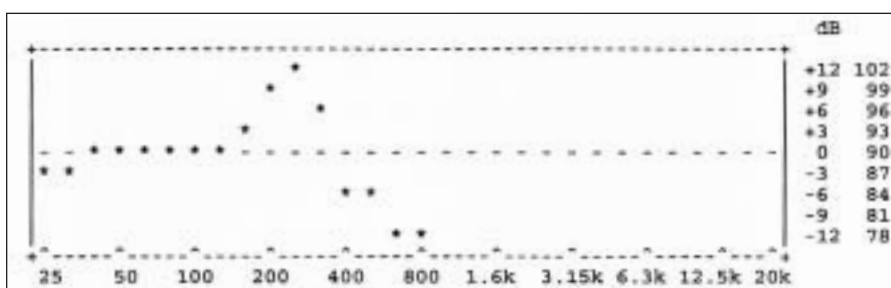


FIGURE 3B: Passive driver voice-coil pink-noise response after differentiator.

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mate 90° phase shift is one indication that the differentiator is working. Another aspect of this particular derivative is that the magnitude is multiplied by the frequency (ω). So, compared to its input, the output of the differentiator has a constant 90° phase shift and an amplitude which increases with frequency.

If the differentiator is working properly and Novak's theory is correct, the frequency response measured at the passive driver cone will equal the output from the differentiator. To verify this, I ran full-range pink noise through the driven speaker and recorded the sound of the passive driver's cone motion with a calibrated microphone and a real-time analyzer (RTA). I captured the response curve in *Fig. 3a*.

Next, I ran the output from the differentiator into the RTA and obtained the response shown in *Fig. 3b*. The two are essentially identical. From this, I concluded that the signal had to be representative of the passive driver's cone velocity.

If the above sounds like a cakewalk, it wasn't. Active differentiators are inherently noisy, and the output of a differentiator increases linearly with frequency. Therefore, solid-state devices can easily reach saturation voltages if the differentiator is not configured to operate within a fixed range of frequencies. I chose the lowest resistance values possible to reduce the noise and experimented with component values for several days before I was satisfied that I had a clean, stable unit with plenty of headroom.

In the *Fig. 2* schematic, the differentiator operating range is set by the combination of R14 and C1 and R13 and C2. For the values shown, the operating range is 15.9Hz to 33.9kHz. To ensure maximum linearity, it is good practice to maintain a minimum ratio of 100:1 between these two.

SERVO CIRCUIT

The next step was to build the driven voice coil's current-sensing circuit to measure the mutual inductance component and the summer to subtract its output from the raw velocity signal. For this operation, I constructed the circuit shown in *Fig. 4*, which also includes the final summing junction and amplifier, which will act as the controller for the servo. The prototype circuit board is

shown in *Photo 3*. In this circuit, op amp C provides scaling for the output of the sensor voice coil before the input to the first summer—op amp D. The power amplifier positive output is connected as shown to R7, the other side of which connects directly to the positive terminal of the driven voice coil. Current flowing through R7 (which has a value of 0.1 Ω) causes a slight voltage drop that is measured by differential op amp A with a gain of one. Its output is scaled

by op amp B prior to summing at the input of op amp D. The output of op amp D represents the cleaned-up velocity signal and is fed to the differentiator—op amp E. When all inputs are scaled properly, the output of op amp E should be equivalent to acceleration and therefore representative of sound pressure level. To test whether the “accelerometer” worked or not, I removed one of the woofers from the test stand and applied a pink-noise signal to the input of the

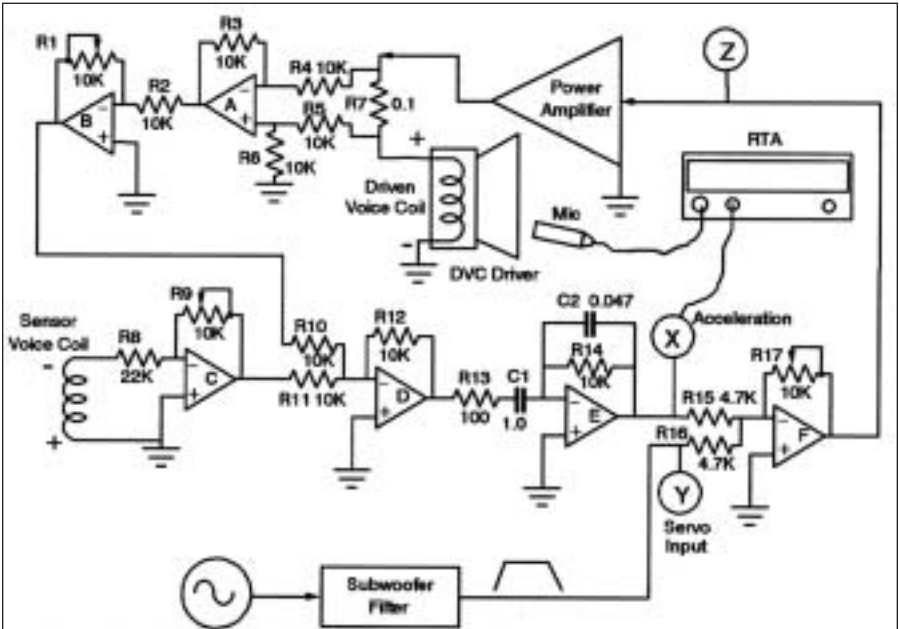


FIGURE 4: Servo circuit.

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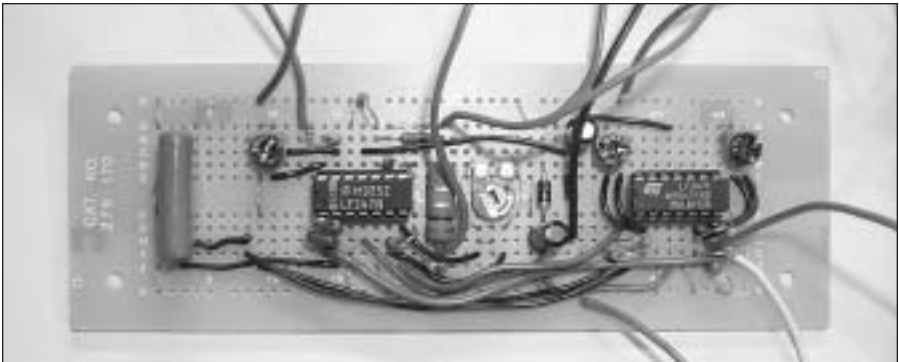


PHOTO 3: Servo circuit board.

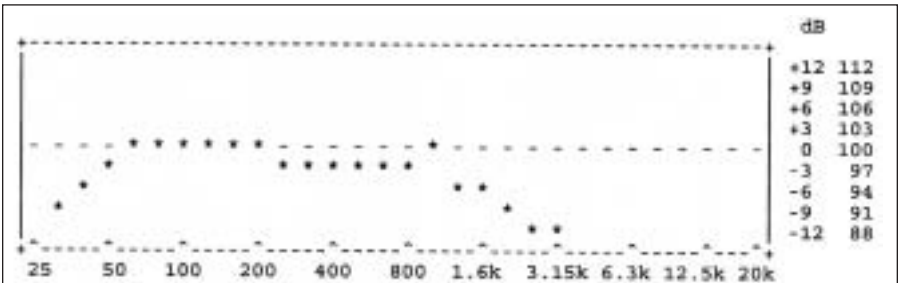


FIGURE 5A: Single driver in test stand acoustic response to pink noise.

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power amplifier (point Z). With the mike set close to the cone, I captured the response on the RTA (Fig. 5a).

Next I connected the output of op amp E (point X) to the RTA and experimented with the scaling pot settings to try to find a combination that would

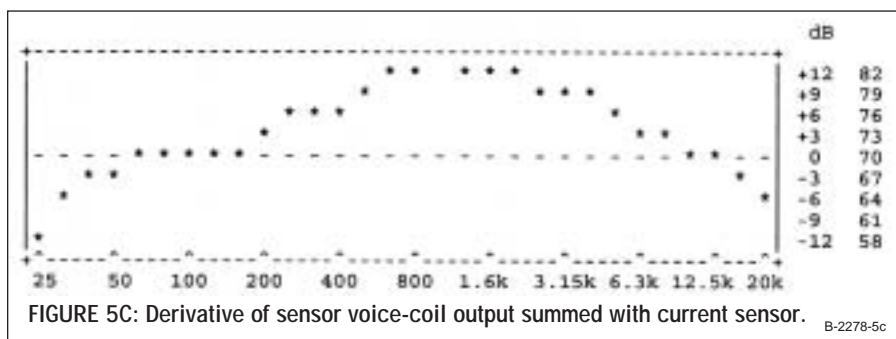
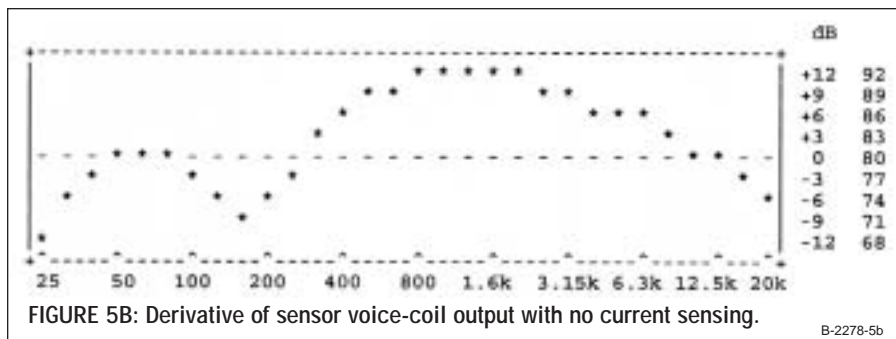
make the two similar. Figure 5b is the differentiator output with the current-sensing circuit gain set to minimum. I then increased the current-sensing gain to what appeared to be optimum and obtained the results shown as Fig. 5c.

While Figs. 5a and 5c are similar

below 200Hz, above this frequency, they diverge. The extended high-frequency output of the sensor voice coil is primarily crosstalk from the active voice coil. The mathematical model indicates that the high-frequency components in the pink noise are easier to transmit by mutual inductance— $M(di/dt)$. Also, phase shifts between the crosstalk and the back emf generated by the woofer's moving mass system allow the higher frequencies to pass through unopposed. Once the high frequencies hit the differentiator, they are multiplied by the frequency and can easily saturate the op-amps.

The presence of all the high-frequency components obscured the data. Clearly, the range of frequencies to be examined would need to be restricted to verify whether the accelerometer worked. I dusted off one of my sub-woofer filters, set it for flat response out to 20Hz, and connected it between the pink-noise source and amplifier. I then re-ran the response curves.

Figure 6a is the woofer SPL response measured with the mike. Figure 6b is the accelerometer response after intro-

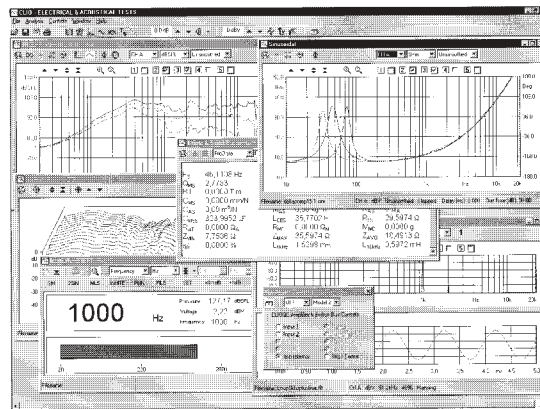


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ducing and scaling the input from the current sensor. The accelerometer RTA curve is now similar to the one produced with the mike.

I then connected the sine-wave generator and swept the frequencies up and down looking for points of interest. The microphone waveforms indicated that the woofer generated visible (and audible) distortion at 22Hz. A sample is shown as the lower trace in *Photo 4*. The upper trace is the waveform generated by the accelerometer. Again, the two appear quite similar. I concluded that, since both waveforms and frequency responses are similar, the accelerometer is, in fact, working. The feedback sensor is ready to be employed in a servo-subwoofer.

SUBWOOFER DESIGN

Moving to the design of a subwoofer, the published Thiele-Small parameters for the Peerless 831858 driver used in this experiment are $f_s = 22\text{Hz}$, $Q_{TS} = 0.23$, $V_{AS} = 79.8\text{ l}$, and $X_{MAX} = 7\text{mm}$. With one voice coil driven, Q_{TS} will be about 0.46—nearly ideal for a closed box. The f_s of 22Hz is very low, and the linear excursion rating of 7mm is very high for an 8" woofer. Both of these parameters are exceptionally good. (Incidentally, this woofer performs outstandingly in normal vented box applications with both voice coils driven. It's by far the best 8" woofer I have found, and its reasonable price makes it even more exceptional).

In the 1ft^3 test box, closed-box Q measured 0.8—close enough to the ideal of 0.707. Closed-box resonant frequency was 44Hz.

To close the loop and transform this to a servo-subwoofer, I completed the hookup shown in *Fig. 4* by connecting the output of op amp F to the input of the power amplifier and connecting various signal sources to the servo's input, point Y. I left the accelerometer settings the same as they were after the earlier

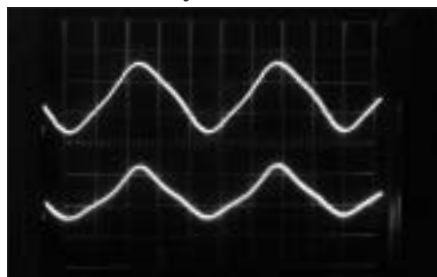


PHOTO 4: Waveform comparison.

“calibration” sessions. Before turning on the power amplifier, I set the final gain setting on R17 to minimum. Now for the moment of truth—I turned on the power amp and began slowly increasing the gain until the system began to oscillate and then backed it down slightly. When I was sure the system was stable, I ran some more tests.

FINAL TESTING

Figure 7a is the pink-noise response curve for the subwoofer filter. If the servo is working properly, it will cause

the woofer to reproduce this same curve. *Figure 7b* is the woofer's open-loop SPL response to the filtered pink noise. With a closed-box frequency of 44Hz, the system is down 3dB at approximately 40Hz. *Figure 7c* is the same test with the feedback introduced, except the scale is reduced from 3dB increments to 1dB. Clearly, the -3dB point has been lowered to approximately 25Hz—a significant improvement.

The response of the servo subwoofer is essentially the same as the filter's response, which is the desired goal. *Fig-*

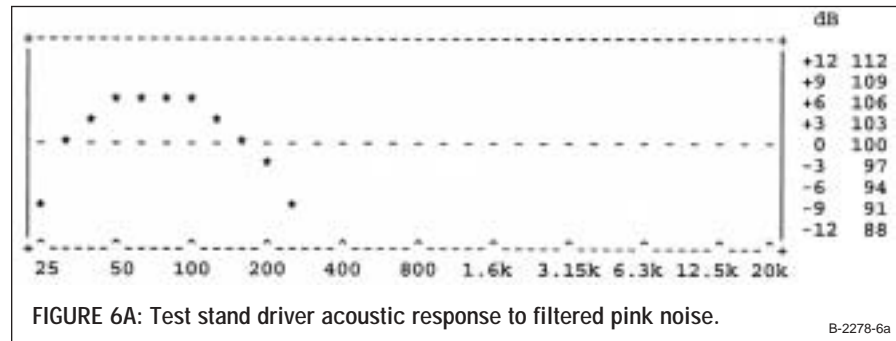


FIGURE 6A: Test stand driver acoustic response to filtered pink noise.

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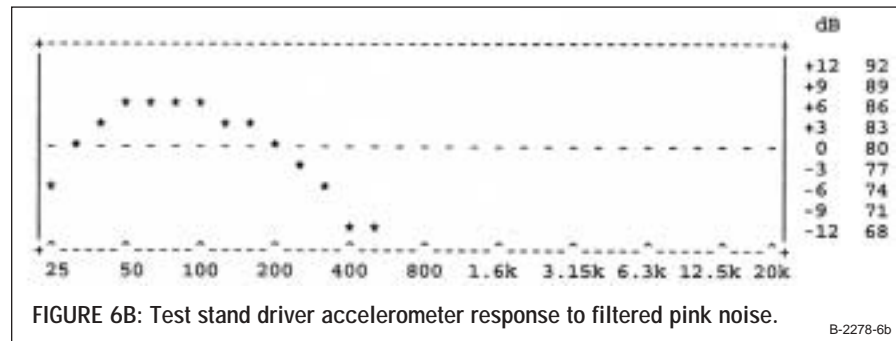


FIGURE 6B: Test stand driver accelerometer response to filtered pink noise.

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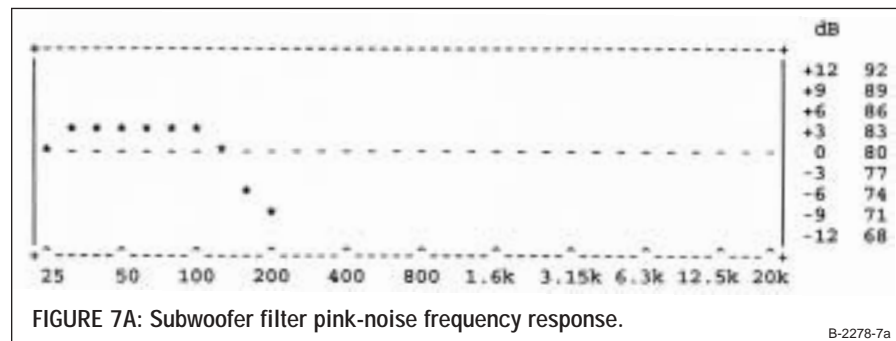


FIGURE 7A: Subwoofer filter pink-noise frequency response.

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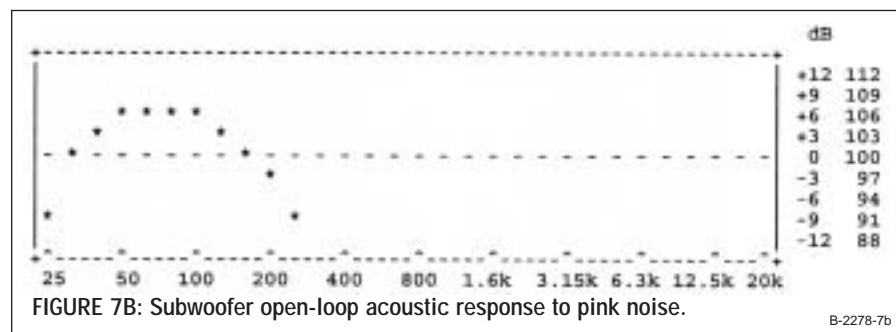


FIGURE 7B: Subwoofer open-loop acoustic response to pink noise.

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ure 7d is the accelerometer's response during this test and is nearly identical to that of the calibrated microphone.

The last test was to see whether the servo would reduce distortion in a real-world situation. In *Photo 5*, the upper trace is the signal-generator sine wave,

again at 22Hz. The lower trace is the subwoofer open-loop waveform captured with a microphone. It is somewhat triangular and produces audible distortion.

Photo 6 shows the same test run in closed-loop mode. The upper trace is the signal-generator waveform, and the

lower trace is the subwoofer waveform captured with a microphone. It now more closely resembles the signal generator and is audibly quieter. Therefore, closed-box distortion levels have been audibly reduced.

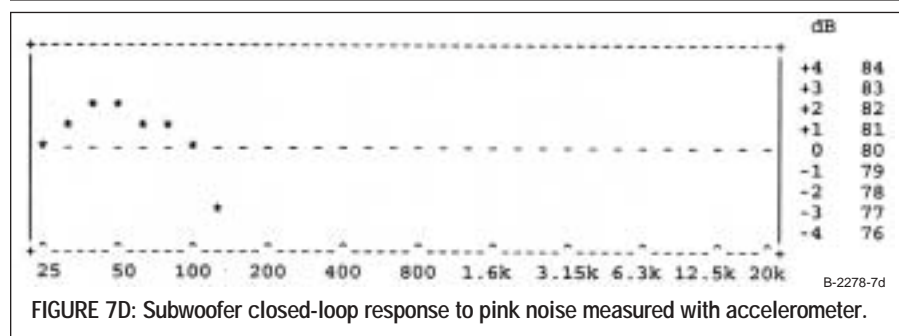
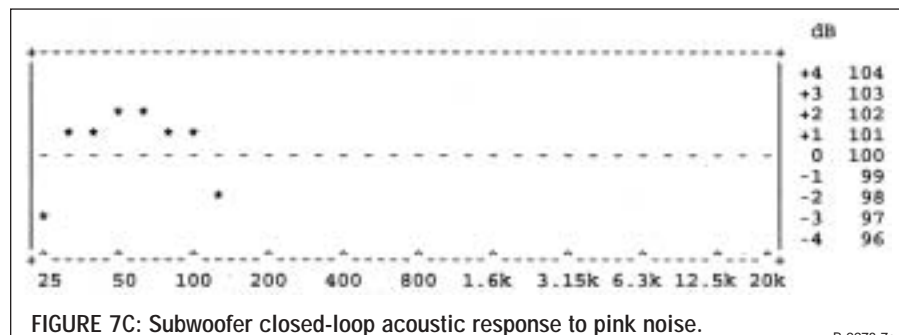
It's important to remember that this is a worst-case stress test of the system. The magnetic system is operating in its nonlinear range at full excursion. For frequencies above 25Hz, the closed-loop waveform appears distortion-free.

EVALUATION

The last question is, will this thing reproduce music? Is it an improvement? The answer is a definite yes to both questions.

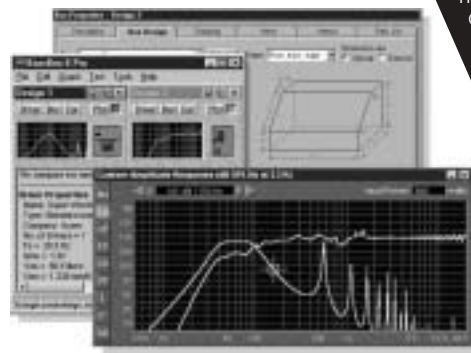
I set up a pair of satellite speakers and hooked up a CD player. I played a number of jazz discs through the system and tested it with and without feedback. As I had hoped, closed-loop bass was much tighter and more defined than open loop.

As a reality check, I asked a friend over to audition the system in my basement. When he saw the maze of wires, he said, "This is a mess!" I played



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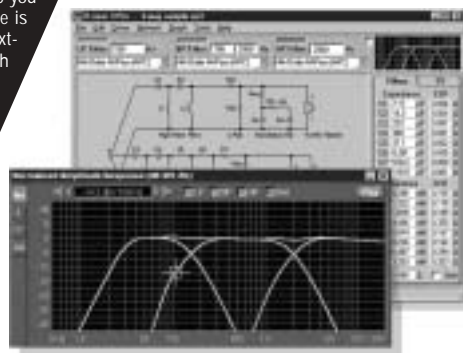
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Steely Dan's *Two Against Nature* CD and turned the feedback on and off.

My friend, John, said that without the feedback, it "sounded like it had an echo." I thought this was interesting since I was using a high-quality woofer in a closed box with a Q of 0.8. It should have sounded tight. The point is that, even to a relatively untrained ear, the "sound" of the servo is much cleaner and more defined than a good open-loop system.

My test rig does suffer from one limitation: it has limited headroom. If I get carried away with the volume control, it makes spitting noises on kick-drum transients. I verified by measurement

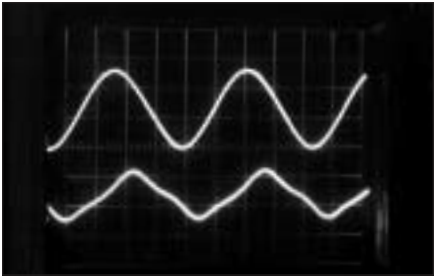


PHOTO 5: Open-loop waveform test.

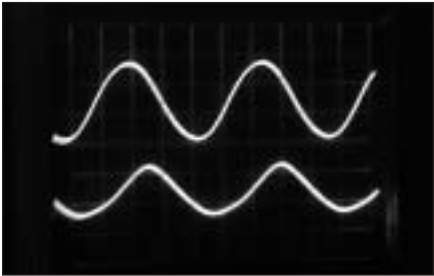


PHOTO 6: Closed-loop waveform test.

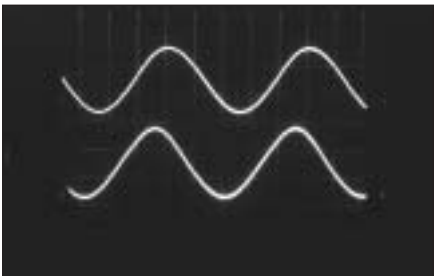


PHOTO 7: Closed-loop waveform test at 30Hz.

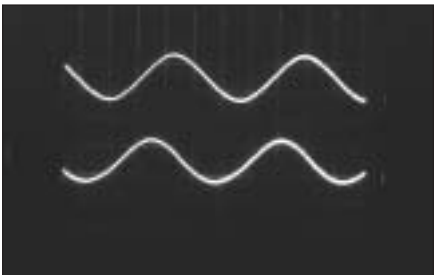


PHOTO 8: Closed-loop waveform test at 20Hz.

that this was due to the driver reaching its excursion limits. So even though the driver I chose for my experiments has unusually good T/S parameters, a single 8" driver doesn't provide enough headroom for reproducing really low bass at high volumes.

If I were building a servo system for my home theater, I would probably use a 15" driver. A 12" high-excursion driver would be the absolute minimum. However, in that setup, box size could be objectionably large unless something can be done to mitigate it. Maybe the servo can do just that.

I needed to know how the servo would perform if the box were grossly undersized. If it flattened the response, the implication is that you could put a large driver in a small box as long as you had extra amplifier power to overcome the loss in efficiency.

For this final test, I removed the woofer from the test box and filled the box with wooden blocks, reducing the box volume from 1ft³ to approximately 0.2ft³. After this, the closed-box frequency rose to 58Hz. *Figures 8a-d* show the test results.

The subwoofer filter response for this

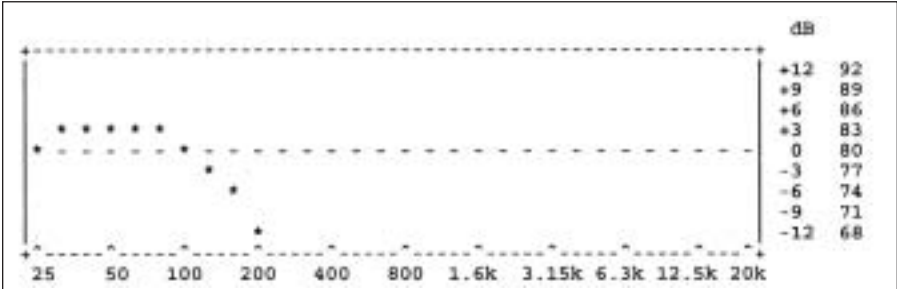


FIGURE 8A: Subwoofer filter pink-noise response.

B-2278-8a

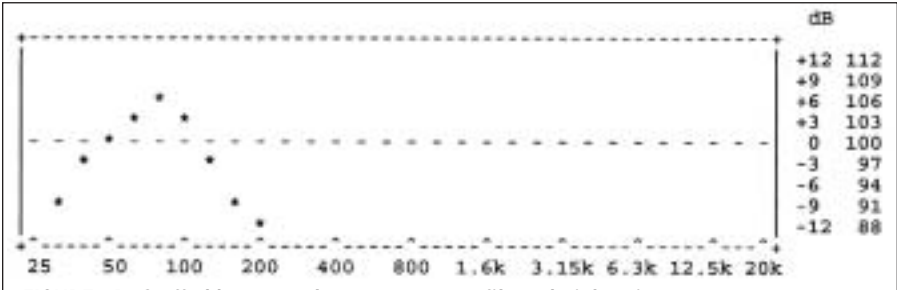


FIGURE 8B: Stuffed box open-loop response to filtered pink noise.

B-2278-8b

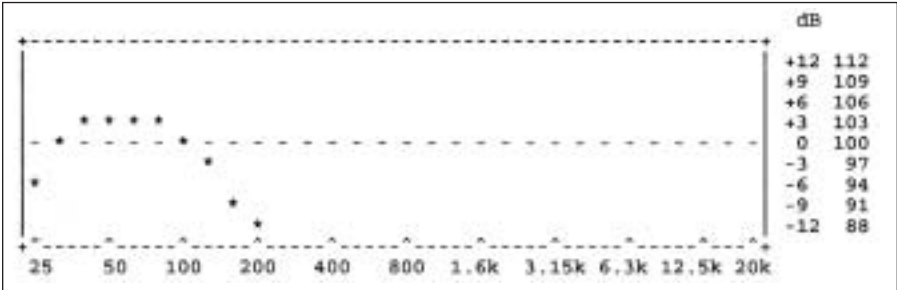


FIGURE 8C: Stuffed box closed-loop response to filtered pink noise.

B-2278-8c

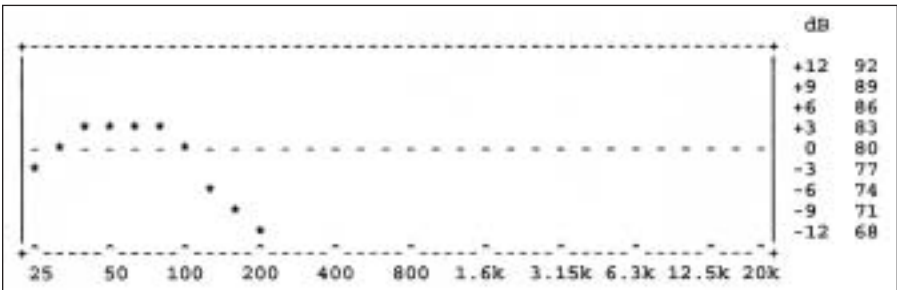


FIGURE 8D: Stuffed box accelerometer response.

B-2278-8d


test is shown for reference as *Fig. 8a*. The SPL open-loop response (*Fig. 8b*) is a "one note" system with a nasty peak. The low-frequency cutoff is somewhere around 70Hz. The closed-loop response (*Fig. 8c*) is a picture-perfect flat response out to about 30Hz. With the stiffened air spring provided by the smaller box volume, distortion correction is outstanding.

Photos 7 and 8 show the closed-loop waveform at 30Hz and 20Hz, respectively. Both appear, at least visually, to be perfectly sinusoidal. From this last test, I am fairly confident that you could construct a compact subwoofer with a large diameter driver that should perform quite well.

That about does it for this adventure. After half a century, the pursuit of good bass is still in progress. In that pursuit, the closed loop woofer has been considered by some to be the "Holy Grail." May be it is. ♦

REFERENCE

1. C-Y Chen, G. T-C Chin, C-C Cheng, and H. Peng, "Passive Voice Coil Feedback of Closed Box Subwoofer Systems," *Proc Instn Mech Engs*, Vol. 214, Part C.



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