Servo Subwoofer Design Revisited

This father and son team up to show us the ins and outs of designing and building a servo subwoofer.

By Art and Jac Brown

Art: I started building speakers in 1950, when I was trying to develop a back-loading horn, using a 12″ driver and the room walls for horn extension. My friends were also trying to build speakers, with one concentrating on an infinite baffle of about 25ft^3, another a ported speaker, and a third, a tuned pipe enclosure. The friend who worked with the ported speaker also invested in the best driver, costing about $35. His system sounded best when compared with the others at my home. Our source of information was *Audio* magazine and some of the references it contained.

During the next few years, I became interested in the acoustic suspension speaker system. I was unable to put much money into drivers ($12 for a 12″ diameter coaxial speaker), so I modified the cone suspension of my existing driver trying foam and chamois as surround materials. I also increased the voice coil travel by rewinding the coil. Some improvement was evident. I had panel vibration out of this world, though, but it was well damped when I had my wife sit on the offending panel, which is *not* a practical solution. I finally found funds in 1960 to buy an AR-1 speaker, which satisfied me for a number of years.

Of course, in the 60s we were listening to monaural sound. I stayed with monaural into the 80s when my son wanted to buy a stereo and took me along to several listening rooms. The system he bought sounded so good that I started having ideas about stereo for myself.

By the mid-80s, my son had grown up listening to my tales of speaker building, so when a co-worker told him about *Speaker Builder* magazine, we became interested. We read a number of issues and I decided to build a two satellites/subwoofer system based on what I learned from *Speaker Builder*. I continued to use the AR-1 as the subwoofer. In the January 1989 issue of *Speaker Builder*, I described my satellites.

By late 1990, I had completed developing a servo subwoofer, which I described in *Speaker Builder* 1/91. I concluded that the subwoofer's "distortion, staging, and transient handling are unmatched by any system to which I have listened." My son decided to build his version of a stereo speaker system with a servo subwoofer. This article discusses the development of the subwoofer.

Jac: Why build a servo subwoofer? Because the bass is so amazingly clean. Over the years, I've built various passive woofer systems, some of which had deep, strong bass, but there has always been a little bit

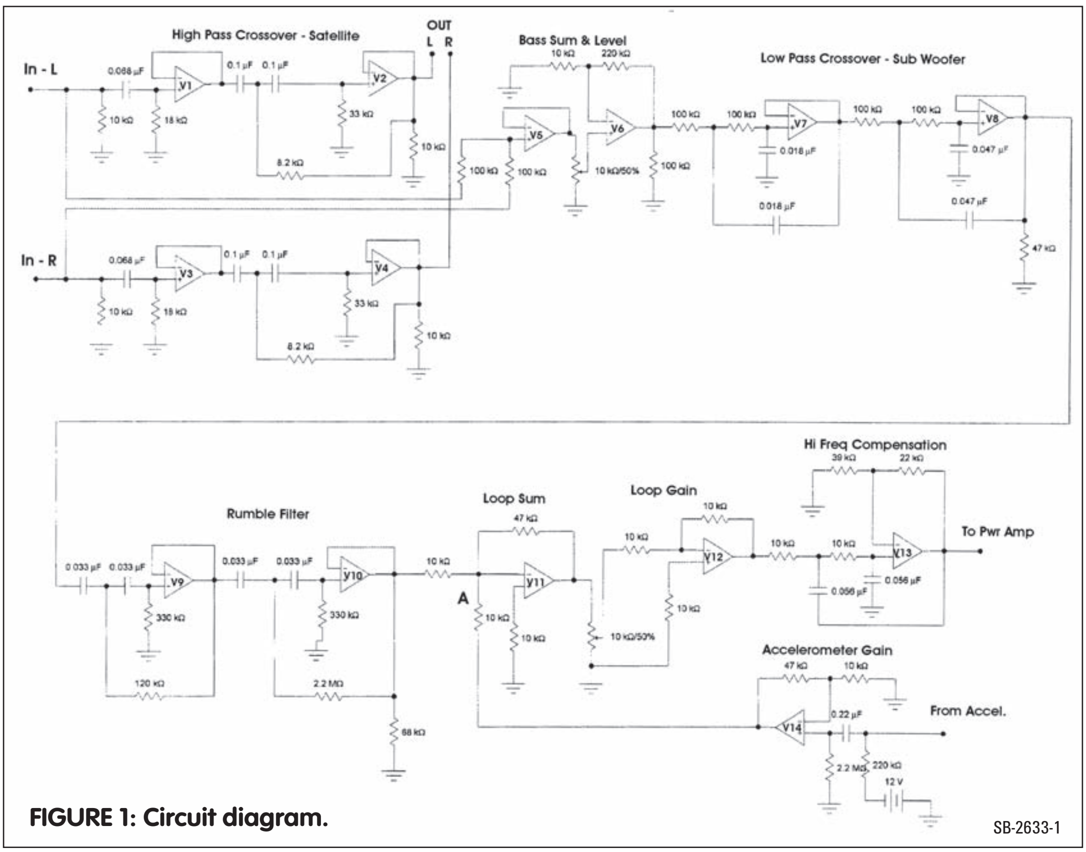


FIGURE 1: Circuit diagram.

of bass distortion. My father's servo subwoofer always seemed so clean that I just had to build one.

SOFTWARE TOOLS

Art: One of the big differences between my project and Jac's was the software and hardware available for measuring and simulating speakers. I used to need 8 hours to characterize a driver, and now with the computer it takes only a few minutes.

Jac: I used LAUD for speaker measurements, Electronics Workbench for circuit design, and an old version of SoundEasy to shape the filters including the speaker response and phase.

OVERALL SYSTEM

Art: This speaker system consists of the two satellites and the subwoofer along with the electronics for crossover and closed loop. The system gets its input from the receiver, which controls the CD player, DVD, and TV. The receiver preamp outputs connect to the servo amplifier board that has an electronic crossover between the subwoofer and satellites. After passing through the high-pass crossover, satellite signals are returned to the receiver, amplified by the receiver power amps, and passed to the satellites.

The signal for the subwoofer is the sum of the left and right channel that is processed through the low-pass filter (crossover) and the rumble filter before being sent to the closed loop amplifier. The signal is compared with the accelerometer signal and the difference amplified via the servo amplifier and subwoofer power amplifier to drive the speaker. Within the servo amplifiers are compensation networks to provide stable loop operation. Loop gain is adjustable as well as output balance between the satellites and subwoofer. Common op amps are used for the satellite crossover and servo controls as shown in the circuit diagram (**Fig. 1**).

SATELLITES

Jac: The satellites are two-way, closed-box towers using an old pair of Dynaudio D-28 tweeters and Dynaudio 17W-75 woofers. The horn-loaded tweeters with their dome recessed into the speaker align the bandpass acoustic centers on the same baffle when measured at 1m. The satellites are crossed with a 4th-order acoustic, passive crossover. The enclosures are stuffed with fiberfill with a passive rolloff at 75Hz. **Photo 1** shows a satellite speaker with the subwoofer speaker.

SUBWOOFER

Jac: A servo subwoofer needs to be a closed-box design. The box size is established to provide a rolloff at low frequencies that will complement the servo design. This calls for a 6 to 10dB down point slightly below the lowest frequency for which you are designing. In general, you want the driver and enclosure to combine with a Qts lower than 0.7.

With a speaker that is overdamped, the phase change at the lower frequencies is smoother and the phase angle limit for the servo loop occurs at a lower frequency. More discussion of this later, but it is important to select a driver and enclosure

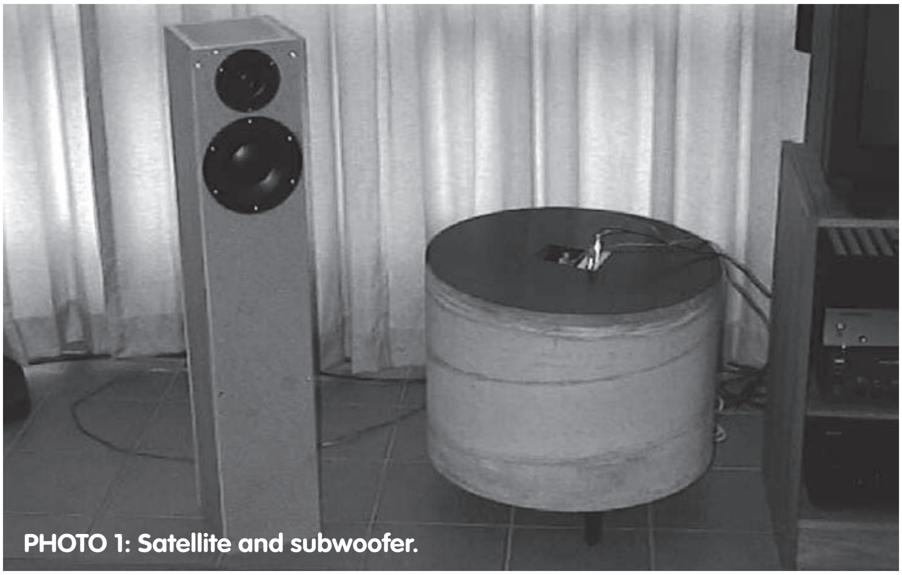


PHOTO 1: Satellite and subwoofer.

design that is well damped.

In choosing the driver for a servo subwoofer, you also need to make sure you have enough power rating plus enough cone area and travel to reach the loudness at the lowest frequency you are targeting. In my case, I targeted 95dB at 20Hz and 1m. I chose the NHT 1259 for its long travel and power handling. I started with the enclosure with a forward-facing driver for appearance reasons, but as many have found out, you can't mount the NHT 1259 horizontally without the voice coil rubbing. After building the speaker enclosure, I changed the orientation to down firing by adding 4″ legs to the speaker baffle (**Photo 2**).

ACCELEROMETER

Art: When I was building my servo subwoofer, it wasn't easy to get a lightweight accelerometer that I could attach to the voice coil of the driver. After some playing around, I decided that I could use the piezoelectric disc from a tweeter as an accelerometer. The piezo disc was mounted on a small post that was attached to the dust cap. The mass of the disc would cause it to flex under the motions of the speaker. When the disc flexed, it generated a small voltage that I could amplify. That was my accelerometer. My son had it much easier.

Jac: By the time I started my project, I could find a small accelerometer in the Digi-Key catalog (ACH-01-04) for less than $25. It had a higher resonant frequency than my Dad's homemade version and had built-in buffering electronics.

I made my accelerometer mount from a cone-shaped, paper drinking cup, fiberglass, and some balsa wood. The drinking cup was the form and it was cut to the size of the voice coil on one end and the size of the accelerometer on the other end. The balsa wood was shaped to fit in the accelerometer end to provide a flat mounting base. The whole assembly was stiffened by glass cloth and 5-minute epoxy that also held the mount to the voice coil and the accelerometer to the mount. The mount became the new dust cap (**Photo 3**).

Art: The accelerometer and its mounting need to have a relatively high natural frequency compared to the frequency of your low-pass crossover. If the frequency isn't high enough, the servo loop will have a phase shift of 180° and at a high enough gain level that the amplifier will tear the speaker apart.

In Jac's case, the accelerometer has resonant frequency of 35kHz and he figures his mounting system resonance is around 3kHz. This provides sufficient margin while designing the servo. If the resonance is 1kHz or lower, you may need a filter to remove the accelerometer resonance from the loop response.

SUBWOOFER ENCLOSURE

Jac: I had been thinking about non-traditional enclosure designs and had come to the conclusion that both shape and material have important roles in enclosure design. I decided to make this subwoofer enclosure as a cylindrical section because the cylinder is naturally stiff. I made the cylinder section from fiber-reinforced concrete, which has very high stiffness and is quite well damped when compared to typical wood products. **Photo 1** shows the finished enclosure.

I made a mold using the thick cardboard tubes (Sono Tubes) that are used to cast concrete lamp bases in parking lots. MDF (medium density fiberboard) circles of different diameters made up the bottom of the mold, held the inner and outer tubes concentrically, and formed a rebate for the speaker baffle to fit flush with the concrete cylinder (**Fig. 2**). I used 20″ and 22″ ID cardboard tubes, 14½″ long to give an internal volume of about 2.5ft³. Because the cardboard tubes are ⅜″ thick, the 20″ ID tube has an OD of 20¾″. The result is a concrete wall thickness of ⅝″ in the concrete cylinder that has worked very well for sound radiation.

In addition to the concrete cylinder, a concrete baffle is cast near the bottom end of the cylinder. This concrete baffle supports the MDF baffle where the speaker attaches and makes the end of the cylinder nice and stiff (**Fig. 2**).

The top of the cylinder is made of


PHOTO 2: Subwoofer details.

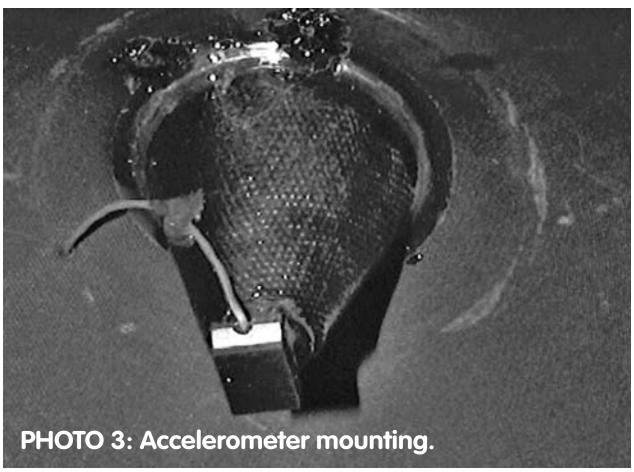
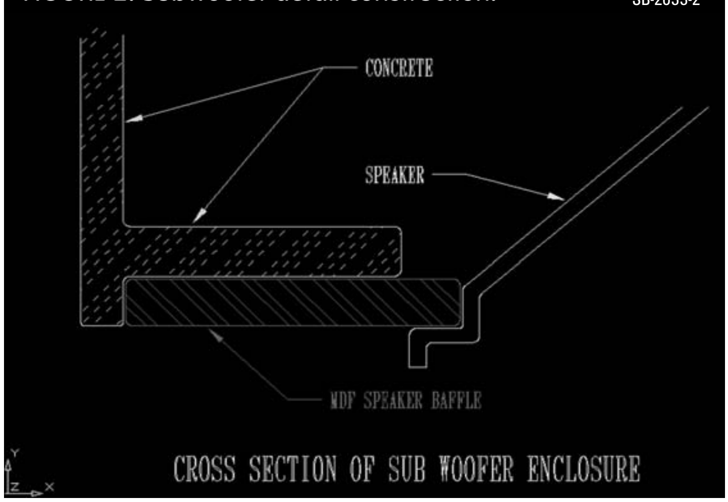


PHOTO 3: Accelerometer mounting.

FIGURE 2: Subwoofer detail construction.



MDF 1½″ thick. The enclosure is stuffed with fiberfill and threaded rods go all the way through from the speaker on the bottom to the top. Without the driver, the enclosure weighs 65 pounds, which is not too bad for concrete.

SERVO DESIGN

Art: A servo system uses the output speaker accelerometer as a measure of how well the amplifier is driving the speaker. Refer to **Fig. 1**. While testing the servo loop, use the normal input to the loop summing amplifier (v11) and look at the accelerometer signal as the output (disconnected at A, the input to the loop summing amplifier). A sweep of the range of frequencies will show how well the speaker can reproduce the input.

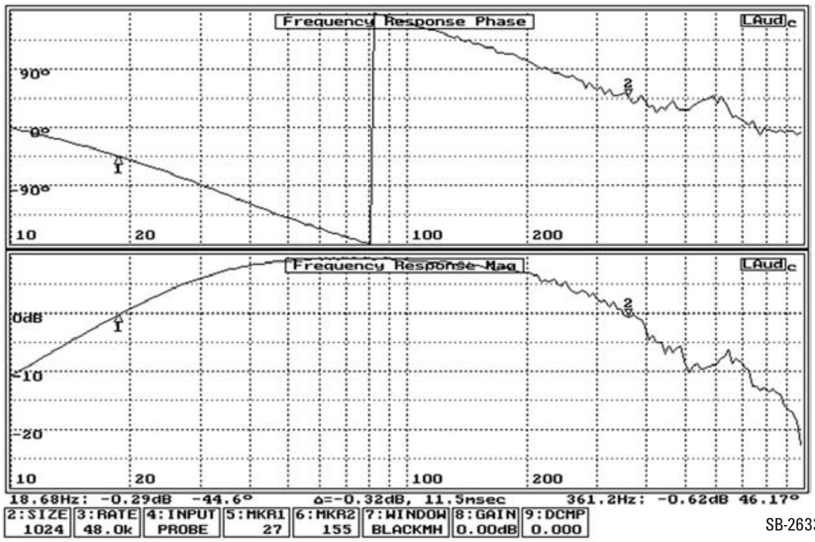
Figure 3, the open loop design curves, shows this response as amplitude and phase shift between the input and the output. The curves show an amplitude bandpass and phase shift *after* we had installed the loop high-frequency compensation filters (amp v13) that attenuate the high frequencies. An important part peculiar to this curve is the speaker/accelerometer response around 660Hz. As discussed below we provided a low-pass filter that would attenuate the loop response to cause this "noise" at 660Hz to be near −10dB gain in this open loop curve. This gave us a desirable margin in the loop design.

The other part of this response curve, **Fig. 3**, is the phase shift that occurs as the frequency is changed. At 80Hz, the phase shift is 180° *out of phase*. This means that the output could cancel most of the input when added together in the summing amplifier (v11). This is desirable because the servo will, in closed loop, allow just enough difference between the input and output signals to drive the speaker at the level we want for the input level. This difference between the output and input depends upon the loop gain—the higher the loop gain, the smaller the difference.

The next part of this design requires you to look at the phase shift between the two signals at the high and low frequencies. If you allow the two signals to sum when they are in phase and the gain is greater than 1 (>0dB), you will allow the signals to reinforce themselves causing an unstable (or blow up) condition. Adjusting the loop gain does not change the loop phase characteristics. We chose to adjust the loop gain so that the 0dB gain point is about 135° phase shift from the central phase (180°). The curve shows this to be 45° at both the high and low frequencies.

The open loop curve may be a different shape, due to a different tuning of the speaker in the enclosure, or at the high frequency end with different high frequency compensation. In either case as you adjust the loop gain, you should select the end of the curve that reaches the 135 (45)° first, and accepting the lower phase shift at the other end (90° for example) so as to not exceed 135° phase shift anywhere in the frequency range. The resultant closed loop response will be stable, but the shape of the closed loop curve will be different. The end with the

FIGURE 3: Open loop response curves.



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lower phase shift will be more damped and the performance of the speaker system will be changed accordingly. The new performance of the speaker may be exactly what you want. It is not wrong but just a decision on the part of the system designer.

CLOSING THE LOOP

Figure 3 shows the open loop gain and phase curves of the servo prior to closing the loop or physically connecting the accelerometer signal to the summing amplifier at A. **Figure 4** shows the servo loop after closing it. The loop includes the summing amp, the loop gain amp, the high frequency compensation filter, the power amplifier, the speaker, the accelerometer, and amplifier—all affecting the response. I measured the closed loop gain as output/input (accelerometer voltage as representing the speaker output/input voltage to the summing amplifier). A speaker acoustical output (microphone) could have been used for the output signal.

1. Note that in **Fig. 4** we have peaks in response at 18Hz and 400Hz. These result from the phase shift and gain that occur at these frequencies, where you see some regeneration, but not enough to be unstable. We decided this was acceptable.
2. At about 660Hz there is a peak that could cause trouble. It also appeared in the open loop curves, so you can assume that it's a cone resonance of some kind. We decided to make sure that the crossover lowers the peak to at least 20dB below bandpass. The 4th-order crossover

FIGURE 4: Closed loop response without filters.

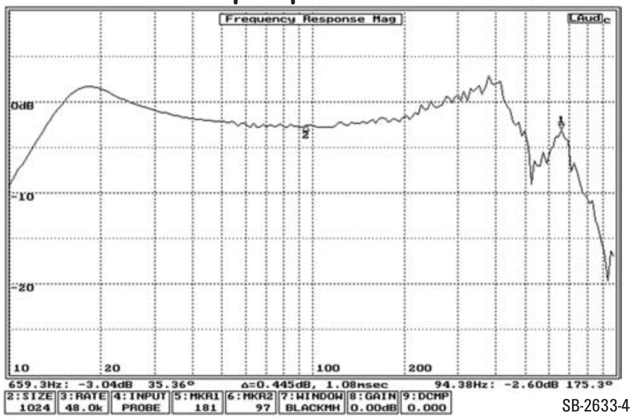

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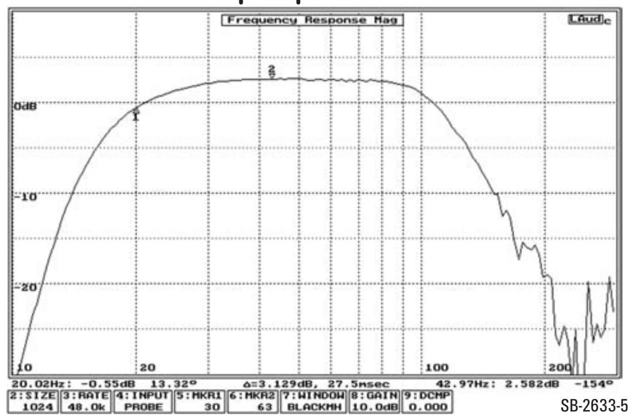
FIGURE 5: Closed loop response with filters.



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at 105Hz in the input amplifier (v7 and v8) was successful in lowering the peak to 20dB down. **Figure 5** shows the closed loop response with the rumble and crossover filters.
3. There was a rising output as the frequency drops from 80Hz to about 18Hz (**Fig. 4**). In this case, the rumble filter in the input amplifier is used to shape the low-end response.

Figure 5 shows the full subwoofer response including the crossover and rumble filters. As you can see, the result is very smooth with an F3 of 20Hz and a crossover frequency of 105Hz.

SUBWOOFER AMPLIFIER

Jac: In addition to the servo circuitry, a high power amplifier is needed to drive the subwoofer. How much power you need will vary depending on your driver, enclosure, and low frequency target. The amp must provide power for the loudness you want at your low frequency and to make up the difference in loudness between the passive response of your speaker and your desired response curve.

For example, suppose your driver has a sensitivity of 87dB at 1W/1m and you want a maximum loudness of 96dB at 1m and 30Hz. To get 96dB from the passive speaker at 100Hz, you need to add 9dB above the 87dB. Because every 3dB doubles the input power, you will need 8W of input power available to get to 96dB at 100Hz.

If the passive speaker is 12dB below bandpass at 30Hz, the servo system needs to provide power to make up that difference. From 8W at 100Hz, you need 128W at 30Hz. Because you need some transient headroom and amplifier damping, you should probably spec the subwoofer amp at a minimum of twice the required power.

I chose to use an Opti-MOS kit amplifier from G. Randy Slone that is rated at a conservative 500W. Mr. Slone is no longer selling these kits, but he has written several excellent books (McGraw-Hill) on high-power amplifiers that include circuit artwork and information to build excellent amps including the Opti-MOS. My power amplifier is shown in **Photo 4**, with the servo amplifier boards on top, the power amp board below, and the power supply.

CONCLUSION

Jac: Building a servo subwoofer system is certainly no easy project. We hope this article gives you an idea of some of the challenges and trade-offs in designing and building a servo subwoofer.

How does it sound? It's the deepest and cleanest bass I've ever heard. The satellites even sound better—I suppose because they aren't trying to produce frequencies below 105Hz. There is no way for me to compare it to other possibilities. All I can say is that all of my friends who have heard it are impressed, and I'm spending much more time listening to music. aX

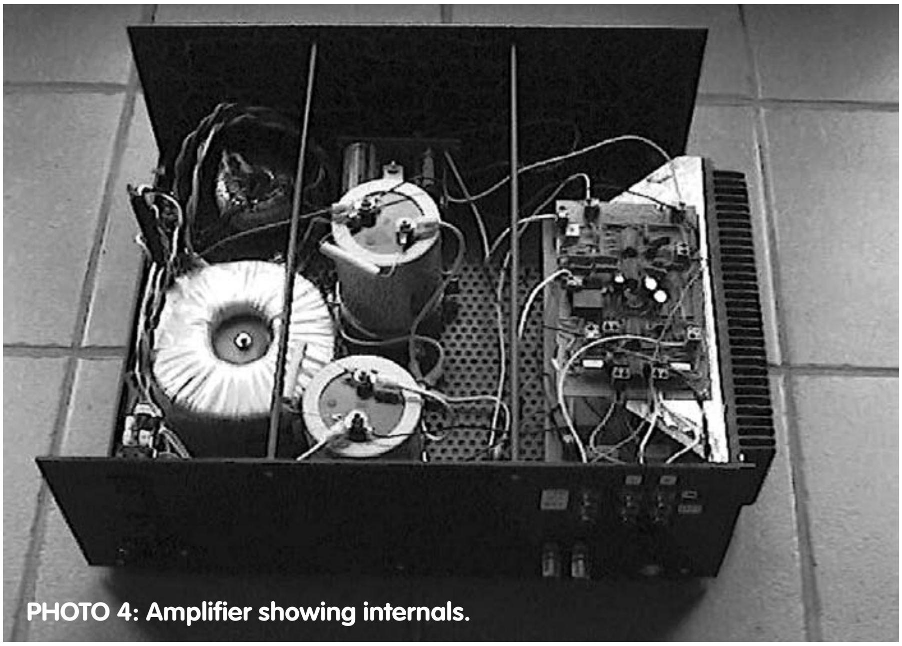

PHOTO 4: Amplifier showing internals.