

the corner of the room, I expect additional gain of several dB at the low frequencies.

## THE CONSTRUCTION OF THE CABINET

For the construction of the subwoofer I used 19mm plywood for every side of the cabinet. The first step is to cut all the panels of the box according to these dimensions:

Panel A: 400 · 340mm (two pieces)

Panel B: 380 · 340mm (two pieces)

Panel C: 580 · 340mm (one piece)

Panel D: Two of these panels are needed, one for the top and another for the bottom cover. The panel has the shape of an orthogonal triangle with each side about 765mm. I used a piece of 19mm plywood with dimensions 765 · 765mm. Then I cut it into two pieces according to its diagonal, producing panel D.

When all the panels of the subwoofer were ready, I cut the mounting holes on the two panels B to place the woofers. The proper diameter of the hole for the INFINITY woofer was 274mm.

Then I cut the top and the bottom panels D as shown in Fig. 6 to produce the common, left, and right openings of

the subwoofer.

Then all the panels of the cabinet were ready for assembly. First I glued and screwed the two panels A on the top panel D. Then the panel C and last the two panels B.

I chose to leave the bottom panel D of the cabinet removable. This is a great help for possible modifications or upgrades of the system (which usually occurs).

Photo 1 shows the subwoofer as constructed up to this point. I waited overnight for the glue to dry completely. Then I applied a lot of hot glue between the joints of all internal sides to prevent possible air leaks.

Also for cosmetics reasons, I painted all the external sides of the subwoofer black using a suitable wood paint. I put the woofers on panels B as shown in Fig. 4; each woofer is facing the other. I did this for symmetry reasons, which I will explain later in the measurements of the subwoofer.

I used weather stripping foam tape between the woofer and the panel and screwed the woofers with M3 bolts. I also used self-adhesive weather strip-

ping foam between the bottom panel D and the rest of the cabinet to eliminate air leaks between them.

The two drivers of each cabinet are connected electrically in series due to their low nominal 4W impedance. You can see how they are connected together and to the amplifier in Fig. 4. The minus (-) terminal of the left driver is connected to the positive (+) terminal of the right driver. The (+) terminal of the left driver is connected to the (-) terminal of the amplifier, and the (-) terminal of the right driver to the (+) terminal of the amplifier. I did this to maintain the absolute phase of the subwoofer with the rest of the system.

You should verify the correct connections of the drivers with a 1.5V battery. When the (+) terminal and the (-) terminal of the battery are connected to the corresponding (+) and (-) terminals of the subwoofer (marked as "subwoofer terminals" in Fig. 4), the left woofer should be moved toward the left opening and the right woofer toward the right opening.

You can see the complete subwoofer cabinet before the two drivers are installed and without the bottom cover in Photo 2. I built two such cabinets, so the whole system includes four 12" woofers.

## SUBWOOFER MEASUREMENT

After I completed the construction of the cabinet, the next step was to equalize the response of the subwoofer. To do this, you need to measure the near-field response.

For all the measurements I used a laptop running the JBL Smart Pro Real Time Module version 2.1. The frequency resolution of all the measurements I took with the Smart was 1Hz.

In the beginning, I placed the subwoofer on the floor in the middle of my listening

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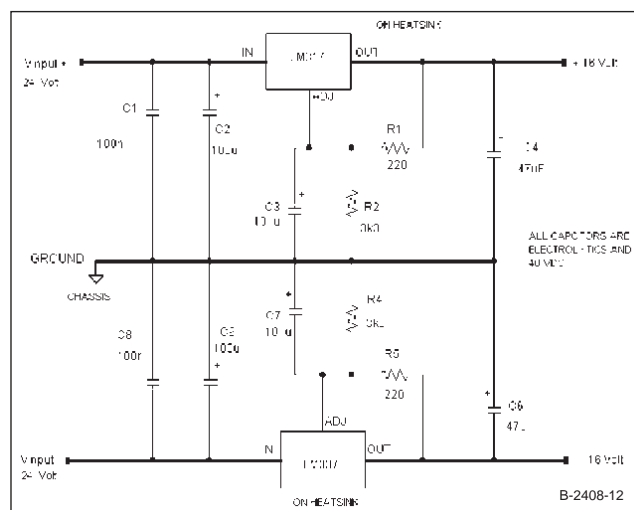


FIGURE 12: The regulated power supply.

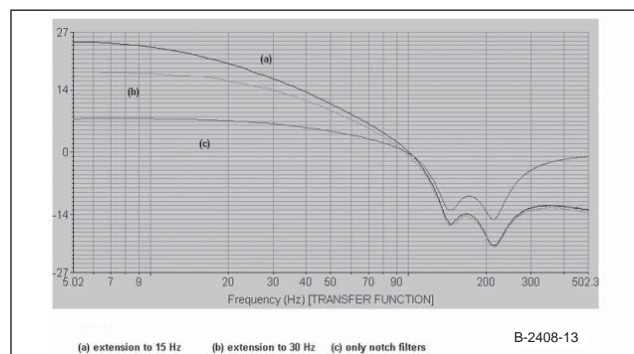


FIGURE 13: Measured response of the equalizer.

room (position M in Fig. 5). It had a distance greater than 1m from any nearby obstacle. The result of these measurements is shown in Fig. 7.

The top line is with the microphone placed in front of the common opening of the subwoofer. The other two lines below are the near-field response with the microphone on the left and on the right opening, respectfully. (Refer to Fig. 4 for the naming of the common, left, and right openings). The measurements on the left and right openings are very similar, proving the symmetry of the two as well as in the placement of the woofers.

The near-field response as measured at the common output of the subwoofer has some differences from the measurements on the left and right openings. The left and right openings have a broader peak response, and the frequency at which the peak occurs is different: 190Hz for the common opening and 260Hz for the other openings. This can be explained since the left and right openings of the subwoofer have different shapes from the common opening and causes the different cavity resonance frequencies. From about 30Hz to 120Hz the subwoofer's range the responses at all three openings are similar.

After this measurement, I placed the two subwoofers one above the other in the corner of the room behind the TV box (Fig. 5) to measure how different the near-field frequency response was from that taken in the middle of the room. The result is shown in Fig. 8. This response is the average of four measurements taken on the two left and the two right openings of the subwoofers.

As you can see, there are many differences between the responses when the subwoofer is installed in the middle of the room and when it is in the corner. The peak at 260Hz is still present but as expected the corner has significantly broadened the peak of the response, so now it starts from about 70Hz and goes up to 200Hz. Also, it has much more output at these frequencies actually, from 100Hz to 200Hz it has a flat response. I was not sure whether this was a problem, but I was thinking of possi-

ble ways to make the response of the subwoofers in the corner similar to the one in the middle of the room.

I found a good solution when I put the subwoofers, in the same corner, 55cm above the floor. The responses in this case are shown in Fig. 9. The main differences are in the range between 70 and 120Hz. The subwoofers at the new position have less output from 4dB at 90Hz to about 9dB at 110Hz.

The response is not the same as the one that I took in the middle of the room and which, I believe, has the lowest resonance, but it was the best I could have by placing the subwoofer in the corner. So I decided that this would be the final position, and I used this response as the reference for the design of the electronic notch filter.

Photo 3 shows the two subwoofers finally installed in the corner of my living room, 55cm above the floor. On the right side you can see the back projection TV that was slightly moved from its position. Below the subwoofers, there are the equalizer box, its external power supply, and the subwoofer power amplifier.

## THE SUBWOOFER EQUALIZER

For the design of the equalizer, I used the Pspice 9.1 Student Version. You can download the demo version of this program directly from the Orcad website (<http://www.orcad.com/downloads/demo/default.asp>). This is an excellent program that can simulate the frequency response of an electronic circuit with excellent accuracy.

The demo version offers the full capabilities of the program, but the circuit must have a limited number of nodes. For this reason I replaced most of the operational amplifiers that I used as buffers with a "voltage-controller voltage source" with the Gain = 1. In PSpice,

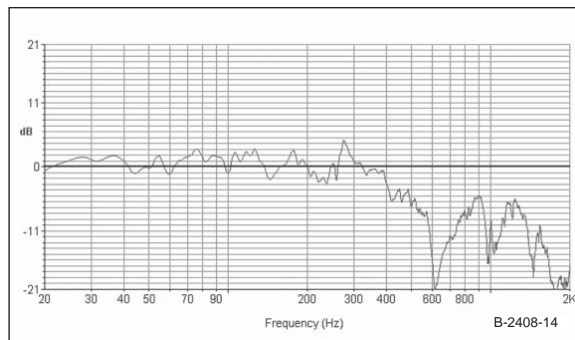


FIGURE 14: Measured response of the subwoofer after the equalization.

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each operational amplifier is a sub circuit that contains many other components and additional nodes. If you used more than one or two operational amplifiers (depending, of course, on the rest of the circuit), you can easily exceed the limits of the demo program, causing it to stop running.

Another valuable capability of PSpice is the EFREQ "voltage-controlled voltage source," which you can program with a table that can have different response with frequency both in amplitude and phase. From the measured near-field response of Fig. 9, I produced a table from 10Hz to 400Hz with the amplitude and phase response of the subwoofer. I then inserted this table in the voltage-controlled voltage source EFREQ (component E10). After that, I changed the components' value of the equalizer on the PSpice simulator to achieve results similar to a new acoustic frequency response of the subwoofer.

This makes the development of the equalizer easier and faster. The circuit of the equalizer as used for the PSpice analysis is shown in Fig. 10. The final electronic diagram of the equalizer as constructed is shown in Fig. 11.

As you can see, both diagrams are equivalent. The differences are that in Fig. 10 there is the source E10 that simulates the near-field frequency response of the subwoofer and the components C20 and R21; this is a high-pass filter at about 1kHz that simulates the loss of 6dB/octave at low frequencies of the subwoofer at the far field. For the analysis of the equalizer, refer to the circuit of Fig. 11.

By examining the circuit, you see the following main blocks:

1. The input circuit before U1B
2. The first notch filter around U1A
3. The circuit around U2B which boosts the very low frequencies around 20Hz
4. The second notch filter around U2A
5. The circuit around U3B, which boosts the 6dB/octave subwoofer frequency response
6. The output circuit around components C16-C18

The first stage with the components R1, R2, C1, and C2 comprises the low-pass input filter, which rejects the frequencies above 10kHz (remember that the circuit is used to drive a subwoofer) so as not to interfere with the rest of the circuit. The capacitor C3 blocks the DC voltage that can possibly come from the output of the previous stage that will be connected to this circuit. It has a very low -3dB point at around 1.5Hz.

The resistors R3 and R4 form a voltage attenuator to match the sensitivity of the subwoofer to the rest of my system. If this attenuation is not needed, you can replace the resistor R4 with a short circuit and the resistor R3 can become 24k $\Omega$ . If a different attenuation is needed, then you should set the resistor R3 to the appropriate value.

The next stage, around R5-R7, C4-C6, and U1A, is the first notch filter. It has a center frequency of 142.4Hz, an attenuation of -14.4dB, and a Q of about 8.9. For the relevant theory concerning the design of the notch filters, refer to the Linkwitz site (<http://www.linkwitzlab.com/models.htm#C1>).

The Appendix, which you can find at our website ([www.audioXpress.com/magsdirx/aX/addenda/index.htm](http://www.audioXpress.com/magsdirx/aX/addenda/index.htm)), also

presents a summary for the design of this notch filter. The U2B op amp buffers the output of the first notch filter and, with the components R21, R22, C14, and C15, boosts the very low frequencies so the subwoofer response will be flat to about 20Hz. It also drives the next stage.

The circuit around R8, R10, R11, C7, C8, C9, C13, and U2A is the second notch filter with a center frequency of 217Hz, an at-

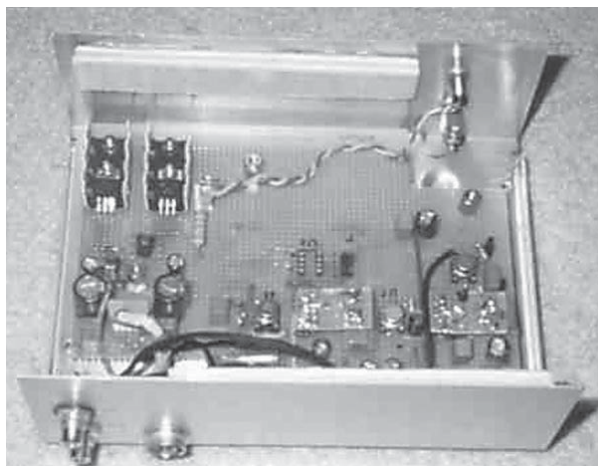


PHOTO 4: Equalizer of the subwoofer.



tenuation of -15.75dB, and a Q of 7.75. Both notch filters around U1A and U2A are needed to flatten the broad cavity resonance of the subwoofer.

The last stage around U3B is the low-frequency boost stage to equalize the subwoofer response at the far field. It has a maximum low-frequency gain of -57 (35.2dB). It equalizes the frequency range from 10Hz to about 320Hz, and it is the driver stage for the power amplifier. Resistors R13 and R20 adjust the low-frequency response limit of the subwoofer. If R20 is short-circuited, then the limit is set to 30Hz, while if both R13 and R20 are active, the limit is set to 15Hz.

I usually set the low-frequency limit of the subwoofer to 30Hz. The output circuit around C16-C18 is the DC blocking stage for the next stage. Two electrolytic capacitors are used back to back and are bypassed with a 2.2mF film capacitor. A small resistance of 220 $\Omega$  at the output buffers the equalizer from the cable and the power amplifier input.

The regulated power supply of the circuit (Fig. 12) is based on the LM317 and LM337 regulators. A small heatsink is necessary for each regulator. Resistors R1-R2 and R4-R5 adjust the output voltage at 16V.

I constructed the circuit of Fig. 11 and the regulated power supply of Fig. 12 on the same general-purpose epoxy PCB. I put the whole PCB in a metal box for shielding.

The DC unregulated voltage should be provided from an external power supply. You can use a common power supply provided that it has an output of about -24V DC at 500mA with low ripple.

The equalizer box with the top cover removed is shown in Photo 4. You can see the general-purpose PCB with the voltage regulators on the top left side and the equalizer circuit on the right side. I constructed the notch filters of the equalizer on small PCBs, which are connected to the rest of the circuit with connectors for easy removal. This was very helpful for the development of the equalizer.

After construction, I measured the frequency response of the equalizer (Fig. 13). Three curves are shown.

The top curve is the total response of the equalizer when the bass extension is set to 15Hz. The middle curve shows the total response with the R20 short-circuited, which sets the bass extension

at 30Hz. The bottom curve is the response with the capacitor C10 short circuited that disables the 6dB/octave boosts for the low frequencies. In this case only the notch filters and the low boost circuit around U2B are active.

All these measurements were in excellent agreement with the simulated responses, and no corrective actions were needed. You can easily observe in Fig. 13 that the difference between the low and the peak value of the response is about 45dB for the top curve and about 39dB for the middle curve from 10Hz to about 230Hz. This difference in the gain is very large; you should take great care with the construction of the circuit to avoid possible noises and disturbances.

After testing the circuit, I installed it before the power amplifier and repeated the measurements of the frequency response of the subwoofer at the near field without using the circuit around U3B (the low-frequency boost for the far-field response). I took the measurements as before at the four openings of the two subwoofers (left and right openings) when these subwoofers were placed at the corner and above the floor, and with the low-frequency limit set at 15Hz.

The average response of the four measurements is shown in Fig. 14.

The subwoofer near-field frequency response remains flat within -2dB between 20Hz and 350Hz. This is an excellent result if you take into consideration the fact that the frequency resolution of the measurement is 1Hz.

## DIPOLE OR MONOPOLE SUBWOOFER

There is much discussion concerning the differences in the bass reproduction between a dipole and a monopole subwoofer. After a long time living with this open-baffle subwoofer, I fully agree that the dipole subwoofer is much better than the corresponding monopole type. Since I have constructed both kinds using the same drivers, I can say that the most important difference that I hear between the closed box subwoofer and the open-baffle subwoofer installed in the same listening room is more clarity in the reproduction than the dipole subwoofer.

I believe that the open-baffle subwoofer will remain in my listening room for a long time. ♦

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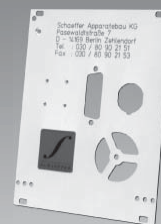
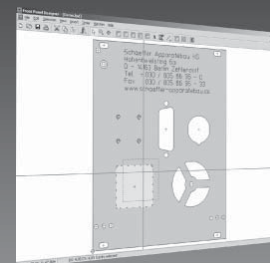
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