The Acoustic Triangulators

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By Julian J. Bunn

This article describes the construction of a floor-standing speaker of unusual triangular cross-section, housing a line array of very inexpensive oval drivers.

PHOTO 1: THE EIGHT ONKYO DRIVERS FROM PARTS EXPRESS.

The idea for these speakers came to me as I was reading an article in *Electronics World*, which expressed the opinion that a line array of identical but perhaps mediocre oval drivers was capable of producing excellent sound. The author argued that the various inhomogeneities between the drivers would be effectively cancelled out if they were all driven at once. This sounded plausible on paper: If there were differences between the units, then they would likely be random, and so would tend to average out. The idea intrigued me, and I began looking online for sources of bargain oval speakers and for a cabinet design.

CABINET DESIGN

The cabinet design I devised was based on several requirements: space for at least four vertically mounted drivers, floor-standing and stable, attractive (but also a little unusual), and fairly easy to construct. Since this was an experiment, and I'd already built a standard rectangular closed box system a couple of years ago, I liked the idea of a triangular box. *Figure 1* shows a schematic of the initial design.

Searching for the oval drive units, I found that Parts Express offered several possible units measuring 6″ × 4″. An Onkyo model caught my eye at the very reasonable unit price of $1.27 ($5.00 list price), and I ordered eight (four for each tower). The specifications included 15W RMS power handling, a ⅝″ voice coil, nominal impedance of 4Ω, and a quoted frequency range of 105–10,000Hz. I could have spent more, but I wanted to keep the experiment cheap and replace the units later with more capable models. *Photo 1* shows the eight Onkyo drivers, labeled 1 through 8, ready for testing.

TESTING THE DRIVERS

I was interested to see whether I could measure any response differences between the eight drivers. I set up a small jig from which I could suspend each one and make a pink noise measurement using my Ivie IE33 Spectrum Analyzer. *Photo 2* shows the setup. The IE33 can generate pink noise on the HP iPAQ Pocket PC's headphone jack, which I connected to the speaker terminals.

Setting the IE33 software into ⅙ oc-

PHOTO 2: TESTING THE PINK NOISE RESPONSES OF A DRIVER USING THE IE33. THE MEASUREMENT MICROPHONE (EMERGING FROM THE IE33 JACKET AND POINTING AT THE SPEAKER) IS A TYPE II DEVICE.

ABOUT THE AUTHOR

Julian Bunn is a member of the Professional Staff at the California Institute of Technology (Caltech), where he is engaged in researching computing solutions for the next generation of CERN's particle physics experiments, investigating contaminant dust particle motion from a future Mars lander, and simulating the motion of the Basilar membrane in the human cochlea. A physicist by training, with degrees from the Universities of Manchester and Sheffield in the UK, he has always been interested in audio electronics and the use of computers for audio. In the early 90s he wrote the AIRR and WinAIRR applications for loudspeaker measurement, which are sold by *audioXpress*. Recently he formed his own company, Bofinit Corporation (www.bofinit.com) which specializes in development of audio applications for the Pocket PC. In this context, he formed a strong relationship with Ivie Technologies, (www.ivie.com) where he holds the position of Senior Scientist. He is the main software architect of Ivie's IE33 audio measurement device. In his spare time he has recently built a 70s vintage Minisonic 2 synthesizer, a SE tube amplifier, the loudspeakers described in this article, and a four digit Nixie tube clock. Julian has a lovely wife, Sarah, and three beautiful daughters, Jessica, Georgina, and Isabella.

tave RTA mode, I averaged the near-field response at the microphone over around 100 samples. Once I had a good average, I saved the spectrum in the iPAQ's memory and measured the next speaker. Finally I measured the ambient noise (i.e., with the pink noise turned off, but retaining the microphone position) as an average of another 100 samples, and stored that too.

At this point I could take each one of the eight spectra and subtract the ambient noise spectrum from it, leaving a spectrum of the frequency response of the speaker.

Figures 2 and *3* show the eight ambient noise corrected spectra, one for each speaker, and the room background, as seen on the IE33 display. In fact, the spectra are stored at a much higher resolution (2048 points) than is seen on the display (60 points), which is a binned representation.

As you can see, the eight units were very similar in capability: There is a rolloff below about 125Hz, a fairly peaked treble at around 2kHz, and then a gentle rolloff from there to higher frequencies. Clearly I got what I paid for!

CONSTRUCTING THE CABINETS

I constructed the cabinets using ¾″ cherry for the side pillars and ¼″ cherry veneered plywood for the panels. I bought three 9′ lengths of the cherry and a 4′ square sheet of the veneered plywood. I was quite shocked at the cost—around $150 total, which violated the first rule of the project, namely, that it should be cheap.

Each pillar needed to be constructed from two lengths of board, each cut along one edge at an angle of 60°, then biscuit-jointed and glued together. This was a job for which I had neither the woodworking equipment, nor the skills. So I sought the help of my friend Roy, whose garage looks not dissimilar from Norm Abram's workshop!

FIGURE 1: ORIGINAL DESIGN FOR THE TRIANGULATORS.

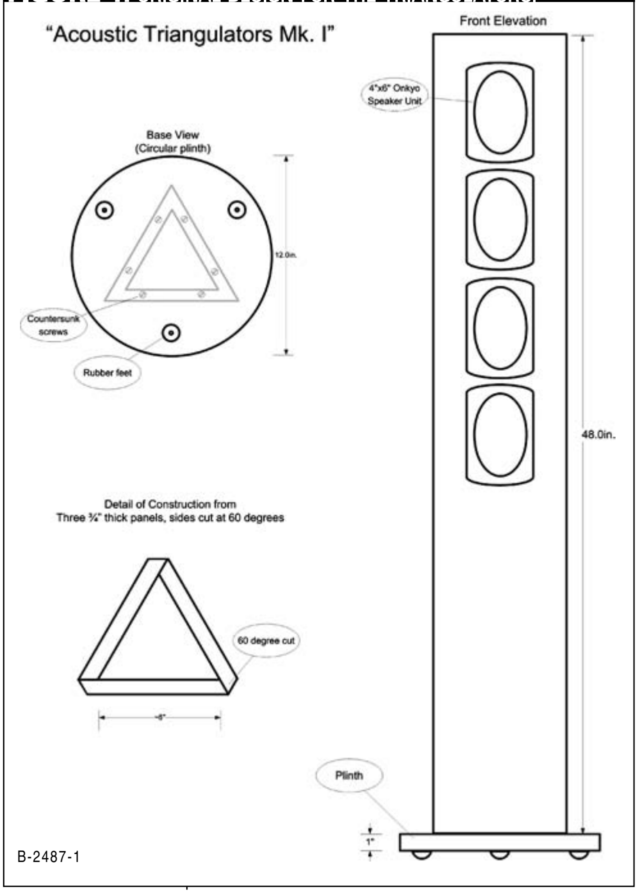


PHOTO 3: PILLAR PIECES: BISCUIT JOINTS.

PHOTO 4: PILLAR PIECES RABBETTED FOR PLYWOOD PANELS.

Photo 3 shows a pair of lengths for the pillar. You can see the angled cut, the grooves cut with the biscuit cutter, and the biscuits in place ready to glue.

The nice feature of the biscuit joint is that the pieces mate perfectly together, giving a nice sharp seamless edge along the length.

Once we had cut all 12 lengths and had biscuited them together in pairs (to form six pillars), we rabbeted them with a groove just slightly wider than the plywood's width. We then secured the plywood panels with their edges in the grooves. *Photo 4* shows the pillars just after rabbetting.

I cut the panels as 4′ long, 6½″ wide strips from the veneered plywood, taking great care to select the most attractive wood grain patterns so that they would appear centered on the front faces of the cabinets. Although this wasted a little of the wood, the end result was well worth the trouble. I ended up with the six required panels, all but one of which had a nicely centered grain pattern.

At this point we could make a dry run with the panels to check their fit and fix the final dimensions of the caps. *Photo 5* shows the result.

To ensure that the sides of the equilateral triangle made by the pillars and panels were indeed the same size, and to provide further space for anchoring the caps, we cut 12 6″ long spacers of ¾″ square plywood and glued them to the rear of each panel and placed them at the top and bottom of the rear of each panel. *Photo 6* shows the panel spacers being glued.

Now we could proceed to making the caps, one for each cabinet. We had

FIGURE 3: THE EIGHT SPECTRA AND THE ROOM BACKGROUND, AS SEEN ON THE IE33 DISPLAY AFTER MEASURING ALL EIGHT UNITS.

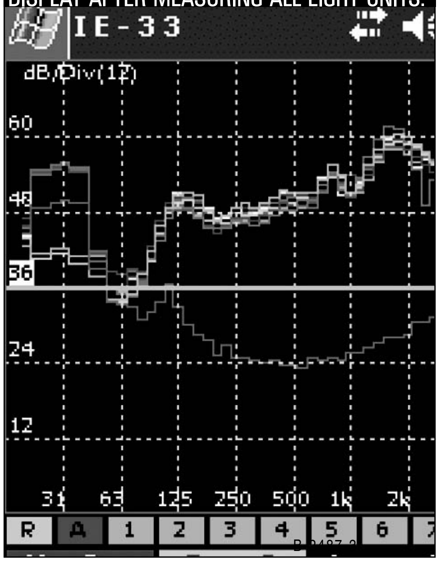


FIGURE 2: THE ROOM-CORRECTED RESPONSE CURVES FOR EACH OF THE EIGHT DRIVERS.

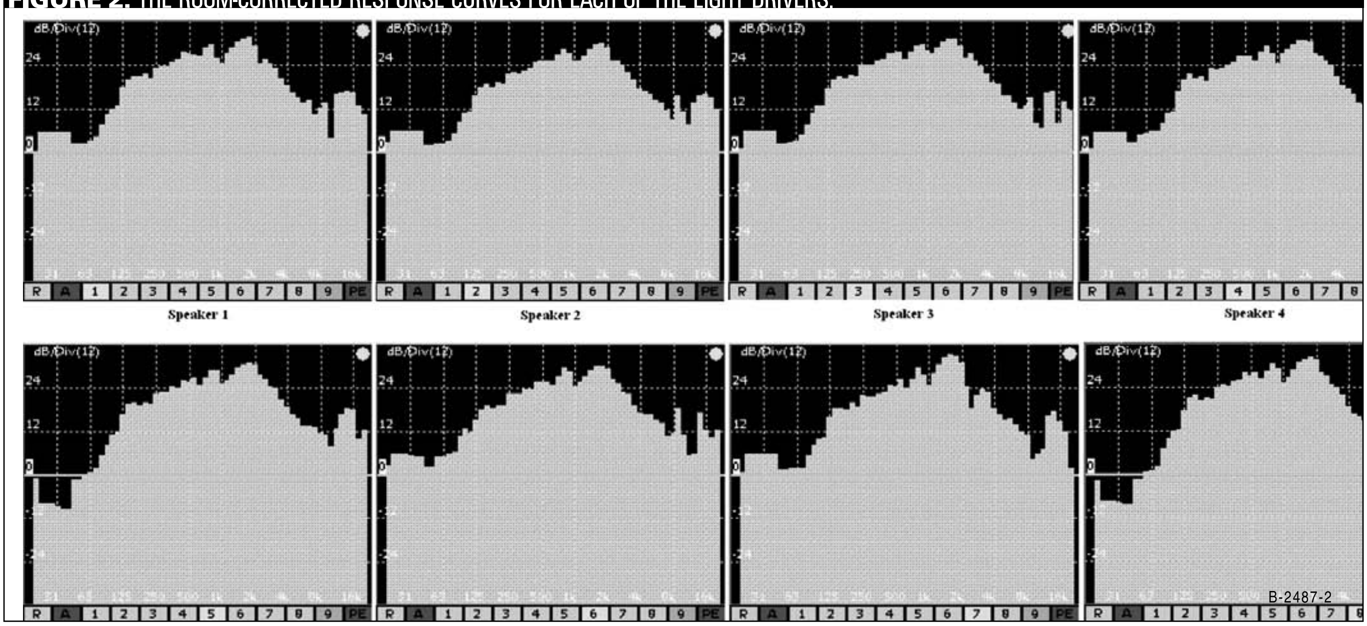


PHOTO 5: SIDE PANELS AND PILLARS DRY-ASSEMBLED.

PHOTO 6: CLAMPING THE SIDE PANEL SPACERS AFTER APPLYING GLUE.

saved the best cherry board with the most interesting grain features for the caps. But this is where the first problem arose. By an error of calculation, the 8″ wide cherry boards were not wide enough to allow us to cut a cap from a single piece of board. To save the day, Roy came up with the ingenious idea of making the caps from three identical triangular-shaped pieces. Although the cuts were challenging (even the slightest error in angle on the table saw multiplies by three when you put the pieces together), we had to re-cut a fine chamfer off only one set of cap pieces; the second set was perfect. *Photo 7* shows the two caps ready for biscuit jointing and clamping.

Once the biscuit joints had set, we cut the edges of the cap pieces a little larger than the tops of the cabinets, beveled at 60°, and then sanded them to a smooth finish. At this point we assembled the cabinets dry and drilled a ¼″ dowel hole at the end of each pillar. We placed dowel centers in the holes and positioned the cap pieces carefully so that the overhang was the same on all sides. We then pressed them onto the dowel centers and drilled holes at the resulting marks. We needed to take care not to drill all the way through the cap, which would have been an annoying mistake to say the least! *Photo 8* shows the caps and dowels.

It was now time to glue the cabinets together. This was complicated slightly by the need to leave the front plywood panel free to slide in and out. So we glued the rear and side panels first, then positioned the front panel without gluing. We fixed the cap in place, using liberal amounts of glue, but making sure that none seeped into the front panel rabbet or onto the front panel itself. Lacking suitable clamps, I bound each cabinet at three positions around its waist using duct tape over cloth (to protect the wood), pulling the tape as tight as I could. I then rested each cabinet on its cap piece and left the pair to dry overnight (*Photo 9*).

On inspection the following day, some small gaps were evident in a few places between the cap pieces and the panels and pillars. I carefully filled these with wood filler, but very little was needed. After this had dried, I meticulously sanded each cabinet with 180 grit sanding blocks, removed all the dust with a slightly damp rag, and liberally applied a coat of Danish Oil, which was soaked up by the thirsty wood. I found I used quite a lot just for this first coat. After about half an hour, I applied another coat, waited for as much of that to soak in as the wood wanted, and then wiped the excess off with a rag.

The grain patterns on the cherry wood were now very apparent; the Danish Oil had brought them out beautifully, and the cabinets began to look like the pieces of decent furniture I'd been hoping for. The next job was to cut the oval holes for the drivers. I extracted the front panel of each speaker and then used an oval template I'd made from a scrap of plywood to mark the cut lines on the back of one panel. I then clamped the two front panels' front faces together and cut the four driver holes through both panels at the same time. *Photo 10* shows the front panels, reinserted in the cabinets, ready for the drivers to be mounted on them.

MOUNTING AND WIRING THE DRIVERS

I used rubber weather-stripping to surround the rear of each driver before inserting it into its oval cutout. Then I bolted the driver in place. After

PHOTO 9: MAKESHIFT "CLAMPS" CONSISTING OF RAGS AND TIGHTLY PULLED DUCT TAPE SECURE THE CABINETS WHILE THE GLUE SETS. NOTE THE PRE-DRILLED HOLES FOR THE TERMINAL BLOCKS.

PHOTO 7: CAPS PIECES READY FOR BISCUIT JOINTING.

PHOTO 8: COMPLETED CAP PIECE AND THE POSITIONING DOWELS ON THE CABINET PILLARS.

PHOTO 10: FINISHED WOODWORK: AWAITING INSTALLATION OF THE DRIVERS.

PHOTO 11: A CIRCULAR PLYWOOD PLINTH, WITH SIX SCREWS ATTACHING IT TO THE CABINET.

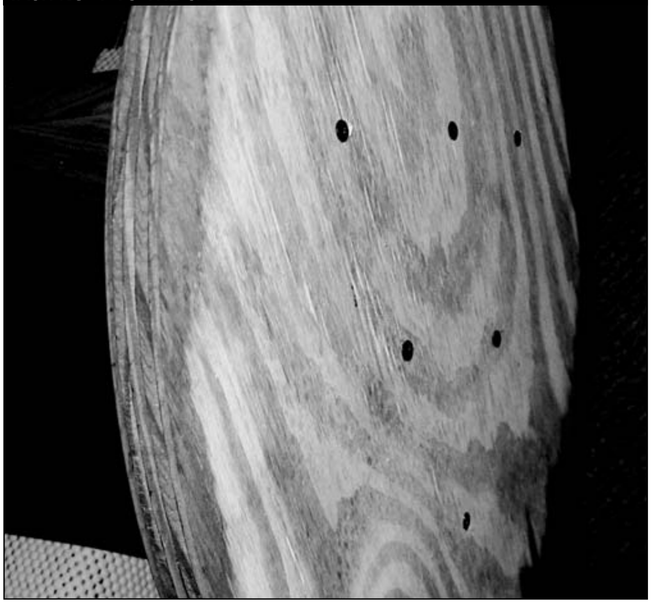


PHOTO 12: THE ACOUSTIC TRIANGULATORS IN POSITION.

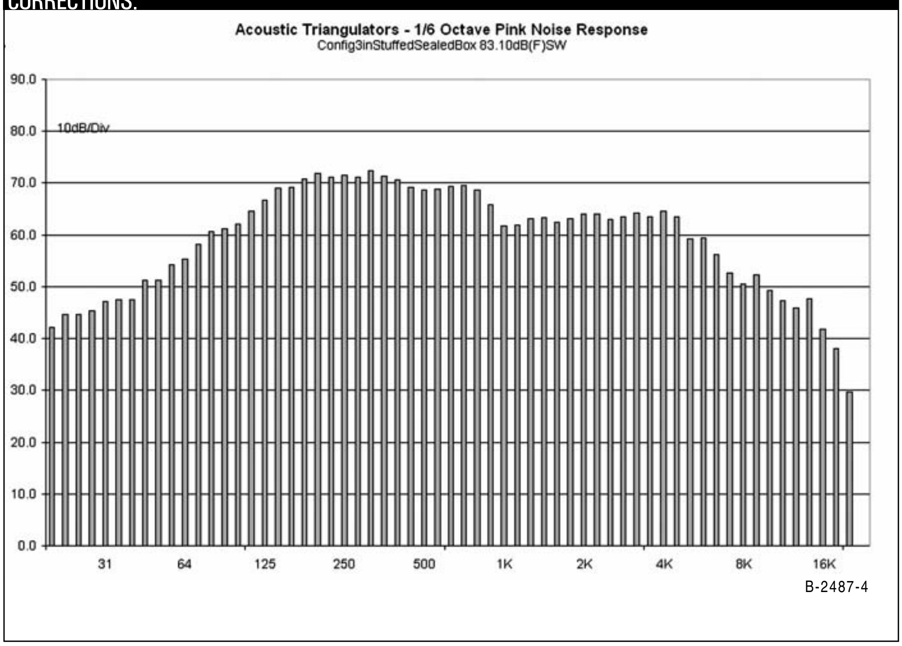
mounting all four drivers, I needed to determine how to wire them.

Because each driver's impedance was a quoted 4Ω, I was reluctant to wire them in parallel, which would make a difficult 1Ω load for the amplifier. First I tried wiring them in series, made a pink noise measurement of the response, then wired each pair in parallel and the pairs in series, and made another measurement. Finally I wired each pair in series and paralleled those. This turned out, for some reason, to produce the more flat response, and is what I eventually settled on. In this configuration the amplifier would see an acceptable 4Ω load.

STUFFING AND SEALING THE CABINETS

I stuffed the cabinets with cushion stuffing, not too tightly, and then inserted the front panels containing the drivers into the front pillar slots and slid them into place. I used six long drywall screws to fasten the plinths, which were made of ¾″ plywood and stained with a Watco cherry stain to approximate the real cherry wood of the cabinets. *Photo 11* shows a secured plinth. Finally, I attached four small rubber feet to each speaker.

FIGURE 4: IN-ROOM FREQUENCY RESPONSE OF AN ACOUSTIC TRIANGULATOR BEFORE CABINET CORRECTIONS.



INITIAL MEASUREMENTS AND LISTENING TESTS

The exciting moment had now arrived: The Acoustic Triangulators were ready to be brought into the house, tested in situ, and auditioned in the living room! I positioned them at either side of the fireplace, about 8′ apart (*Photo 12*), fed them with pink noise, and measured the response (*Fig. 4*).

You can compare the frequency response curve with some of the individual driver response curves shown in *Fig. 2*: It is smoother and more well behaved at low and high frequencies. On the other hand, it is evident just from the curve that these speakers are not going to produce a lot of earth-shaking bass! That was indeed the impression when I listened to the Allegretto from Shostakovich's Symphony No. 8 with Bernard Haitink conducting the Concertgebouw Orchestra (Decca 411 616–2), which taxes even the fidelity of my very fine Jean-Marie Reynaud Millesime V speakers when rendering the drums and crescendo at the end of the movement.

The Triangulators certainly could benefit from wider range drivers, especially in the bass. The other noticeable characteristic was a detailed and clear midrange, with nice imaging that seemed to place the instruments very precisely across the sound stage in Beethoven's Archduke Trio with the Suk Trio (Denon 33CO–1586). But the acid test came when my wife, Sarah, after listening for a few seconds, declared the Triangulators to be "fresh," which I think is an excellent summary of how they sounded to me, too.

CABINET RESONANCES

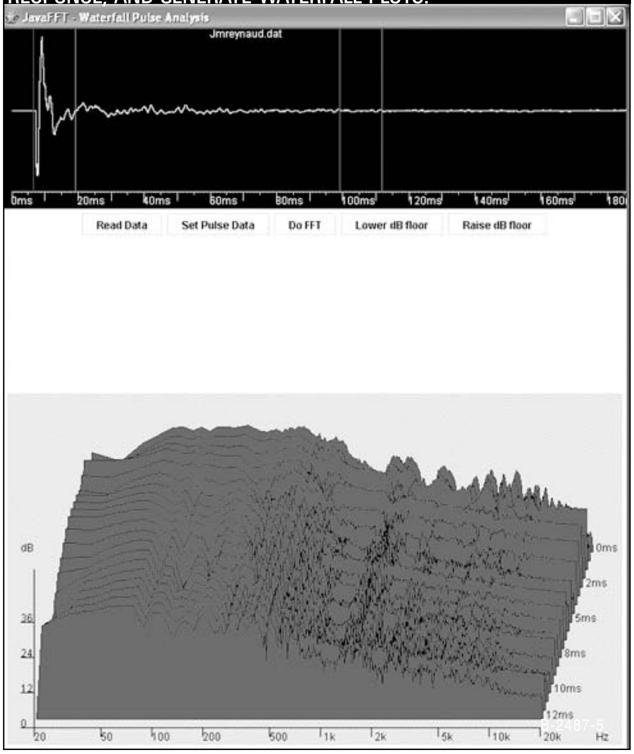
Despite the fact that the Triangulators sounded good, I had a niggling worry whether the ¼″ ply panels were rigid enough. My worries were also echoed by Ed Dell, to whom I submitted a first draft of this article. So I set about making some measurements of the cabinets to understand if—and how much—they resonated at audio frequencies.

My first tests involved feeding the Triangulators with a pulse signal and measuring the impulse response with a good-quality microphone. For this I used my WinAIRR software, setting it into "waterfall" mode, which produces a series of frequency response measurements, one after the other, over a period of a few milliseconds. For a resonant cavity, the waterfall plot will show a pronounced peak in the initial and following impulse response spectra. For an acoustically dead cabinet, there will be no audio energy after a millisecond or so.

The results were inconclusive. There were no pronounced peaks, but the level of other noise was too high to determine they weren't there. Perhaps the microphone was not sensitive enough.

I recorded a set of impulses using the IE33's calibrated Type II microphone, and then wrote a set of Java routines to analyze the audio ADC data. You can see the output from the Java program in *Fig. 5.* In the top panel is the impulse response as recorded by the IE33 microphone, in the center panel is a set of buttons for controlling the processing, and at the bottom is the waterfall plot as derived from the impulse response. (Readers who would like a free copy of the Java program are welcome to contact me.)

FIGURE 5: JAVA PROGRAM TO ANALYZE LOUDSPEAKER IMPULSE RESPONSE, AND GENERATE WATERFALL PLOTS.



Again, the results are inconclusive. I decided that I really needed an accelerometer, rather than a microphone, and

PHOTO 13: THE PANEL BRACING AND ACOUSTIC ABSORPTION MATERIAL STUCK IN PLACE.

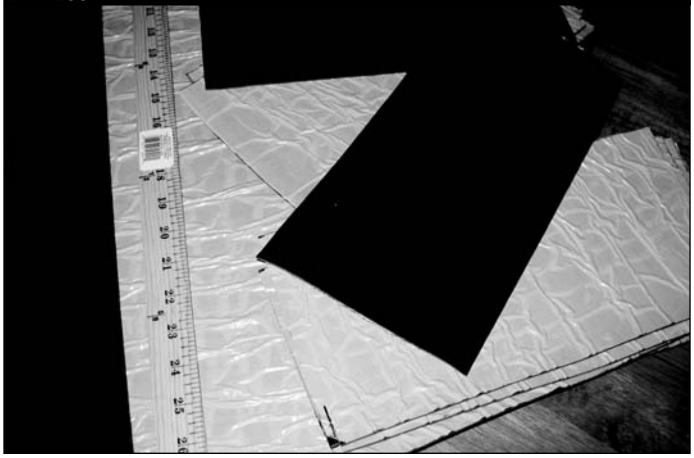


PHOTO 14: THE ACOUSTIC ABSORPTION MATERIAL FROM PARTS EXPRESS.

then with that I would be measuring directly the motion of the cabinet panels, rather than a second-order effect (from any panel vibration moving the surrounding air, which would be picked up as a pressure wave by the microphone). Unfortunately, I didn't have an accelerometer!

Undaunted, I pressed on in my hunt for resonances using the tried-and-true method of sine-wave sweeps. I hooked up both my Precision Audio Frequency Generator and the Triangulators to an amplifier. Using sine waves, I slowly swept the frequency upwards, by hand, starting at a few Hz.

When I reached 80Hz, the front panels on both Triangulators started buzzing very noticeably. I could prevent the buzzing by applying light fingertip pressure to the front panels, near the oval drivers. I continued on upwards, slowly, but didn't discover any other anomalies.

It was now clear that I needed to brace and deaden the panels somehow. I ordered a length of acoustic absorption material from Parts Express. While I was waiting for that to arrive, I dismantled both Triangulators and glued several bracing blocks of ¾″ square pine to the rear of each non-driver panel. On the driver panels I glued long lengths of the pine to each side of the driver array (*Photo 13*).

The acoustic absorption material is very dense; a roll of it felt like several pounds. It has the texture of the back of a linoleum floor tile and bends easily. One side was sticky, underneath a protective layer of blue plastic (*Photo 14*).

I cut oblongs of the material to fit the rear panels, and a length for the base of the rear of the front panels. After sticking the damping material in place, I restuffed the cabinets, inserted the front panels,

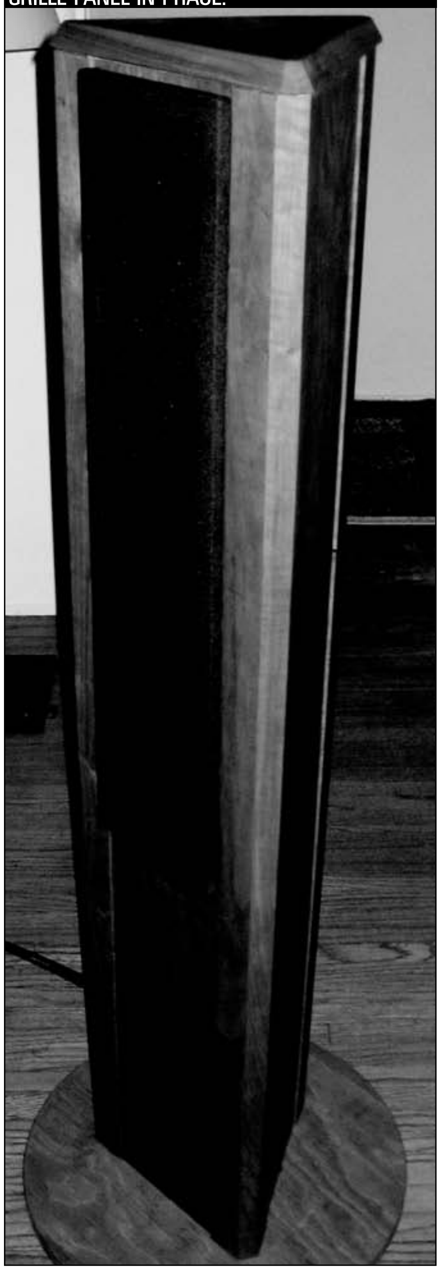


PHOTO 15: ONE OF THE COMPLETED ACOUSTIC TRIANGULATORS, SHOWING THE GRILLE PANEL IN PHASE.

and re-attached the bases. Now the Triangulators were considerably heavier and sounded inert when I rapped on them with a knuckle. Sure enough, a new sinewave sweep confirmed that the 80Hz resonances had gone, and indeed there were no other audible resonances. The last job was to fashion a pair of speaker grilles, using ¼″ × ¾″ square plywood and grille cloth material from Parts Express.

THE COMPLETED ACOUSTIC TRIANGULATORS

Finally, I returned the speakers to the living room for measurement and listening tests. Sarah was especially pleased to see them replace the rather dour-looking Millesime Vs. *Figure 6* shows the measured swept frequency response for the right-hand speaker with its grille off.

The Triangulators have been in regular use now for several weeks and are proving to be very capable at enjoyable renditions of a wide variety of music, opera, soundtracks, as well as the spoken word. If I were embarking on this project again, I would avoid the false economies of a) buying the cheapest oval drivers available, and b) using plywood panels instead of solid wood. Given the time and effort required for a project like this, it makes no sense to save a few dollars by not getting the best parts. Having said that, and given the constraints of the materials, the speakers sound great. ***aX***

REFERENCES AND SOURCES

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2. "Low-cost High-quality Loudspeaker," P.J. Baxandall, High Fidelity Designs, IPC Business Press Ltd., 1974.
3. Sound deadening material – Parts Express #268–020.
4. Onkyo 4″ × 6″ 4Ω Speaker – Parts Express #269–756.
5. Black grille cloth – Parts Express #260–335.
6. Ivie Technologies IE33 Acoustic Measurement device – www.ivie.com/ie33.

FIGURE 6: THE SWEPT FREQUENCY RESPONSE, GRILLE OFF.