Easy-to-build Active Hifi Bookshelf Speakers *with Optional Subwoofers*

Part 1 – by Phil Prosser

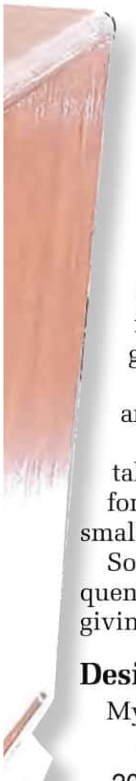
These high fidelity monitor speakers are designed for use with TVs, computers or recording equipment. They're inexpensive and easy to build, yet have excellent audio quality, with low distortion and a fairly flat frequency response. So if you're looking for high-quality DIY bookshelf speakers without spending the earth, these are for you. Optional matching subwoofers extend the bass significantly, and provide much higher output levels.

Modern TVs are becoming thinner and sleeker all the time. As much as this trend shows the great leaps in display technology, there are a few laws of physics that limit the quality and capacity of the internal speakers, which must fit in a similarly tiny space.

Let's face it; the speakers on pretty much all modern TVs sound pretty bad and some provide very poor voice intelligibility.

The ideal solution is an external set of speakers and an

Shown here with their optional subwoofers (which also act as handy stands) these two-way, ported bookshelf speakers are economic and easy to build.



amplifier connected to the TV. For the greatest convenience, the amplifier can be contained within the speakers themselves.

The speakers can generally be plugged into the television line-out (or headphone) output, so the television volume control can still be used.

Any speakers which will work well with a TV are also very suitable for providing high-quality output from a PC, for watching movies and music, playing games or for sound and movie editing.

These high-quality speakers have a built-in power amplifier, so the fit the bill perfectly.

I've designed them to be compact so that they don't take up too much space. But in some cases, particularly for TV and movie use, you may want more bass than a small enclosure can provide.

So the optional matching bass enclosures extend the frequency response and also incorporate their own amplifier, giving a higher maximum volume too.

Design goals

My goals in designing these speakers were to achieve:

1. a modest size for the bookshelf speakers, at around 200mm wide, 300mm deep and 400mm high.
2. a flat and well-behaved impedance curve.
3. a decent maximum volume of at least 100dB SPL at 1 meter without undue distortion.
4. a -3dB frequency response of 40Hz to 20kHz for the bookshelf speakers alone.
5. a flat output, nominally ±3dB across the 40Hz to 20kHz range.
6. a matching subwoofer, extending the bass response and taking over from the monitors up to about 90Hz.
7. timber construction, allowing readily-available materials to be used.
8. simplicity of construction, to make it easy for DIYers.
9. low cost; under $300 for the basic stereo bookshelf system, and no more than $150 on top of that to add two subwoofers.
10. integrated power amplifiers for neatness.

For the optional subwoofers, my additional goals were:

1. response down to about 35Hz, requiring a volume of around 35l and an 8-inch (20cm) driver.
2. the ability to use the subwoofers as speaker stands for the bookshelf speakers.
3. (or) an option to build a subwoofer in a rectangular shape so it could be hidden under a desk.
4. an active crossover that splits the signal between the bookshelf and subwoofer units.
5. integrated power amplifiers for the subwoofers.
6. maximum dimensions of around 200mm wide, 300mm deep and 800mm tall.

The dimensions ended up 210 x 296 x 280mm for the speakers and 210 x 296 x 800mm for the subwoofers.

Trade-offs

When designing this project, we have had to make a trade-off between cost and performance. There are some very costly options for drivers that promise exceptional performance. While serious audiophiles may be happy to spend many hundreds of dollars on a single driver, we believe that such expense is not necessary for excellent performance.

The results we achieved confirm that theory. By using readily-available, reasonably-priced drivers, and a basic crossover, measurements and listening tests show that these shine in a small two-way monitor system.

Performance of the bookshelf speakers alone is very good, but they do lack a little at the bass end, so you can expect a more 'full' sound if you also build the optional subwoofers. Both the bookshelf and subwoofer speakers are 'active', ie, there is an amplifier built into one of each pair. This allows them to be plugged straight into your TV or PC without needing to build a separate amp.

Some of the trade-offs that I needed to make while working on this design include:

- Size: I wanted to keep the speakers relatively small, which limited the driver size and enclosure volume, meaning they don't produce really deep bass.
- Enclosure material: I selected 15mm plywood or MDF, which is cheap and easy to get, even though I would have preferred to use thicker material.
- Finish: I decided on a stained or varnished timber finish to keep the cost down and make construction simple. Paint or carpet could be applied if desired.
- Drivers: the drivers I chose, while low in cost and producing excellent sound quality, had some characteristics which made crossover design a bit tricky. This makes the crossovers a bit more expensive, but the driver cost is low enough to offset that.

Electronics

For simplicity, one bookshelf speaker contains a stereo amplifier to power both speakers, with a passive crossover in each unit. This makes the pair fully self-contained, except for the power supply (see Fig.1). We're using a 'brick' type AC-to-DC switchmode mains power supply, so no mains wiring is required. They are quite cheap and efficient for the amount of power they provide.

Similarly, if you're building the optional subwoofers, one subwoofer contains a stereo power amplifier to drive itself and the other (passive) subwoofer, plus an active crossover which distributes the appropriate signals to both subwoofers, and to the pair of bookshelf speakers. This arrangement is shown in Fig.2. A separate power 'brick' is used to power the subwoofer amplifier, meaning two are required for the whole system.

The amplifier modules we're using are Class-D amplifiers, based on the TDA7498 IC. These produce plenty of power without breaking the bank. We considered using an LM3886-based or discrete amplifier for these speakers, but could not warrant the associated increase in cost and complexity.

The type of amplifier we're using is often described as a "plate amplifier".

We have chosen to use a brick power supply for the speakers as it makes construction much simpler, and eliminates the need for any mains wiring in the project. So if you are

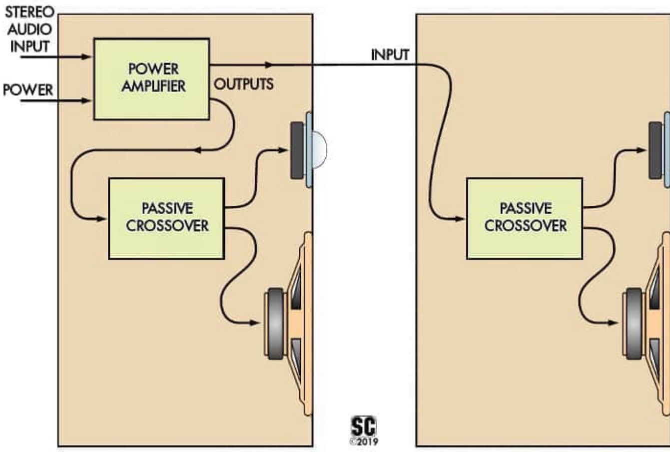


Fig.1: the configuration of the basic bookshelf speaker system. The left and right audio signals, and 24V DC power, is fed into one of the speakers (it could be left or right, depending on how you wire it up internally). One of its internal power amplifier channels feeds the tweeter and woofer via a passive crossover, while the other channel drives a pair of wires connecting to the other speaker. This also has an internal passive crossover, conditioning these signals before they pass to its tweeter and woofer.

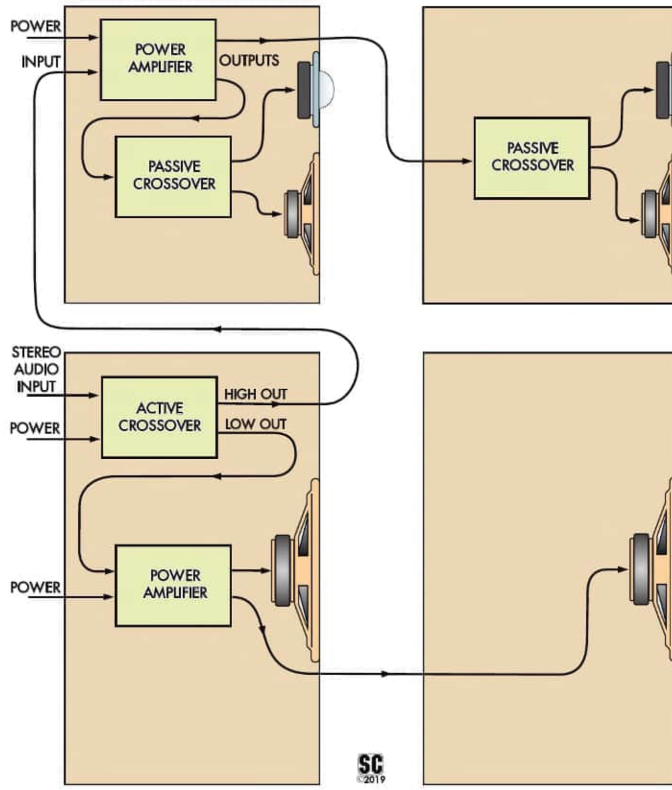


Fig.2: the bookshelf speaker internals are identical if you build the full version with the subwoofers. However, the incoming signal now goes into the first subwoofer, where it's split into high and low components. The two high outputs go to the stereo input on the first bookshelf speaker, and then onto the other bookshelf speaker as before. The low-frequency signals go to a second power amplifier within the first subwoofer, and its outputs directly feed the two larger woofers in each bass cabinet.

confident with woodwork and happy to wire up the amplifiers, this may be a good project to try out.

It is important to note that the line-level output from the subwoofer is high-pass filtered, so when the subwoofers are used, the monitors are not required to produce low-frequency signals. In this configuration, the cone excursion on the monitors is much lower than in the full range configuration. As a result, the mid-range is much clearer, and the system is capable of a much higher sound output level.

Monitor speaker design considerations

The bass driver selected is an Altronics C3038 130mm (5-inch) Aluminium cone driver. After much testing and analysis, we decided upon this as it performed well by itself in a modest enclosure.

This driver can also be used in a two-way system crossing over at about 3kHz, which is above the normal vocal frequency range, leading to less audible distortion. It is also excellent value for money.

We decided on this after surveying several smaller 100mm (4-inch) drivers. All of these fell short in the bass department. We also considered larger drivers, in the 150-180mm (6-7 inch) range.

Many of these can deliver good bass, but all push the enclosure size well above the 16 litres we settled on. This is itself a compromise, as our original design goal was sub-10 litres.

The Altronics C3038 driver has 20-40W stated power handling, a frequency response of 46Hz to 10kHz, voice coil diameter of 25mm, overall diameter of 130mm and 87dB @ 1W/1m sensitivity.

These specifications are mostly typical of a driver this size. Its party trick is its very extended frequency response, right up to 10kHz. That allows us to easily integrate this with a tweeter in a two-way system.

Having said that, it's best to avoid feeding signals right up to 10kHz into this driver, as we found it had some rather unruly behaviour up there, which we had to address with the crossover electronics.

If you drive this unit at 30W, you can achieve over 100dB SPL at one metre. That is seriously loud in a home setting. It's about as loud as a jackhammer at close range. While small in stature, these drivers can provide some solid output.

Modelling this driver in the proposed enclosure showed that we could achieve an "extended bass shelf" alignment (Fig.3), where we are squeezing out a little bass extension at the expense of flatness at lower frequencies. It is a good compromise for smaller speakers. Note that when the optional subwoofers are added to the system, they take over frequencies below 90Hz, so a flatter overall response is achieved.

We chose to make the enclosure reasonably narrow, with an external width of 21cm. This allows the speaker to sit on a desktop or bookshelf without taking up much room. The height and depth of the speaker were then chosen to deliver the required 16 litres internal volume. The remaining dimensions are 297mm deep and 390mm high.

The depth of 297mm allows a standard 1200 by 600mm piece of plywood to be cut in half to make the side and top panels, minimising waste and cost.

A second aspect of the box is the layout of the bass driver and tweeter. You will note that we have butted the tweeter right up to the bass driver. The reason for this is to minimise the separation of the centres of the tweeter and bass driver.

As a listener moves their head around, keeping these close

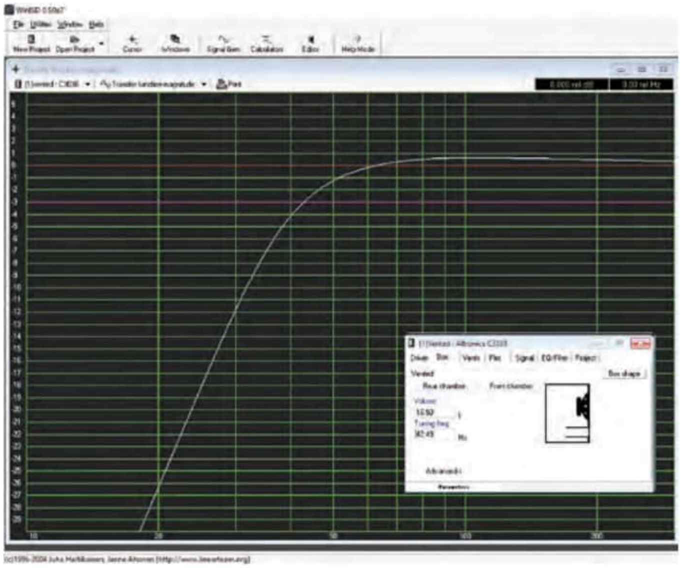


Fig.3: we plugged the Altronics C3038 woofer parameters into WinISD and experimented with the dimensions of a small vented enclosure, achieving the response shown here. This provides a slightly extended bass response at the expense of slightly less flatness in the bass frequency response. Given that the deviation is less than 1dB, you're unlikely to notice it. And the bass response is extended by around 10Hz, which is very worthwhile.

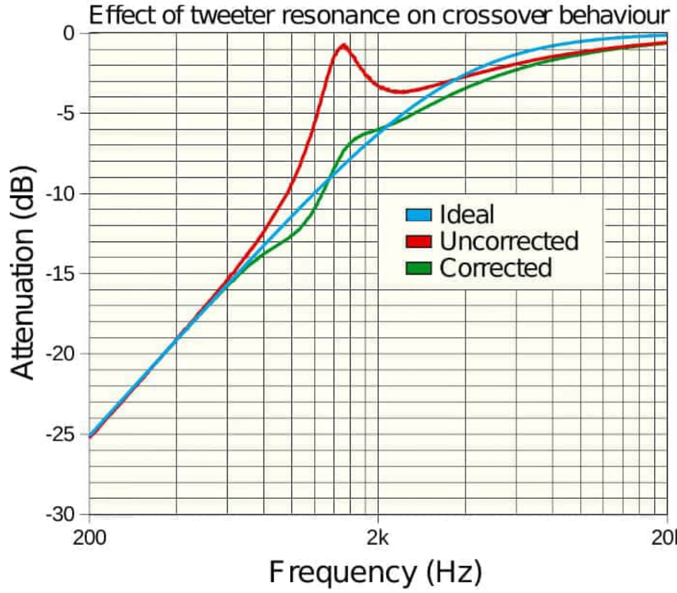


Fig.4: the tweeter's impedance varies with frequency, affecting the operation of the crossover. The blue line shows a simple crossover with a 4Ω resistive load. The red curve shows the same crossover with the Vifa tweeter as the load. The green curve shows the corrected response of our tweaked crossover, with a compensation network to reduce the tweeter resonance effect.

minimises differences in the distance from each driver to the listener's ear. The result is that the sound of the speakers remains constant around the listening area. In other words, these speakers deliver a good off-axis response.

The crossover

The C3038 bass driver performs quite well at lower frequencies. We decided to cross the driver over to the tweeter at about 3.2kHz, allowing it to cover the critical 300-3000Hz range of the human voice.

Unfortunately, this driver has some severe breakup modes in the 9-11kHz frequency range, as a result of the very stiff cone utilised. This creates a group of peaks and dips in the upper-frequency range. At first, we tried a crossover that did not specifically treat these peaks, and quickly realised our mistake!

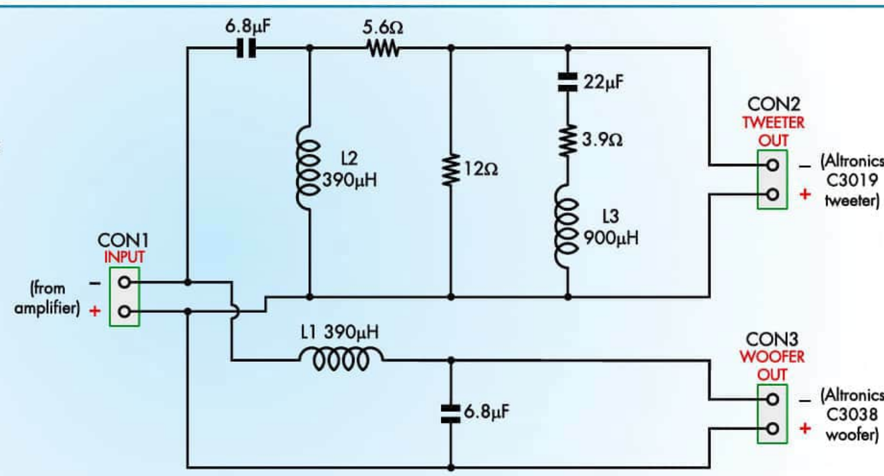
The second version of the crossover included special filters to "notch out" these peaks. This worked but made the crossover very large and expensive. We then decided to try a second-order crossover, and combined the filter into the crossover. The roll-off, and indeed the impedance of the bass section, has been designed to attenuate the 9-11kHz peaks more than usual.

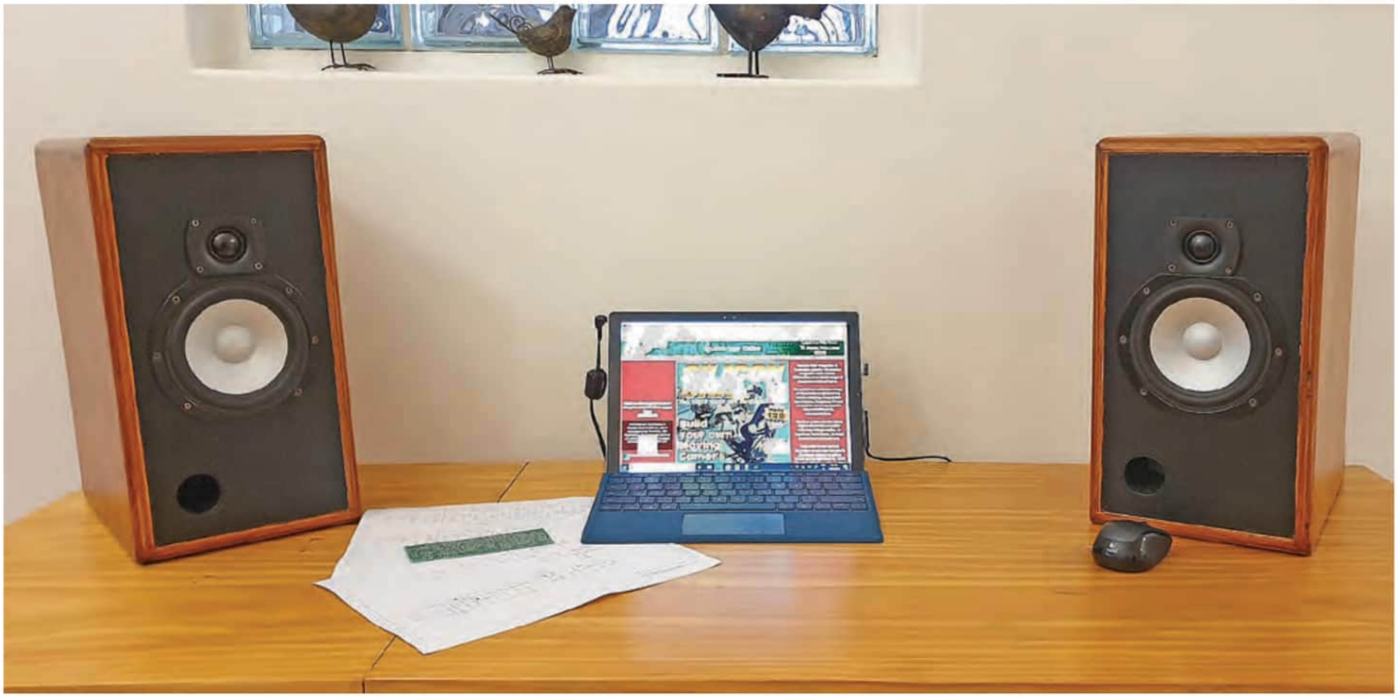
One consequence of this tweaking is that the impedance of the speaker dips to about 4Ω in the 2.5-5kHz range. This will not fuss most amplifiers. The final bass driver output is very clean and has none of the harshness of the unfiltered driver output.

The tweeter

We really wanted to choose a good tweeter, as when a tweeter is too peaky or harsh, the result is a speaker that causes fatigue after prolonged listening. The tweeter chosen also needs to support a crossover frequency as low as reasonable, to allow us to avoid sending signals in the 9-11kHz region to the bass driver.

Fig.5: the final circuit of the crossover, with the extra filtering for the woofer to effectively cut out signals in the 9-11kHz breakup region. This also incorporates an RLC network (3.9Ω/22µF/900µH) to smooth out the tweeter response due to the resonance shown in Fig.4, plus a 5.6Ω/12Ω resistive divider to match the levels and impedances of the two drivers to suit a single signal source.





You don't *have* to build the subwoofers – if you don't want to use the subs as stands, the two main speakers are ideal for use with a computer, MP3 player, etc (albeit at the expense of some bass). Because they're self-powered, they will plug straight into virtually any sound source, from "line out" to headphone sockets . . .

So we selected a Vifa tweeter, Altronics Cat C3019. This is a very good tweeter at a fair price, but does present the designer with the challenge of a significant impedance peak at around 1.75kHz. This impedance peak is a result of tweeter resonance.

The tweeter employs ferrofluid in the air gap in the magnet assembly. This aids in cooling the voice coil, and usually damps the driver resonance. So, in most ferrofluid tweeters, the driver impedance is quite flat through resonance. The C3019 tweeter is kind of 'in-between'. The impedance of the tweeter is nominally 4Ω, but at 1.75kHz it peaks at about 10Ω.

We need to deal with this peak. Fig.4 shows the behaviour of an ideal first-order crossover in blue, the actual response in red and the corrected response in green. The correction is implemented with an LCR trap, comprising (in our case) an inductor of around 1mH, a 22µF capacitor and a 3.9Ω resistor.

This does add cost to the project, but it is essential to achieving a good sound. A peak like the one shown without the correction circuit is responsible for many tweeters sounding harsh and 'tiring'.

The resultant second-order passive crossover circuit is shown in Fig.5. This is a reasonably complex crossover for a two-way speaker, but it's necessary to achieve the desired sound quality.

All three resistors can be 5W wirewound types. The capacitors are not too hard to get, either; the 6.8µF capacitors can be either metallised polypropylene or non-polarised electrolytic types. I decided to go with the former, but electros are fine. Given its high value, the 22µF capacitor needs to be electrolytic.

That just leaves us with the question of where to get, or how to make, 390µH and 900µH air-cored inductors with low DC resistances, so that they are as close to ideal inductors as possible.

Luckily, it turns out that you can simply purchase full reels of enamelled copper wire (ECW) on spools, and the spooled wire will already have roughly the right inductance values! We tested reels from Altronics (and these are specified in the parts list). We're not sure about reels from other vendors. You would have to measure their inductances yourself.

It's really lucky that a 100g reel of 1mm diameter ECW works out to pretty much exactly 390µH. We actually wanted 1mH for L3, but a 100g reel of 0.8mm diameter ECW measures 900µH, and that's close enough.

All that difference does is shift our crossover point from 3.0kHz to 3.2kHz. Using the whole reels like this relieves constructors of the job of tediously winding custom inductors.

The three inductors are mounted on the crossover PCB perpendicularly to one another, ie, one faces north/south, one east/west and one up/down. This means they are 'orthogonal', so their magnetic fields will not interact.

Otherwise, we would get an unwanted air-cored transformer between two or more of the inductors, and the crossover would not work as intended.

Inbuilt amplifier

The pre-built amplifier modules we're using don't cost a lot but still deliver great performance. As avid hobbyists, entertaining the thought of buying a pre-built amplifier module was a hard concept to deal with… but we are thankful we did.

This amplifier will deliver about 30W RMS into two 8Ω speakers, which is more than enough for anything short of a monster party.

When paired with the matching subwoofers, the monitors never see frequencies below about 90Hz, so 30W is actually a very serious amount of power indeed. The amplifier accepts stereo line-level inputs.

As mentioned earlier, the amplifier uses an external power supply, which is connected by a 2.5mm barrel plug. This keeps things very simple and avoids mains wiring inside the speaker.

Bookshelf Speakers Parts List – to build one pair

Enclosures

2 130mm (5in) 40W aluminium cone woofers [Altronics C3038]
2 25mm (1in) 100W Vifa BC25SC55 tweeters [Altronics C3019]
1 plate amplifier assembly (see below)
2 passive crossover assemblies (see below)
2 600 x 1200mm sheets of 15mm marine ply
4 2m lengths of 15 x 15mm or 20 x 20mm 'quad' timber
80 8G x 25-28mm self-tapping countersunk wood screws
20 8G x 15mm self-tapping countersunk wood screws
16 8G x 10-12mm self-tapping countersunk wood screws
2 105mm lengths of 40mm diameter PVC pipe
1 80 x 40mm sheet of 1.5mm thick aluminium
1 roll of thin foam tape (eg, door seal tape)
1 pack of large staples (or a small box of 40mm nails)
1 bag of Lincraft single-size thick wadding or similar lightweight acoustic poly wadding
4 sheets of 120 grit sandpaper
1 sheet of 240-400 grit sandpaper
1 small tin of timber varnish
1 small tin of matte or satin black paint
1 430-475ml tube of acrylic gap filler
1 dual red/black binding post [Altronics P9257A]
1 1m length of heavy-duty figure-8 wire
1 250ml bottle of PVA wood glue

Additional parts for a pair of subwoofers

2 200mm (8in) 70W polypropylene woofers [Altronics C3088]
1 subwoofer plate amplifier assembly (see below)
3 600 x 1200mm sheets of 15mm marine ply
6 2m lengths of 15 x 15mm or 20 x 20mm 'quad' timber
2 130mm lengths of 75mm diameter PVC pipe
100 8G x 25-28mm self-tapping countersunk wood screws
16 8G x 15mm self-tapping countersunk wood screws
8 8G x 10-12mm self-tapping countersunk wood screws
1 80 x 40mm sheet of 1.5mm thick aluminium
6 sheets of 120 grit sandpaper
1 sheet of 240-400 grit sandpaper
1 dual red/black binding post [Altronics P9257A]
1 1m length of heavy-duty figure-8 wire

Plate amplifier assembly

1 135 x 160mm sheet of 1.5mm thick aluminium
1 TDA7498-based 100W + 100W amplifier, blue PCB (available from eBay)
1 24V 5-6A "brick" type mains power supply with 2.5mm ID DC barrel plug
1 2.5mm inner diameter chassis-mount DC barrel socket [Altronics P0623]
1 red panel-mount RCA socket [Jaycar PS0259]
1 black panel-mount RCA socket [Jaycar PS0496]
1 dual red/black binding post [Altronics P9257A]
1 dual 10kΩ logarithmic potentiometer [Altronics R2334, Jaycar RP3756]
1 3-way 3.96mm crimp housing and pins [Altronics P5643 + 3 x P5640A, Jaycar HM3433]
1 knob to suit potentiometer
8 M3 x 6mm machine screws
8 3mm ID shakeproof washers
4 10mm to 25mm long M3-tapped Nylon spacers
1 1m length of single-core shielded wire
1 1m length of dual-core shielded wire
1 1m length of heavy-duty figure-8 wire
1 length of 5mm diameter heatshrink tubing
1 small tube of thermal paste
1 can of flat black spray paint, suitable for aluminium

Passive crossover

1 double-sided PCB, code 01101201, 137 x 100mm
3 2-way 5/5.08mm pitch PCB-mount terminal blocks (CON1-CON3)
1 900μH air-cored inductor (L1; full roll 0.8mm diameter ECW#) [Altronics W0407]
2 390μH air-cored inductors (L2,L3; full roll 1mm diameter ECW#) [Altronics W0408]
1 22μF 100V axial crossover capacitor [Jaycar RY6912]
2 6.8μF 100V axial crossover capacitor [Jaycar RY6956 or RY6906]
1 12Ω 5W 5% wirewound resistor
1 5.6Ω 5W 5% wirewound resistor
1 3.9Ω 5W 5% wirewound resistor
4 large plastic cable (zip) ties

 # ECW = Enamelled Copper Wire

Subwoofer plate amplifier assembly

All the parts specified for the bookshelf plate amplifier assembly above, except the aluminium sheet, plus:
1 250 x 165mm sheet of 1.5mm thick aluminium
1 red panel-mount RCA socket [Jaycar PS0259]
1 black panel-mount RCA socket [Jaycar PS0496]
1 double-sided PCB, code 01101202, 132 x 45mm
6 2-way 5/5.08mm pitch PCB-mount terminal blocks (CON4-CON9)
6 8-pin DIL sockets (for IC1-IC6; optional)
2 ferrite beads (FB1,FB2)
8 M3 x 6mm machine screws
8 3mm ID shakeproof washers
4 10mm to 25mm long M3-tapped Nylon spacers
6 NE5532 dual low-noise op amps (IC1-IC6)
1 LM317 1.5A adjustable regulator (REG1)
2 1N4004 400V 1A diodes (D1,D2)
1 1N4148 small signal diode (D3)

Capacitors

1 470μF 50V 105°C electrolytic
2 220μF 25V electrolytic
8 47μF 35V 105°C electrolytic
1 10μF 35V electrolytic
8 150nF 63V MKT
6 100nF X7R multi-layer ceramic
3 100pF NP0/C0G ceramic

Resistors (all 1/4W 1% metal film)

3 100kΩ	2 33kΩ	4 22kΩ	8 12kΩ	2 10kΩ
4 7.5kΩ	2 5.6kΩ	4 4.7kΩ	1 3.3kΩ	1 1.8kΩ
1 270Ω	2 100Ω	1 10Ω		

We have specified a TDA7498-based amplifier module available from eBay. These are theoretically capable of driving 80W into an 8Ω speaker, but we are running it from a lower voltage than the maximum. We selected this TDA7498-based module after purchasing and testing many other amps.

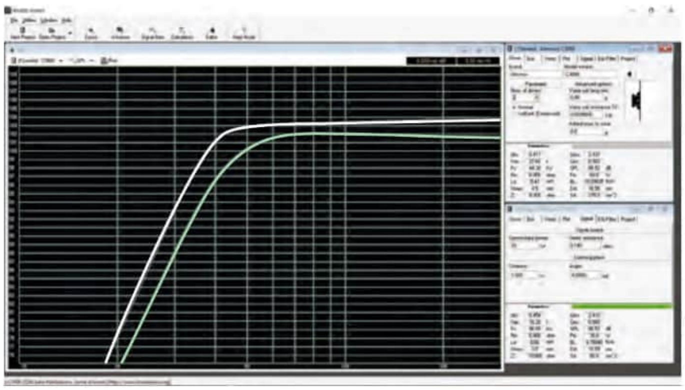


Fig.6: the expected SPL output levels of the 130mm woofers (green) compared to the 200mm woofers (grey), both at 30W. Not only do the larger diameter woofers put out a higher SPL across the board, but they also have -3dB roll-off point around 10Hz lower, at about 35Hz compared to 45Hz.

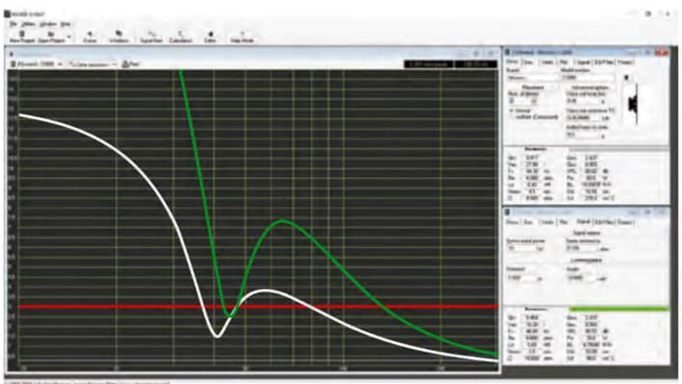


Fig.7: the simulated speaker cone excursion values (in mm) for the 130mm woofers (green) and 200mm woofers (grey). The 200mm woofers have reasonable (<4.5mm) cone excursions down to their -3dB point of 35Hz, while the 130mm woofers run into excursion limitations and thus distortion at a much higher frequency at this power level; around 100Hz.

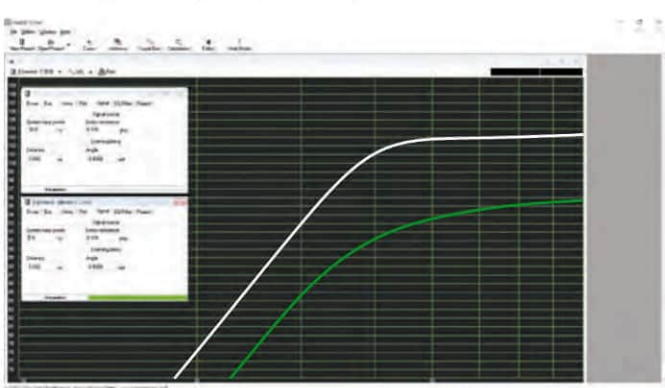


Fig.8: SPL output vs frequency for the 130mm woofers (green) and 200mm woofers (grey) at the highest practical power level for each; 7.6W and 30W respectively. By limiting the 130mm bass power to 7.6W, cone excursion is kept within reason, but the maximum SPL is around 10dB lower compared to the larger woofers.

Two main groups of amplifiers were credible candidates for this project, based on the TPA3116 and TDA7498 ICs. Both are Class-D amplifier chips, and both operate from a single supply rail. They are highly efficient, have a tiny heatsink by linear standards and are very affordable.

We considered using linear amplifiers, for example, discrete amplifiers or amps based on the LM3886 IC. These would deliver slightly better performance, but they all require dual-rail power supplies, and that leads us down the path of putting transformers, rectifiers and mains wiring inside the speaker. They would also cost more, and generate more heat inside the enclosure.

Looking at the Class-D options of the TPA3116 and TDA7498, we bought a range of devices to test. We found a few problems with most of the Class-D amplifiers on the market at the current time.

Some are marketed as "2.1 channel" amplifiers, with a subwoofer output and stereo main speaker outputs. Unfortunately, none of these incorporate filtering on the main outputs, meaning that full-range signal, including the range sent to the subwoofer, is sent to the main speakers. This is a failing that makes these devices virtually useless.

The heatsinking of many of the designs is very poor. In many cases, the heatsink is held down with a single screw. This is such a fragile design we cannot bring ourselves to use it inside a loudspeaker.

It seems random as to which amplifiers have good contact between the amplifier IC and the heatsink. But that is something we can fix.

Also, the voltage rating of capacitors on many of these products is very close to the operating voltage. That might not sound worrying, but it is. The reliability of electrolytic capacitors is strongly dependent upon how far from their maximum ratings they are operated (this includes temperature, voltage and ripple current).

We pulled the 25V rated capacitors from one amplifier, which ran them at 24V, and tested them on a power supply. Every single one failed catastrophically at 26-28V. This is far too close for us to recommend their use.

The TDA7498-based amplifiers can operate at up to 32V DC, and the amplifier we selected has solid mechanical construction. Given we are specifying a 24V plugpack to power the amplifier, we have a good voltage margin on the electrolytic capacitors.

As a bonus, the amplifier we recommend does not include volume controls, and has simple input and outputs on screw connectors/plugs. This makes it very affordable. You should be able to find the recommended amplifier for about USD $9 (~AUD $14) each, which is far less than we could build a discrete or LM3886-based amplifier for.

We also picked up a 24V 6A plugpack from eBay for less than AUD $35.

By integrating the amplifier, input connectors, speaker output sockets and volume control to an aluminium panel, we can build a standalone amplifier, ready to install inside the rear of a monitor speaker.

Subwoofer design

The optional subwoofers provide several benefits. Their larger 200mm (8-inch) drivers can handle significantly more continuous power than the drivers in the bookshelf speakers, as they have 40mm (1.5-inch) voice coils. Additionally, the length of the voice coil and suspension allows greater

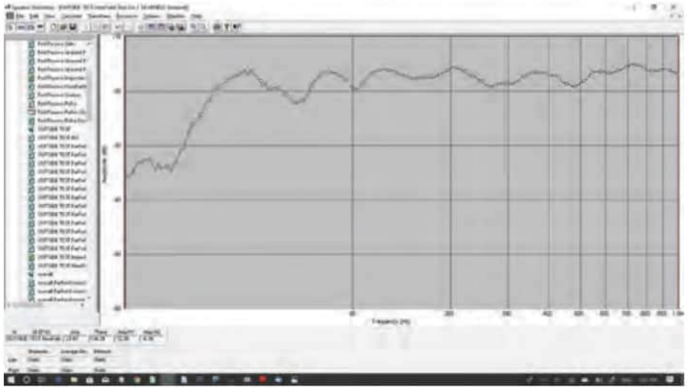


Fig.9: a 'far-field' measurement of the loudspeaker system response, for one monitor and one subwoofer. The response is fairly flat from around 60Hz to nearly 20kHz, varying by just a few dB. The peak at 50Hz was reckoned to be due to sound reflections off a nearby wall.

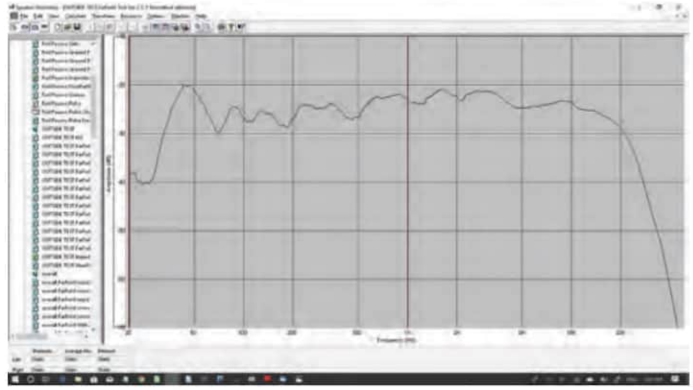


Fig.10: these 'near-field' measurements paint a more accurate picture of the system's low-end response. The 50Hz peak is no longer so noticeable, and the bass can be seen to extend down to a little below 40Hz.

cone excursion. This results in the driver having a linear travel of well over ±4.5mm.

This, combined with the fact that the cones have a greater area than the bass drivers in the bookshelf speakers, means that the subwoofers are much better-suited to handling low frequencies at high power levels.

To illustrate the difference, Fig.6 shows the output of WinISD simulating the sound pressure levels (SPL) across a range of frequencies, from the subwoofer driven at 30W (grey curve) and from the bookshelf speaker at 30W (green curve).

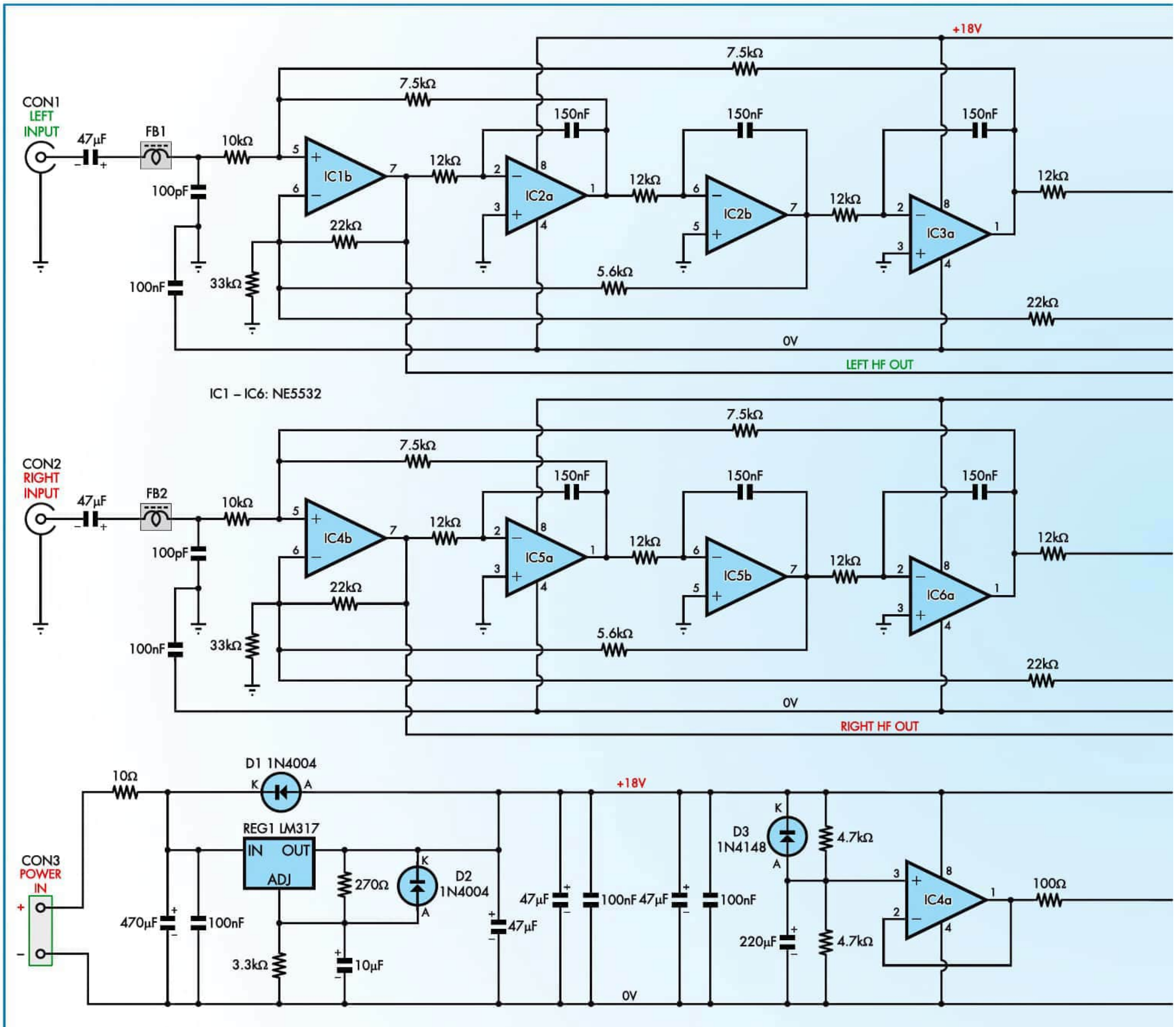
This shows that the subwoofer increases the bass output by about 3-5dB and extends the bass response by about 10Hz, down to around 35Hz.

But this is not the whole story. Fig.7 shows the modelled cone excursion for both speakers. At 30W, the Altronics C3088 driver in the subwoofer remains well below its 4.5mm linear excursion to about 35Hz. When driven hard, this driver gracefully limits the excursion without damage.

But at 30W, the much smaller driver in the monitor speaker would be trying to move ±7mm at about 38Hz, which is far beyond its capability. The speaker simply cannot do this, and the cone hits the end of its mechanical excursion, causing distortion.

Also, while the speaker is at its excursion extremes, the voice coil is not entirely in the magnetic field of the 'air gap'. So not only is there distortion in the bass, but all

. . . but if you *do* build the subwoofers, they make fine stands for the main speakers. And because bass is non-directional, you can aim the boxes where little fingers won't do any harm to the speaker drivers.



SC ©2019 **ACTIVE CROSSOVER FOR BOOKSHELF SPEAKERS**

other output from the driver is distorted too.

Obviously, by turning the volume down, the monitor speaker works very well, but we do need to recognise that the laws of physics impose limitations on what we can ask of the speaker. Adding the subwoofers then allows us to avoid sending frequencies below 90Hz to the bookshelf speakers, thus avoiding the distortion described above. These signals are instead reproduced by the subwoofers.

This has the additional benefit of significantly increasing the power available for the monitor speakers to generate mid-range and treble frequencies, as all the bass signal has been diverted to a separate amplifier.

Ideally, the monitor speakers should not reproduce any more than about 7-10W worth of sub-100Hz signals, as this limits the cone excursion to a more manageable 3-4mm. The achievable bass SPL in this case is obviously less. Fig.8 shows the maximum practical low-frequency output achievable by the C3088 and C3038 drivers.

The active crossover we use to split the signal between the subwoofers and monitor speakers allows the monitors to be driven at full power across their range, bringing the achievable SPL up to match the subwoofer.

Regarding the subwoofer enclosures, we have kept their width and depth the same as the monitor speaker. This allows the subwoofers to be "hidden" as speaker stands. This gives us a convenient 35-litre enclosure in which to mount the Altronics C3088 driver.

You may have noticed a problem with this: the 200mm woofer drivers are unlikely to fit in the usual way into a 210mm-wide cabinet. But because this is a subwoofer, and operates only up to 90Hz, its sound propagation is quite omnidirectional.

We exploit this fact, and mount the driver on the side of the enclosure, rather than on the front.

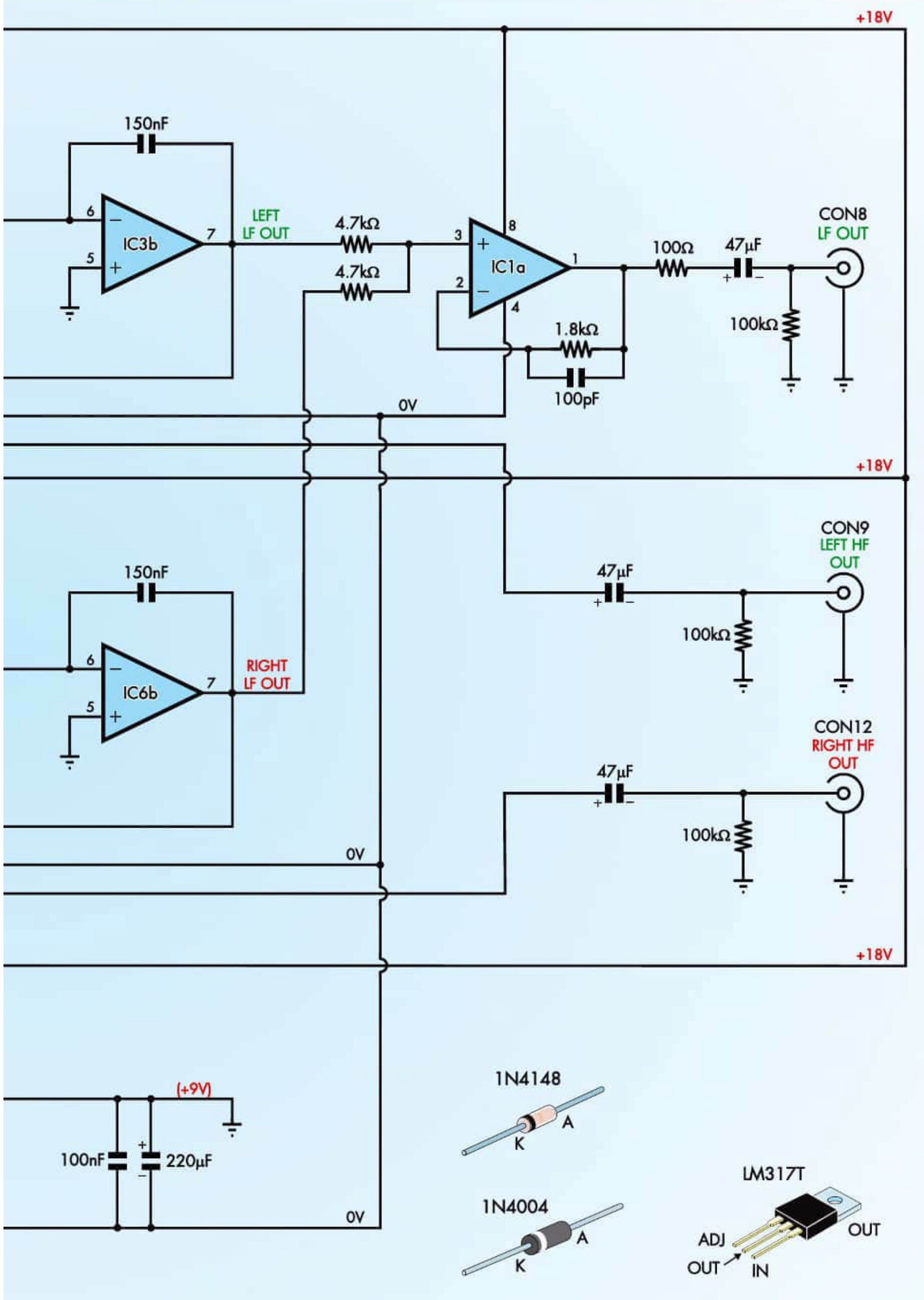
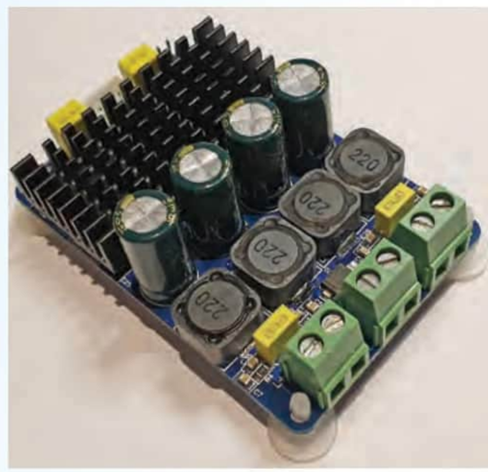


Fig.11: the full circuit of the active crossover which is used to split the incoming stereo signal, so that the high-frequency components can be fed to the pair of monitor speakers. The low-frequency components are mixed to a mono signal, buffered by IC1a and then fed to the subwoofer amplifier, which can drive one or two subs. The circuit runs off the same nominally 24V DC supply used to power the subwoofer amplifier, regulated to 18V and with a 9V half-supply rail generated for signal biasing.



(Inset above): the 2 x 80W class-D stereo amplifier which we purchased on ebay for less than $20 including postage. You couldn't build one for anything like this price and it does the job nicely!

Similarly, we have placed the port on the rear of the box, as its exact location is not critical. These can all be moved if your application demands.

Overall performance

Measuring speaker frequency responses is difficult if you don't have an anechoic chamber. However, we gave it a go, using a Behringer ECM8000 measurement microphone, a low-noise microphone preamplifier and the Speaker Workshop PC software.

Near-field measurements can be made with accuracy up to a modest frequency (say, around 1kHz). Far-field measurements are heavily affected by reflections and room resonances, but are more representative of how a speaker system actually sounds in use.

The measurements presented here are a mix of both. First, let's look at the far-field measurements shown in Fig.9. These were made outdoors, with the speaker about 3m from the nearest structure. You can see a peak at 50Hz, which is due to reflection from the structure. The near-field measurements below give a better insight into the low-frequency response of the speakers.

Moving the mic to a location closer to the boxes, approximately 50cm from the speaker and located equidistant between the subwoofer and monitor speaker, gives the bass response shown in Fig.10.

The measured -3dB point is 34Hz. There remains a small artefact in the 50Hz region. Other than this, the response is as expected, very flat indeed.

The keen-eyed will note that the second plot is a couple of dB higher than the first. This is just because the microphone is closer to the speaker.

The response is as smooth and deep as the graphs suggest. Should you build these speakers, we think you will be delighted with the sound, and your wallet won't be too much lighter!

Active Crossover design

As mentioned earlier, an active crossover is used to split the incoming stereo audio signal into three different paths: left and right signals to feed to the monitor speakers, which contain little information below 90Hz, plus a third mono signal for the subwoofers which has the signals below 90Hz from both channels (bass sounds in recordings are often in mono anyway, as having them in stereo doesn't add much).

The subwoofer amplifier is identical to the monitor amplifier, except for the addition of this active crossover, which is custom-designed. We cannot stress how important this is to achieve good performance in an active system, and in protecting the monitor speaker from unwanted bass signals.

The active crossover board implements a fourth-order Linkwitz-Riley filter, which has a roll-off of 24dB per octave. The crossover point is at 90Hz.

A fourth-order crossover giving a very steep filter slope has been chosen to ensure that, even when the subwoofer is very close to the listener, you cannot localise the sub. This makes it seem like the bass signals are coming from the same place as the other signals, ie, the monitor speakers.

The second benefit is that with a fourth-order crossover, minimal bass is sent to the monitors, and this prevents the excessive cone excursions mentioned earlier, which can dramatically increase distortion (and not just in the bass, either).

At 90Hz, the high-pass filtered signal level is just one-quarter of the unfiltered level. At 45Hz, just 1% or so of the signal power is sent to the monitors. The reproduction quality of the monitors is therefore significantly enhanced, because the cone is effectively stationary, and not moving with the bass. So the voice coil is always in the air-gap.

The passive crossover (shown here close to life size) will be described (along with box details) in Part II next month.

The crossover is implemented as a "state-variable filter", which is essentially four integrators in series. Its circuit is shown in Fig.11.

The input signals are fed through a ferrite bead and 100pF capacitor to ground, to filter out any RF signals which may be picked up, then are AC-coupled to the active filter integrators. The phase shift of each integrator is set by the RC values; in our case, 12kΩ and 150nF.

The left-channel crossover is implemented with op amps IC1b, IC2a, IC2b, IC3a & IC3b along the top, while the right channel comprises IC4b, IC5a, IC5b, IC6a and IC6b. They are otherwise identical.

One unusual aspect of this filter is that it uses nested feedback. The second and fourth stages have feedback resistors to the non-inverting input of the first stage, while the third and fifth stages have feedback resistors to the inverting input of the first stage.

The high-pass output is taken from the output of the first stage in each case. The low-pass outputs are from the fifth stages. These are mixed 1:1 using a pair of 4.7kΩ resistors, then fed to buffer IC1a, which then sends the signal for driving the subwoofer amplifiers.

Usually, the op amps in a circuit like this would run from positive and negative rails (a "split supply"), with the signals being ground-referenced. But in this case, we want to operate the amplifier from a DC switch-mode supply, ideally 24-32V.

The 24-32V input is low-pass filtered by a 10Ω series resistor and 470µF capacitor, then fed to REG1, an LM317 adjustable regulator, to give a nice clean 18V DC output to run all the op amps. Two 4.7kΩ resistors across this 18V rail generate a 9V half-supply rail which is buffered by op amp IC4a and an RC low-pass filter. This is used to DC-bias all the signals, so they stay within the op amps' 0V and 18V supply rails.

The signals are then AC-coupled again at the outputs, and re-biased to 0V to remove this DC offset.

Conclusion

If you're interested in building these loudspeakers (whether as standalone bookshelf speakers or with the subwoofers), now is a good time to start gathering the parts required, as shown in the parts list.

Next month, we'll describe how to build both sets of cabinets, along with the required electronics. SC

The tools you'll need . . .

- Circular saw
- Sawhorse
- Jigsaw
- Drill with drill bits and screwdriver bits
- Countersinking bits
- Large adjustable hole saw (a jigsaw could be used instead)
- Caulking gun
- Router
- Sanding block
- Set of large clamps
- Staple gun (not essential but makes construction easier)
- Heavy gloves (protect hands from splinters when sanding)