The Hummingbird Audio Amplifier

Like a hummingbird, this miniature amplifier is nimble, small in size but strong, delivering up to 60W into 8Ω or 100W into 4Ω. It is ideal for building multi-channel amplifiers for applications like surround sound or when using an active crossover. Despite its compact size, only a few compromises were made compared to much larger designs – it even has output protection!

Image Source: https://pixabay.com/photos/hummingbird-bird-flight-wings-2139279/

By Phil Prosser

Readers frequently ask us for advice on building amplifiers with more than two channels. We've published many Hi-Fi amplifier module designs over the years, but mainly they have been designed for maximum power and minimum distortion, resulting in modules that will only fit one or two per case (unless you use a huge case!).

We have published amplifier designs using all-in-one IC 'chip' amps like the LM1875T. They are always quite compromised, both in terms of maximum power output (typically topping out at around 30-40W) and performance, with distortion and noise figures far worse than a discrete amplifier.

This design offers an excellent compromise between the two. It's cheaper and easier to build than our best Hi-Fi amplifiers while still delivering plenty of power with very good performance. And because it's so compact and has modest power supply requirements, you can quite easily jam half a dozen (or more!) of them into a reasonably sized chassis.

We designed these for driving multi-way loudspeaker systems using an active crossover to split the signals into frequency ranges to suit each driver. This approach needs one amplifier per driver (woofer, tweeter and so on) but you generally don't need as much power per amplifier, since they are working together.

Initially, we looked at using small, low-cost Class-D amplifier modules which could deliver 30-50W. After quite a bit of searching, we concluded that there was nothing readily available with distortion performance within an order of magnitude of what we'd call 'Hi-Fi'. Many smaller Class-D amplifiers exhibit high-frequency distortion above 0.5%, worse than many decent loudspeaker drivers!

In the end, we looked at larger high-quality amplifiers and shrunk the design. The result is the *Hummingbird Amplifier Module*, which packs a surprising punch for its size, while keeping many of the low-distortion characteristics of the larger amplifiers from which it takes inspiration. It can achieve up to 60W into 8Ω or 100W into 4Ω with distortion below 0.0008% at 1kHz and less than 0.008% all the way up to 20kHz. That's way better than 'CD quality'.

Design

If you are familiar with larger amplifier topology, then an examination of the circuit diagram (Fig.7) will show many similarities between the *Hummingbird* and larger siblings. On the other hand, for compactness, the principal differences are:

- We opted for one pair of output transistors, rather than two
- We chose inexpensive NJW21193/4 output transistors
- The maximum supply rail voltages are just ±40V (larger amplifiers often go to ±60V).

It's also worth noting that the PCB is not large – just 64mm wide – and circuit simplification lets us use through-hole components exclusively.

The width of the PCB is defined by the two output devices and thermal compensation transistor. This is also a neat fit for the emitter resistors required for a stable operating bias point.

Despite their relatively large size, we have used DC rail fuses in this design, as they form an important protective layer for the amplifier in case something goes wrong in use.

The SOA protection is tightly coupled with the output stage and sits between this and the voltage amplifier stage (VAS). The VAS and driver come next, and sit between the fuses, again with little room to spare. At the front end of the board is the input stage. How the various sections of the amplifier fit on the PCB is shown in Fig.1.

We are only using one output device per side, so we have chosen a robust device with a generous safe operating area (SOA). Few devices are sturdier than the NJW21193G/NJW21194G (or their beefier MJL21193/4 siblings). These are rated at 16A, 250V and 200W.

We decided to add output SOA protection to the amplifier that monitors the output current and voltage and shuts off the output in case of a short circuit or severe overload. This protects the amplifier from all but the worst abuse.

Calculations confirmed that using a mains transformer with a 25-30V AC secondary providing rail voltages of ±35-42V would be safe with a single pair of output devices into 4Ω, 6Ω or 8Ω, delivering 60W into 8Ω loads and 100W into 4Ω loads. With a 25V transformer, that's reduced slightly to 50W for 8Ω.

For those of you who follow audio amplifier design, the topology here is basically the 'blameless' amplifier (as it is dubbed by Douglas Self), which just works. The innovation in this project is more about our aproach to simplification and minimisation.

No doubt using SMDs would have let us make the PCB less, err, packed.

Features

- Low distortion and noise
- Extremely compact PCB
- Fits vertically on a 75mm heatsink and can be stacked in a 2RU case
- Produces specified power output continuously with passive cooling
- All through-hole parts
- Low in cost, simple to build
- Onboard DC fuses
- Output over-current and short-circuit protection
- Clean overload recovery with low ringing
- Clean square wave response with minimal ringing
- Tolerant of hum and EMI fields
- Quiescent current adjustment with temperature compensation

Specifications

- Output power (±32V rails): 100W RMS into 4Ω, 60W RMS into 8Ω
- Frequency response (–3dB): 1Hz to 150kHz
- Signal-to-noise ratio: 118dB with respect to 50W into 4Ω
- Input sensitivity: 1 2V RMS for 60W into 8Ω; 1.04V RMS for 100W into 4Ω
- Input impedance: 22kΩ || 1nF
- Total Harmonic Distortion (8Ω, ±32V): <0.008%, 20Hz-20kHz, 50kHz bandwidth 32W (see Fig.2 and Fig.6)
- Stability: unconditionally stable with any nominal speaker load ≥4Ω
- Power supply: ±20-40V DC, ideally ±34V DC from a 25-0-25 transformer
- Quiescent current: 53mA nominal
- Quiescent power: 4W nominal
- Output offset: typically <20mV (measured)

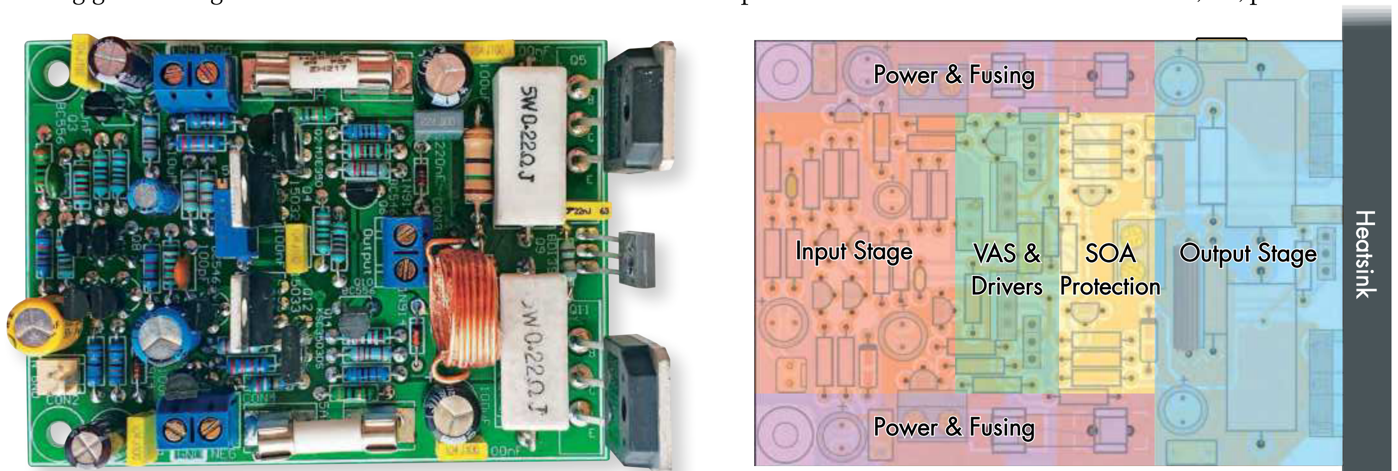


Fig.1: this depiction of the Hummingbird PCB is at 90% of life-size and shows the purpose of each set of components. The input stage is responsible for setting the gain and distortion cancellation while the VAS and drivers buffer the signal from the input stage to provide suitable drive for the output transistors. The SOA protection circuitry keeps the output transistors within their 'safe operating areas'.

Still, we managed to fit all the required through-hole components into an area of just 88 by 64mm. That will easily fit standing on its side in a standard two rack unit (2RU) high case, and assembly is not especially difficult.

Performance

We took total harmonic distortion (THD) measurements of the prototypes at 10W and 35W into 8Ω by powering it from a bench supply, shown in Fig.2. The 35W measurement required using a 40dB attenuator with our test equipment, while the 10W level only needed a 20dB attenuator. That is why the distortion results at 10W look so much better than at 35W.

Given that the shapes of the two curves are very similar, it's likely that the actual performance of the amplifier is closer to the 10W figures, even up to its maximum 60W power output. We can confidently say that this amplifier generates very low distortion levels, and at 10W, is below 0.002% THD over much of the audio range.

Note that Fig.2 also shows partial distortion curves for various alternative output/driver/VAS transistors, and we will explain those options a bit later.

The amplifier behaves well at clipping. The most common problem is the output 'sticking' as the amplifier exits clipping from the negative rail, when the VAS transistor comes out of saturation. The *Hummingbird* behaves well coming out of clipping, as shown in Fig.3 and Fig.4.

We also tested with a square wave signal, and the result is in Fig.5. There is not a lot to show here; it generates a bandwidth-limited square wave output as shown, with no overshoot and minimal undershoot.

Finally, Fig.6 shows one of the spectral plots taken while gathering the measurements for Fig.2. The left channel is connected to the output of the amplifier via an attenuator, while the right channel is monitoring the signal into the amplifier. As you can see, the distortion at the output is hardly any higher than the input signal, and the second and third harmonics are roughly equal at around −110dB.

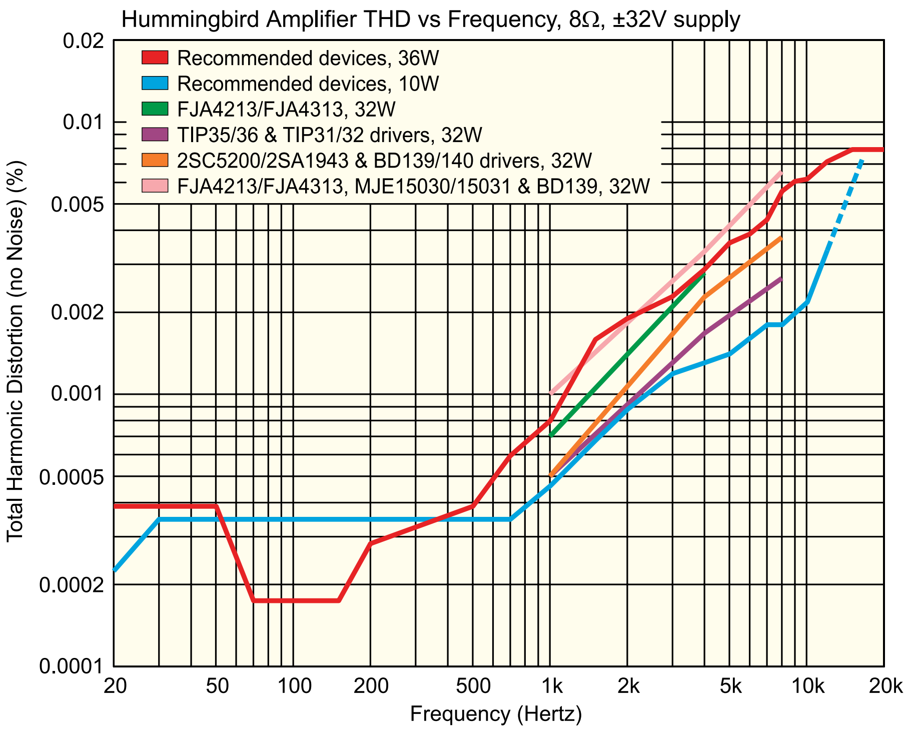


Fig.2: total harmonic distortion (minus noise) plots for the Hummingbird at two different power levels: 36W (red) and 10W (blue). The other curves show the test results with various combinations of output transistors, driver transistors and, in one case, a different VAS transistor (BD139, pink curve). Regardless of which devices you choose, the performance is pretty good.

Circuit description

Fig.7 shows the *Hummingbird* circuit. A 220kΩ resistor biases the input signal at CON2 to 0V DC. The input signal passes through a 10μF bipolar capacitor and then a 100Ω resistor shunted by 1nF and 22kΩ to the low-noise signal ground. This connects to the output ground via a 10Ω resistor. The 10μF and 22kΩ combination at the input sets the −3dB low-frequency cutoff point below 1Hz.

The 22kΩ input resistor is selected to match the 22kΩ feedback resistor so that each side of the differential amplifier formed by PNP transistors Q7 and Q8 has matched DC input impedances. Assuming that these transistors have equal current through each leg and similar h_{FE}, the offset voltages at the bases of Q7 and Q8 will be about the same.

This should ensure a low output offset voltage on the amplifier. We measured less than 20mV on our prototypes.

We have specified BC556 transistors for Q7 and Q8, although you could use low-noise BC560 devices if you can find them. These are commonly available and perform well in this application. 100Ω emitter degeneration resistors are used for Q7 and Q8. These assist with achieving balance and linearity in the differential amplifier. This reduces its sensitivity to transistor and temperature variations.

The input stage operates with 3mA of bias current. This is set by the 220Ω resistor in the emitter leg of PNP transistor Q3, which serves as a constant-current source.

The keen-eyed will note that we have omitted a resistor from between the constant-current source and the differential amplifier. Our lower voltage rails mean this is not necessary, as Q3 can handle the resulting 100mW dissipation.

The collector legs of the differential amplifier feed into a current mirror made using NPN transistors Q15 and Q16. A current mirror works by exploiting the fact that with a matched set of transistors at the same temperature, the V_{BE} (base-emitter voltage) relationship vs current will be the same.

So by connecting the bases of Q15 and Q16, and putting the same resistance in their emitter circuits, if we drive 1.5mA through Q16, Q15 will similarly seek to conduct 1.5mA as it has the same base-emitter voltage.

This ensures that the differential pair of Q7 and Q8 operates with the same current in each leg, which means it operates optimally as a linear differential amplifier.

The output of the differential amplifier is a current that flows into the base of NPN transistor Q13. If the amplifier output is higher than the input, the input to Q8 increases, which reduces the current into Q16. Because the current mirror 'tries' to keep the current through Q15 and Q16 the same, this excess current flows into Q13's base.

Q13 forms part of a quasi Darlington transistor pair with Q14, which ultimately drives the amplifier output. These transistors together form the voltage amplifier stage (VAS). It transforms the current from the front end into a voltage.

Q14 is a KSC3503DS transistor, which is specialised for this sort of application. These are available from Mouser, Digi-Key, element14 and RS.

The VAS transistor needs to have a very low C_{OB} or output capacitance.

There are not many really suitable devices being made these days, most likely as the best VAS transistors were also video amplifier transistors for cathode ray tube (CRT) monitors, which have gone the way of the dodo! We used the BF469 video transistor here in the past, but they are now obsolete.

The load on the VAS is the constant current from PNP transistors Q1 and Q2, which is set to about 8mA, plus the current required to drive the output stage.

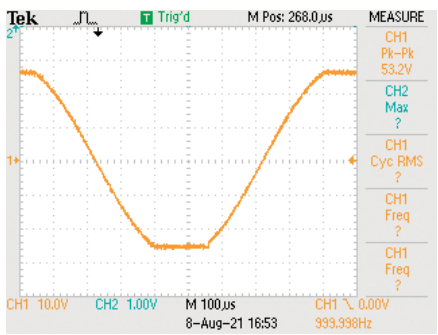


Fig.3: a scope plot of the amplifier's output waveform into an 8Ω resistive load, driven into clipping. You can see there's a tiny bit of 'sticking' to the negative rail as it comes out of clipping, but not enough to be concerned about.

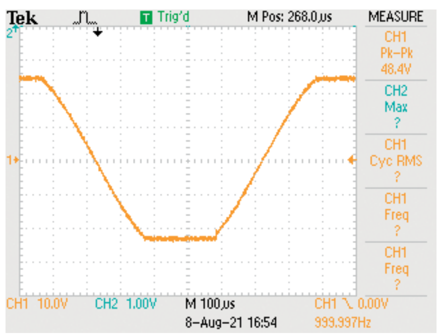


Fig.4: this time, the amplifier has been driven into clipping with a 3Ω resistive load, representing pretty much the worst-case situation it will have to deal with when driving a real 4Ω (nominal) loudspeaker. Once again, the recovery from clipping is fine.

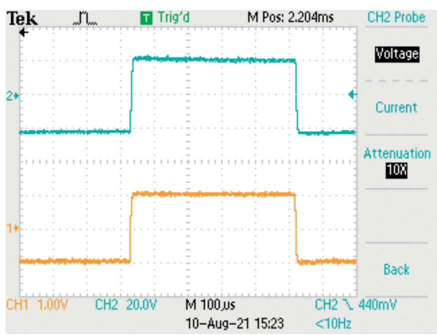


Fig.5: we fed a square wave signal (orange) into the Hummingbird and connected its output to a 3Ω resistive load (harsh, we know). It handled this very well, with no sign of overshoot or undershoot; clearly, it's a very well-behaved amplifier.

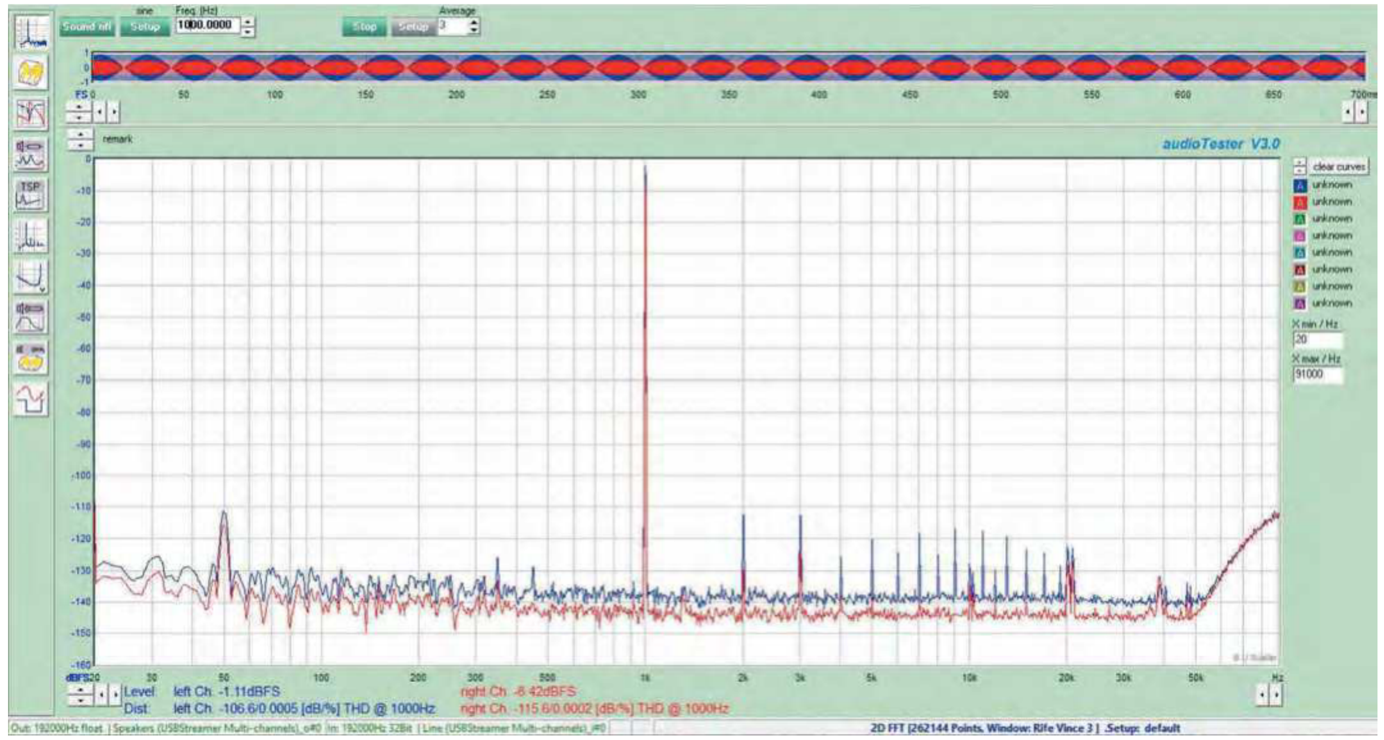
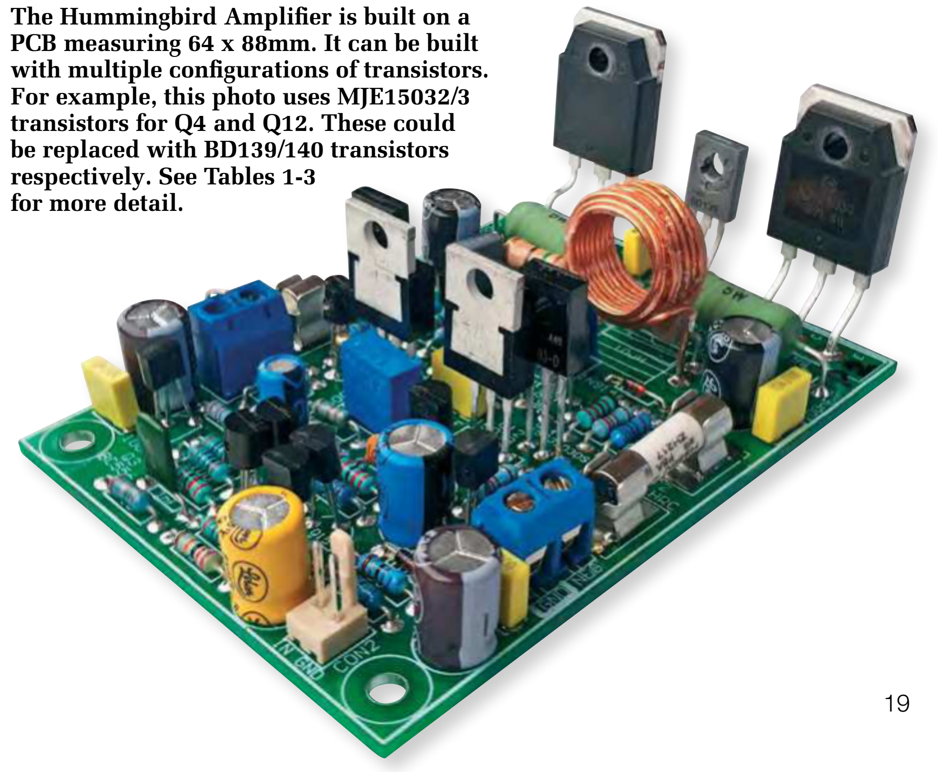
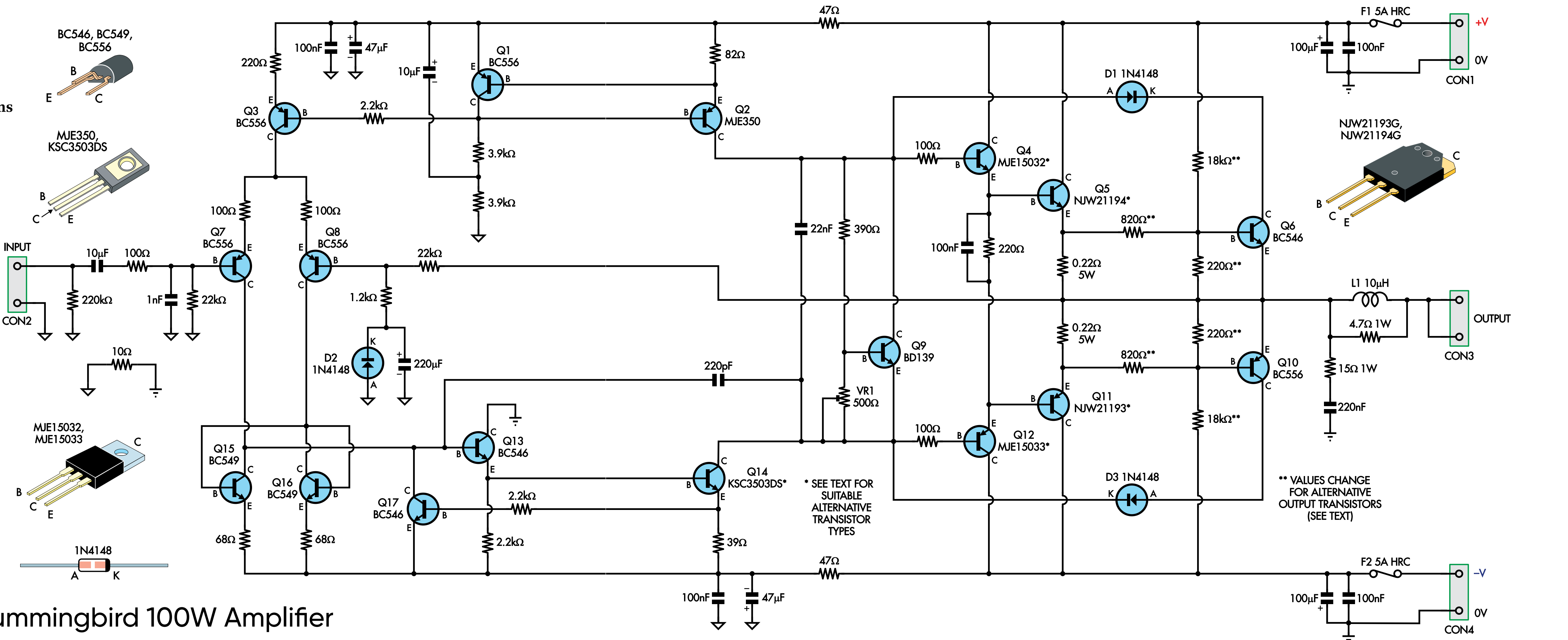


Fig.6: one of the many spectral plots we produced as part of the performance tests. You can see the THD readings of the input (red) and output (blue) signals towards the bottom. You can also see all the harmonics of both signals in the central area. The test signal is at 1kHz, so the first harmonic is at 2kHz, third at 3kHz and so on. The amp's output was passed through a 40dB attenuator, reducing the fundamental to −15dB and dropping the measured noise floor to that of the instrument.



The Hummingbird Amplifier is built on a PCB measuring 64 x 88mm. It can be built with multiple configurations of transistors. For example, this photo uses MJE15032/3 transistors for Q4 and Q12. These could be replaced with BD139/140 transistors respectively. See Tables 1-3 for more detail.

Fig.7: the Hummingbird amplifier circuit is pretty standard if a bit minimalist. It has a lot in common with our previously published, higher-power amplifiers like the SC200. Note NPN transistor Q17, which has been added to protect Q14 during negative clipping excursions and the SOA protection transistors, Q6 and Q10, with three resistors each to set the I/V limit slope and intercept.



Between Q2 and Q14, we have NPN transistor Q9 and its base-biasing resistors. This forms a simple 'V_{BE} multiplier' that allows us to set the voltage between the bases of the output stage and driver transistors Q4, Q5, Q11 and Q12. These are arranged in standard emitter-follower connected pairs.

The amplifier must operate in Class-AB for good performance, where both the positive (NPN) and negative (PNP) output devices are conducting for output voltages around the 0V crossover point, as shown in Fig.8. We want to bias the amplifier to draw about 50mA in the quiescent state as this gives the best output stage linearity around the crossover point.

To achieve this, we need to set a 'constant' voltage to bias the four base-emitter junctions at just over their turn-on voltage (about 0.6V each), for a total of around 2.4V.

But the base-emitter threshold voltages of Q4, Q5, Q11 and Q12 all vary with temperature, so Q9 is mounted on the same heatsink as Q5 and Q11, and Q9 is used to multiply its own V_{BE} voltage using a 390Ω fixed resistor and potentiometer VR1. This way, the bias voltage will track the V_{BE} voltages of those two transistors, giving a mostly constant bias current.

When properly adjusted, VR1 will be about 130Ω. Q9's base-emitter voltage is across this resistance, around 0.6V, giving about 4.6mA through VR1 and also the 390Ω resistor. That gives 1.8V (390Ω × 4.6mA) between Q9's base and collector, for a total of 2.4V (0.6V + 1.8V).

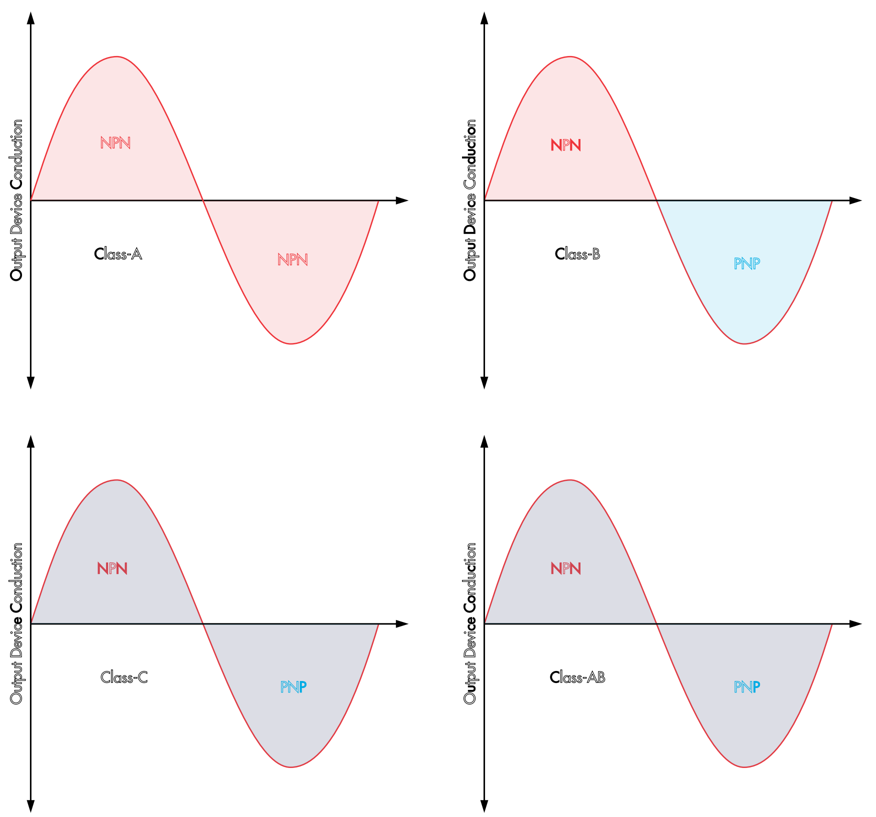


Fig.8: four common amplifier classes; Class-C is mainly used for RF, not audio, where distortion is less of a concern. Class-A has a single transistor that varies its conduction over the whole cycle, while the other three classes use complementary pairs. In Class-B, one device conducts for the positive half of the cycle; the other conducts during the negative half. Class-AB is like Class-B except that both devices conduct when the output is near 0V (the purple area is where they overlap), while for Class-C, neither device conducts in the crossover zone.

Our output stage is a single pair of transistors, Q5 and Q11. The NJW21193/4 types, as stated earlier, have been selected for their SOA large (safe operating area). These are driven by MJE15032/33 driver devices, as there is not enough current available from the VAS to drive them directly.

The output devices both have 0.22Ω resistors in series with their emitters, providing a small amount of negative feedback for their bias currents.

The driver devices are capable of much higher current and dissipation than demanded in this application. However, they are widely available and reasonably priced, so they suit this application well. They do not dissipate enough power in this application to require heatsinking.

However, suppose you are pushing your luck by increasing the rail voltage or driving very low impedances with continuous waveforms, or you wish to achieve ideal bias tracking. In that case, you might benefit from fitting them to the heatsink (or the back of the output devices) on flying leads.

Ideally, we would have mounted them on the main heatsink so that their V_{BE} voltages track those of the output devices, as Q9 will multiply its own V_{BE} changes by a factor of four. We did not do that, to keep this module as compact as possible.

The driver transistors still heat up and cool down as the load changes, which provides some thermal tracking, but it won't be exact.

The result is that under transient application of a heavy load, the output stage bias will tend to decrease slightly as the module gets hot delivering a significant amount of power. It does not experience thermal runaway, nor does the performance change due to this change in bias, so it is a worthwhile compromise to keep the module compact.

SOA protection

We are using a single pair of output devices so we feel it prudent to protect them against unexpected overload or short circuits. Shorting the output of a typical amplifier often leads to the failure of output devices, driver transistors and ultimately the fuse, often in that order. We get around that by adding some basic safe operating area (SOA) limiting components.

The SOA curves for each pair of recommended output devices (taken from their data sheets) are plotted in Fig.9 and Fig.10, along with curves representing the maximum specified output power being delivered into purely resistive and reactive loads, the latter represents worst-case loudspeaker load.

As you can see, except for the TIP35/36 pair, all devices will be within their SOAs under these conditions. However, some loudspeakers can have significant impedance dips at specific frequencies that could cause the transistors to operate outside their safe areas, and also accidents can happen with the wiring (accidental shorting together).

Fig.11 shows the same SOA curves as Fig.9 and Fig.10, but also adds dashed 'SOA protection' lines. These are the limits we've chosen to 'program in' for each pair of output devices to ensure they stay within their SOAs.

The effect of driving the *Hummingbird* into a 1Ω load is shown in Fig.12. The input signal is at the top, while the 'clipped' output waveform below shows the protection kicking in. This will not save you from ultimately overheating the output transistors, but it will prevent the immediate loss of 'magic smoke'.

Some people claim that this type of protection degrades the amplifier's performance, but the measured specifications speak for themselves.

To understand how the SOA protection works, consider the top half, based on NPN transistor Q6 and diode D1 plus three resistors: 18kΩ, 820Ω and 220Ω.

In normal operation, the voltage across the 0.22Ω emitter resistor of Q5 is less than 0.6V. Ignoring the extra resistors for now, this means that Q6 is biased off and has no effect.

Under fault conditions, the voltage across the 0.22Ω resistor increases to the point that Q6 starts to switch on. This diverts current from the base of driver transistor Q4 to the output, starving the driver of base current.

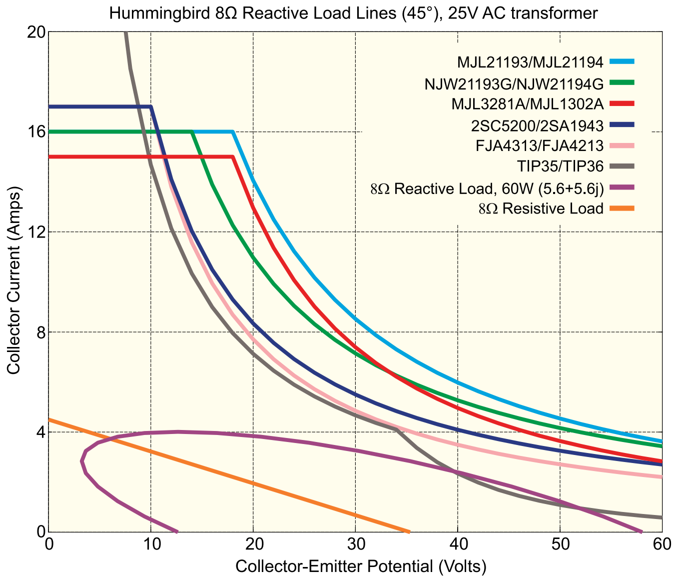


Fig.9: SOA curves for all the output devices you can use in the Hummingbird, plus load lines for 8Ω purely resistive and 45° reactive loads (representing a worst-case loudspeaker). This shows that all the output devices are safe for driving such loads with the recommended supply voltages, except perhaps the TIP35/36, so it's probably best to avoid those if possible.

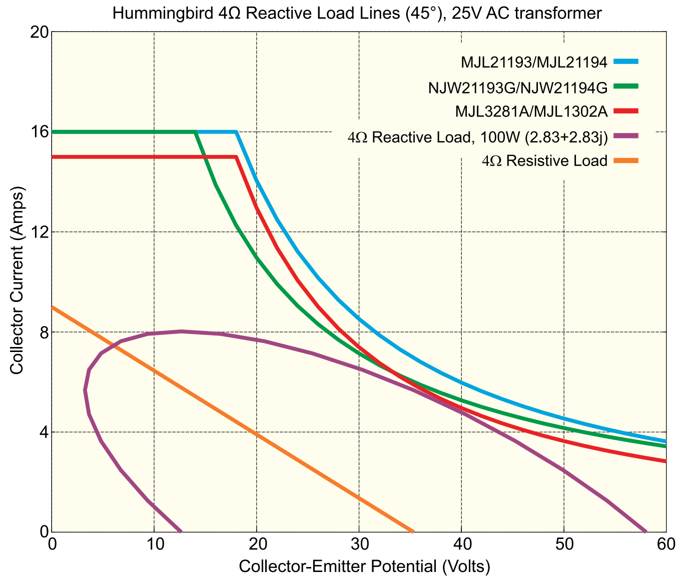


Fig.10: a similar plot to Fig.9 but this time, the load lines are for 4Ω resistive/reactive loads and we've eliminated those output devices that we don't recommend for driving 4Ω loudspeakers. All three options are pretty safe; the MJL3281A/MJL1302A pairing comes pretty close to the reactive load line, but the SOA protection circuitry is there to save the day if necessary.

This, in turn, starves the output device of base drive until the output current reduces to the point that Q6 is no longer switched on so hard.

This creates a local feedback loop that limits the output current, thus protecting the output stage. Diode D1 is included so that the opposing current protection circuit is not reverse-biased by heavy output loads.

In the absence of the three extra resistors, Q6 would switch on at an output current of about 3A (0.6V across a 0.22Ω resistor). This is too early, so to allow more current, the 820Ω and 220Ω resistors form a voltage divider with a division ratio of 0.21. Thus, a current of about 13A through the emitter resistor is required to turn the over-current protection on.

Without the 18kΩ resistor, the current limit will be the same regardless of the output voltage. Adding that resistor injects more current into the voltage divider formed by the other two resistors, so that at low output voltages, more current is injected, and the current limit kicks in earlier.

This results in the SOA protection being 'sloped' to fit the SOA of the output devices, and allows more current at high output voltages, because the voltage *across* the devices is lower. Thus they dissipate less power for the same current.

Output device selection

The pinout of the output devices is very common. The *Hummingbird* delivers the measured performance with the parts specified, but we have checked that the amplifier works properly with a range of other output transistors. You do need to change the SOA protection resistor values, though, as per Table 1. You also have options for the driver transistors (Table 2) and VAS transistor (Table 3).

Construction

All parts are through-hole, and they fit on the 64 x 88mm, double-sided PCB coded 01111211, shown in Fig.13 and availabel from the *PE PCB Service*. The parts are closely spaced but not too tight. We have kept the pad sizes generous to make soldering easier.

Before we continue, we strongly advise you to use transistors from a reputable supplier. There are cheap transistors on internet auction/sale sites. Do not be tempted by these. Fakes are prolific, even in surprisingly simple devices. All the devices recommended for this amplifier are available at reasonable prices from major suppliers.

Start by fitting all the small resistors and diodes – make sure the orientations of the diodes match what's shown in Fig.13 and on the PCB silkscreen. Follow with the trimpot, orienting its adjustment screw as shown. This is critical because we need to be able to set the quiescent current to a minimum before the module is first powered up.

Next, mount the input and output connectors. We have used parts with the common 5/5.08mm spacing on these (except the input, a 2.54mm-pitch header).

You should consider how you will mount the modules before choosing either screw terminals or pluggable connectors. Access to a screw terminal may be obstructed in some arrangements, so in that case, use pluggable connectors.

Now install all the non-polarised capacitors. Fit the MKT parts close to the PCB. Ensure you use a 100V-rated device for the 220pF capacitor.

Follow with the 5A fuses and their clips. We find it easiest to put the fuses in their clips and then solder that as an assembly to the PCB. This ensures everything is well-aligned.

Fit the electrolytic capacitors next, noting that they must all be installed with their + (longer) lead to the left when the PCB is oriented with the output devices at the top. Ensure that you have adequate voltage ratings on these parts (ie, at least what is specified in the parts list).

Now install the TO-92 transistors. It is worth finding matched pairs for Q7 and Q8 and also Q9 and Q10, if you can. To do this, check the h_{FE} figures of a handful of each type. Select pairs that have reasonably similar h_{FE} measurements; within 10% is fine. Also, try selecting pairs that have high h_{FE} figures compared to the others.

With the BC549 and BC556, an h_{FE} figure below 100 is cause to throw the part in the bin, although such a low reading is rare indeed.

Now is a good time to mount the remaining resistors. The only ones that get warm are the 0.22Ω output stage emitter resistors, and that's only when delivering full-power sinewaves from the amplifier, which will not happen with musical material. But it is still good practice to mount these a few millimetres proud of the PCB.

The PCB will accept standard 5W cast resistors, but we liked the look and fit of some smaller resistors from Mouser (see the parts list). They need to have a rating of at least 3W in this application, so 5W is quite conservative.

Making inductor L1

The output inductor is made from 0.8mm enamelled copper wire (ECW) as follows:

1. Find a mandrel that is a bit over 10mm in diameter and has a slight chamfer so that once complete, you can push the inductor off. We used a large 'Sharpie' brand permanent marker.
2. Put masking tape around this mandrel but ensure the sticky side is facing *outwards*.
3. Place a bend in the enamelled copper wire (ECW), 30-40mm from the end, and wind nine turns onto the masking tape.

Table 1 – alternative output transistors

NPN output	PNP output	SOA protection resistors			Comments and limitations	Status
NJW21194G	NJW21193G	18kΩ	820Ω	220Ω	Performance as presented	Verified
MJL21194	MJL21193	22kΩ	750Ω	220Ω	Performance as presented; THD <0.001% at 1kHz with MPSA42 VAS	Verified
FJA4313 or 2SC5242	FJA4213 or 2SA1962	22kΩ	470Ω	270Ω	Limit to 25V AC transformer if driving difficult 4Ω loads	Verified
2SC5200	2SA1943	18kΩ	560Ω	220Ω	Performs as specified	Verified
MJL3281A	MJL1302A	18kΩ	820Ω	220Ω		Not checked
TIP35B/C	TIP36B/C	27kΩ	1kΩ	390Ω	Limit to 25V AC transformer, prefer 8Ω load. Surprisingly good performance	Verified
TIP3055	TIP2955	12kΩ	680Ω	270Ω	Limit to 25V AC transformer and 8Ω load	Not checked

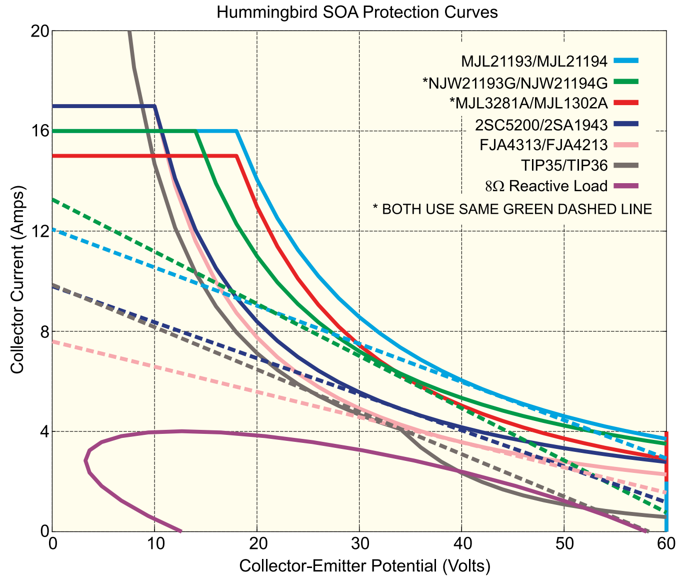


Fig.11: this shows all the output transistor SOAs again, as well as the SOA protection lines (dashed). While the protection lines are straight, they're positioned to stay below the SOA curves in almost all cases, so the amplifier can't drive the transistors outside of their SOA curves. The SOA protection lines for the NJW21193G/NJW21194G and MJL3281A/MJL1302A are identical (green dashed line) since, despite being different curves, they cross over at a critical point.

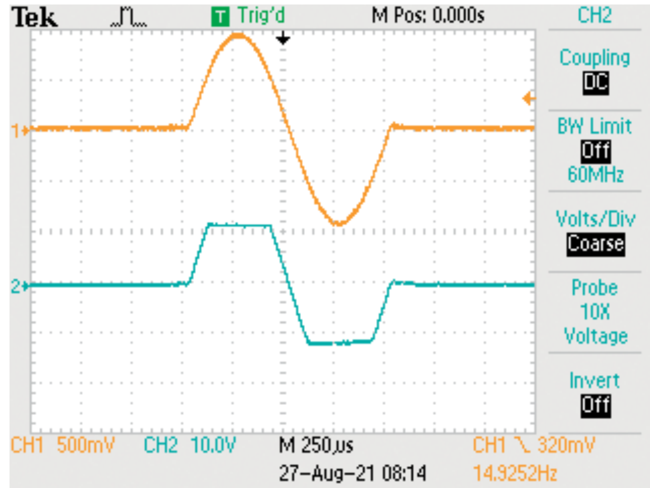


Fig.12: we deliberately overdrove the amplifier by connecting its output across a load of just 1Ω and fed it with a single sinewave pulse. This causes the output transistors to deliver so much current that it triggers the SOA protection circuitry. You can see from the bottom trace how it limits the output voltage/current to protect the transistors.

Table 2 – alternative driver transistors

NPN driver	PNP driver	Comments	Status
MJE15032	MJE15033	As specified (MJE15034 and MJE15035 have not been tested but should be similar)	Verified
MJE15030	MJE15031	These perform well with 8Ω and 6Ω loads. At 3Ω, distortion increases faster than the specified devices, but they are still a fair choice	Verified
TIP31B/C	TIP32B/C	Performs close to specifications. With 3Ω loads, distortion increases faster than the specified devices, but they are still a fair choice	Verified
BD139	BD140	Install in opposite orientation (ECB vs BCE pinout). The −16 gain group parts are the best choice. Limit to 25V AC transformer	Verified
MJE350	MJE340	Install in opposite orientation (ECB vs BCE pinout). Not ideal. Marginal on maximum current. Limit to 8Ω and 25V AC transformer	Not checked

Table.3 – alternative VAS transistors

NPN VAS	Comment	Status
KSC3505DS	As specified	Verified
BF469	As specified	Verified
BD139	Slightly elevated distortion, but a surprisingly good performer – rumour has it that there are many 'types' of BD139, so 'your mileage may vary'.	Verified
MPSA42	Pinout is different. Measured THD <0.001% at 1kHz with MJL21193/4 output transistors. More negative rail 'sticking' than KSC3505DS, but not excessive	Verified

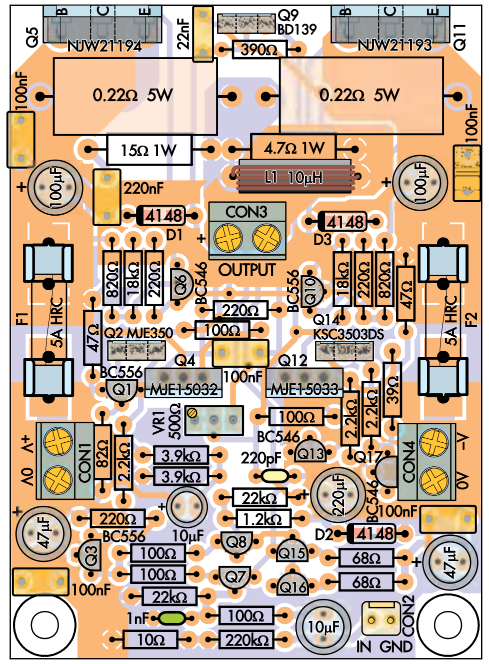


Fig.13: building the Hummingbird is straightforward; fit the components to the PCB as shown here. Watch the orientations of all diodes, transistors and electrolytic capacitors. For the TO-220 and TO-126 devices, the metal tabs face as shown here (if your TO-126 device lacks a metal tab, it would typically be opposite the side with writing on it). Don't forget that if any of your transistors are substitutes for the recommended devices, they will have different part codes than those shown here – see Tables 1-3.

4. Put a few drops of super glue on the ECW. Don't worry if it gets on the masking tape, but you probably don't want to get it on your mandrel!

5. Give this a minute to set, then wind another layer on top of the first nine turns. You might only be able to get eight more in; that is OK. Add more superglue and again let it to set.

6. Add the final winding of nine turns over that and glue again.

7. Push the inductor off the mandrel. Don't be scared to give it a solid push.

8. Tease the masking tape from inside the inductor; we used long-nose pliers. Then we added some extra super glue.

9. Trim the ends, scrape the enamel off them and mount it to the PCB above the 4.7Ω resistor as shown.

Finishing construction

Now fit the remaining transistors: solder Q2, Q4, Q12 and Q14 directly to the PCB. The BD139, NJW21193 and NJW21194 devices that mount on the main heatsink (Q5, Q9 and Q11) come last.

Before proceeding, check your mounting arrangements and ensure that you load these at the right height for mounting on the main heatsink. The best way to mount these transistors to the heatsink is with the insulating kits and machine screws. Bend their leads to fit the board and then solder them. If you can, tap the heatsink to accept the screws, otherwise, drill through between fins and use long screws/nuts.

Adjustment and testing

It is critical that the bias adjusting potentiometer is set to maximum resistance so that the initial bias current is very low. Do this by turning it clockwise a minimum of 20 turns. Check with a multimeter that there is close to 500Ω between the cathode (striped end) of diode D3 and the right-hand end of the 390Ω resistor, just to the left of Q11.

Do this now – if you forget, you might blow the fuses when you power it up, and fuses aren't always fast enough to protect semiconductors.

You can do some initial testing without mounting the amplifier to a heatsink. This test will check that the amplifier is operational. Remove the 5A fuses from the board and install the test (blown) M205 fuses with 10Ω 5W resistors soldered across them. We refer to these as 'safety resistors'.

Connect a voltmeter between the output and ground, set to a 200V range (or similar). Connect another voltmeter across one of the 10Ω resistors, set to a 20V range or similar. If you only have one meter, run an initial check monitoring the output voltage only.

With the input to the module disconnected, apply power. Anything over about ±15V is fine. If you can, set the current limit on the power supply to about 100mA.

Check that the output voltage settles to 0V ±50mV. We built 14 test units, and all were within that range. Also check that the voltage across the 10Ω safety resistor is less than 1V.

If either of these tests fail, immediately power it off and check for the cause.

Have you got the bias pot set at the right end of its travel? Are all the capacitors in the right way around? Do you have a signal feeding the input? If so, disconnect it. Are all the transistors and diodes in the right places and the right way around? Check that those output devices are in the right spot!

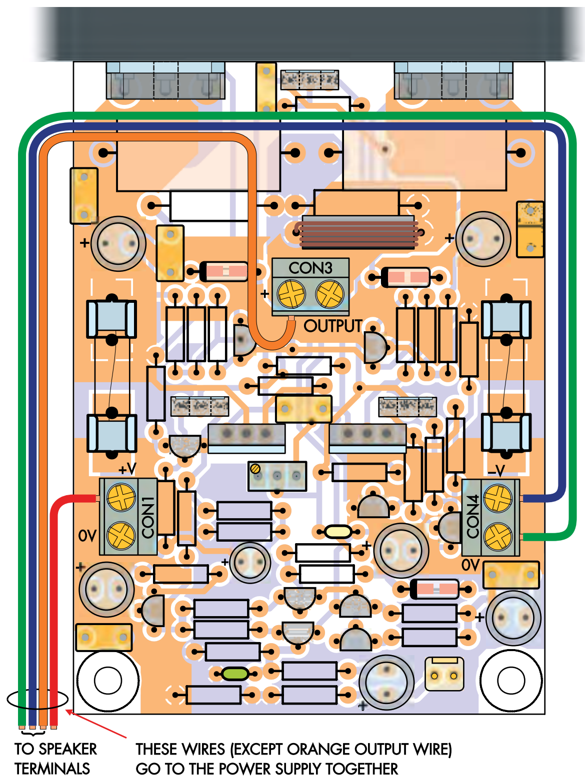


Fig.14: route the wiring to each module like this to ensure you get the stated performance. Current flowing through these wires will cause magnetic fields, which affect the operation of components on the amplifier. Routing the cables this way keeps those magnetic field strengths low. Once you've run them, use cable ties and cable clamp to hold them in place and keep everything neat.

Parts List – Hummingbird (for one amplifier)

1 double-sided PCB coded 01111211, 64 x 88mm, avavaiable from the *PE PCB Service*
1 split rail power supply delivering ±20V to ±40V DC (eg, 15-28V AC mains transformer, bridge rectifier, filter capacitors, mains socket, mains-rated wiring, heatshrink tubing etc) – see Fig.15
3 2-way 5/5.08mm pitch mini terminal blocks (CON1, CON3, CON4)
1 2-way polarised/locking pin header (CON2)
4 M205 fuse clips (F1, F2)
2 5A 5mm ceramic fuses (F1, F2)
1 1m length of 0.8mm diameter enamelled copper wire (L1)
1 500Ω vertical or side-adjust multi-turn trimpot (VR1)
2 TO-3P insulating kits (washers and bushes)
1 TO-126 insulating kit (washer and bush)
3 M3 x 25mm panhead machine screws
3 flat washers to suit M3 screws
3 crinkle washers to suit M3 screws
3 M3 hex nuts
2 blown 5mm fuses (for testing, or purposefully blow 100mA fuses)
1 heatsink, type depending on intended application (we used one Altronics H0545 for six modules)
1 small tube of superglue
1 5cm length of masking tape

Altronics kit
Australian company Altronics offer a kit for this project, code K5158, at around £35 per module PLUS p&p – see: www.altronics.com.au

Semiconductors
5 BC556 65V 100mA PNP transistors, TO-92 (Q1, Q3, Q7, Q8, Q10)
1 MJE350 300V 500mA PNP transistor, TO-126 (Q2) **[Altronics Z1127, Jaycar ZT2260]**
1 MJE15032G or MJE15034G 250V/350V 8A NPN transistor, TO-220 (Q4) **[element14 9556621, Digi-Key MJE15034GOS-ND, Mouser 863-MJE15032G]**
1 NJW21194G or MJL21194 250V 16A NPN transistor, TO-3P (Q5) **[Jaycar ZT2228, element14 2535656, Digi-Key NJW21194GOS-ND, Mouser 863-NJW21194G]**
3 BC546 65V 100mA NPN transistors, TO-92 (Q6, Q13, Q17)
1 BD139 80V 1A NPN transistor, TO-126 (Q9) **[Altronics Z1068, Jaycar ZT2189]**
1 NJW21193G or MJL21193 250V 16A PNP transistor, TO-3P (Q11) **[Jaycar ZT2227, element14 9555781, Digi-Key NJW21193GOS-ND, Mouser 863-NJW21193G]**
1 MJE15033G or MJE15035G 250V/350V 8A PNP transistor, TO-220 (Q12) **[element14 9556630, Digi-Key MJE15035GOS-ND, Mouser 863-MJE15033G]**
1 KSC3503DS 300V 100mA NPN transistor, TO-126 (Q14) **[element14 2453955, Digi-Key KSC3503DS-ND, Mouser 512-KSC3503DS]**
2 BC549 30V 100mA NPN transistors (Q15, Q16)
3 1N4148 75V 250mA small signal diodes (D1-D3)

Capacitors
1 220µF 25V electrolytic **[Altronics R5144, Jaycar RE6324]**
2 100µF 50V 105°C electrolytic **[Altronics R4827, Jaycar RE6346]**
2 47µF 50V low-ESR electrolytic **[Altronics R6107, Jaycar RE6344]**
1 10µF 50V low-ESR electrolytic **[Altronics R6067, Jaycar RE6075]**
1 10µF 50V non-polarised electrolytic **[Altronics R6560, Jaycar RY6810]**
1 220nF 63V MKT **[Altronics R3029B, Jaycar RM7145]**
5 100nF 63V MKT **[Altronics R3025B, Jaycar RM7125]**
1 22nF 63V MKT **[Altronics R3017B, Jaycar RM7085]**
1 1nF 63V MKT **[Altronics R3001B, Jaycar RM7010]**
1 220pF 100V NP0/C0G ceramic **[eg, element14 2860112, Digi-Key 445-173535-1-ND, Mouser 810-FG28C0G2A221JNT6]**

Resistors *(all ¼W+ 1% metal film axial unless otherwise stated)*

1 220kΩ	5 100Ω 0.5W or 0.6W 1% metal film	2 22kΩ	1 82Ω
2 18kΩ	2 68Ω	2 3.9kΩ	2 47Ω 0.5W or 0.6W 1% metal film
3 2.2kΩ	1 39Ω	1 1.2kΩ	1 15Ω 1W
2 820Ω	1 10Ω	1 390Ω	2 10Ω 5W 10% **(for testing)**
4 220Ω	1 4.7Ω 1W		

2 0.22Ω 5W 5% **[element14 1735119, Digi-Key BC3440CT-ND, Mouser 594-AC050002207JAC00]**

Is your power supply delivering both positive and negative rails, and do you have the ground connected?

Setting the bias

This requires the amplifier to be mounted to a heatsink with appropriate insulators for the output devices and V_{BE} multiplier transistor. Power it up and adjust the bias by turning potentiometer VR1's screw anticlockwise while watching the voltage across the 10Ω resistor. Nothing will happen for quite a few turns; then, the bias current will rapidly increase. Adjust this to achieve 500mV across the resistor.

Allow this to settle and readjust. It will take a while to settle; depending on your mounting arrangement this should be done with the full supply voltage applied (ie, the final voltages you intend to use).

Re-install the 5A fuses, and you are ready to go. You can check the bias

The Amplifier can be cleanly mounted to a 75mm heatsink as shown above. The SOA protection resistors are missing as we wanted to compare the performance with and without them. After which you can daisy-chain them together to form a larger system such as a six channel setup shown adjacent. This setup was mounted in a 2U rack case.

later by measuring the voltage across the 0.22Ω resistors; you should see 10mV across each. If you're mounting multiple modules on a heatsink sideways as we did, the side-adjust style trimpot specified makes this quite easy.

Installation

To minimise distortion to the levels presented requires careful attention to layout and the power supply wiring. Our recommended wiring layout per module is shown in Fig.14, and the recommended power supply configuration is shown in Fig.15.

The wiring from the main supply capacitors should have the positive, negative and ground wires twisted together. The output should fold back toward the output devices, run parallel to the 0.22Ω output resistors, then follow the power wires.

The output wire should follow the power wires back past the power supply and pick up a ground wire, minimising the loop area created, then run as a pair from there to the speaker terminals (see above).

Ensure that the power supply has a 'star earth point' from which you connect to the input ground, the amplifier ground and the speaker output ground. Also check that the way you connect the rectifier and its ground connection to the capacitors does not inject noise onto your star earth point. Connect the input shielded cable screen to the star point.

Make sure all connections are secure and have low resistance; poor connections can easily double the distortion levels, or more. We found this measuring a batch of modules we built to verify our results; we had to tighten the connections to achieve consistent results.

Getting the most out of it

We expect this module to find use where a small, low distortion, rugged and reasonably priced multi-channel amplifier is required. As these modules will fit on a 75mm heatsink, many of them can be mounted vertically in a 2U rack case.

Our original application for this amplifier was to provide six channels for a stereo system using three-way loudspeakers with active crossovers. With two channels for subwoofers, two for mid-range two for tweeters, we expect the maximum continuous power to be 60W on each subwoofer channel, possibly half this for the mid and a tiny fraction of this on the high.

As a result, a power supply based on a 300VA transformer will be more than enough for all six channels. Even a 160VA transformer might cut it if you don't plan on driving it especially hard. If your application calls for high power levels, there are more appropriate options, such as the *SC200 Amplifier Module* (see *PE*, January to Match 2018). You could use a pair of those for the low-frequency channels and the *Hummingbird* for the others.

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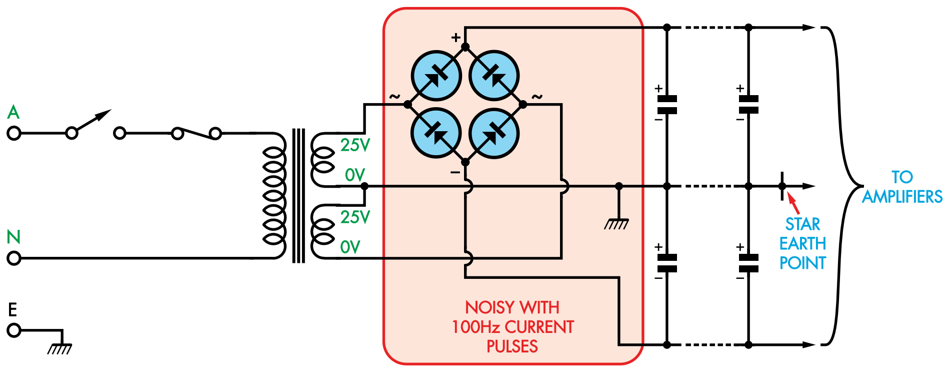

Fig.15: we've left the power supply for the Hummingbird somewhat open-ended, as it has pretty standard requirements. It just needs split DC rails without too much ripple, somewhere between ±20V and ±40V. The configuration above will produce around ±34V, which is right in the sweet spot and uses commonly available parts. Make sure your filter capacitors have a high enough voltage rating (above the highest expected peak DC voltage) and enough capacitance to 'hold up' the supply between 100Hz recharge pulses at the maximum sustained output power you're expecting. Generally, you will need at least a few thousand microfarads per rail; ideally, at least 10,000µF per rail for multiple amplifier modules.