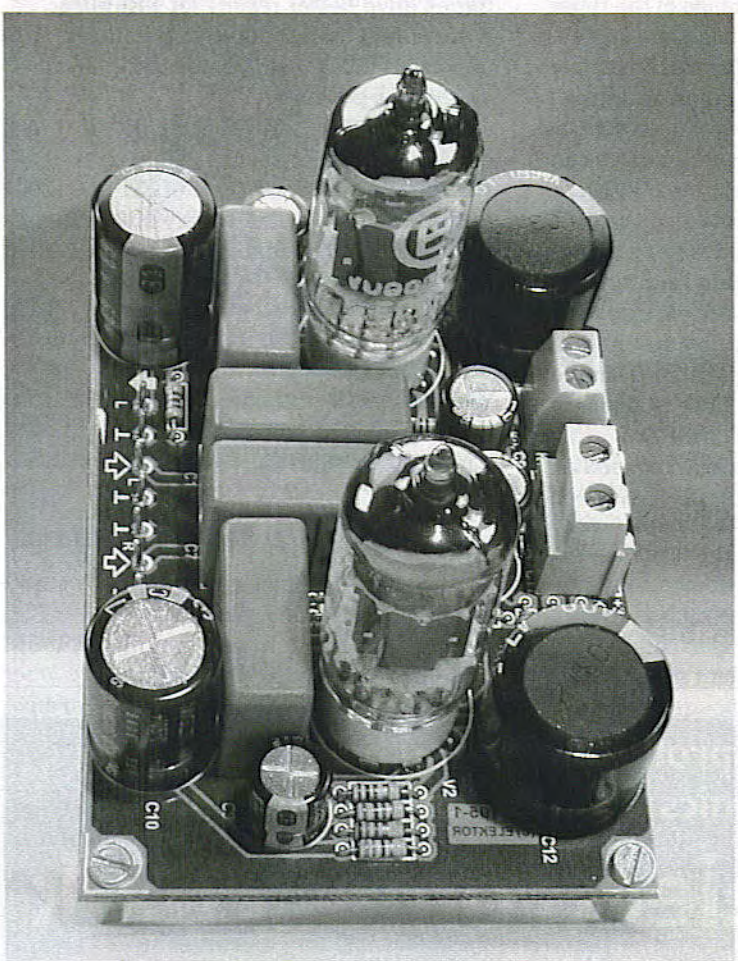
OTL Headphone Amplifier with ECC82 (12AU7)

An 'iron-free' valve amplifier

Design by H.-J Friedli, PhD

A headphone amplifier with outstanding sound quality can be built using readily available modern components. Omitting the output transformer, avoiding overall negative feedback and using good coupling capacitors guarantees a highly linear frequency characteristic, while certain construction methods yield low channel crosstalk.



Measured values (with filter)

Supply voltage:	187 V
THD+N: (1 mW / 600 Ω)	2.3 % (right channel)
	1.86 % (left channel)
S/N: (1 mW / 600 Ω)	>93 dB
	>100 dBA
Filament supply ripple voltage:	30 mV_{pp}
Total power consumption:	17 W

Valve experts know that even power valves that can deliver several hundred milliampères of anode current can never drive a loudspeaker with an impedance of 8 Ω, since the internal resistance of a valve is several kiloohms. The two impedances are thus almost always matched using a transformer. In principle, there isn't any objection to using this form of impedance conversion, but every transformer tends to degrade the sound quality. Keeping this effect to a minimum requires very careful and complicated coil winding techniques, good-quality transformer iron and large core cross-sections.

However, if the load impedance is not just a few ohms but instead several hundred ohms, as is the case with many types of headphones, and if in addition the required power level is not overly high, an amplifier with no output transformer — sometimes referred to as an 'output transformerless' (OTL) amplifier — can be a feasible option. In this case, the load is driven directly by the valve.

The OTL amplifier described here is a cathode follower design suitable for use with a single or dual headphone, with each headphone element having a rated impedance of at least 300 Ω.

The circuit

The circuit shown in **Figure 1** uses the readily available ECC82 double triode (equivalent to the North American 12AU7) to provide amplification. In Europe, 'special quality' (SQ) versions of this valve with better specifications and longer service life are also available under type numbers E802CC and E82CC, respectively.

A preamplifier stage is necessary to generate signal amplitudes sufficient to adequate drive a headphone. The triode section with base pins 1, 2 and 3 is used for this purpose. The input signal arrives at the circuit board via an external 50-kΩ logarithmic potentiometer (P1, not shown in the schematic) that serves as a volume control, and it is directly coupled to the preamplifier stage via C1. R1 provides the necessary negative grid bias. The gain is essentially determined by R8, while the maximum input voltage is determined by R2. R9 is dimensioned such that the quiescent anode current is situated in the most linear possible portion of the characteristic curve.

The inverted and amplified input signal on the anode is coupled to the grid of the second stage via C2. The cathode resistor of the second stage is split into two resistors (R5 and R6). The series resistance of R5 and R6 forms the load resistance, while the voltage division provided by the resistor pair allows the grid bias to be set to the proper level. The bias voltage is decoupled from the load and stabilised by R4 and C3 before being applied to the grid. The anode current flowing through the triode, which depends on the grid voltage and corresponding characteristic curve, generates a voltage across the combination of R5 and R6 that is exactly proportional to the current. This voltage is in turn fed to the headphone via coupling capacitor C4. R7 holds the output at ground potential for DC signals in order to avoid crackling noises when the headphone is plugged in.

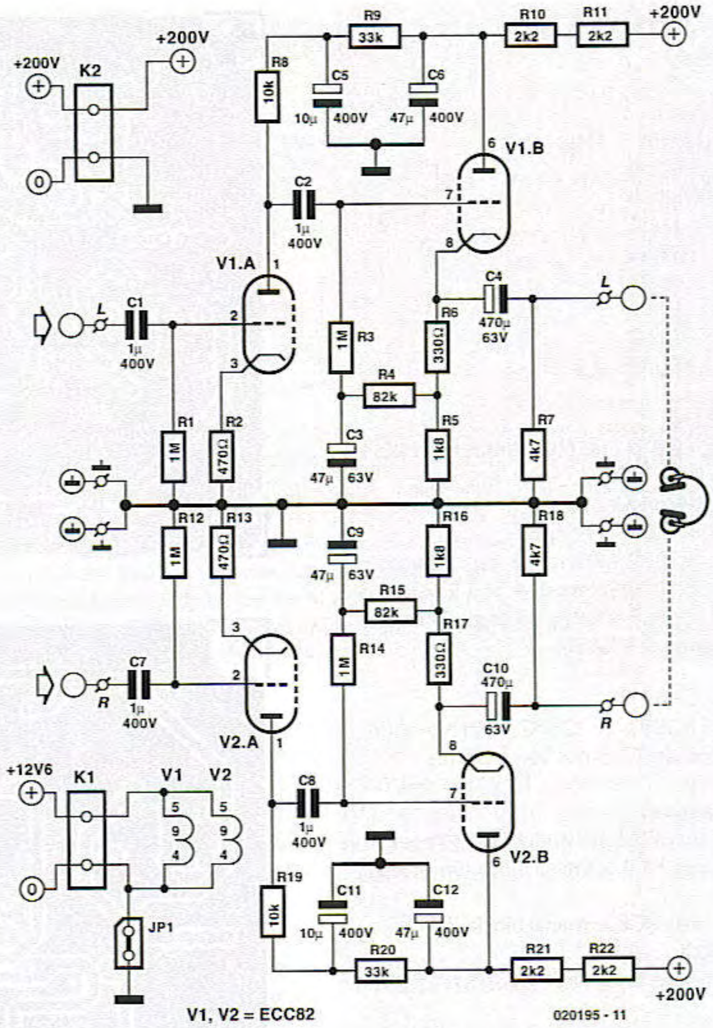


Figure 1. Schematic diagram of the amplifier using two ECC82 (12AU7) valves.

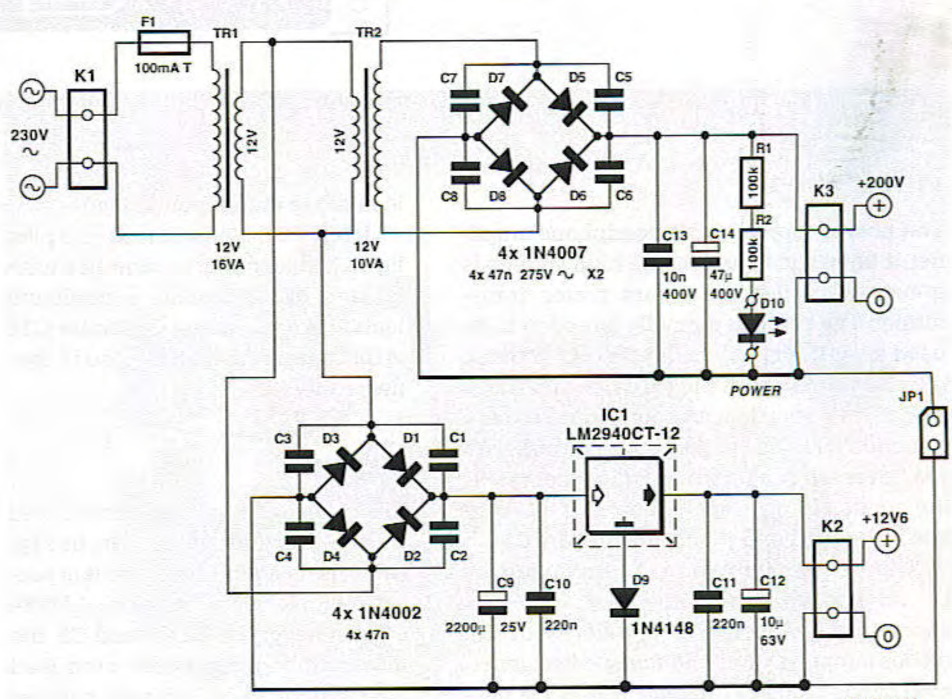


Figure 2. Two mains transformers are used to generate the high voltage.

COMPONENTS LIST
(Amplifier)

Resistors:
R1,R3,R12,R14 = 1MΩ
R2,R13 = 470Ω
R4,R15 = 82kΩ
R5,R16 = 1kΩ8
R6,R17 = 330Ω
R7,R18 = 4kΩ7
R8,R19 = 10kΩ
R9,R20 = 33kΩ
R10,R11,R21,R22 = 2kΩ2

Capacitors:
C1,C2,C7,C8 = 1µF 400V (MKP4 or MKS4, 250V)
C3,C9 = 47µF 63V radial
C4,C10 = 470µF 63V radial
C5,C11 = 10µF 400V radial, e.g., Panasonic ECA2GHG100n (Farnell # 219-9320)
C6,C12 = 47µF 400V radial (e.g., Conrad Electronics # 475858)

Valves:
V1,V2 = ECC82 or 12UA7, with Noval (9-way) socket (Chelmer Valve Corp.)

Miscellaneous:
JP1 = 2-way PCB pinheader with jumper
K1 = 2-way PCB terminal block, 5mm lead pitch
K2 = 2- way PCB terminal block, 7.5mm lead pitch
PCB, available from The PCBShop

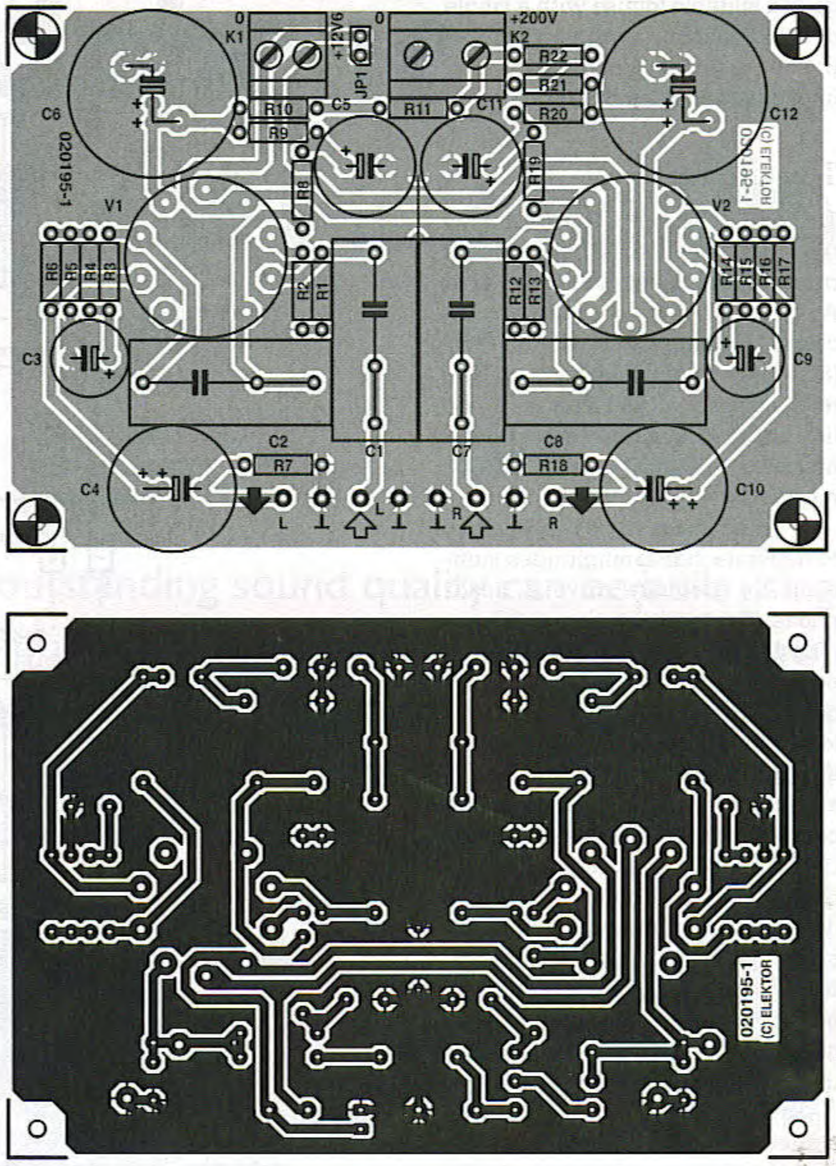


Figure 3. Layout of the amplifier printed circuit board.

Power supply

The power supply for the headphone amplifier is shown in **Figure 2**. The high voltage is generated using a standard mains transformer. The winding normally intended to be used as a secondary winding is connected to the 12-V terminals of the actual mains transformer. This results in an open-circuit voltage of around 200 VAC on the primary winding of the 'reversed' transformer, which serves as the anode supply transformer. This AC voltage is rectified and then smoothed by C14.

The DC filament voltage is rectified by D5–D8 and then smoothed by C15. The capacitors connected in parallel with the diodes suppress high-frequency noise generated by the diodes. A voltage of 12.6 V is generated in a simple manner using an LM2940CT12 (for low voltage drop) with a silicon diode in the ground lead.

LED D10 not only serves as a pilot light, but also works together with R1 and R2 to provide a minimum load and ensure that capacitor C14 is discharged, even if no load is connected to K3.

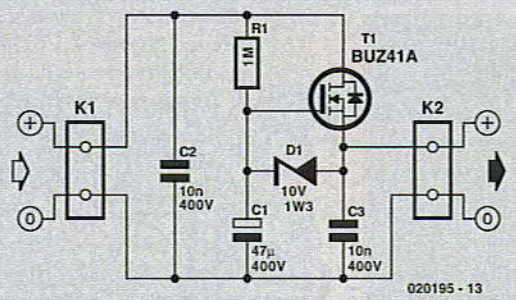
Layout

The layout of the printed circuit board for the amplifier, as shown in **Figure 3**, is designed such that it is possible to use not only 'normal' MKS4 capacitors for C1, C2, C7 and C8, but also coupling capacitors with lead spacings of 15 or 22.5 mm, such as WIMA MKP4 types. These capacitors have higher breakdown voltages and are physically larger, which makes them better for audio purposes.

For the large-volume electrolytic capacitors (C6 and C12), types with lead spacings of 5 or 7.6 mm can be used, or radial snap-in types with lead spacings of 10 mm. The latter type of capacitor has a larger diameter and thus absorbs less heat from the nearby valves. Low-inductance electrolytic capacitors designed for high-frequency switching applications should preferably be used, and in any case they must be specified for operation at 105 °C .

Power is supplied to the individual channels via the combination of R10 and R11 or R21 and R22, respectively. These resistors dissipate

Anode voltage filter



The circuit forms a power RC filter that reduces the ripple component of an unstabilised supply voltage. Naturally, this results in a voltage drop of a few volts. Here a MOSFET suitable for use with high voltages (a BUZ41A, rated at 500 V / 4.5 A) is wired as a simple source follower. The gate is very slowly brought up to the desired voltage via the R1/C1 network. It takes four minutes (five RC time constants) for the output voltage to reach 99 percent of its nominal value. As the valves also take a while to warm up, this delay does not matter. The effect of using the filter can be clearly seen in Curve B.

The voltage drop across T1 is primarily determined by the gate–source cutoff voltage and is approximately 3.5–4 V. The gate is protected against excess voltages by Zener diode D1. C2 and C3 are necessary to eliminate the tendency of the circuit to oscillate. No circuit board layout has been designed for the filter circuit, but it can easily be built on a small piece of prototyping board. The filter dramatically reduces the amplitude of the ripple voltage.

around 0.18–0.25 W, depending on the supply voltage. Be sure to use resistors with adequate power ratings. There are resistors available that can dissipate 0.3–0.4 W with the same package size (such as 1/4-W metal film resistors), and the PR01 series from BC Components can even handle 1 W. In any case, it won't do any harm to fit these four resistors well clear of the circuit board in order to improve their cooling.

In the circuit board layout, attention has also been given to keeping the signal paths of the two stereo channels as widely separated as possible. The connections between the ground terminals of the four anode decoupling capacitors and the common ground point are routed separately for each channel. Incidentally, there is one wire bridge on the amplifier board (between C5/C11 and C1/C7).

The power supply circuit is housed on a second printed circuit board, to which the amplifier board can be attached in sandwich fashion. However, the amplifier is somewhat sensitive to the stray fields emanated by the transformers, whose magnitude depends on the type of transformer used. The 50-Hz components in the frequency spectrum (see measurement curves A and B) clearly indicate the presence of the two transformers, which were located at distance of 20 cm. Diodes D1–D4 are 'solid' 1N4002 types, but there is enough room for even more robust types. Capacitors C5–C8, which have a lead spacing of 15 mm, **must** be X2 types.

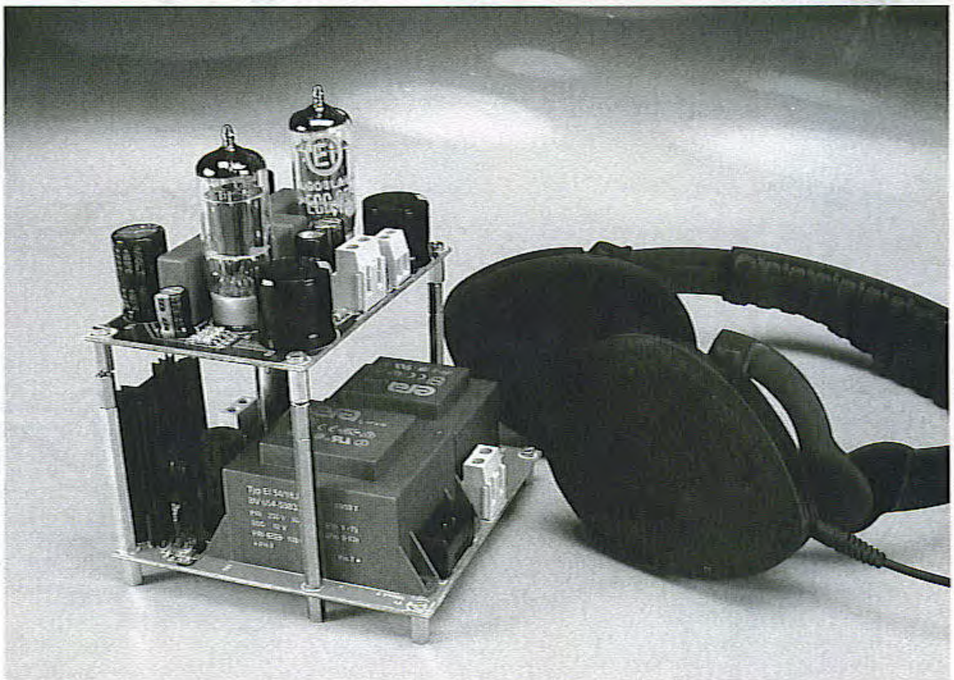
If you want to fully eliminate any ripple in the filament voltage, you can use a 15 V / 20 VA transformer for TR1. As this is a slightly larger type, it will not fit on the circuit board. Although the dissipation of IC1 will increase in this case, the specified heat sink is fully adequate. We also tried using a 15 V / 16 VA transformer, but it drew 23 VA from the mains (significantly overloaded). You are welcome to experiment with various transformers; a wide variety of results may be obtained, depending on the transformer type, open-circuit voltage, loaded voltage, core size, and material. The winding ratio is always determined by the design value of the open-circuit secondary voltage. For a transformer with a nominal secondary voltage of 9 V, this can easily be 12 V.

To balance out the reactive power, an X1-type capacitor rated at around 150 nF / 250 V can be connected across the secondary winding of TR2. This will cause the anode voltage to actually increase slightly, but the mains power consumption and current will decrease by around 6–7 percent.

An advantage of using two transformers is that the high voltage is isolated from the filament voltage. Nevertheless, the two ground potentials must be interconnected. This can be done on the amplifier board and/or on the power supply board (JP1).

Construction

Fitting the components to the circuit boards should not present any problems. All components are fitted on the 'normal' component side.



The voltage regulator requires a heat sink. Its cooling tab is connected to its middle lead, which is 0.6 V above ground potential in this circuit due to the diode.

As everybody knows, the electrolytic capacitors must be fitted with the correct polarity. However, it is also necessary to observe the proper polarity when fitting the four 1-µF capacitors. As the grid terminal is the most sensitive point in a valve circuit, it must be connected to the inner foil of the capacitor. The outer foil, which is sometimes marked by a stripe, then has a screening effect.

The Cinch sockets, potentiometer, phone socket and mains switch must be wired externally, which leaves considerable room for personal choice in selecting an enclosure and arranging the controls and connectors.

The circuit board layout (Figure 3) has been kept highly symmetric with

COMPONENTS LIST
(Power supply)

Resistors:
R1,R2 = 100kΩ

Capacitors:
C1-C4 = 47nF ceramic
C5-C8 = 47nF 275 VAC, Class X2, lead pitch 15mm
C9 = 2200µF 25V radial
C10,C11 = 220nF
C12 = 10µF 63V radial
C13 = 10nF 400V, lead pitch 7.5mm or 10mm
C14 = 47µF 400V radial (BC Components # 22215266109, Farnell # 322-7984)
(BC Components # 22215266479, Farnell # 322-8009)
Panasonic ECA2GHG470 (e.g., Farnell # 319-9356)

Semiconductors:
D1-D4 = 1N4002
D5-D8 = 1N4007
D9 = LED red, low current
IC1 = LM2940CT-12 with heatsink, Fischer type SK104 (50.8 mm)

Miscellaneous:
JP1 = 2-way PCB pinheader with jumper
K1,K3 = 2-way PCB terminal block, lead pitch 7.5mm
K2 = 2- way PCB terminal block, lead pitch 5mm
F1 = fuse, 100mAT (slow), with PCB mount holder
TR1 = mains transformer 12V / 16VA (ERA BV054-5383.0K (Conrad Electronics # 506575)
TR2 = mains transformer 12V /10VA (ERA BV048-5383.0H (Conrad Electronics # 506478)
PCB, available from The PCBShop

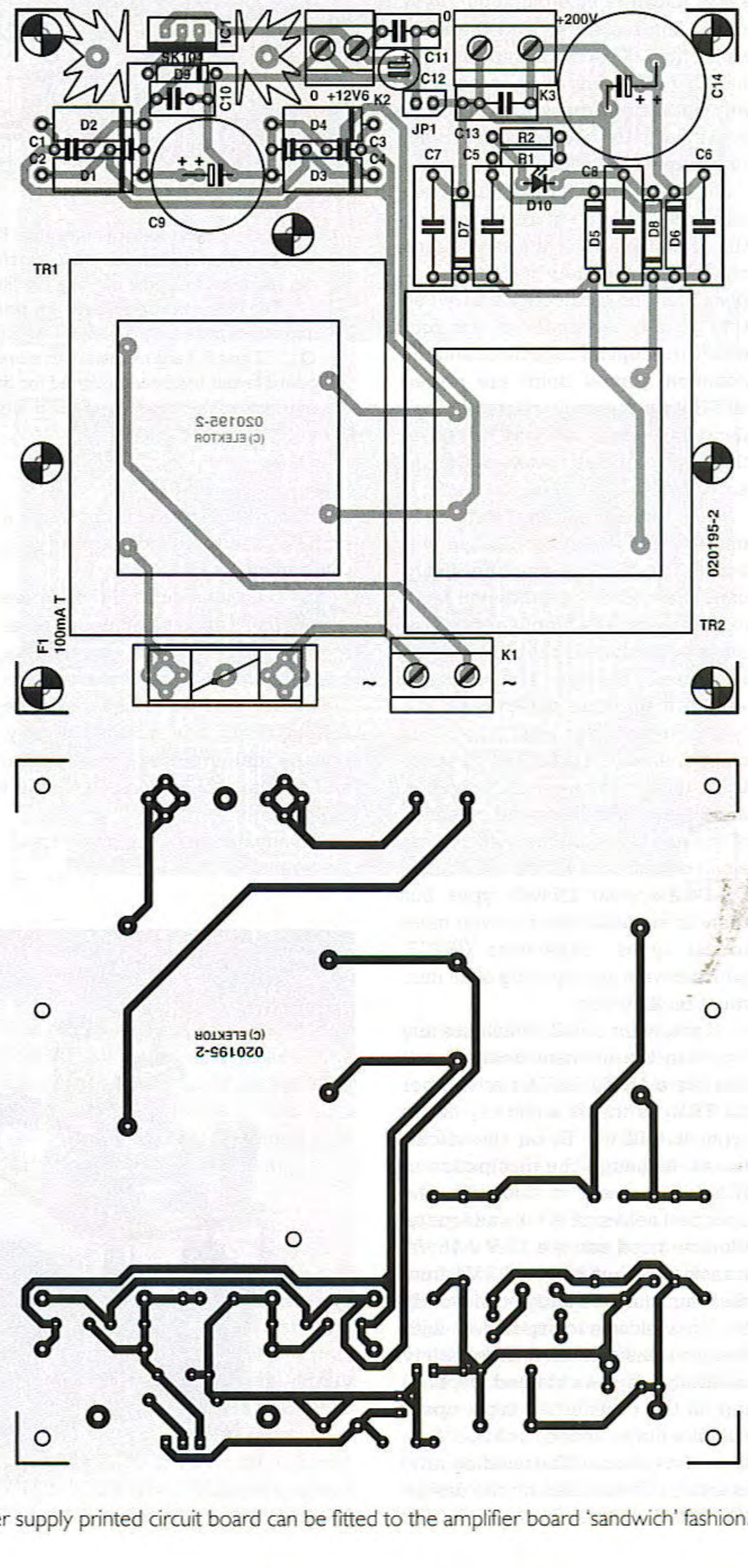
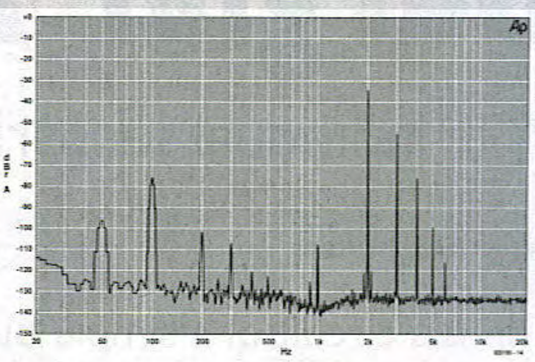


Figure 4. The power supply printed circuit board can be fitted to the amplifier board 'sandwich' fashion.

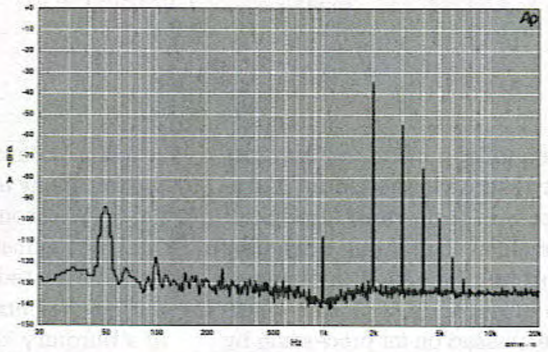
Curves and sound

Curve A shows the frequency spectrum of a 1-kHz signal (1 mW into 600 Ω). The distortion components (right channel) amount to 2.3 percent, but this is primarily due to the second harmonic. Besides this, an enormous effect can be seen from the ripple voltage of the unstabilised anode voltage supply. To remedy this, we developed an active filter (see box) that almost fully suppresses the 100-Hz component and its harmonics. The results obtained using this filter can be seen in Curve B. The third curve, C, shows the distortion as a function of output power. The distortion level increases quite linearly with the output power level. The amplifier 'runs out of room' at around 5 mW.

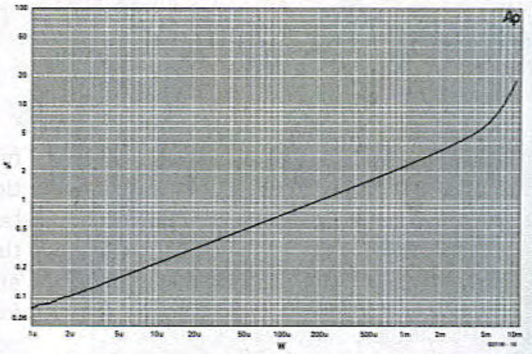
It's almost impossible to describe the performance of a piece of audio equipment using bare figures alone. The most noticeable aspect of the sound is dynamic range: what is supposed to be loud is loud, and what is supposed to be soft is soft. The sound is warm and spacious, and although it is perhaps slightly lacking in clarity of detailing at the upper edge of the frequency spectrum for high volume levels, this by no means reduces the enjoyment of opera voices. The sound is very pleasant and remains so during extended listening. Low tones do not present any problems, and it is certainly quite enjoyable to listen to music with strong bass components, such as rock, pop and jazz.



Measurement curve **A**. Frequency spectrum without a pre-filter for the anode voltage.



Measurement curve **B**. Using a filter provides a clear benefit, with significantly reduced 100-Hz components.



Measurement curve **C**. The distortion level increases linearly with output amplitude.

regard to its visual aspect, so there is no reason not to use an enclosure design featuring a visible circuit board with its valves and other components. If you would rather conceal the circuit board but still wish to have the valves visible, you should etch the circuit board using a mirror image of the layout. In this case, the tube sockets are fitted to the copper side of the board, with all other components being mounted in the usual manner so they face downward after the board is fitted in the enclosure. All polarisations remain the same.

All 230-V wiring must be made using wire with sufficiently thick insulation. It is essential to apply additional insulation to the solder points and fit an insulating sheet between the mounting panel and the undersides of the transformers. You must also provide for good ventilation. A double-pole on/off switch must be fitted in series with the 230-volt wiring. The transformers should be fitted in the enclosure as far away as possible from the signal inputs. If the transformers are too close to the inputs, a typical 50-Hz hum will be heard if the Cinch sockets are open and the volume control is turned up full.

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