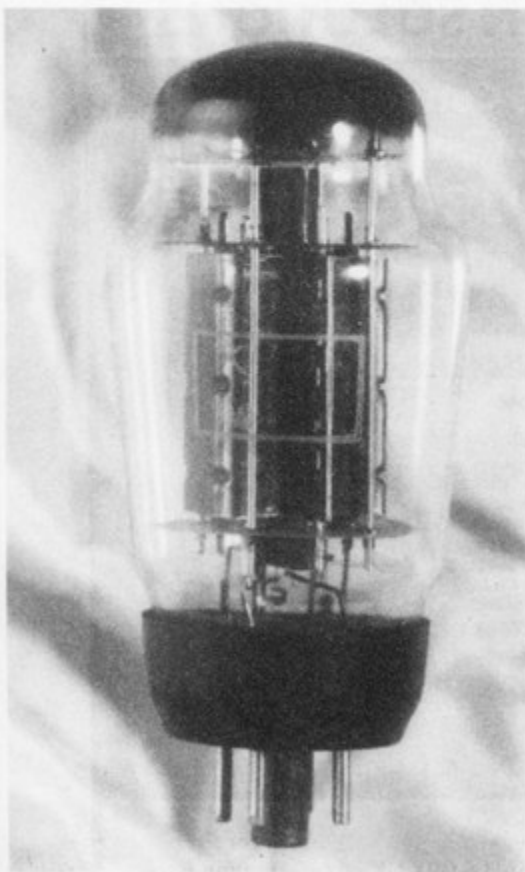


Hot audio power



Despite rapid advances in semiconductor technology that have occurred over the past few decades, there are many audiophiles who believe that valves are best. Although at first sight this idea may seem ludicrous, it may not be quite as fanciful as some of the dubious products that the high fidelity industry has come up with of late.

Despite disadvantages of separate heater supplies and the need for high voltage supply lines, valves do have some advantages over their semiconductor rivals.

Why use valves?

Firstly, valves are easy to drive. At low frequencies the grid of a valve has an impedance approaching $100\text{M}\Omega$, but without the large parallel capacitance of a v-fet. Similarly, being mechanical devices, the characteristics are far better matched between samples than, say, transistors from the same batch. Consequently, a class-AB amplifier output stage built with valves can be far more linear than a solid state equivalent. Most surprisingly of all, for those of us weaned on silicon, is the amazing amount of abuse that valves can take without disappearing in a puff of smoke.

It was in the spirit of curiosity that the design described here was developed. It uses a pair of formerly widely used EL34s driven by a solid state circuit.

There are several reasons why the EL34 is a good choice of output valve. Primarily, it has

Fig. 1a. Simplest form of valve amplifier is Class-A. Relative to the loudspeaker, a valve is very high impedance so a transformer is essential.

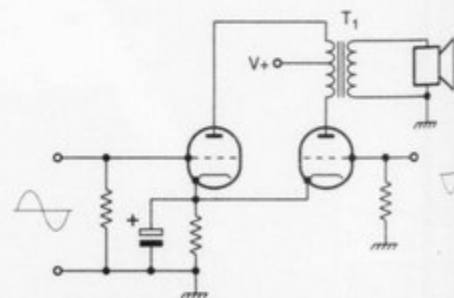
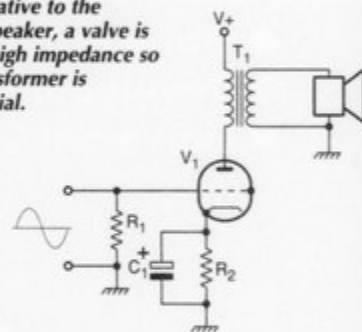


Fig. 1b. In the conventional valve output stage, equal and anti-phase signals are applied to the grids to generate push-pull output.

a high 25W anode dissipation. It also fits into a standard octal relay socket and is relatively cheap. Reasons for the solid state driver will become apparent as the article progresses, but first it will be useful to get to grips with some output stage basics.

The simplest form of valve output stage is the single-ended class-A triode, **Fig. 1a**). Because valves have limited current handling capacity and rather large internal resistance, anode drive is applied to the loudspeaker through an impedance matching transformer. This system works fine but its maximum theoretical efficiency is only 50%. Usually because of the anode characteristics practical efficiency is more often in the region of 25%. If I had been writing this article a couple of years ago, I could have said that single ended triode output stages were a thing of the past. However audio 'purists' have resurrected them. If you have the money and inclination you can purchase one particular triode amplifier for a cool £30,000.

Valve output stages

The conventional valve output stage is shown in **Fig 1b**) where for simplicity the valves are shown as triodes. Output is fed from the valve

anodes to the output transformer primary. The centre tap of this winding is connected to the positive supply.

When equal and antiphase input signals are applied to the valve grids, push-pull operation is obtained. As with solid state designs the operating class is decided by bias current.

This push-pull stage has the usual advantages of cancelling even-harmonic distortion and increased power output. In addition hum voltages at the anodes cancel, producing an inherently high power supply ripple rejection.

Using *EL34*s in this type of circuit, it is possible to get outputs in the 20-50W range with reasonable ht voltages. However, the main problem with valve output stages is the output transformer – particularly in terms of frequency response.

A real transformer, as opposed to a theoretical model, requires considerable primary inductance for good bass. Similarly at the high end, leakage inductance and winding capacitance limit response.

A modelled real transformer is shown in **Fig. 2**. **Figure 2a**) shows an equivalent circuit at low frequencies. Here primary inductance forms a high-pass filter with the valve's anode impedance. Clearly, the greater the inductance

Components

Resistors 1%, 0.5W metal film unless indicated

R_1	56k	[2]
$R_{2/5}$	10k	[4]
$R_{3/4}$	1k8	[4]
$R_{12/13}$	68k	[4]
$R_{6/9}$	60k	[4]
$R_{7/8}$	220k	[4]
R_{10}	470R, 3W ww	[2]
R_{11}	6k8	[2]
$R_{14/15}$	470R, 1W	[4]
R_{16}	1k, 1W	[2]

Capacitors

$C_{1,2}$	100nF, 1000V WKG polyprop	[4]
C_3	100µF, 100V	[2]
C_4	220µF, 25V	[2]
$C_{5,6}$	470µF, 400V	[2]
$C_{7,8}$	1000µF, 63V	[4]

Active devices

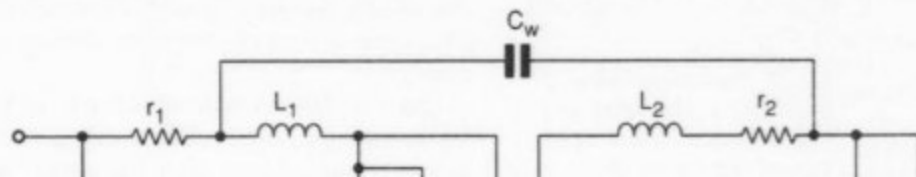
A_1/A_2	TL072	[2]
V_1/V_2	EL34	[4]
$Tr_{1,2}$	2SC2547E	[4]
$D_{1,2}$	1N4001	[4]
BR_1	W08	[1]

Wound components

T_1	Output transformer 20:1 ratio, centre tapped. Primary inductance >8H, Leakage inductance <10mH	[2]
T_2	Mains, 240V prim. 280V, 700mA second. 6-0-6V 4A second.	[1]

Transformer availability

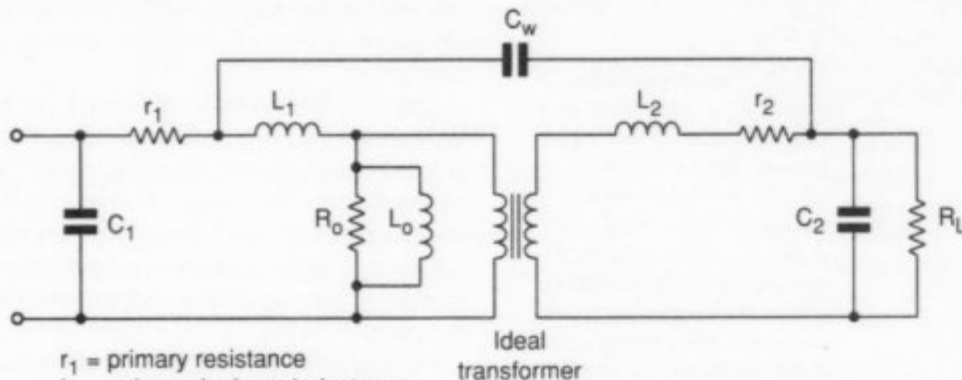
Three transformers especially wound for this design have been produced by Antrim Transformers. The set is available to UK readers for £99.99 plus £8 postage – fully inclusive of VAT. Antrim Transformers Ltd is at 25 Randalstown Road, Antrim, Co Antrim BT41 4LD, tel. 018494 28734, fax



Valve output stages

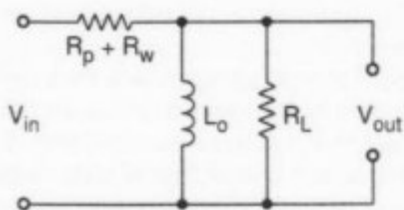
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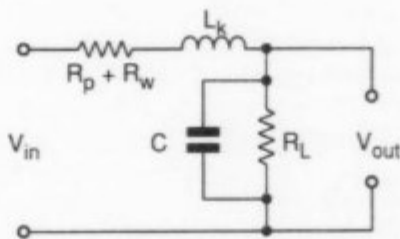


r_1 = primary resistance
 L_1 = primary leakage inductance
 r_2 = resistance of secondary
 L_2 = equivalent secondary leakage
 R_0 = equivalent core loss resistance
 L_0 = primary inductance
 C_1, C_2 = equivalent lumped capacitance of primary and secondary
 C_w = interwinding capacitance
 R_L = secondary load

Fig. 2. Model of the output transformer, above. For good bass, the transformer requires significant primary inductance. Low and high-frequency equivalents are shown below in a) and b) respectively.



R_p = anode resistance
 R_w = winding resistance
 L_0 = primary inductance
 R_L = secondary load x turns ratio squared
a) low frequency equivalent circuit



L_k = leakage inductance
 C = winding capacitance
b) high frequency equivalent circuit

Transformer availability

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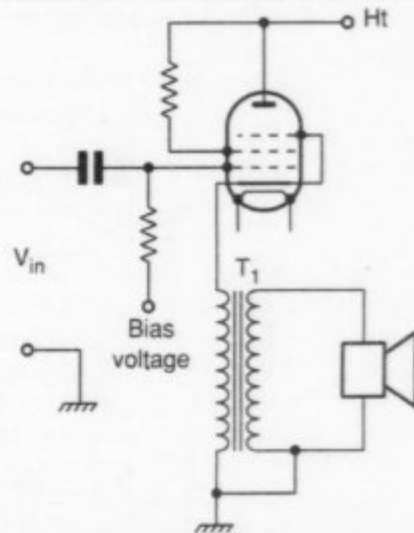


Fig. 3. Valve equivalent of the emitter follower. Putting the transformer in the cathode improves performance but driving the circuit needs a prohibitively large supply rail.

here the better if good bass response is to be secured.

Figure 2b) shows a corresponding equivalent circuit of the transformer at high frequencies. At these frequencies primary inductance has no influence but leakage inductance in conjunction with the winding capacitance forms a second-order low-pass filter.

Both leakage inductance and winding capacitance are functions of the way the transformer is built. Reducing these factors is usually done by sectioning the transformer windings. Again you can see from the equivalent circuit that leakage inductance needs to be minimised for good *ht* response.

When calculating values of these inductances for a given anode resistance, calculations show how rapidly required inductance falls when anode resistance is lowered. In fact, if output impedance could be made zero the required primary inductance would also disappear. Similarly, it can be shown that transformer distortion is also highly dependent on anode resistance and similarly drops to zero with zero impedance drive.

One argument which can be put forward in defence of triode output stages is that they

Supplying *ht*

Power supply for the circuit is conventional. *Ht* is derived from the 280V secondary coil of T_2 – full-wave rectified by BR_1 and smoothed by the parallel combination of C_5 and C_6 . Apart from extra ripple rejection this combination of capacitors stores a huge amount of energy – around 68J. This helps maintain supply lines even when feeding awkward loads.

Supply lines for the op-amp circuit are derived from the heater secondaries. For a stereo amplifier, 6V at 3A minimum/channel is required. A 6-0-6V, 50VA transformer is suitable.

Secondaries connect in series and the voltage doubler D_1 and D_2 provides the dual dc supply, smoothed by C_7 and C_8 . Heaters connect in series/parallel across the 12V supply as shown in the schematic overleaf.

Because of the totally balanced operating mode of the amplifier, ripple voltages effectively cancel out – simplifying psu design.

have lower anode impedance than pentodes. Hence, primary inductance can be made lower for a given bass extension. Most practical designs use overall negative feedback to lower effective anode resistance.

Normally the loop is taken from the output winding of the transformer – including it within the feedback loop. However, due to reactive

elements present in an output transformer the amount of feedback that can be employed in this manner is strictly limited.

One of the best ways of solving the problem is to use a cathode follower, Fig. 3. It is analogous to the more familiar emitter follower with similar features. Voltage gain is always less than unity and output impedance is significantly lower than that obtained from a triode used in a normal grounded cathode stage. Distortion is typically an order of magnitude



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with similar features. Voltage gain is always less than unity and output impedance is significantly lower than that obtained from a triode used in a normal grounded cathode stage. Distortion is typically an order of magnitude smaller.

These limitations make the circuit more of a laboratory curiosity, since driving it fully would require almost twice the signal swing allowed by the ht voltage. However, the circuit is tantalising and I played with the idea of a push-pull cathode follower output driven by an inter-stage transformer before developing the present circuit.

There is however another way of producing a cathode follower style output stage which possesses all the virtues and few of the vices of a conventional valve output stage. The circuit is an amalgam of a transconductance and a transresistance amplifier, **Fig. 4**.

I cannot understand why this particular circuit is not used more often since it allows very high performance with a low component count. Figure 4a shows a transimpedance amplifier operating as a conventional virtual earth amplifier.

If open-loop gain is very high then closed-loop performance is determined by the ratio of R_1 to R_2 . If R_1 were to be substituted for a constant current source, **Fig. 4b**), the amplifier would 'see' 100% negative feedback at its inverting input and voltage gain would be zero.

Replace the current source with a transconductance amplifier and the amplifier will give an output of IR_1 . Distortion generated by the transimpedance stage will be very small because feedback factor B (the proportion of

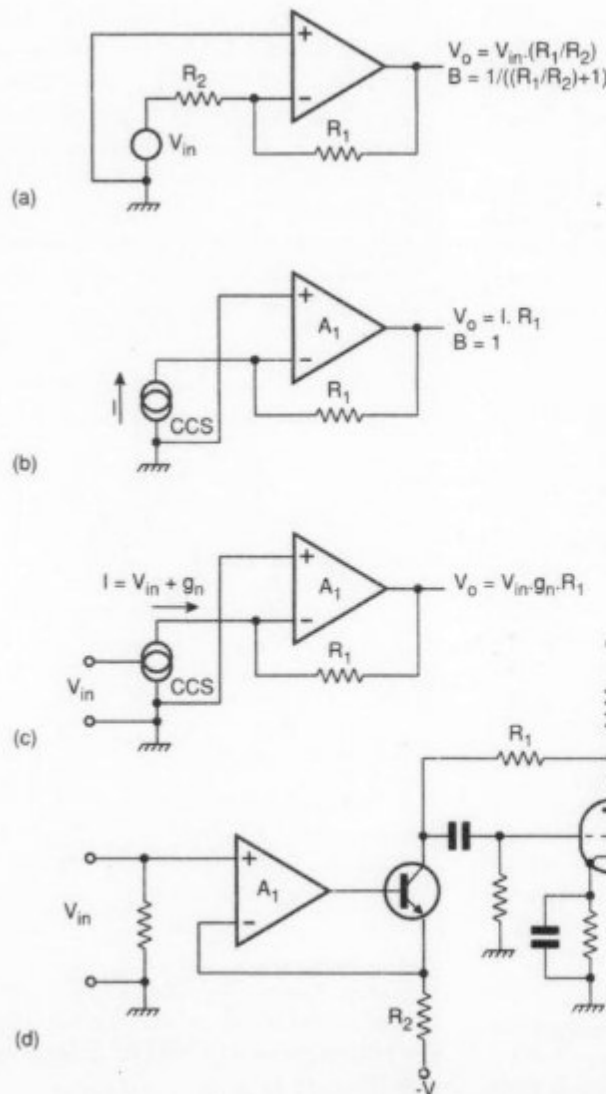
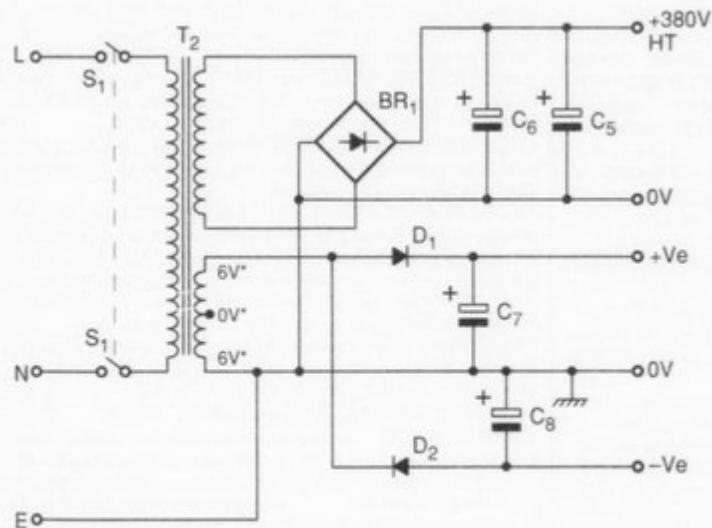


Fig. 4. Transimpedance amplifier a) operating as a conventional virtual-earth circuit. Replacing the resistor with a constant-current source results in 100% negative feedback appearing at the inverting input, making voltage gain zero, b). Substituting a transconductance amplifier for the constant-current source makes distortion very small since feedback factor B is nearly unity c). Circuit c) translated into a hybrid valve circuit, d).



Being entirely balanced, the amplifier effectively cancels out ripple, simplifying design of the power supply. Voltage for the op-amps is derived from the transformer heater windings. For stereo, two heaters connect to each 6V winding.

the signal fed back) is almost unity. As the transconductance amplifier can also be made with unity gain a very well-behaved circuit is obtained.

In the present circuit the transimpedance amplifier is replaced by the valve. A transistor in the feedback loop of an TL072 op-amp is the basis of the transconductance amplifier. Across the audio band the circuit gives an output impedance greater than $10\text{M}\Omega$.

Required voltage gain can be achieved by altering the transconductance ratio R_2 – both transconductance and transimpedance amplifiers have unity voltage gain. A well balanced push-pull output from the driving circuitry is also required to drive the push-pull output stage. This can easily be obtained by linking inverting inputs of the op-amps via a resistor and dc blocking capacitor.

Unfortunately a valve driver – though possible – is very difficult to design. An EF86 pentode valve is a possibility but the only way of obtaining the requisite high impedance

drive is to use low operating current. High current drive is required from this stage since impedance seen at the output valves grid is low due to feedback employed.

Figure 5 shows the amplifier's complete circuit. Input signals are fed across R_1 to the non-inverting input of A_1 which sets input impedance. Op-amp A_1 in conjunction with Tr_1 form a transconductance amplifier as discussed previously. Feedback is taken from emitter resistor R_3 to the inverting input via R_6 . Resistors $R_{12,13}$ connect to the supply rail and provides bias for $Tr_{1,2}$ setting the quiescent current of the stage.

Output current from the collector of Tr_1 feeds into R_7 which connects in shunt between the anode and grid circuit of V_1 . Capacitor C_1 isolates the valve from the dc level present at Tr_1 collector and R_6 returns the grid to ground. At ac, R_7 and R_6 appear as a parallel load to Tr_1 . This impedance is effectively reduced by around 9.2 times by the valve gains.

Biasing of the output stage is effected by

this is tried, R_{11} should be reduced to increase open-loop gain

Implementation

Building this design is straightforward. I used a readily available chassis and tagstrips. For the heater wiring, 5A loudspeaker cable is ideal. It should be laid close to the chassis but need not be twisted together as in low-level valve circuitry.

Potentially lethal voltages are present on capacitors C_5 and C_6 and all ht lines, and there is of course live mains around the transformer primary circuit. Always power up the amplifier with the EL34s *in situ* and make sure that the heaters heat up before turning off again. As long as the valves are in circuit and conducting, they will discharge the decoupling capacitors rapidly after turn off. If they are not installed, high voltage will linger for hours – sometimes days.

The amplifier requires no setting up. Provided it is wired correctly the circuit will operate first time.

Conclusion

Was it worth the effort? Yes, I certainly think so. The prototype gives out 32W continuous per channel with a full power bandwidth of 5Hz to 55kHz, -3dB . Measured thd at 1kHz and 20W output is 0.07% while output impedance is a mere 0.6Ω – minuscule by valve amplifier standards.

Mainly though, the amplifier excels at driving awkward loads and can suffer short circuits on the output without complaint. Last, but by no means least, it was fun to design. ■