Tube Sound

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It is 100 years ago this year that the triode was invented by Lee de Forest. It is remarkable that triode output stages still occupy an important place in high-end audio amplifiers. Triode amplifiers are often very expensive. The design presented here is based on a combination of optimal quality and reasonable construction cost.

Specifications

Test measurements carried out with a load of 8 Ω

Output power (1 kHz, 2%):	9.5 W into 4 Ω and 8 Ω	
Input sensitivity (9 W, 1 kHz):	200 mV (without negative feedback)	600 mV (with negative feedback)
Output impedance (1 kHz):	2.3 Ω (without negative feedback)	0.8 Ω (with negative feedback)
Bandwidth (1 W):	20 Hz to 27 kHz (without negative feedback)	< 20 Hz to 64 kHz (with negative feedback)
THD + noise (1 W, 1 kHz):	0.15% (with negative feedback)	0.3% (without negative feedback)
Hum/noise:	–72 dB (without negative feedback)	–82 dB (with negative feedback)

The subject of "Tubes versus Transistors" has already been frequently discussed in literature. Instead of repeating it all, we are offering a reference instead. A comprehensive comparison is presented in the article 'Vacuum Tubes and Transistors Compared' (refer http://milbert.com/TVTFC.bdc). In addition to triodes, pentodes are also used for audio amplifiers. The choice between these two is made on the basis of a number of considerations.

Triode or pentode?

With triodes, the influence of the anode voltage on the anode current (negative feedback) is quite large (see **Figure 1a**). The result of this is a lower output impedance and a smaller amplification factor 'μ' (this is the maximum achievable voltage amplification when there is a DC current source in the anode path).

With pentodes (see **Figure 1b**), the screen grid voltage in particular determines the anode current. As a result, the influence of the anode voltage on the anode current is smaller, which results in a higher output impedance and therefore a higher μ.

The disadvantages of pentode output stages are:

1. Loudspeaker damping is practically zero and negative feedback is required to reduce the output impedance of the amplifier to an acceptable value.

2. The damping of transformer resonances is so small that in the absence of a load (open-circuit output) very strong oscillations can be generated with voltages that can become so high arc-over occurs in the valve sockets or output transformer.

With triodes, the loudspeaker damping and transformer resonance damping are much more favourable because of a lower μ.

The disadvantages of triode output stages are:

1. The consequence of a lower μ means that the driving stage has to be able to supply a signal with relatively large amplitude.

2. Because of the lower output impedance the influence of power supply ripple is larger with triodes than it is with pentodes. This means that the power supply smoothing filter has to meet higher requirements.

Single-ended or push-pull?

The distortions of a triode and a pentode are compared in **Figure 2**. This shows that with triodes d2 is dominant

Class-A triode push-pull amplifier

and d3 with pentodes. Even-numbered harmonics are largely cancelled in push-pull circuits, odd-numbered harmonics are not. The result of this is that a triode push-pull amplifier has a lower open-loop distortion than a pentode push-pull amplifier, mostly due to the third harmonic (d3).

The second advantage of a push-pull amplifier is that with correct DC biasing there is no DC bias in the core of the output transformer. The core can there-
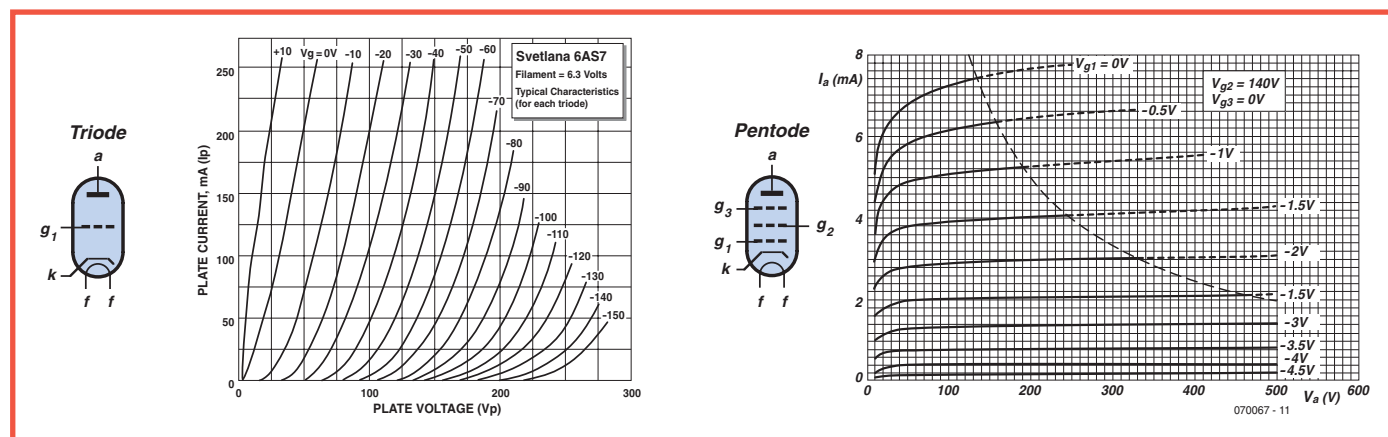

Triode

Svetlana 6AS7
Filament = 6.3 Volts
Typical Characteristics
(for each triode)

PLATE CURRENT, mA (Ip)

PLATE VOLTAGE (Vp)

+10 Vg = 0V -10 -20 -30 -40 -50 -60 -70 -80 -90 -100 -110 -120 -130 -140 -150

Pentode

I_a (mA)

$V_{g1} = 0V$
-0.5V
-1V
-1.5V
-2V
-1.5V
-3V
-3.5V
-4V
-4.5V

$V_{g2} = 140V$
$V_{g3} = 0V$

V_a (V)

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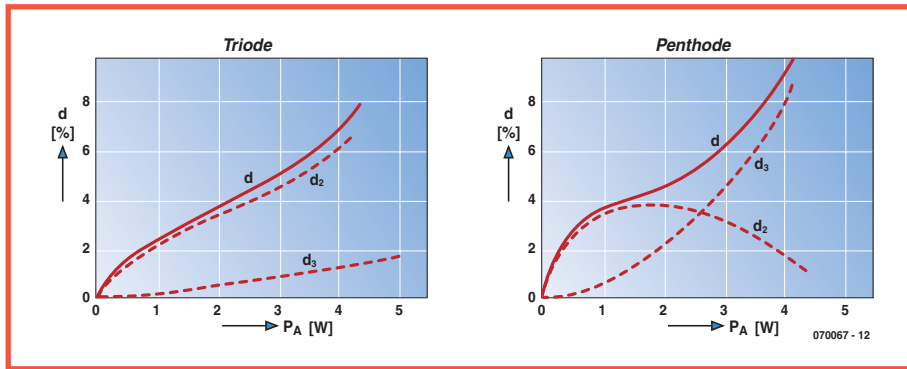**Figure 1.** The characteristics of a triode and a pentode.
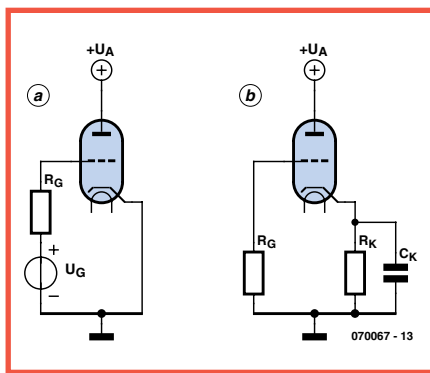
Figure 2. Distortion with a triode and a pentode.

Figure 3. a: Fixed value of grid voltage. b: With the aid of a cathode resistor a simple automatic negative grid voltage adjustment can be made.

Figure 4. Principle schematic for the triode push-pull amplifier.

fore be smaller, and as a result the transformer is cheaper to make. Also, the effect of the power supply ripple is mostly cancelled in the output stage.

A disadvantage of a push-pull amplifier is the requirement of a phase shifter to drive the output stage with two signals that have equal amplitude and opposite phase.

Output power and efficiency

It is incorrect to think that sound appears twice as loud to the ear when the power rating of the amplifier is two times larger. The sensitivity of our ears is logarithmic and has a range of 0 dB (threshold of audibility) to 120 dB (pain threshold). Doubling the output power of an amplifier gives a power gain of 3 dB.

The amplifier published in this article delivers an output power of 2×9 watts at a THD (total harmonic distortion) of 2% (open-loop). This is a reasonable amount of power considering the logarithmic characteristics of our ears, and also because of the soft-clipping behaviour (excessive signal peaks do not lead to 'aggressive' distortion). If desired, high-efficiency loudspeakers could also be used.

The valve handbook from Philips [3] states that a pentode push-pull output stage with 2× EL34 has an efficiency of 53%. This does, however, not take into account the dissipation of the screen grid. This should be included for a fair comparison between triode and pentode output stages. Including the screen grid dissipation the efficiency is 42%. The efficiency of the triode push-pull amplifier presented here amount to 35%, so that is still competitive.

Distortion

The audibility of distortion is strongly dependent on the spectrum. Crossover distortion in transistor amplifiers is very annoying because it has a very broad spectrum. In addition, this distortion increases at lower output powers. With valve amplifiers, the concerns are with lower-order harmonics and according to Douglas Self [4] the threshold of audibility in this case is around 1%. There is therefore very little motivation to design valve amplifiers with lower distortion.

DC bias setting

A fixed negative grid voltage (**Figure 3a**) has the disadvantage that the DC bias setting is dependent on device tolerances and ageing of the valve. It is often necessary to make manual corrections for the DC bias setting to obtain the desired result. With an automatic negative grid voltage (**Figure 3b**) the grid-cathode voltage is determined by the voltage drop across cathode resistor R_k, which is caused by the cathode current. In this method of negative feedback, R_k determines the DC bias setting in a significant way and the effects of valve parameters are strongly reduced. If AC negative feedback is not desired then R_k typically needs to be decoupled with an electrolytic capacitor.

Simplified schematic

In **Figure 4**, the simplified schematic for the amplifier, the RC coupling components between the different stages have
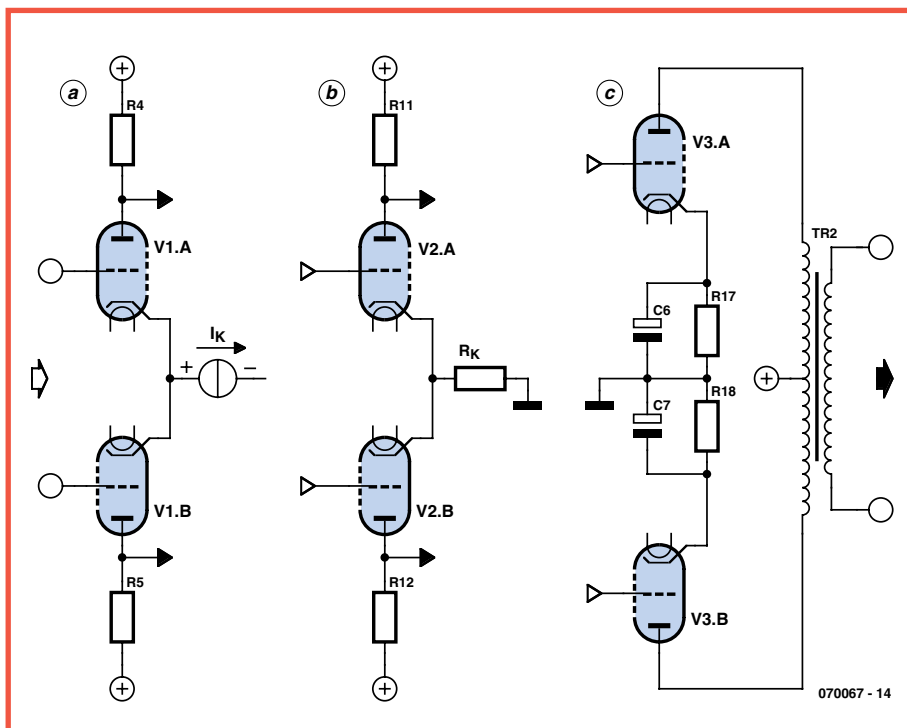
been omitted for simplicity's sake.

The low μ of the triodes used makes a 3-stage approach necessary. For the DC bias setting of the output stage, an automatic negative grid adjustment was chosen, separate for each triode. As a result, the DC offset is much smaller compared to a common cathode resistor and this is advantageous with respect to the potential DC bias in the output transformer. Decoupling of the cathode resistors is necessary to prevent the preamplifier from having to deliver an even larger drive voltage.

The output stage of a push-pull amplifier is often driven by a phase shifter. This is not recommended with triode output stages because the wave shapes of the output signals of the phase shifter are not equal at very large signal swings, which would result in more distortion in the output stage than is necessary. The second stage in this amplifier employs a push-pull amplifier with a common cathode resistor. This resistor is not decoupled because the AC cathode currents are in opposite phase and therefore do not cause a voltage drop across R_k. The first stage is a differential amplifier, used as a phase shifter. From all the circuits that are suitable for this purpose, this is the only type where both input terminals remain freely available. By doing so, the design becomes similar to that of an opamp, which means that the usual methods for negative feedback around opamps can be used here as well. The implementation of the current source I_k can be a resistor, the ohmic value of which must be much greater than the $1/S$ of the valves (where S is the mutual conductance). This requires a negative power supply voltage of $\geq 50\ V_{DC}$.

An important advantage of this design is the complete push-pull structure so that the distortion and sensitivity to hum and interference are minimal.

The complete amplifier

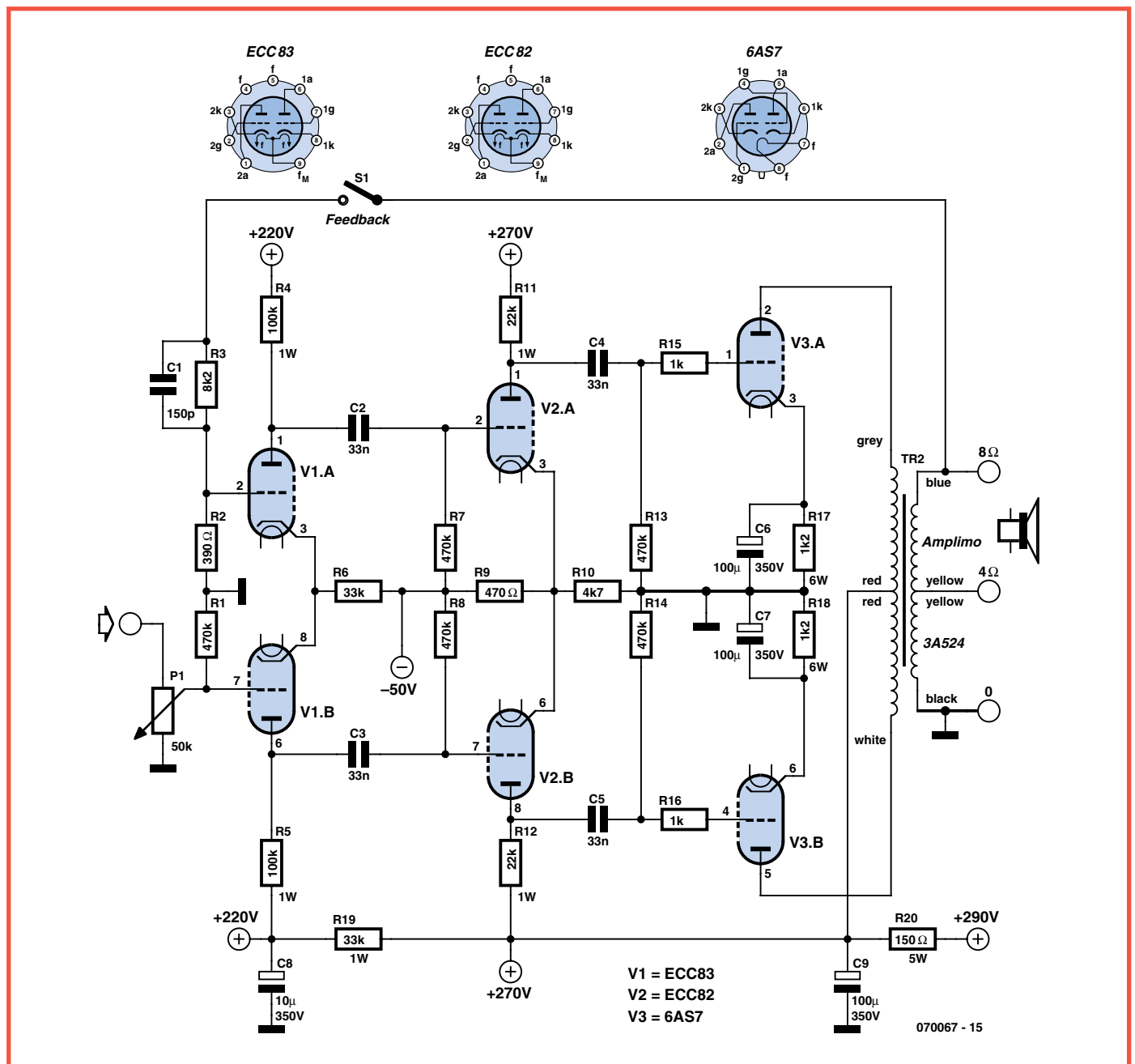**Figure 5** shows the complete schematic

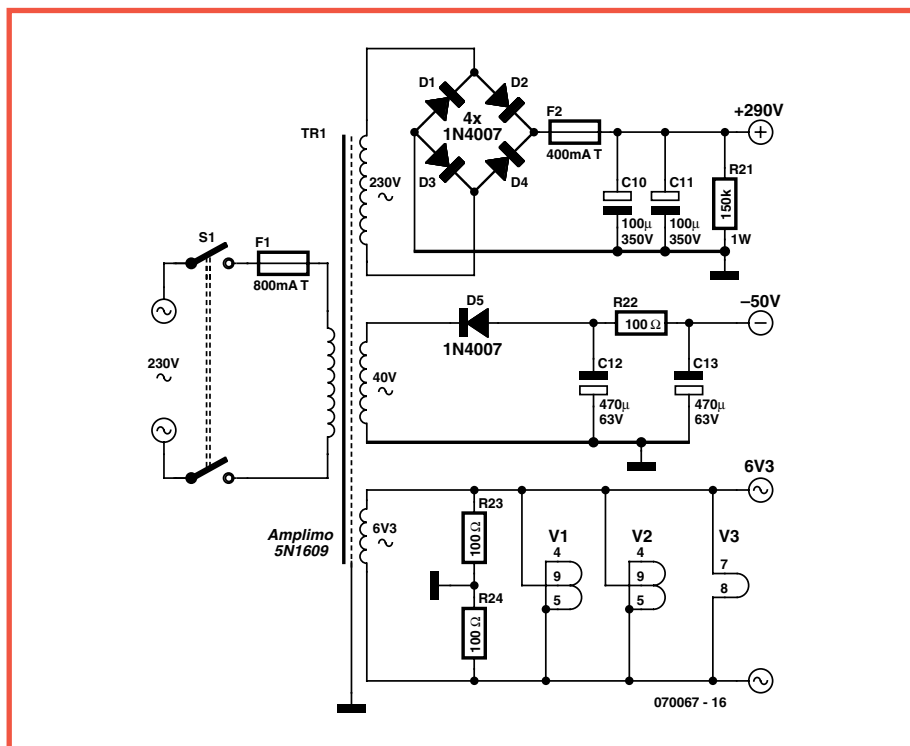Figure 5. The complete schematic of the amplifier (one channel shown). Note the switchable negative feedback.

Figure 6. The power supply uses a special mains transformer which is available from Amplimo.

operates as discussed below.

Suppose that, because of the drive signal, the anode current of V3a increases significantly, U_a of V3a will then reduce significantly. The influence of V3a on the output transformer is now dominant and this causes an increase in U_a of V3b. Since the U_a of triodes has a large effect on anode current, V3b does not stop conducting despite the increase of U_g (more negative), which results in a class-A operation of the output stage.

The 'quiescent current' of about 10 mA has very little effect on the efficiency. Because of this class-A behaviour 'crossover distortion' is precluded and the current consumption from the power supply is almost independent of the output drive.

The preamplifier (V2) has to be able to deliver two drive voltages of up to 70 V_{AC} to the output stage and that places high demands on the dynamic range. An ECC82 (12AU7) is very appropriate for this. To obtain the highest possible drive voltage, R7, R8 and R9 are connected to –50 V instead of ground. This increases the power supply voltage to V2 by 50 V to 320 V.

A 'hybrid DC bias setting' was selected here. R9 is a common cathode resistor (automatic negative grid adjustment). The voltage across R9 is partially determined by the current through R10. The consequence of this is that the DC bias setting is a hybrid of automatic and fixed-negative, which results in better drive capabilities. Because V2 is a push-pull circuit of triodes as well, the distortion is also small because of the cancellation of the even order harmonics.

The DC bias setting combined with the values of R11 and R12 ensures that sufficient capacitive current can be delivered to the output stage at higher frequencies. The input capacitance of V3a and

for the triode push-pull amplifier. The power supply is shown separately in **Figure 6**.

The cost of the output valves and output transformers often make the most significant contribution towards the final price tag of a valve power amplifier. For this design we chose the 6AS7 valve in combination with the 3A524 output transformer. The 6AS7 is a high quality valve for a relatively low amount of money (for details and pricing refer to www.amplimo.nl). The 6AS7 is a dual power triode (maximum dissipation 2×13 W) which was originally designed to be the series-pass element in regulated high-voltage power supplies. This

can be seen from the maximum allowable value for the voltage between the cathode and the filament (±300 V). This indicates high quality isolation. The remaining properties of the 6AS7 are comparable to those of other power triodes. The 3A524 output transformer (maximum 40 W) is generously sized for a 9-watt amplifier. The primary impedance is 3545 Ω. For optimal output drive the DC settings for the output valves are:

U_a = 270 V, I_a = 67 mA, U_k = 80 V and R_k = 1k2.

Triode push-pull output stages have, by their very nature, a class-A characteristic

components list

Resistors (all metal film 1%, 0.25W or 0.6W unless otherwise specified)
R1 = 470kΩ
R2 = 390Ω
R3 = 8kΩ2
R4,R5 = 100kΩ 1W
R6 = 33kΩ
R7,R8 = 470kΩ
R9 = 470Ω
R10 = 4kΩ7
R11,R12 = 22kΩ 1W
R13,R14 = 470kΩ
R15,R16 = 1kΩ
R17,R18 = 1kΩ2 6W (wire wound) (1)
R19 = 33kΩ 1W
R20 = 150Ω 5W (wire wound)

R21 = 150kΩ 1W
R22,R23,R24 = 100Ω
P1 = 50kΩ logarithmic law potentiometer

Capacitors
C1 = 150pF ceramic
C2-C5 = 33nF 400V
C6,C7 = 47µF 100V electrolytic
C8 = 10µF 350V electrolytic
C9,C10,C11 = 100µF 350V electrolytic
C12,C13 = 470µF 63V electrolytic

Valves
V1 = 12AX7 or ECC83
V2 = 12AU7 or ECC82
V3 = 6AS7

Semiconductors:
D1-D4 = 1N4007 or bridge rectifier 400V

piv @ 1A
D5 = 1N4007

Miscellaneous
Tr1 = mains transformer type 5N1609, primary 230 V, secondary 230V/40V/6.3 V (www.amplimo.nl)
Tr2 = output transformer type 3A524 (www.amplimo.nl)
F1 = fuse, 600mA, slow
F2 = fuse, 300mA, slow
Aluminium corner profile, e.g. # 04.90.2208 (www.tessatronic.nl; www.display.nl)
Self adhesive standoff, e.g., Conrad Electronics # 532037-89
Self adhesive mounting for cable strap, e.g., Conrad Electronics # 543234-89

(1) matching desirable

V3b amounts to about 40 pF.

For the phase shifter an ECC83 (12AX7) is the most suitable, in particular because of its relatively high μ, the gain of the first stage is as high as possible. The influence of R6 on the offset (the non-ideal current source functionality is of concern here) is about 4%. Further improvement by increasing the negative power supply voltage and a larger value for R6 is not worthwhile.

The input signal for the amplifier is connected to V1b and the negative feedback signal, via a switch and R3||C1 and R2, to V1a. Swapping the input terminals results in positive feedback, which causes the amplifier to oscillate badly. It is therefore very important to carefully check the numbering on the valves and the colour codes of the output transformer.

Because of the good open-loop characteristics, a moderate negative feedback factor of 3 (9.5 dB) was selected. The negative feedback can be switched on and off to be able to determine the difference in listening tests. When the negative feedback is switched on, the input signal needs to be larger by a factor of 3 (600 mV instead of 200 mV for an output power of 9 W).

It is important to consider that with valve amplifiers, large negative feedback can cause RF instability in addition to AF instability. Because of the AF phase shift resulting from the RC coupling between stages and the output transformer, a very low frequency oscillation can occur. In the past, this has sometimes been called 'motor-boating'. Resistors R15 and R16, the so-called 'grid stoppers' reduce the risk of RF instability in the output stage.

The power supply

The power supply section can be seen in **Figure 6**. The power supply transformer, with the part number 5N1609, has been specifically designed by Amplimo Netherlands for this project, and is available from them (www.amplimo.nl). The electrostatic shield has to be connected to the chassis and its task is to divert mains borne disturbances to earth that could otherwise be capacitively coupled through the transformer to the power supply.

Triodes make high demands on the power supply ripple filter. The design of these filters is based on a so-called π-network, such as C10||C11, R20 and C9. The series resistor has a comparable effect to that of the forward resistance of a valve rectifier. This forms a low-pass filter which effec-
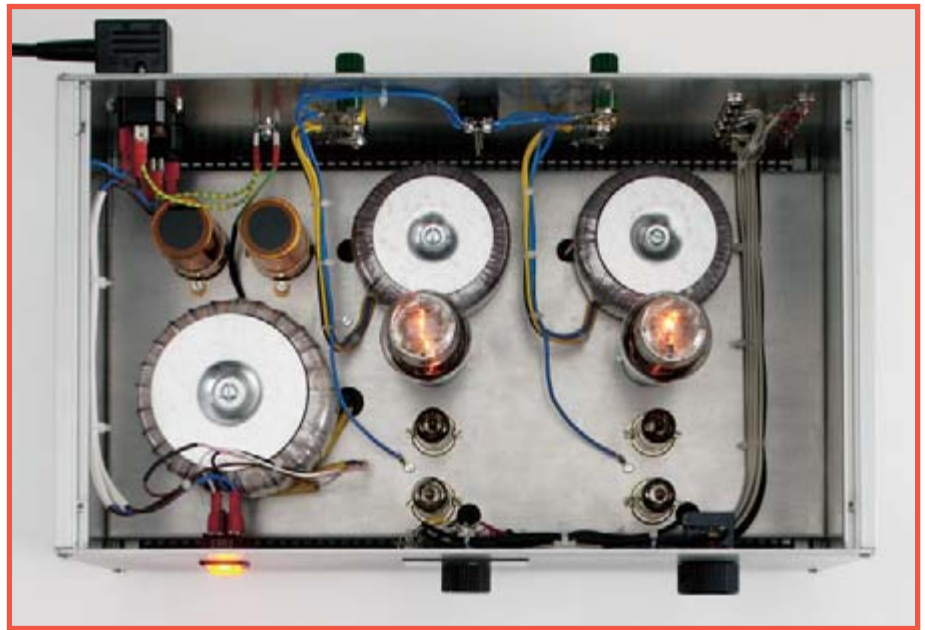
tively suppresses the ripple voltage (the higher harmonics in particular), mains disturbances that are inductively coupled through the transformer and switching pulses from the rectifier diodes. Since the amplifier (including the output stages) operates in class-A, the current consumption from the power supply is practically constant and the use of series resistors is not a problem.

In order to limit the hum from the filament supply, the 'electrical centre' of the filaments is connected to ground via R23 and R24.

Under certain circumstances, when, for example, the amplifier is switched off shortly after is has been switched on, it is possible that the high voltage electrolytic capacitors in the power supply filter can take a very long time to discharge completely. This is undesirable, particularly from a safety perspective. Connecting a 'bleeder' resistor (R21) in parallel with C10 and C11 discharges the electrolytic capacitors to less than 50 V_{DC} in about two minutes.

Realisation

The starting point for the construction

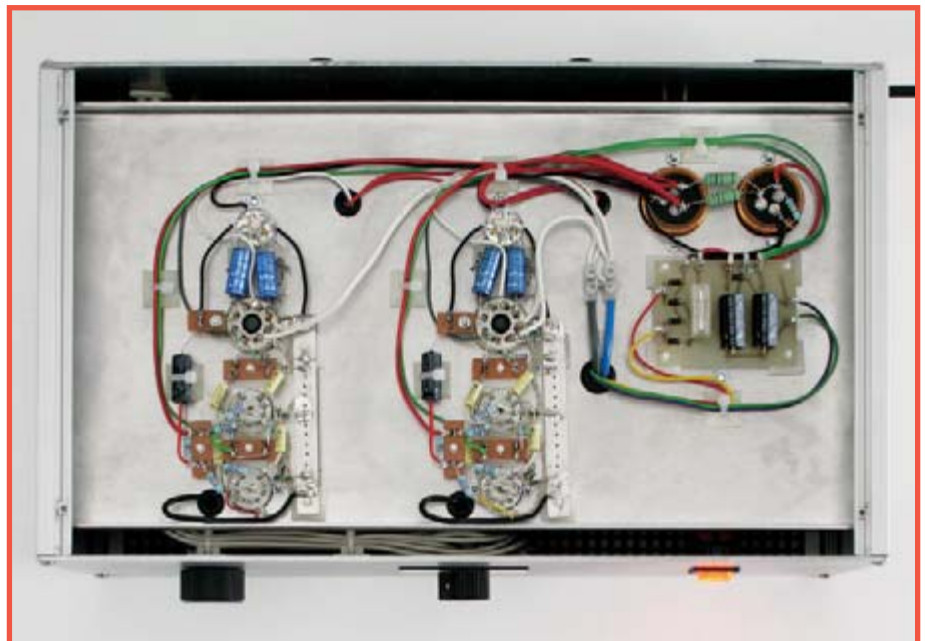**Figure 7. The amplifier viewed from above.**

Figure 8. This is how the components are mounted on the bottom side.

of the enclosure (**Figures 7 and 8**) is an aluminium corner profile (for example type 04.90.2208, available from Tessatronics, Display and others). The profile is normally supplied in a length of 1 m and can be used for four corner profiles of 25 cm each. The front and rear panels are made from 3-mm thick hard aluminium sheet and are attached to the ends of the corner profiles with M5 bolts. The side panels (1.5 mm thick aluminium sheet) fit in the slots of the corner profiles. These side panels support the chassis plate (2 mm thick aluminium plate with 4 cornered edges) with M5 nuts and bolts. Between the chassis and the front and rear panels is a gap of 15 mm to ensure sufficient cooling. The top and bottom plates (perforated steel plate, 1 mm thick, with cornered front and rear edges) is attached with M3 bolts and square nuts that fit in the corner profile.

The connecting and the mounting of the components is done using the 'hard-wired' method. This takes a little bit more time compared to assembling a printed circuit board, but that shpild not be an objection considering the simplicity of the circuit. An added benefit is that the results are better, among other things because twisted wiring for the filaments has a lower risk of hum and is better suited to handle large currents. The assembly (see **Figure 8**) uses discs cut from circuit board for the star-point ground, strips of circuit board for ground and cable supports. The discs, strips and cable supports are attached to the chassis with self-adhesive stand-offs. There are two options regarding the coupling capacitors C2 to C5: cheaper polyester foil from, for example, ERO or high-quality paper-in-oil from Jensen.

It is recommended to use 1 W/1% metal film resistors for anode resistors R4, R5, R11 and R12. That is because the larger dimensions of these resistors are better suited for dealing with high voltages.

Since this amplifier is implemented as a 'complete amplifier', the front panel has a power switch, input selector switch and a volume control. On the back of the enclosure you can add, in addition to the usual inputs and outputs, the switch for turning the negative feedback on and off, so that it becomes very easy to experiment with this.

Test results

With valve amplifiers it is customary to give the maximum output power at THD = 5%. Because this amplifier can also be used open-loop we assumed a
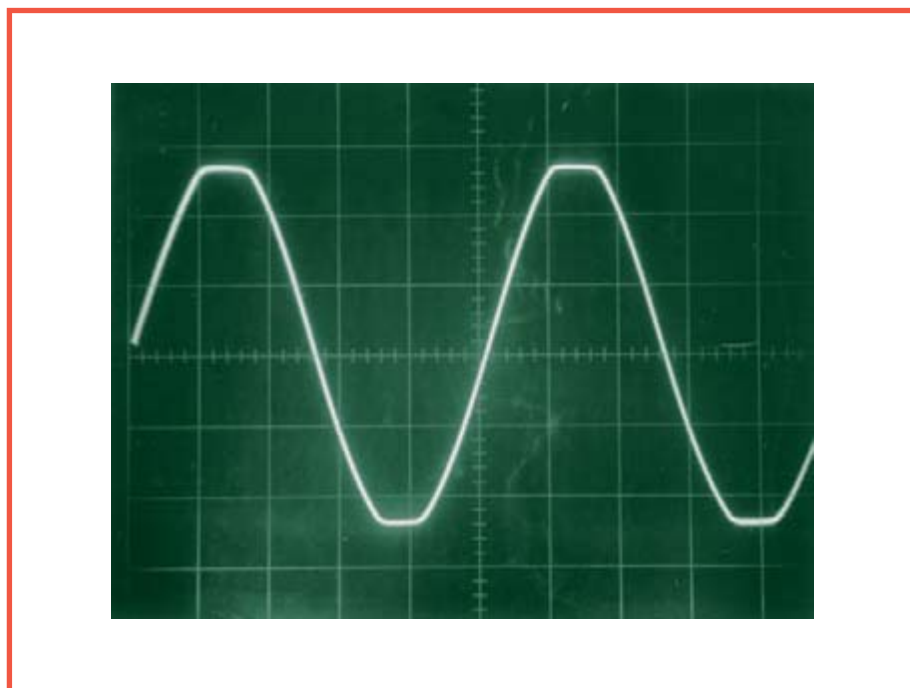

Figure 9. Clipping behaviour at 11 W/1 kHz (5 V/div.).

value of 2%. This value also corresponds to the limit before clipping occurs.

Figure 9 shows the soft-clipping behaviour at an output power of 11 W (5 V/div.). **Figure 10** shows the open-loop square-wave response at 2 kHz and 5 V/div.

It is of interest to note that this amplifier, because of the characteristics of the triode output stage, is open-loop stable.

Literature

[1] Lecture Notes on Electronics, Technical University Delft, 1957.

[2] Audio Frequency Amplifier Design, E. Rodenhuis, 1959 (reprinted by Audio Amateur Press, 1994)

[3] Electron Tube Handbook, Volume 1, Philips, 1964.

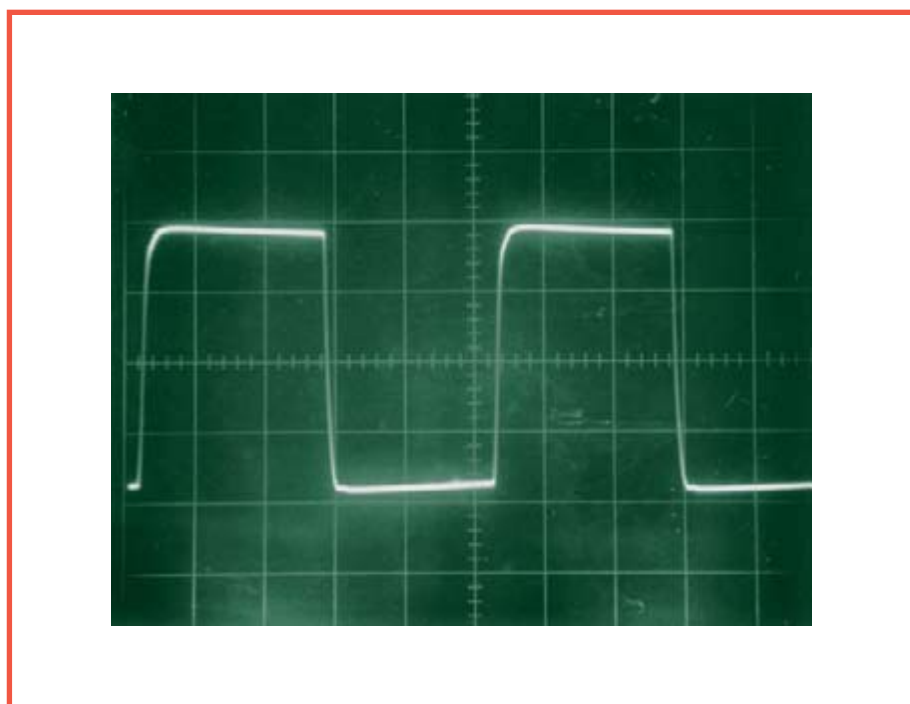[4] Audio Power Design Handbook, Douglas Self, page 9.

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Figure 10. Square-wave response without feedback (2 kHz, 5 V/div.).