Summary

This article collates information relating to hum and how it is caused within a valve amplifier.

Hum is the addition of any AC mains power related signal to the output signal of the amplifier. The main hum ingress mechanisms relate to valve heater powering, DC power supply ripple and noise, and electrostatic/magnetic coupling.

Most commercial valve amplifiers exhibit negligible levels of hum, due to careful design and manufacture. A faulty or failing part is the usual reason for objectionable hum appearing in a commercial amp.

Modifying an amp for higher gain can raise the awareness of hum, and lead to a search for the main hum source or sources, so as to suppress them. Vintage amps used inefficient speakers and poor quality signal sources, so they are likely to exhibit objectionable hum now, and hence benefit from improvement.

This article doesn't focus on signal sources connecting to an amp, or how best to connect those sources, and doesn't provide a step-by-step guide to eliminating hum, but may assist in tracking down causes.

Contents

Hum sources

AC mains power typically passes through a power transformer, with secondary AC heater windings providing heater power to all the valves, and a higher voltage winding used to provide B+ power to the amplifier stages. There are many possible ingress mechanisms for AC power related signals to couple in to the signal being amplified, and not from just internal to the amp.

Hum problems usually relate to three general ingress mechanisms:

- Valve heater powering
- AC to DC rectification, filtering and power distribution
- Electrostatic and magnetic coupling and layout

The hum signal typically includes specific frequencies related to the mains fundamental frequency 'f', including f (50Hz or 60Hz), 2f (100Hz), 3f (150Hz), and a smattering of higher harmonics at n.f (where n>3). Hum can also include other frequencies that are unrelated to f, but are related is some way to the AC powering process, such as inter-modulation of any signal frequency with a mains harmonic (ie. a form of vibrato modulation), specific circuit resonances, or even signals or interference borne on the mains AC system.

Valve Heater Powering

Each valve needs a heater to raise the cathode temperature sufficiently for it to efficiently emit electrons. For input stage valves, that typically places a 6V AC voltage in very close proximity to low mV signal circuitry. This section describes how AC heater power related signals can couple in to the amplified signal.

Directly heated cathodes

Early in the 1900's, valves were only available with cathodes that also functioned as the cathode heater. Filament was the term used for a directly heated cathode, but is also used for the heater in an indirectly heated cathode. As the cathode was in close proximity to the input grid, the heater AC voltage easily couples in with the grid signal, causing hum in the amplified output of the valve stage. A giant of the times, Terman (Radio Engineering, 1932 [1]) described four mechanisms that generate hum related signals for directly heated cathodes:

#1. Non-symmetric heater-to-grid capacitance between each end of the heater causing a difference current to return to the cathode via the grid leak resistor [2]. This mechanism is proportional to heater voltage and frequency components, grid leak resistance, and capacitances. Hum signal is predominantly at line frequency (=f).

#2. Magnetic field of heater current deflecting electron flow away from anode, due to the left hand rule. This mechanism is proportional to heater current. Hum signal is at twice line frequency (=2f).

#3. Voltage difference to ends of heater changing the amount of emission from the cathode at that end. This mechanism is inversely proportional to anode-heater voltage, and proportional to heater voltage. Hum signal is at twice line frequency (=2f).

#4. Inter-modulation of any input signal by the hum signal.

A humdinger can usually reduce #1 hum to a negligible level. Measurements have shown that #2 hum is very low [3]. Mechanism #3 appears to be the significant hum issue observed in amps.

Although the hum signal is predominantly related to the mains frequency (either the fundamental frequency f, or twice the fundament = 2f), the heater voltage often has a significant level of waveform distortion (both from the incoming mains voltage waveform, and from the transformer impedance interacting with the B+ rectifier current pulses), which means higher frequency harmonic components may be available to couple in as well.

Nowadays, one continued use of directly heated valves is in hi-fi with DHT (directly heated triode) valves like the 2A3, 45 and 300B, but only for the output stage. Even in the output stage, hum ingress can be noticeable, and many have used DC powering of the heater to side-step the issue of hum with those valves.

Figure 1.

Indirectly heated cathodes

The change to indirectly heated cathodes in the 1930-40's has had the following influences on hum generating mechanisms #1-3:

#1. The cathode, which is now a separate tube encasing the heater, minimises the difference in capacitance between the heater ends, and the grid, as the majority of the heater length now has effectively the same voltage as seen from the grid, due to the cathode acting as a shield. Each unshielded end of the heater forms only a small stray capacitance to the grid.

Philips 12AX7 datasheet [4] indicates grid-to-heater capacitance is no more than 0.15pF, however a similar valve like a 12AT7 has a 2.5pF specification. The EF86 has an even lower grid-to-heater capacitance specification of no more than 0.0025pF, due to careful shielding of the heater wiring. A humdinger can usually null out any residual capacitive imbalance, so this mechanism is easily managed. Dual heater valves (ie. 12AX7) typically have a physically large 'centre' tab (pin 9), and this significant asymmetry may be noticeable when comparing hum from 6V versus 12V heater configurations.

#2. The loop area of the heater that causes a magnetic field to extend into the main electron path between cathode and anode is minimised. The closely folded ‘U’ shaped heater wire within the cathode will generate some stray field due to asymmetry of the wire, and whether the wire is single ‘U’ or double helix, and any such stray field is very close to the electron path, and only partly shielded by the cathode. The base section of the heater has a much more open loop area, and the loop area depends on the pinout arrangement of the valve.

The 7025 valve (12AX7 equivalent) was introduced in 1958 with a double-helix spiral wound heater filament to reduce this hum generating mechanism compared to previous heater types. Not only does the filament form a ‘U’, it also twists the filament wires along the length of the ‘U’. The EF86 also uses this filament type, and keeps heater pins (4,5) and internal supports close together, and includes a shield around the heater.

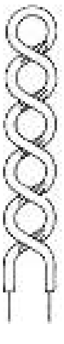


Figure 2.

#3. The ends of the heater (external to the cathode shield) that are capable of emission to the anode are quite short and often isolated from the anode by a mica spacer. Also, improvement in cathode emission efficiency has meant that any residual heater emission has a diminished effect.

However, an indirectly heated cathode introduces two new hum generating mechanisms.

#5. The heater and the inside of the cathode shield tube form a capacitor, and hence ac voltage variation between portions of the heater and cathode will cause a capacitive current to flow.

The total capacitance from heater to cathode for each triode of a 12AT7/ECC81 is 2.5pF, which is likely to be similar to 12AX7. Only part of that capacitance couples hum current from heater to cathode, depending on the AC voltage developed along the length of the heater-to-cathode interface, and dissimilar distance of heater wire to the cathode wall along the length of the ‘U’. Similar to #1, a humdinger or centre-tap effectively nulls any dissimilar capacitive AC current flowing to the cathode along the length of the heater ‘U’.

#6. The heater and the inside of the cathode shield tube are not made of highly emissive material, but a hum current still flows between them due to emission and the absolute voltage variation between portions of the heater and cathode during the heater AC voltage cycle.

This hum current flows in a typical cathode biased circuit to the ground return for both heater and cathode power supply circuits. The voltage difference between heater and cathode has a significant impact on the emission flow. Terman [1] plots the current-voltage curve characteristic for two surfaces in a vacuum where one surface is sufficiently hot (ie. the hot cathode in a diode valve). When the heater-cathode voltage differential is low, the resistance is relatively low with operation of the two electrodes in the space charge limiting region (similar to the normal on-voltage region of a diode valve). But as the voltage difference exceeds 5-10V then the resistance increases as voltage saturation sets in and all electrons emitted from the negative electrode are collected at the positive electrode.

In 1936, Klemperer [5] measured this heater-cathode resistance for a number of different valves. For a heater and cathode with negligible impurities, the resistance characteristic is somewhat symmetric around 0V, with the role of 'cathode' and 'anode' electrodes swapping between the heater and the cathode tube - as both electrodes are equally hot and have similar emission when acting as a ‘cathode’. Kock [36] summarises the influence heater bias in the extract shown in Figure 3.

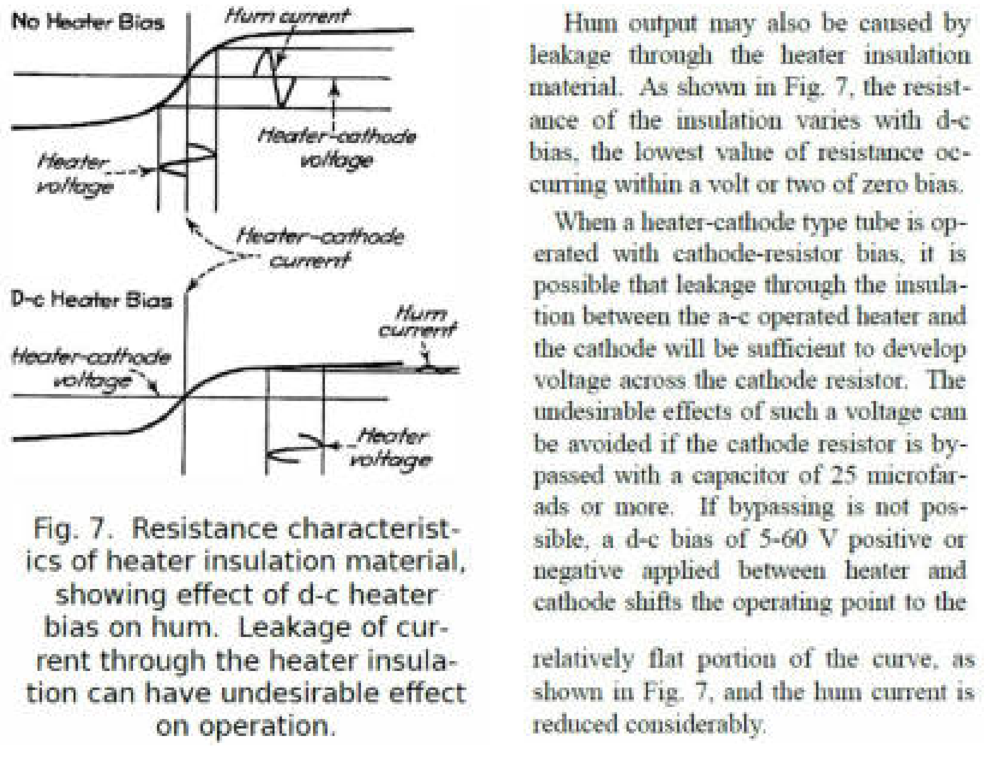


Fig. 7. Resistance characteristics of heater insulation material, showing effect of d-c heater bias on hum. Leakage of current through the heater insulation can have undesirable effect on operation.

Hum output may also be caused by leakage through the heater insulation material. As shown in Fig. 7, the resistance of the insulation varies with d-c bias, the lowest value of resistance occurring within a volt or two of zero bias.

When a heater-cathode type tube is operated with cathode-resistor bias, it is possible that leakage through the insulation between the a-c operated heater and the cathode will be sufficient to develop voltage across the cathode resistor. The undesirable effects of such a voltage can be avoided if the cathode resistor is bypassed with a capacitor of 25 microfarads or more. If bypassing is not possible, a d-c bias of 5-60 V positive or negative applied between heater and cathode shifts the operating point to the relatively flat portion of the curve, as shown in Fig. 7, and the hum current is reduced considerably.

Figure 3. Extract from [36], by D.G. Kock, 1952

The advantage of elevating the heater to a DC voltage, typically +20 to +60VDC, can now be appreciated, as the resistance between heater and cathode is at a much higher value compared with the low changing resistance when there is no heater elevation. Even when the ac heater voltage swings from peak to peak, the absolute voltage difference between a part of the heater and cathode is going to biased well away from near the zero volt region due to the elevation voltage. Some circuit configurations inherently elevate the cathode voltage by a substantial positive level, such as a cathode follower stage, a cathodyne/split load PI stage, and a cathode biased output PP stage. With the cathode elevated, a heater at 0V is negative, which is likely to be just as effective, but the issue of heater-cathode voltage breakdown within an amplifier usually dictates the need for a positive heater elevation.

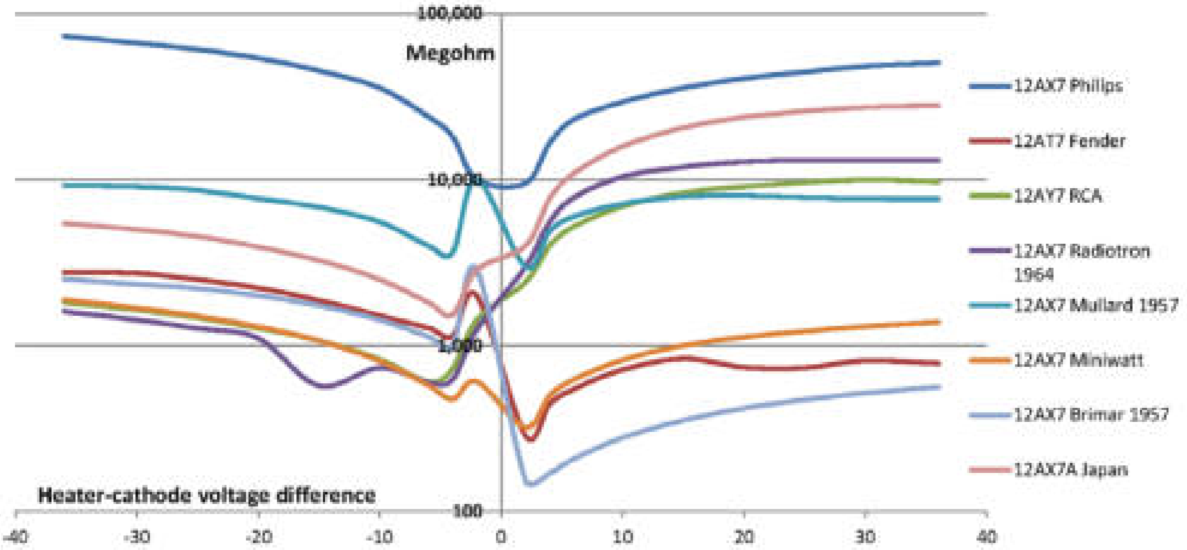


Figure 4. 12AX7 heater-cathode resistance.

Measurement of heater-cathode resistance for a batch of ten old 12AX7 from a variety of manufacturers shows the variation to be expected [6]. Some samples show generally low resistance, whilst others are eminently high. Some samples show symmetry around 0V, whilst others have higher resistance when negative biased or positive biased. All samples measure total h-k resistance of > 100MΩ, and many were > 1,000MΩ. The variable response at 0V bias is partly due to measurement resolution and the decay/polarisation effect due to changing a static test condition, but may also be due to non-zero electron emission current at 0V [7].

Many forum threads indicate that the TungSol re-issue 12AX7 consistently exhibits hum in preamp stages, which can be alleviated by heater DC voltage elevation.

A 1957 patent [8] focussed on the heater 'burn-in' process used during tube manufacture. The data showed that 12AT7 heater-cathode resistance at ±100VDC was > 600MΩ for nearly all valves after aging with the patented technique, but normally there may be a significant percentage of valves in the range 10M - 300MΩ. Of interest is that the technique may be capable of restoring a poor or degraded valve.

In general, life test studies have shown that heater-cathode leakage level increases with operation, due to migration of impurities. Large batch studies have also shown that leakage levels can vary between samples by up to 100:1, and that is likely due to the distribution of impurities in the aluminium oxide insulation, and due to variations in the degree of heater contact along the cathode tube length.

Some old moulded valve bases can have relatively low material resistance, and reduce pin-to-pin resistance to just a few MΩ. However, a typical non-black socket from ≥ 1960's would present pin-pin resistance in excess of 10,000MΩ, and ceramic or ptfe should achieve 10x higher [9].

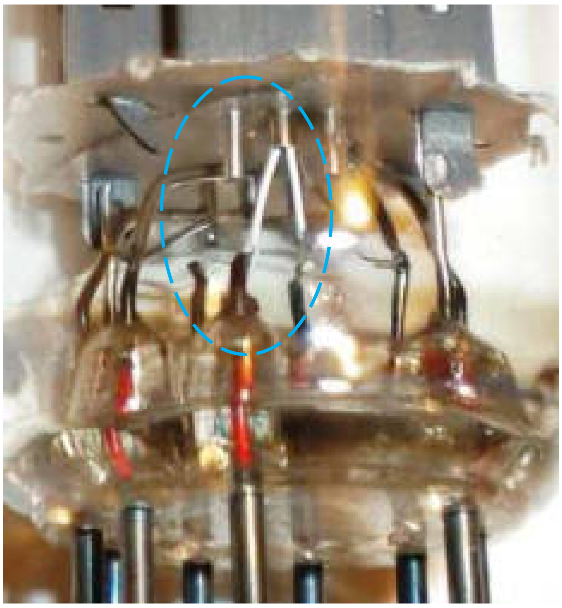


Figure 5. Heater loop entering cathode in 12AX7.

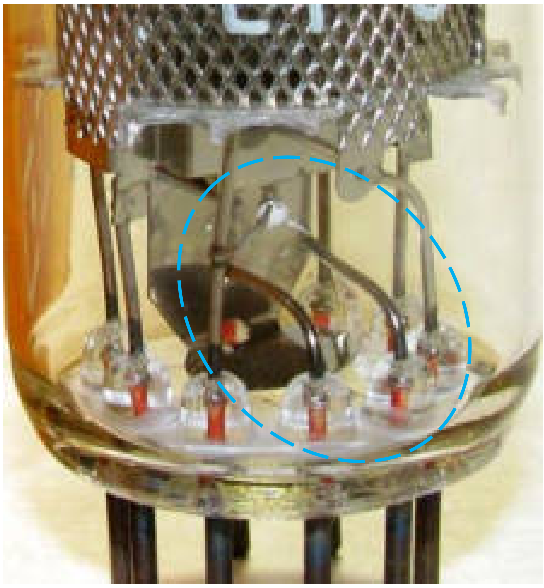


Figure 6. EF86 heater pins 4,5 with screen behind, above and below.

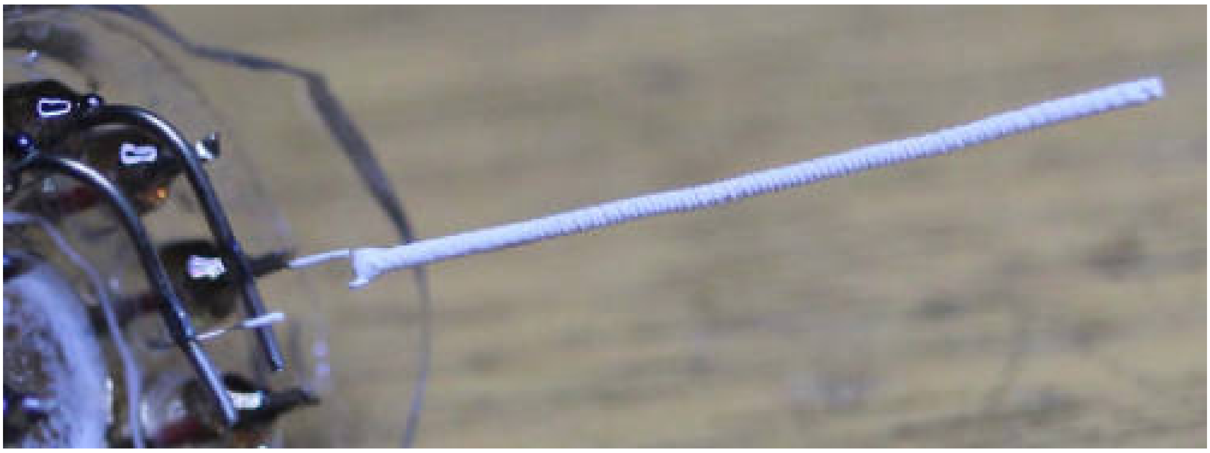


Figure 7. EF86 double helical heater.

Hum ingress in an input triode stage

The following table summarises the heater hum coupling paths in to an indirectly heated triode amplifier stage.

Hum mechanism	Main contributors	Hum ingress voltage	Main solution
#1 (heater capacitive coupling to grid)	C_{h-g} (heater to grid capacitance) Z_g (input source impedance) heater ground path heater driving voltage	V_g (grid voltage)	Humdinger
#2 (em coupling)	Heater wiring loop area and current	Nearby receiving loop	Wiring layout
#5 (heater capacitive coupling to cathode)	C_{h-k} (heater to cathode capacitance) Z_k (cathode impedance) heater ground path heater driving voltage	V_k (cathode voltage)	Humdinger
#6 (heater resistive coupling to cathode)	R_{h-k} (heater to cathode resistance) Z_k (cathode impedance) heater ground path heater driving voltage	V_k (cathode voltage)	Humdinger

Table 1.

The diagram in Figure 8, from [10], illustrates the hum current paths related to mechanisms #5 and #6 in a circuit with a humdinger. The equivalent circuit makes it easier to follow the two main hum current paths, but is just a very simplistic representation of a much more complex layout formed by a ‘U’ shaped heater inside a cathode tube.

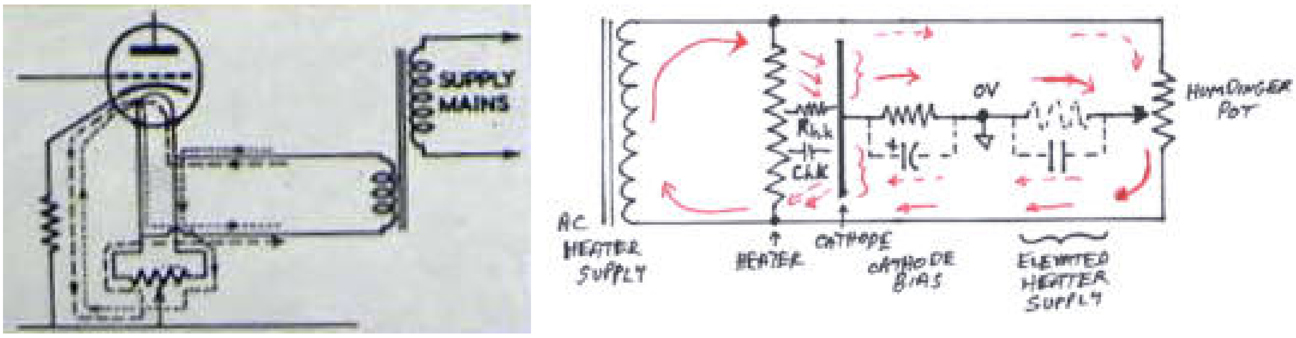


Figure 8. Humdinger equivalent circuit.

The heater voltage is a sinewave, and when one end of the heater winding voltage is different from the other end, current flows directly through the heater resistance, and directly through the humdinger pot resistance, and back to the heater supply winding. However, there are also parasitic hum current paths, as shown by the current loop arrows. One hum current path is shown as passing through the top half of the heater resistance, and seeping across the heater-cathode interface via net local contributions of C_{h-k} and R_{h-k}, and then passing through the cathode bias impedance to 0V, and through any heater elevation supply if used, and returning through the bottom half of the humdinger to the other end of the heater supply winding. The second (dashed) hum current path is shown as passing through the top half of the humdinger, and through any heater elevation supply if used, and through the cathode bias impedance and seeping across the lower half of the heater-cathode interface via net local contributions of C_{h-k} and R_{h-k}, and returning to the other end of the heater supply winding.

The resulting voltage across the cathode impedance caused by those parasitic hum currents represents the hum ingress signal. Tuning the humdinger pot can equate the hum current levels through the cathode impedance, and null the net current, and hence null the hum voltage. A null may not be achieved with a CT, or simple humdinger, or even with a humdinger pot due to irregularities like heater voltage waveform distortion. Any remnant hum signal depends on the voltage available to drive hum current, the impedance of the hum current loop, and the impedance of the cathode bias element. The impedance of the loop is dominated by the effective (net) values of C_{h-k} and R_{h-k}, which are higher in impedance than the base values as only part sections of the heater length are implicated when there is a net imbalance. Bypassing the cathode bias resistor can substantially reduce any remnant hum, and would certainly tame higher frequency mains harmonics.

Grounding the cathode would require either using a high resistance grid leak, or a fixed bias connected to the grid. Capacitive coupling to the grid would be more noticeable with the grid leak, although a tuned humdinger may be able to effectively null that hum.

Baxandall also investigates hum in a cathode biased triode input stage in a 1947 WW article on high-gain amplifiers [11]. The article illustrates the lowering of one aspect of the hum waveform by elevating the heater to +4.5VDC. In general, it should be better to AC bypass (ie. capacitor filter) the elevated DC supply, although Baxandall doesn't include this in his preamplifier circuit.

Screening between the heater and grid is enhanced within the valve socket by using a socket with a central spigot, and grounding the spigot. If needed, additional small screens can be soldered to the spigot to provide enhanced shielding around the grid pin, and even anode pin [12].

Even in dual triodes, the internal arrangement of pins and wiring used for each triode are subtly different, and Philips ECC83/12AX7 datasheets recommend using the triode with pins 6,7,8 to achieve a lower hum.

Figure 9. Socket with spigot & collar

Older octal input valves with a grid top-cap will have lower hum coupling to grid from the heater, but are more susceptible to hum picked up from transformer stray fields (valves like glass envelope 6J7 usually came with split-metal covers). Many vintage amps did not use shorting signal input sockets, so hum is to be expected unless the socket is upgraded.

Heater to anode capacitive coupling can be a concern due to pin assignment (given that heater to grid coupling is screened by other pins). A 6AU6 pentode application note makes g2 the anode, and ties anode and g3 to cathode, so as to provide balanced screening of both grid and g2 from the heater [13].

If hum is not significant, then just one side of the heater need be grounded (preferably a heater pin that is the next pin to a control pin on the input valve), and bypassing each heater with a capacitor may attenuate higher frequency harmonics.

If heaters must be connected in series, then ensure the heater of the input stage is at the ground end of the series string, otherwise the heater will have a higher AC voltage swing around ground than normal.

Feedback around a stage that mixes the input signal with the feedback signal will attenuate hum that ingresses within the stage, but not hum that couples in with the input signal.

Neutralisation

Neutralisation can be used to null out a hum signal by carefully mixing in to the amplifier the same hum signal but opposite in phase. The mixing needs to be done close to the point of hum ingress, and preferably before the phase of frequency components in the hum signal are modified by any amplifier stage filtering (eg. low pass filters or tone controls).

From the 1940's, the most common form of neutralisation is the humdinger. With directly heated tubes in the output stage, a humdinger pot is typically used to obtain a better null than relying on the heater winding centre-tap. Similarly, for preamp stages, a humdinger pot allows subtle differences in wiring and tube pin layout to be neutralised by altering the level of signal reaching the grid from each side (or phase) of the heater AC signal. Often only the heater powering the preamp valves used a humdinger pot, as shown in the 1949 Williamson 807 clone circuit from Radio-Electronics.

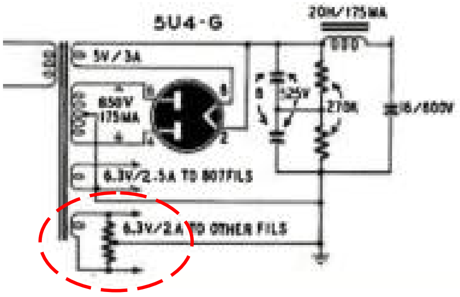


Figure 10. Humdinger pot.

In some situations, a local hum source is introducing hum in to an amplified signal. One of many techniques used in the 1940-50's to neutralise hum caused by B+ ripple was to feed back some B+ ripple to an input stage grid, or screen (as in the example circuit in Figure 11 [14]). That feedback signal is specific to the stage and amp, and may or may not neutralise the net effect of other hum contributors (perhaps generating phase shifted hum signals). For the simple Silvertone 1431 SE amp, C_1 was also used to neutralise output stage hum.

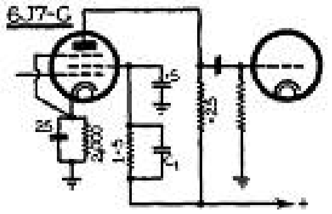


Figure 11. Neutralisation.

In an amplifier with an SE output stage, where the B+ supply has significant ripple voltage, a portion of the output transformer (OT) primary winding (YEL-RED) can be used as a choke to filter the B+ for screen and preamp stages, as shown in Figure 12.

The DC current through that YEL-RED winding is used to offset the DC idle bias current in the SE output stage (allowing a higher audio throughput from the OT before core saturation starts).

The ripple voltage across that YEL-RED winding neutralises the ripple voltage appearing across the output stage plate YEL-BLUE primary winding.

Feedback would attenuate the ripple introduced in to the output stage, as any power supply introduced ripple voltage appearing across the speaker would appear as a ‘distortion’ component within the feedback loop.

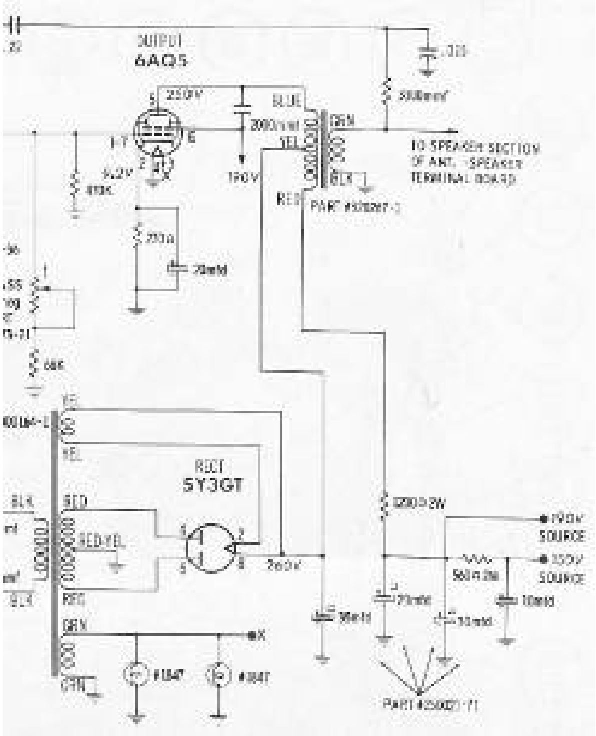


Figure 12. Single ended output transformer with integrated choke winding

AC used for Powering

Rectifying the AC voltage from a power transformer secondary winding generates an AC waveform with a DC level. Power supply filtering aims to attenuate the AC waveform component, to just leave a DC level to distribute to the amplifier stages. However the high level of AC power flowing within the rectifier and filter circuitry makes it difficult to lower the level of AC ripple on the DC supply to negligible levels before it is passed to amplifier stages. The distribution of DC power attempts to further lower any residual AC ripple voltage, but also has the role of isolating the AC signal currents to just the stage being powered.

AC to DC Rectification

A full-wave diode rectifier produces an output voltage waveform comprising a train of half-sinusoids.

The waveform has a DC level to generate the B+ DC supply.

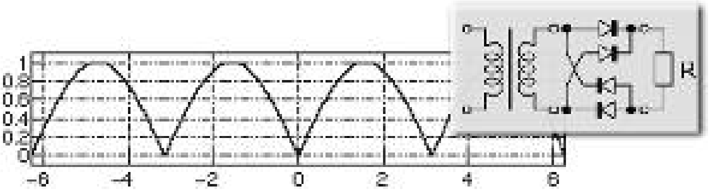


Figure 13. Rectifier voltage waveform.

Without any filtering, the AC voltage V and current passed to the load resistor R has harmonic levels of $V/(n^2-1)$, and $V/R(n^2-1)$, where n=2,4,6... (ie. only even harmonics of the mains frequency) [15]. Levels of the low order harmonics are high, although levels of higher order harmonics drop off rapidly, but do extend throughout the audio range.

Any mismatch in the power transformer windings for a HT-CT-HT arrangement (eg. winding DCR differences), or between the diodes (especially valve diodes), can cause some fundamental (n=1) frequency level to also pass through. Coupling of ripple frequencies in to the amp can be a major contributor of hum, and so filtering of the rectified waveforms is needed.

The disadvantage of a common silicon rectifier diode like a 1N4007 is that it can allow some current to flow in the reverse direction when the diode is turning off, which causes a short transient current pulse to circulate at twice the mains frequency. A simple alternative is to use UF4007 diodes, as they reduce any reverse transient to a much lower level.

The extent of reverse recovery in a solid-state pn junction diode is very dependent on the rate of current change (dI/dt) at the time of turn-off, and the level of forward current being conducted just prior to turn-off. Although the current waveform plots to the right [16] are for a high current diode, they are illustrative of the influence of dI/dt (top plots) and forward current level (bottom plots) on the extent of reverse recovery current. Reverse recovery is a major issue for switchmode power supplies, where dI/dt (A/us) and current levels (A) are typically much higher than in a mains rectified power supply.

For a valve amp B+ supply, the current in the diode at the time of diode turn off has fallen back to the load current level (eg. ~100 mA or so). That current reduces to zero in the time it takes for the voltage waveform to drop about 1V (the diode on-voltage).

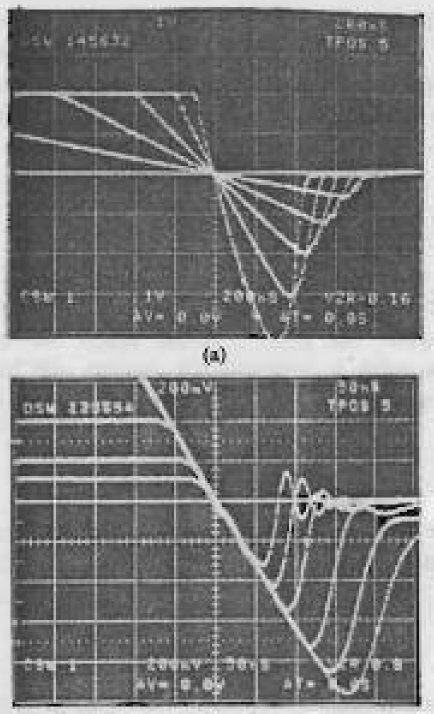


Fig. 3. (a) Family of recovery waveforms for a 490-V structure. The ramp rate is varied (10, 25, 50, 100, and 200 A/μs) with the forward current fixed at 20 A. (b) Waveforms for the 200-V device. The forward current is varied for each measurement (1, 2, 10, 25, and 60 A) but the ramp rate is held fixed (66.7 A/μs).

Figure 14. Solid state diode reverse recovery.

For a PT secondary 240VAC 50Hz sinewave, the voltage changes about 1V in at least 10μs, so dI/dt is in the region of 0.1A/10μs = 0.01A/μs (ie. much lower than a typical switchmode power supply).

In circuits with higher supply current (such as a heater DC supply, or a doubler rectifier for B+ in a high power amp), the transient disturbance caused by a diode turn-off may force a noticeable damped resonant current to flow in the power transformer secondary winding – that resonant waveform has a fundamental frequency related to circuit components, but is also repetitious at 2f. A snubber circuit connected directly across the power transformer winding [21] is recommended to direct the transient winding leakage inductance energy through a minimised loop area, and to dampen the resonance quickly, rather than allow the transient energy to find other ill-defined pathways. Nowadays, fast recovery diodes typically alleviate the need for snubbering.

A valve vacuum diode has no ‘reverse recovery’ effect, and so the forward current reduces to just zero, with no negative excursion. In addition, a valve diode’s incremental resistance (r_p) increases smoothly and significantly as the plate current level approaches zero, such as shown in the plot for a 6H6 diode [17].

This smooth change in resistance characteristic substantially alleviates the dI/dt in the transformer winding and associated circuitry at the time of diode turn-off.

As such, there is usually no need to add snubber circuitry across power transformer windings. If a snubber is added, then a simple shunt capacitor of low value (1-10nF) may be effective, as the series resistance of the high voltage winding is typically 100-300Ω and hence provides sufficient dampening.

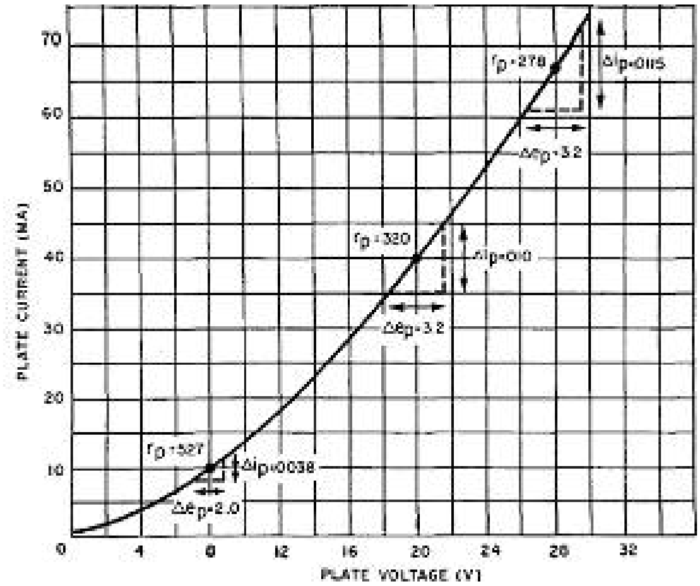


Figure 15. Valve diode V-I curve.

The relatively large on-voltage of a vacuum diode (compared to a solid state diode) also reduces the peak current level during diode conduction, and hence substantially changes the shape of the diode current waveform (lower crest factor, and longer conduction time). Such a waveform has lower levels of higher order harmonics, and hence allows easier filtering of AC from DC.

Filtering AC from DC

For a B+ power supply with a choke input filter, the AC voltage at the output of the diode rectifier is applied across the choke. This choke filter is actually an LC filter, which increases attenuation of ripple frequencies, especially the higher order harmonic frequencies. However typical power choke impedance starts falling above a few kHz due to self-capacitance within the winding, so the attenuation rate of harmonics then slows down for the remainder of the audio range.

Capacitors and chokes do not present zero or infinite impedance to harmonic current flow across the audio range. The choke has a finite inductance, and with the output filter capacitance, the output ripple voltage is mainly mains second harmonic, as the higher order harmonics are more effectively attenuated.

A typical vintage 10-14H choke with DC current rating of 60-125mA has an increasing impedance with frequency to about 3-5kHz, above which the self capacitance of the winding starts to lower the effective choke impedance.

Electrolytic capacitors exhibit a falling impedance at low frequencies, and then a near constant low impedance over a wide range of frequencies, before finally increasing due to parasitic inductance. The 180uF 400V capacitor impedance curve (coloured blue in **Figure 17**) indicates the impedance is still falling up to about 10kHz. Valve amp filter capacitors are often only up to 50-100uF, so will have an impedance curve positioned higher, and the lowest impedance part may not go much below 1Ω. Radial electrolytic capacitor packages have very low internal inductance, with capacitor impedance remaining low up to near 1MHz. Paralleling an electrolytic capacitor with a poly or ceramic capacitor is not recommended, and can introduce high Q changes in impedance at higher frequencies.

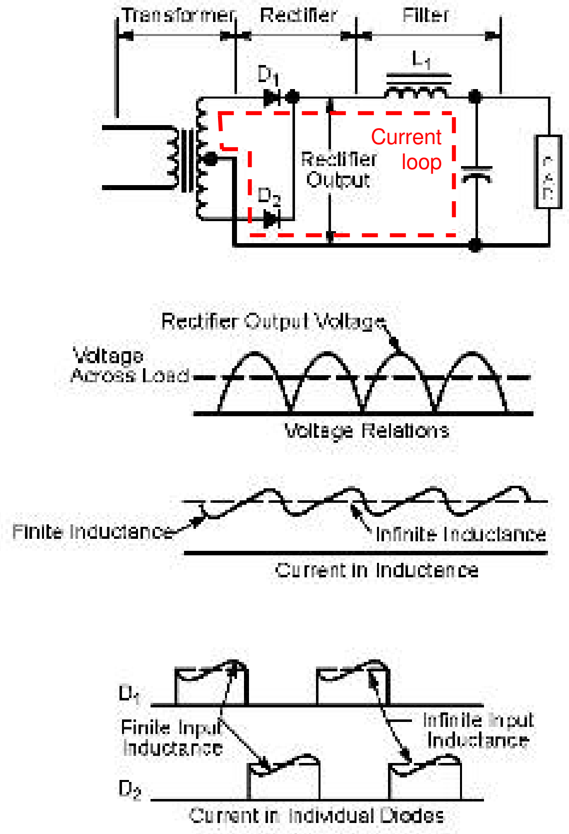


Figure 16 Choke input filter. [Rectifier applications handbook HB214/D]

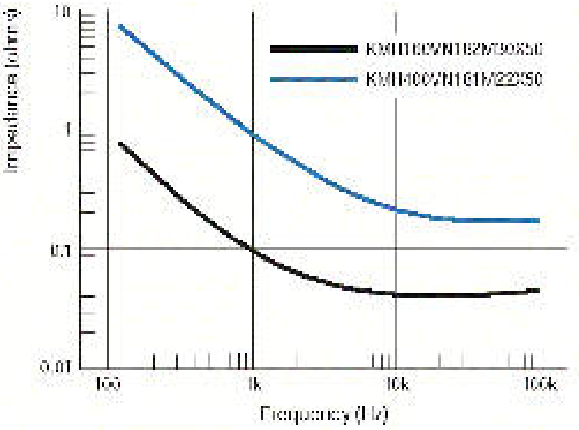


Figure 17. Capacitor impedance.

In practise, caution is required when choosing electrolytic capacitors due to the low ripple current rating of small uF value parts, and due to the high peak voltage that can arise at power on. Ripple current can be determined using PSUD2. Many amplifiers require two capacitors connected in series, with parallel divider resistors, to cope with the high B+ voltage.

Although the current through the choke is nearly constant, choke current commutates from one transformer half-winding to the other half-winding abruptly as the diodes turn from off-to-on, and on-to-off. This commutation can cause large transient voltages at the diode-to-choke connection point that need to be carefully managed [18]. A low value shunt capacitor is normally used before the choke, to provide a smaller current loop for high frequency noise resulting from commutation dI/dt and the circuit inductances. A tuned snubber across the HV winding may also alleviate commutation noise [21].

The distributed nature of a vintage power transformer's secondary winding leakage inductance, inter-winding capacitance and significant resistance can mean there is negligible benefit to adding a snubber circuit across the winding (or half-windings to a CT), especially when using valve or fast-recovery ss diodes.

Chokes are preferably placed in the non-grounded side of the filter (eg. positive side), as noise will bypass a choke from CT to ground via the transformer's secondary winding capacitance to ground [19].

If possible, connect the diode end wire to the choke terminal that connects to the innermost core winding layer, so that the outermost winding layers are at the near constant load DC voltage, so as to minimise local capacitive coupling. Similarly, the transformer winding leads to the diodes need to be carefully managed.

For a B+ power supply with a capacitor input filter, the current waveform through each diode and the filter capacitor has a high harmonic content, extending throughout the audio range. As the capacitor has a finite capacitance, the output voltage has a ripple voltage comprising mainly the mains second harmonic, with the capacitor providing increased attenuation of higher order harmonics seen by the load (although not as effectively as a two stage LC filter).

The high level of harmonic currents can cause hum through magnetic field coupling from the wiring loop around the diodes and filter capacitor and return to transformer.

Due to the high current pulses through the filter capacitor, any parasitic resistance and inductance within the capacitor (known as ESR and ESL) and up to the points of connection to the load, will cause the DC voltage passed to the load to have additional AC rectifier noise voltages as well as the AC ripple voltage.

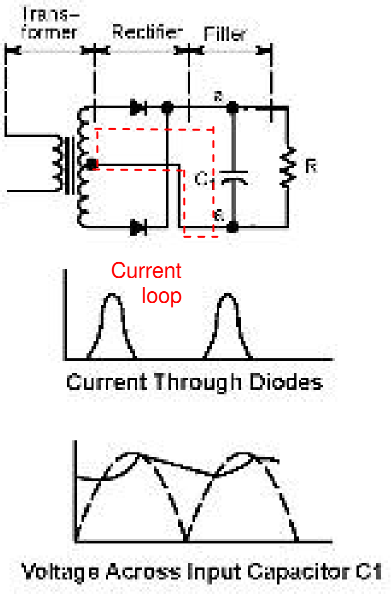


Figure 18. Capacitor input filter.

Additional passive filtering stages are typically used after the first main filter capacitor, to reduce the ripple voltage to a level compatible with the amplifier design and the circuitry being powered. Vintage amps often used star connected RC stages, as in Figure 19. Nowadays, RC filter stages are typically connected as a ladder, with the resistance in each filter stage causing a step down in B+ voltage applied to each circuit stage moving back to the input stage.

When the supply decoupling capacitor for each stage is large, and the AC signal current is relatively small compared to the idle DC bias current through the valve, then the current flowing in the 0V ground lead between stages has almost no AC current due to power distribution.

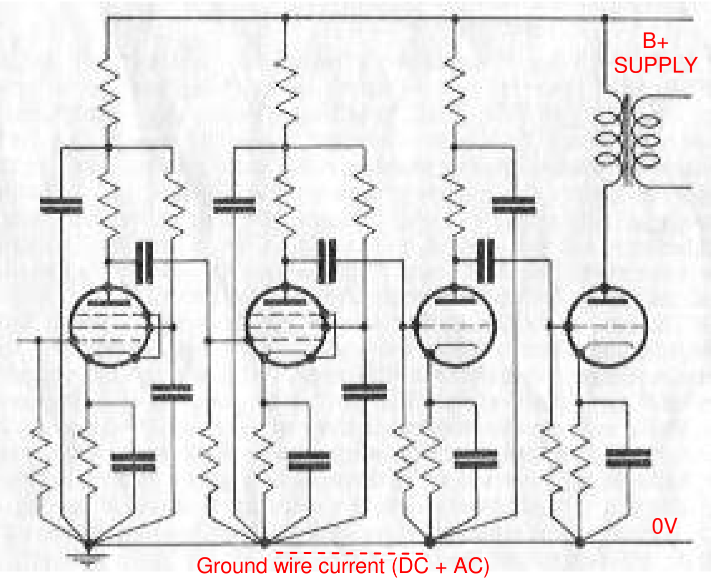


Figure 19. Star connected RC stages [17]

Any AC current flowing in the 0V ground wiring between stages will cause a small AC voltage across the ground wire resistance. Ensuring the ground wire has low resistance, and is as direct as possible, minimises any hum or signal leakage voltage from adding to the previous stage signal voltage that is being coupled to the next stage.

A high level of ripple voltage can be accommodated in the B+ supply powering a push-pull output stage (output transformer centre-tap), as the symmetry of the push-pull circuit effectively nulls that common ripple voltage when the amp is in idle and operating linearly in class A. Trimming the DC bias current in each push-pull valve may null output hum from the output stage, which can result from ripple voltage and the mismatch differences in valve trans-conductance and output transformer windings.

Additional active filtering is another means to attenuate power supply ripple voltage. A few vintage amps used a regulator circuit – some designs regulated the main B+ supply, whilst some just regulated the screen voltage supply, due to its sensitivity to ripple, and its lower power requirement. Nowadays, regulators can be made much more simply, and with better performance, using solid-state power devices like a power FET, without the need for an additional heater winding and valve socket. For hi-fi amps that aim to replicate datasheet operating conditions, such regulated supplies are very appropriate.

For guitar amps, the sag characteristic of an unregulated power supply is almost mandatory. One method to lower the level of power supply ripple during idle conditions (when hum is most noticeable), but retain the sag and ripple characteristic during signal amplification, is to use a 'top-up' regulator that adds just enough current in to the main filter capacitor in the ripple valleys to suppress the ripple voltage. The top-up regulator sources power from the common 5V rectifier heater winding, and dc/dc boosts it to a rail sitting above the B+ supply, and a power FET then linearly controls the current added to the B+ filter capacitor so as to fill in the ripple voltage 'valleys' [22].

Power Distribution

Managing hum when distributing power around an amplifier requires an understanding of how and where current flows. Within each amplifier stage that uses DC power, AC signal current will loop around the supply decoupling capacitor and the valve, as indicated by the red dashed lines in the schematic in Figure 20.

The impedance of the supply decoupling cap needs to be small compared to the power distribution resistances that connect to and from other stages, in order to minimise AC signal current passing between stages and causing positive feedback. 'Motorboating' is when positive feedback causes a slow oscillation, and often occurs in old amps when an electrolytic decoupling capacitor has degraded. As the decoupling capacitance reduces, the capacitor impedance increases, especially at low AC frequency. For example, a new 20uF 400V supply capacitor would have an impedance about 10x higher than the 180uF example in Figure 15, with the capacitor impedance rising to about 10kΩ impedance at 1Hz - the power distribution dropper resistor values are likely to be of similar resistance. In an RC ladder form of distribution, the dropper resistor value typically increases along the ladder towards the input valve, as less DC current is consumed.

The highest AC current in an amp occurs in the rectifier diode loop (or loops). The next most significant loop would be the output stage.

Merlin Blencowe provides a great presentation on grounding [24], including nice drawings of multiple star grounding. R.G. Keen provides a nice schematic of star grounding a valve amp [27]. Radiotron Designer's Handbook 4th edition [28] has a few technical discussions that are well worth reading.

The awareness of hum in high fidelity amplifiers grew through the 1940's, and books such as Briggs & Garner [25] were showing the use of local star grounds, compared to the common practise of soldering to the nearest convenient chassis location, or a multiple grounded heavy gauge bus wire meandering around the chassis.

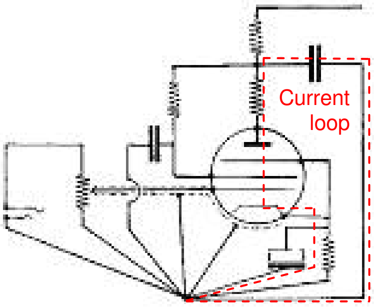


Figure 20. Local star grounding [25]

Mains side ingress

The mains AC voltage waveform couples over to the power transformer secondary voltage waveform through normal transformer action. Although a power transformer frequency response is usually not as good as an output transformer, it is certainly in to the kHz. In addition, higher frequency signals can couple from primary to secondary via capacitive coupling.

The example spectrum shows the no-load secondary voltage of a 10VA transformer – odd-order harmonics are about 35dB below the fundamental – due to the local flat-topped waveshape of the mains.

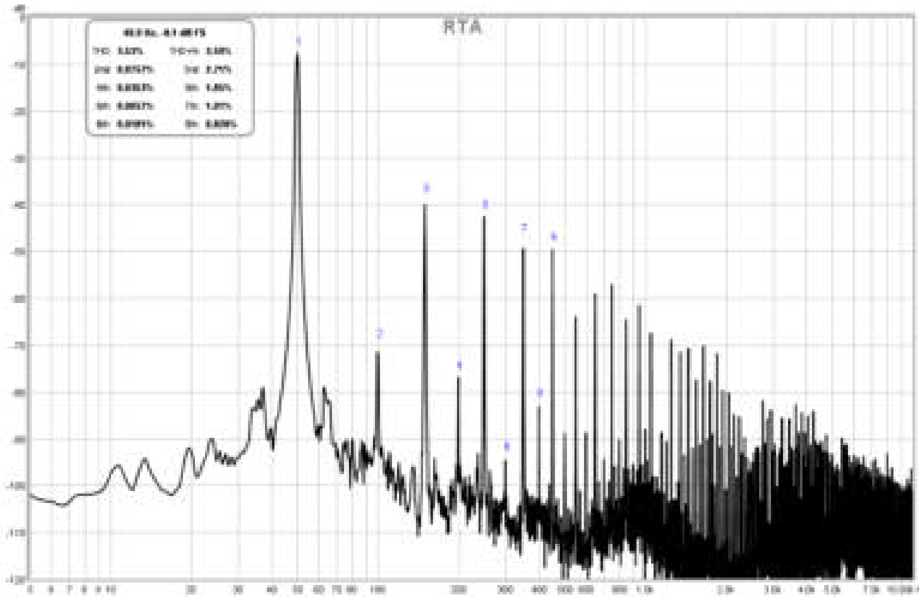


Figure 21. Mains voltage spectrum using REW V5.1 software.

Some power transformers come with a single electrostatic screen, which forces capacitance coupled signals from the mains side, as well as signals from the amp side, to pass just through the shield connection to chassis ground, and not transfer to the other side. The screen is benign to low frequency 'noise' coupling.

The signals in the screen wire from the amp side include:

- mains frequency from the secondary HT winding (usually placed next to the screen layer). That HT voltage is large, but the frequency is low, so only a minor screen current flows to chassis, and then back through the chassis-ground link, and then back to the winding CT (in a typical full-wave CT configuration).
- Mains harmonics and any rectifier resonant frequencies. Those voltages are relatively low, but as their frequency increases, then so does the capacitive current flow.

If the screen wire current is significant, then it would be better to connect the screen to a star ground point close to the power supply, and possibly better to make the chassis-ground link at the same point (so that mains side screen current doesn't flow in the amplifier side ground).

External interference conducted by the mains AC wiring is preferably shunted to chassis as quickly as practical, with a short direct connection of the screen wire to the star ground that is directly connected to chassis (ie. trim the screen wire to length, rather than coil any excess length).

B+ ripple transfer to speaker output

A push-pull output stage presents the B+ ripple voltage across each half-primary winding of the output transformer. At idle, an output stage valve presents a resistance of circa 10kΩ (eg. 300V/30mA to 500V/50mA), and a half-primary winding presents an inductance of circa 10-25H (eg. 6-15kΩ impedance at 100Hz). So about 70% of the B+ ripple voltage will be presented across each half-winding. The symmetry of the OT half-primaries, and the general matching of valve idle currents, will typically null out the hum voltage seen at the speaker winding. In addition, any feedback from the speaker output around the output stage would further reduce that residual hum.

A single-ended output stage simply transforms ripple voltage on the primary winding over to the speaker secondary, with no ability to null the ripple signal. The output transformer primary inductance will typically be much lower, to allow a DC bias, so less ripple voltage will appear across the primary winding.

Output transformers can have significant coupling capacitance from primary to secondary, due to the interleaved winding design, of hundreds of pF. However at 100Hz, a 500pF impedance is about 3MΩ, so very little primary side ripple voltage will appear across the speaker resistance. Even 10kHz noise on B+ would transfer little signal, even though speaker impedance can increase substantially.

Powering heaters from a DC supply

DC powering the heater of the input valve(s) can remove a number of opportunities for hum ingress.

A method used in some vintage amps is to make the input valve(s) heater part of the cathode bias resistance in the output stage, as shown in Figure 22. A typical input stage valve has at least a 150mA heater current rating. For a push-pull output stage, then each output valve must idle with at least 75mA in order to allow 150mA heater current to flow. The use of cathode bias for the output stage, and the minimum output stage bias current requirement, limits the type of amp that can use this technique. Two 12AX7 heaters in series are shown in the schematic from an AWA PA872 amplifier.

Large audio frequency currents flow through the cathode bias bypass capacitor, so it needs to be located at the output stage so that those currents don't pass through wiring near the input stage. A concern with cathode bias heater powering is the rise in cathode bias voltage in class B operation, especially overdriven outputs for guitar type amps. Some limiting of the cathode bias (or just the heater voltage) may be needed, such as with a zener-resistor.

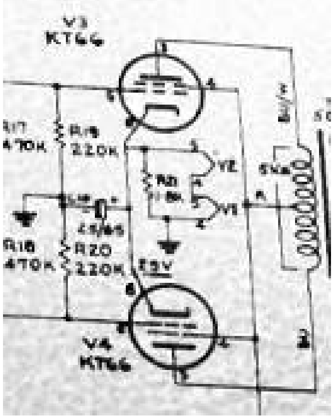


Figure 22. Preamp heater powering.

Generating a back-bias voltage in the CT leg of the B+ supply rectifier circuit was not too uncommon in vintage amps needing a fixed bias supply for the output stage. The back-bias is generated across either a resistor, or inductor, and so it too could be used for DC powering heaters (no examples are known of).

A common method used nowadays is to rectify and filter a power transformer winding that generates sufficient DC voltage for the input stage heaters. Using a full-wave bridge rectifier across a 6.3VAC heater supply, with a substantial capacitor filter, will generate about 6.3VDC at sufficient current for a single EF86, or 12AX7 wired for 6V heater. However, the effective loading on the power transformer heater winding is increased (due to the rectifier current pulse waveform).

Grounding the heaters is also not straight forward, as the DC heater voltage can't be simply grounded if the AC heater side is also grounded (eg. by a CT). If the power transformer heater winding CT remains as the heater ground connection then when the diode bridge is conducting, the CT (ie. ground) is effectively at half the heater DC voltage. But with such a large filter capacitor, the DC heater voltage floats for a large portion of time when the diode bridge is not conducting. If the DC side is grounded, then that should preferably be a humdinger, rather than just connecting the pos or neg end to ground, as the AC side heaters will then be symmetric to ground. With AC side grounding, there may be some advantage then to also connecting the DC powered heater midpoint to ground (eg. pin 9 of a 12AX7, or a humdinger) via some resistance.

Electric and magnetic field coupling & layout

Heater wiring layout

Stray capacitance increases between a heater cable and a grid or cathode cable as the cables come closer together. The amount of stray capacitance also depends on the dielectric of material between the wires. Locating a heater wire close to a grid wire for even an inch would add about 1pF [23], which is far more capacitive coupling than occurs in a 12AX7 valve and base.

The level of hum signal from electrostatic coupling via the electric field depends on the AC voltage available to drive the hum current, and the impedance of the loop, which includes the series impedance |1/ωC| from the stray wiring capacitance. This hum coupling mechanism is external to the valve, and similar to #5 above, and can be managed by careful design/layout.

The AC heater current generates a magnetic field that can couple to a valve circuit loop by electromagnetic induction. The level of coupled hum depends on the external field generated by the heater current in the heater wiring, and also by the amount of that field that passes through a sensitive circuit's loop. This coupling mechanism can also be managed by careful design/layout, and is influenced by:

- A lower heater current lowers the field strength that can couple to other loops.
- Twisting the heater cable dramatically reduces the nearby field strength.
- A tighter twist pitch and reduced separation of heater conductors more rapidly reduces nearby field strength.
- Reducing the 'area' formed by the sensitive circuit's loop reduces the ability of the heater field to couple over.
- Increasing the distance between the heater wiring and the sensitive circuit reduces the ability of the heater hum to couple over.

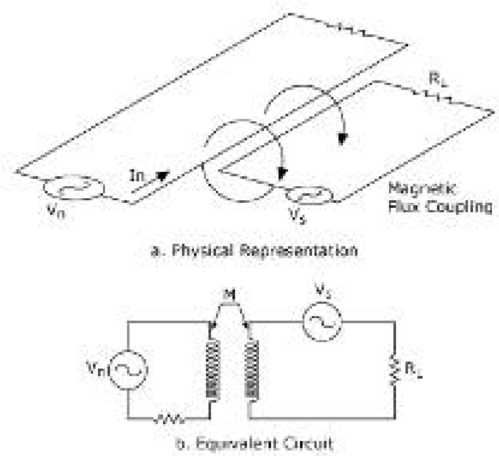


Figure 23.

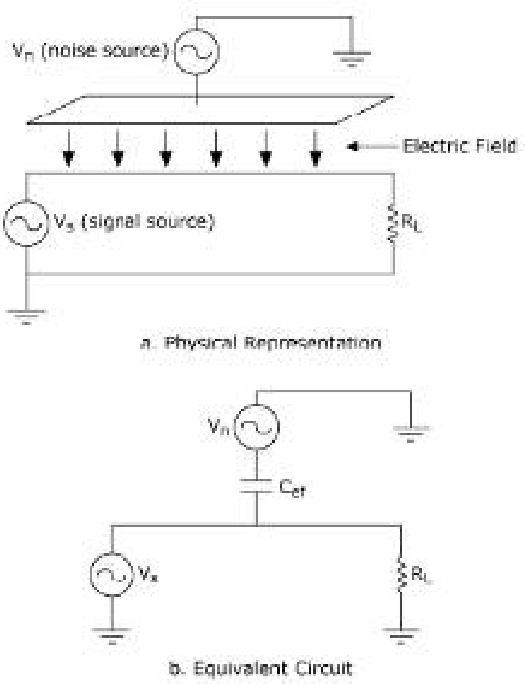


Figure 24.

[Images: NI-Tutorial-3344, 2014]

Keep in mind that the heater voltage waveform may include mains source derived harmonics (eg. from a ‘flat-topped’ mains waveform), as well as rectification noise from the B+ supply that is coupled through common impedance paths in the power transformer and line.

A B+ power supply draws a high crest factor current waveform from the power transformer winding, as shown in photo (a). The voltage waveform has a clipped top, due to many other devices drawing such current waveforms in the local mains network. The harmonic spectrum of the voltage waveform shows that low-order harmonics up to about 650Hz are of significant magnitudes.

Due to transformer and mains impedances, the heater voltage can often have similar harmonics.

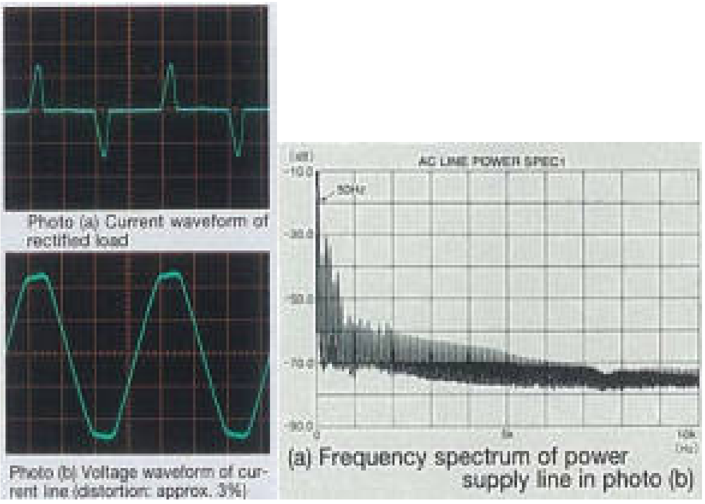


Photo (a) Current waveform of rectified load

Photo (b) Voltage waveform of current line (distortion: approx. 3%)

(a) Frequency spectrum of power supply line in photo (b)

Figure 25. **[Accuphase PS1200 brochure images]**

Transformer layout

The power transformer generates a stray magnetic field comprising a mains fundamental frequency, plus harmonics due to magnetising current and secondary rectification currents. The stray field from a typical transformer depends on the orientation, the addition of any bell-ends, and any nearby chassis. A stray field exists due to current flowing in windings, so the level of stray field will increase with current level, and in particular for higher crest factor waveforms such as with ss diode rectification. Most amp transformers are vertical style in order to reduce chassis footprint area, and usually include a bell end (for safety and ease of mounting more so than stray field reduction).

As shown in the simulated magnetic field lines around a transformer winding on an isolated transformer core (see figure below), the stray field mainly loops around from one end of the winding layers to the other end (ie. the ends where the wires exit). Locating a preamp valve near to the windings of a power (or output) transformer without bell-end covers (such as where the can capacitor is in the photo of the horizontal mount style transformer) may cause hum from magnetic field modulation between cathode and anode, and from induction in to the grid-cathode circuit loop area.

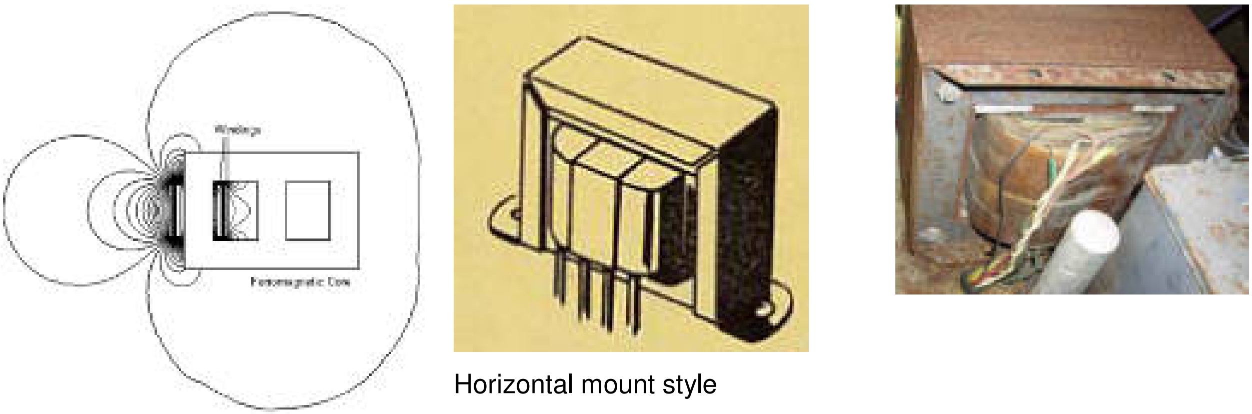
For a transformer mounted on the top of a chassis, and with circuitry underneath the chassis, then a metal chassis acts as a shield to divert most of the stray field to above the chassis, and attenuate any stray field extending underneath the chassis. The vertical mount style presents a high field to the chassis directly underneath the exposed winding near the core base, and that field is not well constrained by a bell end, and hence relies on the chassis to provide shielding. An aluminium chassis is not as good a shield as a steel chassis, and so some care is needed when locating sensitive circuitry underneath.

A flat mount transformer exposes the circuitry underneath the chassis directly to the stray field, so care in direction, spacing, and screening is definitely needed.

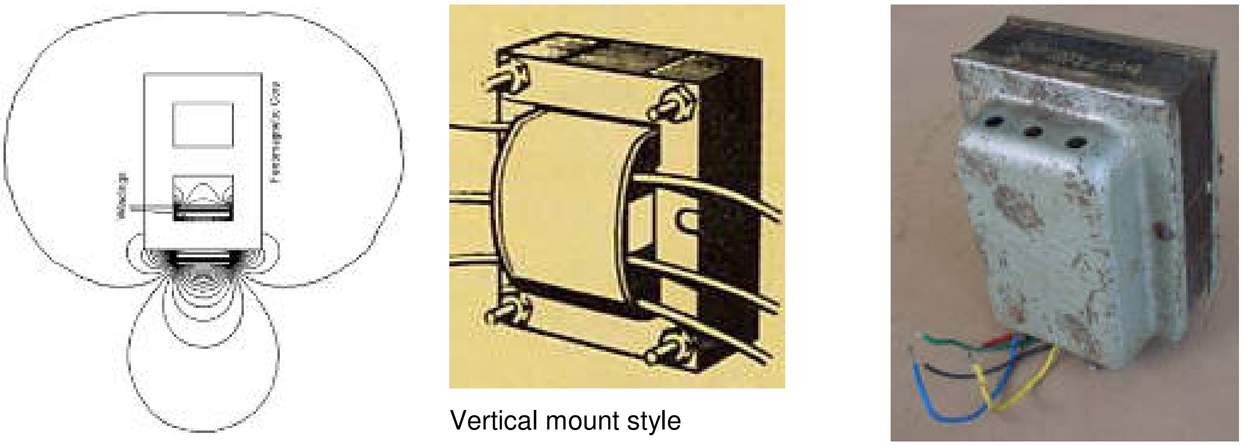
The stray field of a power transformer can couple over to a choke, or the output transformer, especially when placed close together. When building an amp from scratch, the common technique to select a good layout for minimum coupling between the power transformer and choke and output transformer is to connect headphones (or an oscilloscope) to the choke or output transformer winding, and energise the power transformer (carefully!), and move the transformers around.

Magnetic field screening may be needed, especially for transformers or chokes without steel bell ends. The attenuation provided by varying the thickness and type of metal shield is shown below, with steel being the simplest effective material to use. However, attenuation falls with frequency and so at 50-100Hz there is little attenuation occurring. So even with steel bell-ends and chassis, there is still a paramount need to constrain any nearby sensitive signal circuit loop area.

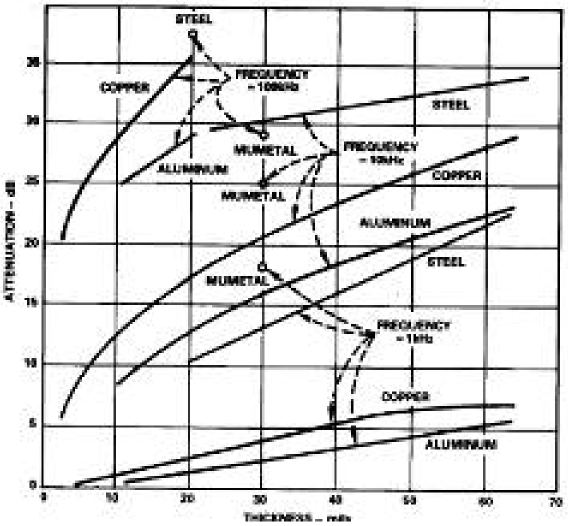
Few vintage transformers came with a flux band (also known as a belly band, hum strap, gauss band or similar) comprising a flat wide copper strip encircling the core and winding as a single shorted turn that is quite effective in minimising leakage flux normal to the face of the winding. Retrofitting such a band needs to be done with caution, so as to maintain insulation, creepage, and clearance performance to the windings.

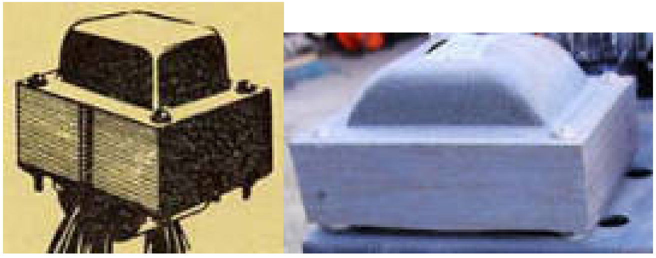


Horizontal mount style



Vertical mount style



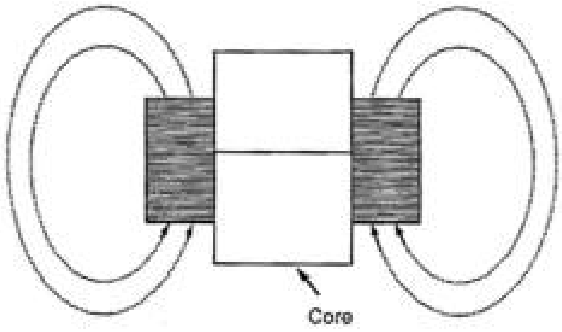


Flat mount style

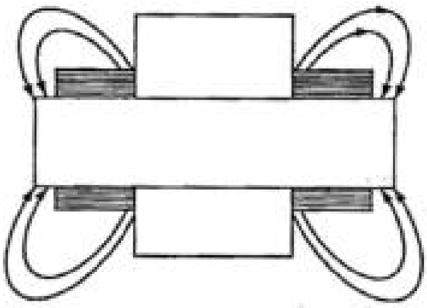
Figure 26. Transformer orientations.

Figure 27. Magnetic field attenuation through metal sheet.

[Analog Device AN-347 application note] 40 mils = 1mm



Flux from an E-Core transformer.



Flux from an E-Core transformer with a flux band.

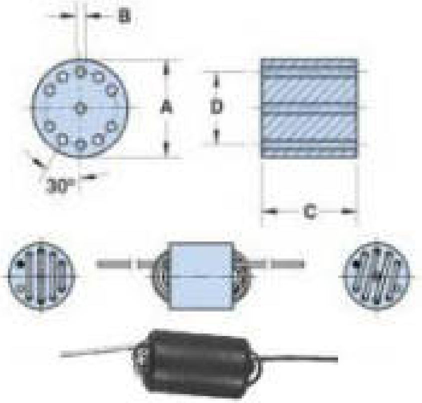
Figure 28. Illustration of magnetic flux constrained by using a flux band. [Power line filter design for switched-mode power supplies, M.J.Nave, 1991]

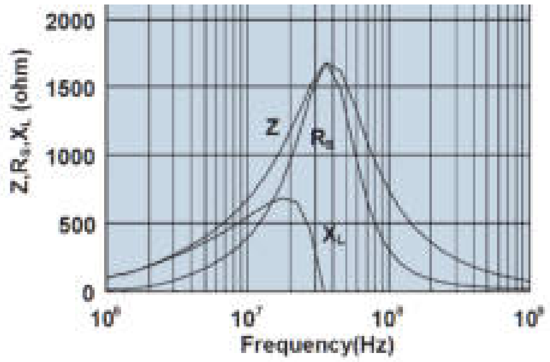
Electromagnetic field sources near to the amplifier may couple in to sensitive circuitry such as the input stage. The standard connection scheme of an isolated input socket with grounding switch, and shielded cable connection (both ends of shield used) to the input stage socket, and low value grid stopper on the grid pin, may not be sufficient in some noisy environments.

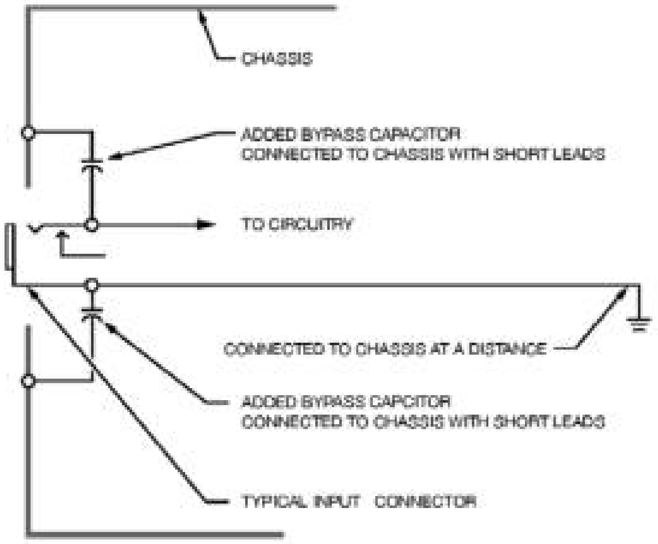
New communication methods like Ethernet Over Power use 4-21 MHz signals, whereas mobile/cell frequencies are up near 10^9 Hz. A strong MHz signal can cause grid conduction from overload, resulting in audible interference.

Some commercial amps use ferrite bead inductors to attenuate MHz signals. However a 10mm long, multi-turn bead only presents a few kΩ series impedance, with the ferrite material type determining the frequency response. The impedance of a grid stopper resistor typically decreases with frequency above 1-10Mhz, especially for R>10kΩ parts.

Low pF bypass capacitors to chassis for signal and ground at the input socket are recommended if the incoming audio cable does not provide sufficient screening.







Interference could also enter from a speaker lead, via the feedback circuit. The output transformer winding presents a high Z to MHz type frequencies. Bypass capacitors to chassis are similarly recommended.

Rectifier and filter wiring layout

The key with rectifier and filter wiring layout is to define the circuit loop paths of the worst levels of AC current. The earlier sections on AC powering illustrate the rectified AC current paths, and which paths may include additional higher frequency rectification noise. The coupling and layout advice in the section on heater wiring layout is similarly applicable to rectifier and filter wiring.

The wiring between power transformer secondary winding and the rectifier diodes carries high levels of dV/dt due to the high voltage mains waveform, and due to the step in voltage at the end of diode turn-off. Figure 29 shows the voltage induced in to a CRO probe when placed about 1cm from twisted transformer secondary wiring to a ss diode doubler rectifier circuit. The largest transient is at diode turn-off when the winding voltage steps down a few volts. The mains waveform has some distortion, so dV/dt is not an ideal sine wave in between diode conduction.

Capacitive coupling to any high impedance signal circuit needs to be managed – such as by twisted wiring and separation. Any screening of high voltage wiring should only be done with suitably rated cable, where the screen is grounded just at diode end, and to the main filter ground.

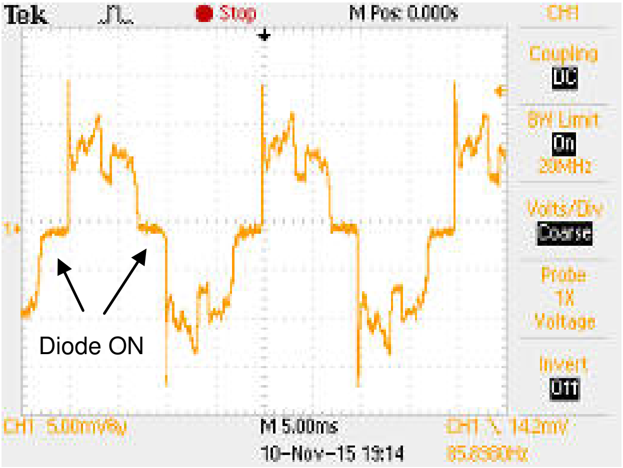


Figure 29. Capacitive coupled signal from wiring

The capacitance of reverse biased diode junctions will also pass parasitic current in to the following filter circuit due to the substantial dV/dt levels of the secondary winding.

An advantage of using series ss diodes (for PIV reasons) also effectively halves the stray coupling capacitance. Using a diode of lower current rating also helps – a 1A rated 1N4007 or UF4007 has capacitance (15pF @ 4Vr) about 10 times less than a 6A rated diode (P600M, 150pF @ 4Vr).

The turn-off voltage step in Figure 30 shows dV/dt ~ 10V/20us = 500k, to give a peak step current i ~ 15pF x 0.5V/us = 7mApk.

As a comparison, the PT secondary 240VAC 50Hz sinewave has a maximum dV/dt of 2.π.f.Vp ~ 100k.

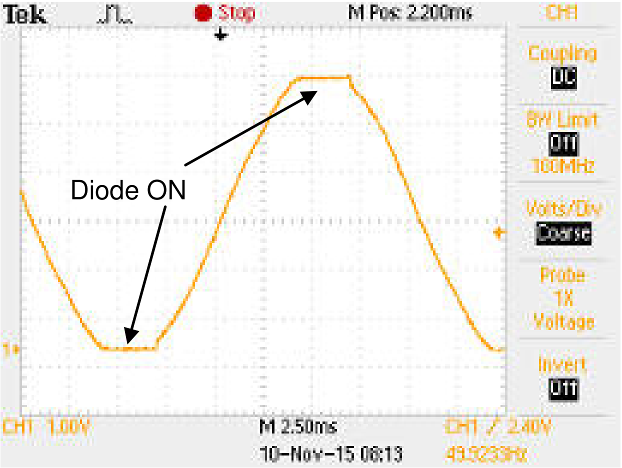


Figure 30. Voltage of secondary winding in doubler rectifier – diode junction to 0V (~100V/div)

Electrostatic screening of sensitive circuits

Electrostatic screening places a metal barrier between high AC signal circuits and high-impedance low signal circuits, so as to avoid parasitic capacitive coupling. Any thin metal sheet should suffice, such as aluminium, copper or steel. A typical location for a sheet screen is between output transformer speaker tap wiring (especially PA style 50V - 100V tap windings [1]), and preamp stages. Similarly, if power transformer mains or high voltage secondary wiring is close to a preamp stage.

A shielded cable, grounded only at one end, can screen a sensitive signal wire from parasitic capacitive coupling to nearby large AC signal voltages, or vice versa can screen a large signal voltage (such as a feedback circuit) when laid close to sensitive circuitry. This is quite important for wiring to front panel volume and tone pots. The screen adds some shunt capacitance to ground, which may introduce unwanted high-frequency roll-off when transferring a high impedance signal. Electrostatic screening does not attenuate magnetic field coupling, and so the screened cable should be routed in such a way as to minimise loop area wherever possible.

Heater wiring to a preamp stage can benefit from being routed by a shielded twisted pair cable – the twisted pair minimises egress of magnetic field, and any net capacitive coupling, and the screen further minimises stray capacitive coupling.

Even capacitors can be orientated to shield the more sensitive end terminal of the capacitor. Many non-polarised capacitor types are made with one terminal forming the outside foil layer of the capacitor package, which should be the end that is connected to ground or a more stable node (ie. B+), or the lower impedance driven end (as in an anode for a coupling cap, compared to the more sensitive grid of the next stage). A dark band identifies the outer layer terminal for some capacitors, otherwise a simple test can usually identify the outer foil.

Figure 31. Capacitor outer foil markings.

---

[1] If taps on an output transformer aren't being used, especially PA line transformers, then unsoldering the unused leads at the winding, or rolling up the wiring and tucking in to the bell-end, is worthwhile.

In vintage amps with top-cap grid connect valves like the 6J7, a pressed metal shield was needed around glass-envelope tubes to provide a combination of electrostatic and magnetic shielding due to the close proximity to power and output transformer windings. Noval valve bases also commonly had an aluminium shoulder for mating with a shield can, or came with a split sheet steel slip on tube that was connected to the chassis with a wire braid. And the venerable EF86 had a special internal screen.

Figure 32. External and internal shields.

Ground to chassis link

Amplifier circuitry normally has a single link connection from the circuit's 0V node to the equipment chassis – which allows the circuit to be safely ground referenced when used with a mains AC supply that provides a protective earth connection (ie. 3-pin supply socket/plug). A mains AC powered amplifier has the mains supply protective earth cable terminating to the equipment chassis (preferably at a separate point than any other connection). The equipment chassis can act as a metal screen encompassing all the amplifier circuitry – as per a faraday cage – although many amplifiers just have an open chassis.

The 0V-to-chassis link can carry stray currents due to the following possible mechanisms:

a) Stray capacitance between mains AC circuit and 0V.

Stray capacitance from power transformer primary winding to transformer core causes stray current in the chassis, not in the link. Some transformers include a screen winding between primary and secondary windings, which shunts the primary winding stray capacitance current to the screen – and then to the chassis as the screen is typically connected to chassis. Without a screen winding, stray capacitance from power transformer primary winding to secondary windings can be significant and cause stray current in the link, as the secondary side circuitry is connected to 0V (the main secondary HT winding is normally placed over the primary winding).

b) Stray capacitance between amplifier circuitry and chassis.

Amplifier circuits with large signal voltage may induce noticeable stray capacitor current to chassis metalwork, causing stray current in the link. Perhaps the largest contributor would be stray capacitance between the output transformer primary windings (connected to output stage anodes) and the transformer core.

The power transformer secondary HT winding(s) may also cause stray current to the core, or of more significance to a shield winding, causing stray current in the link - that secondary-side voltage waveform would normally have higher levels of diode rectifier induced harmonics and dV/dt diode turn-off transients. If secondary side induced stray current is larger than primary side induced stray current, and has higher levels of harmonics and transients, then the screen is preferably connected to the 0V side of the link.

c) Speaker circuit connected to chassis.

The speaker circuit is sometimes connected to chassis for convenience. This will cause stray current in the link due to capacitance between output transformer windings and speaker windings.

When speaker side feedback is used, the speaker 0V connection should be made directly to the feedback summing resistor, to avoid extraneous 0V bus noise from being added to the feedback signal. The speaker is then grounded through connection to 0V and the link to chassis.

d) Ground loop with other mains powered equipment connecting a signal to/from the amplifier.

A good reference for hum arising from interconnected equipment is [29].

Appealing forms of hum

Most would think of hum as an unwanted signal, tainting the amplified sound being listened to. However, one investigation [30] of a classic guitar amp (Fender Bassman 5F6-A) compared the default 'tone' character, to the same amp when it was specially modified to eliminate B+ ripple of the power supply. The subjective conclusion was that the lack of 100Hz ripple in the modified amp made it sound 'completely different' (ie. not as pleasant).

The example spectrum shows inter-modulation of a 500Hz signal by the100Hz hum signal. The 400/600Hz sidebands are significant, and effectively introduce a subtle 100Hz vibrato effect.

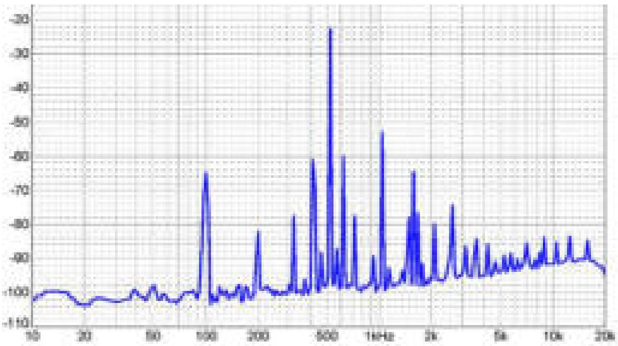


Figure 33. Spectrum from a Philips 1173 push-pull 6M5 PA amp.

That signal coloration could be retained, whilst suppressing residual hum under idle conditions, by regulation of B+ using a top-up regulator [22] designed for vintage amps that only had a small main filter capacitor.

Measuring hum

If you hear hum through the speaker, and it sounds louder than any background 'noise', then a true-rms AC meter should provide a suitable measurement of hum voltage across the speaker output, but no information on frequency is provided. With no inputs connected, and the selected input shorted to ground (eg. an RCA shorting plug), then turning up and down an amplifier's gain, tone and volume controls and recording the AC voltage at the amplifier's output may help identify which stages within the amplifier introduce hum.

An oscilloscope may help interpret the hum signals as well if you can sync to mains frequency and identify the period of any displayed signals. Care is required when probing a signal, as extra signals can couple in to the probe and distort or add hum and noise beyond what is sent to the speakers. The most common concern when using a measuring instrument (of any type) is that the measurement probe ground clip is earthed through the instrument's AC mains power cable, and you want to connect it to the amp's speaker wiring, which is also earthed through the amplifier's mains power cable – hence forming an earth loop. Even galvanically breaking the earth loop can still allow an AC noise loop through parasitic capacitance between power supply transformer windings. A hum/noise loop can be alleviated in a few ways, depending on the test setup, such as using a battery powered instrument, or a differential probe, or a signal isolator (eg. USB isolator), or a well set up isolation transformer.

A spectrum analyser provides the best interpretation of hum signals, as it shows signal magnitude and frequency.

A spectrum analyser application on an Android or iPhone can be used to simply sense speaker hum levels from the amplifier under test using the phone's microphone. The spectrum in Figure 34 was from a subwoofer with amplifier volume up high (but no input signal), and clearly shows 50Hz mains fundamental hum plus even and odd harmonics rising above the background ambient.

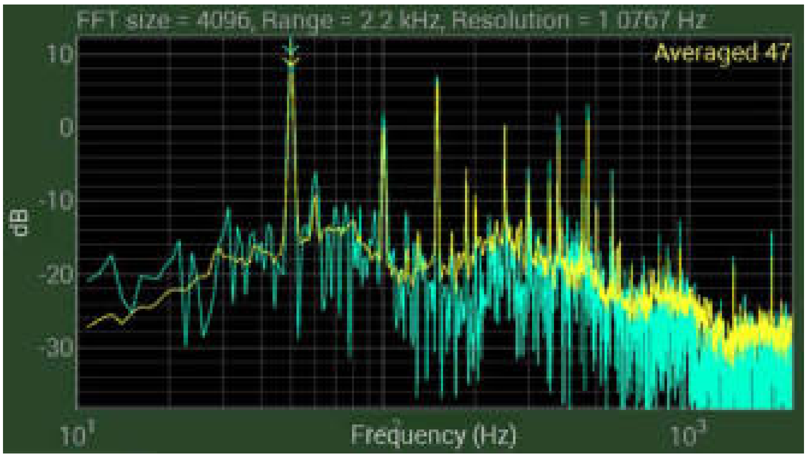


Figure 34. Audible hum measured on Android phone.

A permanent workbench setup can be very convenient. The latest commercial bench-top oscilloscopes include a spectrum analyser function (eg. Rigol), effectively bypassing the need for commercial spectrum analyser equipment that was quite expensive. At almost zero cost, a simple voltage divider probe connected to a $1 USB soundcard connecting to a battery powered laptop running a freeware spectrum analyser program like REW V5.1 or VA64 can achieve a good view of hum signals across the audio range (eg. see Figure 21). Enhanced performance can be obtained using specialist devices such as a high voltage differential probe (more expensive than an oscilloscope, but worth every $), a better outboard soundcard with higher sampling rate up to 192kHz to increase signal bandwidth up to near 100kHz (cheap), or a battery powered USB isolator (cheap).

Apart from measuring hum at the speaker output of an amp, investigatory probing of the output of each stage is usually required to confirm the relative hum level from each stage. Lowering a gain or volume pot to min, or pulling a valve from its socket, can usually isolate any signal from prior stages, however hum pickup can occur between the pot and the valve grid, which can only be confirmed by a temporary short link from grid terminal to local ground (eg. valve base spigot).

A simple but important tool for hum assessment is a 6V VRLA battery of about 4Ah for temporarily powering preamp tube heaters. Another adjunct is the temporary connection of a filter capacitor, to assess if B+ ripple or a high impedance bypass is contributing to hum.

Although lowering distortion was the main interest for amplifiers when the Williamson design came out, hum levels were also just starting to be reported. The 1947 Radiotronics A515 version of the Williamson amplifier [31] reported 0.34mV at 50Hz, and 0.06mV at 100Hz across 16Ω for a rated 15W output with 1.55Vrms input, which gives a signal to noise ratio SNR [2] of about 90dB. The amplifier's voltage gain is 20dB, and the power gain[3] was rated at 44dB at that time [32].

Not much has changed over the decades because the circuitry and 'best practices' are fairly similar. A modern, well designed, premium hi-fi quality amplifier can achieve a signal to noise ratio SNR better than 90dB with AC powered heaters, and exceed 100dB for DC powered heaters, in which case any signal is predominantly non-hum related noise. But SNR can be a poor metric to use, as it makes higher powered amps look better, even though they may have the same equivalent input hum and noise level. Bear in mind that the audio signal source can easily be the noise floor limit, with an LP record only achieving about 65dB dynamic range, but CDs capable of beyond 90dB.

Interestingly SNR is based on the output noise/hum level at idle, not the noise/hum level when the output signal is at rated power level. For background white noise, the SNR figure is a good indicator of performance, but for hum the picture is not so absolute, as some prospective contributors to hum may change when operating at rated power out – such as B+ ripple, and inter-modulation components. Nowadays, a better method to determine SNR could be to asses a spectrum of the output at rated power – the REW V5.1 application can calculate THD+N% as well as THD%, and so THD+N% - THD% would indicate the sum of all noise/hum contributors when the full rated signal and its harmonics are removed.

Nowadays, a good ear placed next to a sensitive speaker, when all background noise is kept very low, may be able to detect a hum level of -90dB below amplifier rated output, given that a hum signal is somewhat more discernible than white noise of the same rms level. A report on the 90W Maestro amplifier [33] from 1952 observed that noise (and presumably hum) was inaudible at 1 foot from an 'efficient modern' speaker, where that amp had a 77.5dB SNR, and a 50dB signal gain.

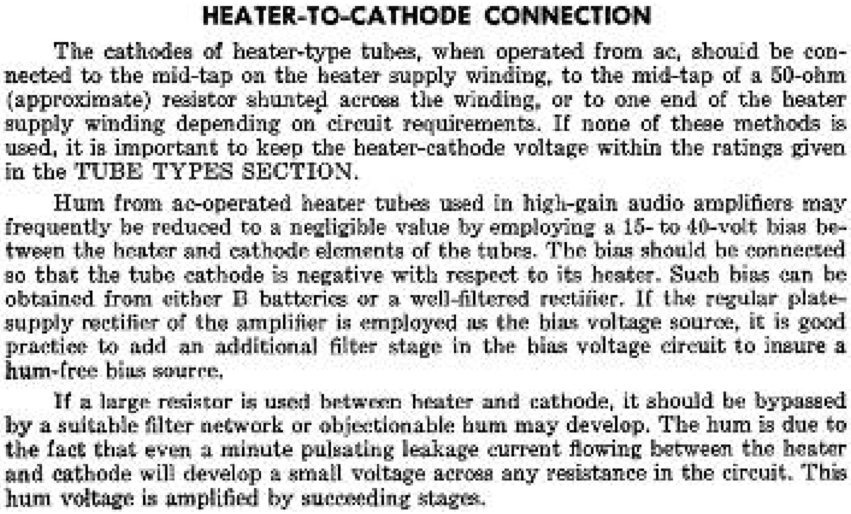
General Advice

Most general-purpose technical references, such as tube manufacturer yearly manuals, have assisted amp designers over the decades with quality general advice on hum reduction, which many people will steadfastly follow. That advice was typically brief and generically applicable, as befitted the aim of the publication. An example is RCA's Receiving Tube Manual from 1947 [34], which didn't change until the early 1960's [35].

---

[2] For a 15W amplifier, and 16Ω load, the signal output voltage is $\sqrt{(15*16)}=15.5$Vrms. SNR of the 50Hz signal is SNR = 20 log (15.5/0.00034) = 93dB.

[3] Input signal power was related to a 1kΩ resistance voltage source driving a 1kΩ load, so input power was $(1.55V/2)^2/1k\Omega = 0.0006W$, and hence power gain = 10*log(15W/0.0006W) = 44dB.



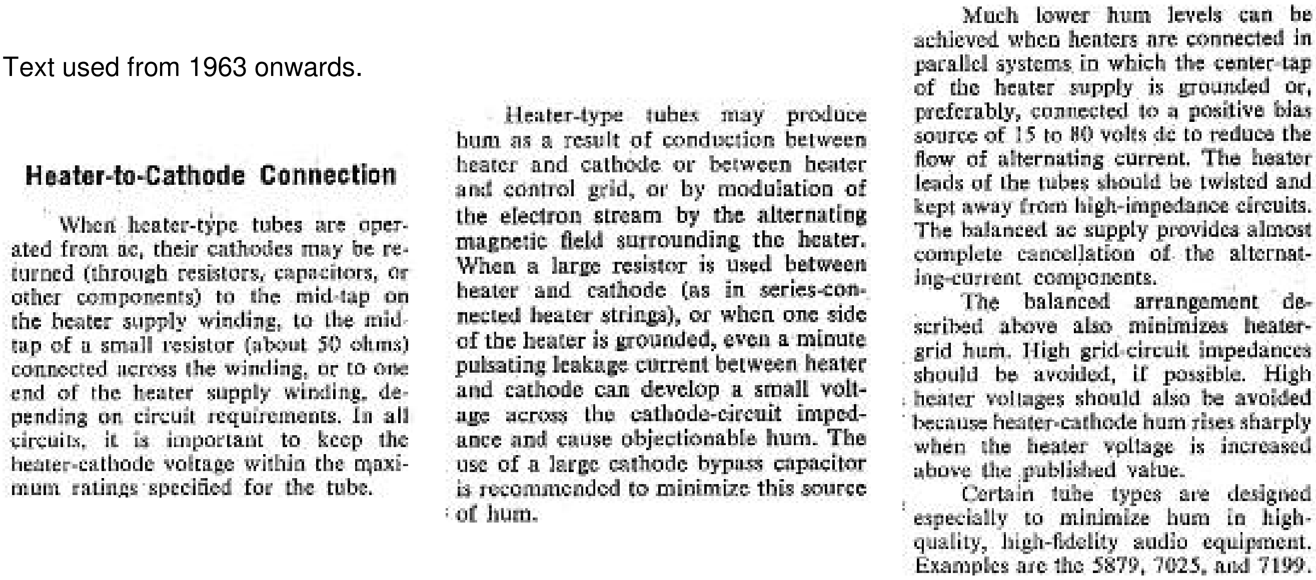
HEATER-TO-CATHODE CONNECTION

The cathodes of heater-type tubes, when operated from ac, should be connected to the mid-tap on the heater supply winding, to the mid-tap of a 50-ohm (approximate) resistor shunted across the winding, or to one end of the heater supply winding depending on circuit requirements. If none of these methods is used, it is important to keep the heater-cathode voltage within the ratings given in the TUBE TYPES SECTION.

Hum from ac-operated heater tubes used in high-gain audio amplifiers may frequently be reduced to a negligible value by employing a 15- to 40-volt bias between the heater and cathode elements of the tubes. The bias should be connected so that the tube cathode is negative with respect to its heater. Such bias can be obtained from either B batteries or a well-filtered rectifier. If the regular plate-supply rectifier of the amplifier is employed as the bias voltage source, it is good practice to add an additional filter stage in the bias voltage circuit to insure a hum-free bias source.

If a large resistor is used between heater and cathode, it should be bypassed by a suitable filter network or objectionable hum may develop. The hum is due to the fact that even a minute pulsating leakage current flowing between the heater and cathode will develop a small voltage across any resistance in the circuit. This hum voltage is amplified by succeeding stages.

Text used from 1963 onwards.



Heater-to-Cathode Connection

When heater-type tubes are operated from ac, their cathodes may be returned (through resistors, capacitors, or other components) to the mid-tap on the heater supply winding, to the mid-tap of a small resistor (about 50 ohms) connected across the winding, or to one end of the heater supply winding, depending on circuit requirements. In all circuits, it is important to keep the heater-cathode voltage within the maximum ratings specified for the tube.

Heater-type tubes may produce hum as a result of conduction between heater and cathode or between heater and control grid, or by modulation of the electron stream by the alternating magnetic field surrounding the heater. When a large resistor is used between heater and cathode (as in series-connected heater strings), or when one side of the heater is grounded, even a minute pulsating leakage current between heater and cathode can develop a small voltage across the cathode-circuit impedance and cause objectionable hum. The use of a large cathode bypass capacitor is recommended to minimize this source of hum.

Much lower hum levels can be achieved when heaters are connected in parallel systems in which the center-tap of the heater supply is grounded or, preferably, connected to a positive bias source of 15 to 80 volts dc to reduce the flow of alternating current. The heater leads of the tubes should be twisted and kept away from high-impedance circuits. The balanced ac supply provides almost complete cancellation of the alternating-current components.

The balanced arrangement described above also minimizes heater-grid hum. High grid-circuit impedances should be avoided, if possible. High heater voltages should also be avoided because heater-cathode hum rises sharply when the heater voltage is increased above the published value.

Certain tube types are designed especially to minimize hum in high-quality, high-fidelity audio equipment. Examples are the 5879, 7025, and 7199.

Repair

A commercial amp that hums is almost certain to have a faulty or degraded part or connection (sometimes multiple items). Performance of parts degrade: electrolytic capacitors age and are typically replaced after 10-30 years; valves degrade; capacitors leak; resistors drift causing imbalanced circuit operation. Electrical contacts (valve pins to base; plug/sockets; pot wipers; switch contacts; grounding screws/bolts) often need cleaning and tightening. The list goes on, and some amps often exhibit specific age related problems.

Acknowledgement

Thanks to Scott Reynolds for advice during final preparation of this article, especially on measured hum levels.

References

[1] dalmura.com.au/projects/Terman%201932%20emission%20hum.pdf

[2] Examination of conditions which give rise to hum.pdf. Radiotronics 119, 1946.

[3] Web article by Dmitry Nizhegorodov on DHT hum. www.dmitrynizh.com/filament-ac-harmonic.htm

[4] Philips datasheet. www.scottbecker.net/tube/sheets/010/e/ECC83.pdf

[5] Heater-cathode insulation performance. H. Klemperer, Sept 1936, Electrical Engineering. dalmura.com.au/projects/Heater%20cathode%20insulation%20performance.pdf

[6] dalmura.com.au/projects/Heater-cathode%20conduction%20plots.pdf

[7] Electron tube design, RCA, 1962. pp.232. http://frank.pocnet.net/other/RCA/

[8] 'Insulating heater within cathode sleeves', US Patent 2,915,355 submitted 1957 by T.H. Carlstrom from Sylvania.

[9] Valve Amplifiers, 4th Ed, Morgan Jones, 2012.

[10] Valve Hum. C. E. Cooper, July 1944. Electronic Engineering.

[11] Hum in high-gain amplifiers. P J Baxandall. Feb 1947, WW. http://mike.wepoco.com/Home/docs

[12] EF86 Mazda datasheet.

[13] http://www.retrovox.com.au/6AU6pAWV.pdf

[14] Radiotron Designers Handbook 3, RCA, 1940, www.tubebooks.org/technical_books_online.htm

[15] Fourier Analysis, Lucas Illing, 2008 http://www.reed.edu/physics/courses/Physics331.f08/pdf/Fourier.pdf

[16] Determination of carrier lifetime from rectifier ramp recovery waveform. B.Tien and C.Hu, Oct 1988, IEEE Electron Device Letters.

[17] Basic theory and application of electron tubes, Feb 1952, Army Technical Manual. www.tubebooks.org/technical_books_online.htm

[18] http://dalmura.com.au/projects/Choke%20measurement.pdf

[19] Note on a cause of residual hum in rectifier filter circuits. Terman & Pickles, 1934.

[20] Audio Handbook No.1, N.H. Crowhurst, 1951.

[21] Mark Johnson's Quasimodo test jig for snubbers. quasimodo_jig_reva.pdf

[22] Top-up ripple regulator .

[23] http://www.eeweb.com/toolbox/twisted-pair/

[24] Merlin Blencowe's article on grounding. http://www.valvewizard.co.uk/Grounding.pdf

[25] Amplifiers – the why and how of good amplification, by G.A. Briggs and H.H. Garner, 1952.

[26] Predicting the magnetic fields from a twisted pair cable, Moser and Spencer, Sept 1968, IEEE trans Electromagnetic Compatibility.

[27] R.G.Keens article on grounding. http://www.geofex.com/Article_Folders/star%20grounding%20amps.pdf

[28] Radiotron Designers Handbook 4, RCA, 1953, www.tubebooks.org/technical_books_online.htm

[29] Understanding, finding & eliminating ground loops. Bill Whitlock. 2008. EST016_Ground_Loops_handout.pdf

[30] Project Wildcat. http://www.ampbooks.com/mobile/classic-circuits/class-AB-ripple/

[31] The design of a high fidelity amplifier, F.Langford-smith & R.H.Aston, Radiotronics No.128, Nov.1947.

[32] Amplifier gain measurement, S.J.Haefner, Proc. IRE, July 1946.

[33] The Maestro – a power amplifier, D.Sarser and M.C.Sprinkle, Audio Engineering, Nov 1952.

[34] Receiving Tube Manual, RC-15, RCA 1947. RCA-RC-15-1947.pdf

[35] Receiving Tube Manual, RC-28, RCA 1971. RCA-RC-28-1971.pdf

[36] Increasing tube reliability in industrial circuits, by D.G. Kock. June 1952, Product Engineering.