Study Collection

A pre-amplifier for use with electronic voltmeters and oscilloscopes

Kees Pronk, Piet Trimp

Around 1953 Philips developed a pre-amplifier to increase the sensitivity and input impedance of electronic voltmeters and oscilloscopes. Although the sensitivity of such measuring equipment in those days was already quite high, measurement applications arose where more sensitivity was needed. The Philips GM 4574 to be described here has been developed to have an input impedance of 5 MΩ and a gain of 100 x for AC voltages. This article is an adaptation of an article by F.G. Peuscher and J. van Holthoon published in Philips Technical Review in December 1953 (Ref 1). The amplifier (type GM 4574), available in the Study Collection of EWI, is depicted in figure 1 and forms the subject of this contribution.

General description

In the design of this amplifier, the principal objective was to produce a small unit that would not occupy more space than strictly necessary on a work bench on which room has also to be found for equipment under test and numerous measuring instruments. For this reason, sub-miniature vacuum tubes of the kind originally designed for hearing-aids (Ref. 2) were decided upon, these being operated from dry batteries. The need for a mains transformer, rectifier tube and smoothing equipment is thus dispensed with. Only a small amount of power is consumed by the filament circuits of these sub-miniature tubes, and therefore only small batteries are required. There is another advantage in the use of batteries: the voltage surges invariably occurring in mains voltages, as well as ripple voltages, are completely avoided. This is very important from the point of view of the purpose for which the amplifier is intended, since the input voltages concerned are often very small, viz. of the order of 0.1 mV.

Figure 1. *Amplifier GM 4574, giving an amplification of 100 x.*

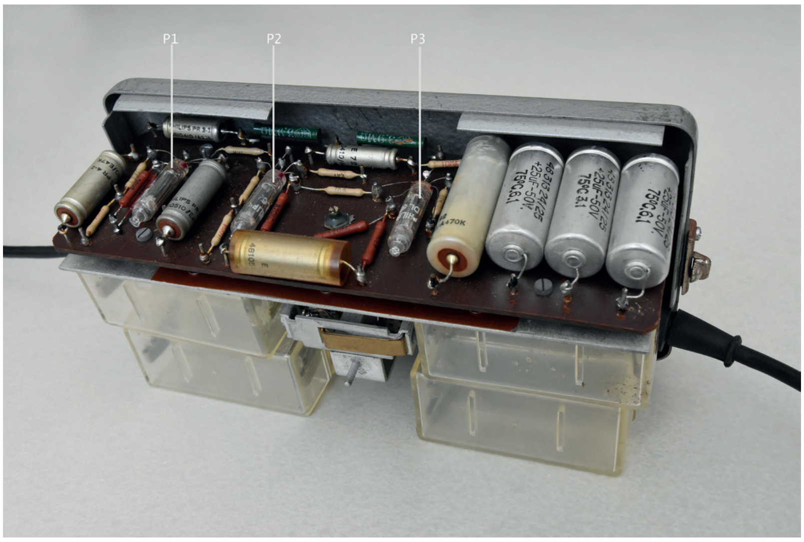

Figure 2. *Interior of the GM 4574. P1, P2 and P3 are the DL 67 miniature tubes. The four boxes are the battery compartments.*

At the same time, batteries are not without their disadvantages; they tend to produce substances which would set up corrosion or endanger the insulation. In the present amplifier this difficulty has been overcome by housing the batteries in insulated boxes (figure 2) which entirely prevent contamination of the amplifier, and which can be quite easily removed and rinsed in water if necessary.

In order to ensure that the amplification shall remain as constant as possible, this being of course an essential feature where measurements are concerned, considerable negative feed-back is employed. This is particularly desirable because the slope of the tubes varies fairly widely as a result of the gradual drop in the battery voltages. The 'slope' of the tube is defined as ia/vg (Δ-anode current / Δ-voltage on the steering grid; expressed in mA/V). This slope is also known under the names transconductance and mutual conductance (see ref. 5).

For an overall amplification of 100 x, the gain that would be obtained without negative feed-back (open loop gain) must accordingly be much more than 100 x. Two stages in cascade are provided, each giving an amplification of

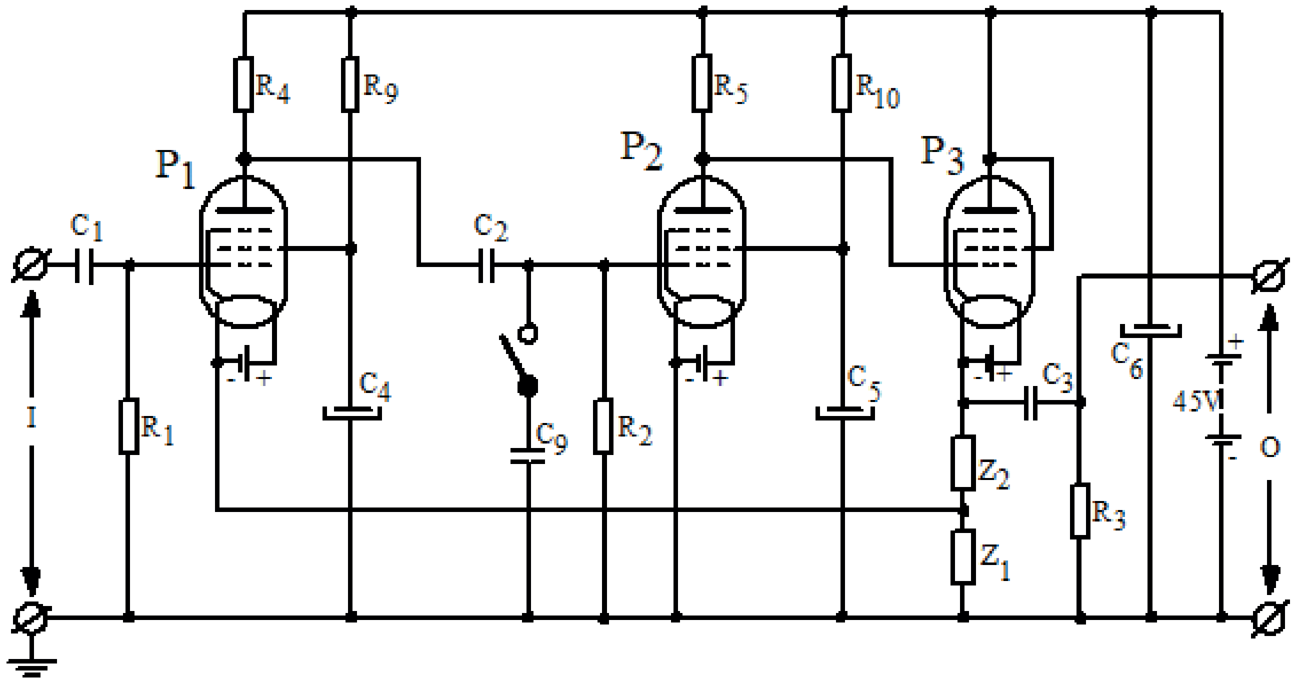

Figure 3. *Circuit diagram of the amplifier. I = input, O = output*

about 63 x, and both stages thus give an open loop gain of 4,000 x. These stages precede a third, cathode-follower circuit, the purpose of which is to keep the output impedance low (less than 5000 Ω), so that the amplification shall be independent of the (high) input impedance of the equipment connected to the output terminal of the GM 4574. The amplification obtained from this third stage is slightly less than unity.

The circuit

The schematic circuit is shown in figure 3. The three tubes are pentodes, type DL 67. For more information about pentodes, please see ref. 3. As the cathodes are not interconnected in this circuit, each filament (current 13 mA) is fed from its own battery (1.5 V). The battery boxes mentioned above, guarantee adequate insulation between the batteries themselves and with respect to earth. Since the DL 67 uses a directly heated cathode, the cathodes cannot be connected and should be heated from individual batteries (see also ref. 4).

The DL 67 is designed to give sufficient anode current even on low supply voltages (max. 45 V), this being ensured by incorporating in it a screen grid of closely spaced wires. A detailed picture showing how the DL67 has been soldered directly into the circuit is given in figure 4.

The mutual conductance of the screen grid is accordingly very high, which means that variations in screen voltage have a pronounced effect on the working point of the tube. In order to prevent the working point from drifting too much as a result of diminishing voltage from the anode battery, the screen grids of the first and second tubes are fed through high resistances (the third tube is connected as a triode). When the battery voltage drops, the screen current also drops slightly and the voltage loss in the feedback resistor is reduced, thus partly compensating the drop in the battery voltage. Consequently, the screen grid current, and hence also the anode current, are much less dependent on the battery voltage than if the screens were connected direct to a tapping on the battery. Differences in the mutual conductance of the screen between one tube and another are thus also smoothed out.

The screen grids are decoupled by capacitors C4 and C5, which are electrolytic capacitors of high capacitance (25 μF), each having in parallel with it a paper capacitor of much lower capacitance (not shown in figure 3). Electrolytic capacitors have the advantage of a very small volume per μF, especially at the low working voltages occurring in this amplifier.

The objective of the paper capacitor is to ensure effective decoupling also at high frequencies, at which electrolytic capacitors have a fairly high impedance (their series resistance increases with frequency). A third electrolytic capacitor (C6) is connected across the anode battery, to avoid undesirable coupling across the internal resistance of the battery, which can become fairly high as the battery gets older.

Capacitive coupling is employed between the input and first tube (C1-R1), between the first and second tubes (C2-R2) and at the output (C3-R3), the second tube is DC-coupled to the third. The cathode connection is in each case the negative side of the battery.

Grid bias for the first and second tubes is established with respect to the negative side of the filament, across the high-value leak resistors (R1, R2); this bias is increased slightly for the first tube by the voltage drop across the impedance Z1 which is part of the negative feed-hack circuit.
The slope of the tubes at the working point is about 0.1 mA/V; the input impedance is roughly 5 MΩ .

Negative feedback

The negative feedback circuit is shown in figure 5. It consists of two impedances Z1 and Z2; a feedback of $\beta = Z1 / (Z1 + Z2)$ is produced, this representing that part of the output voltage which is returned to the input. The ratio in which the amplification A (without negative feedback) is thereby reduced, is 1: $(1 + \beta A)$. In the present case A is about 4000 and the required amplification is A' = 100, so that $\beta = Z1 / (Z1 + Z2)$ must be roughly 1/100. Variations in the amplification are thereby reduced in the ratio of 1: $(1 + \beta A) = 1/40$, which is sufficient to ensure that the amplification (except at the very highest frequencies concerned) is not reduced by more than 10% when all the battery voltages have dropped to one half their rated values. Non-linear distortion is also attenuated in a ratio of 1/40 and this is particularly important when the amplifier is employed with an oscilloscope. Figure 5 gives further details of the negative feedback circuit. At frequencies in the region of 1000 Hz the capacitances Cp and C7 may be neglected, and C8 can be regarded as a short circuit. Z1 then consists only of the resistor R6 and Z2 consists of the resistors R7 and R8 in parallel. The required amount of amplification (100 ± 3%) is obtained by using the appropriate value for R6.

Figure 4. Detail of the circuit board containing the DL 67 pentode.

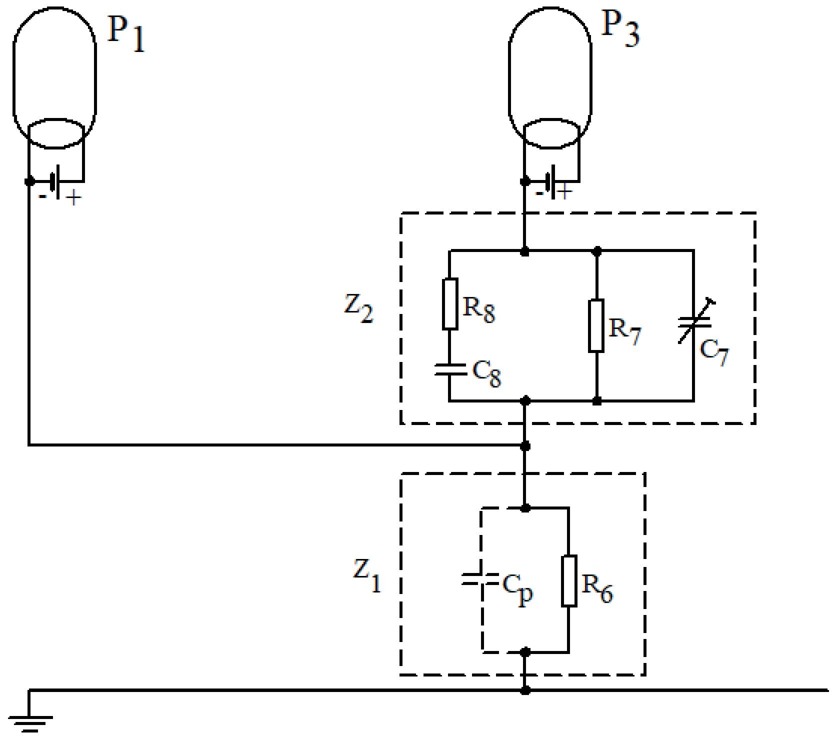

Figure 5. Detail of the negative feedback circuit of the amplifier.

In figure 5, Cp represents a stray capacitance, this being mainly the capacitance to earth of the filament battery for the first tube. At high frequencies the effect of Cp is not negligible, but this can be counteracted by means of a small trimmer C7, since the ratio $Z1 / (Z1 + Z2)$ is independent of frequency when C7 satisfies the condition $C7\ (R7\ R8)/(R7{+}R8) = Cp\ R6$.
To ensure that voltages of square waveform will be amplified without distortion, C7 is very carefully adjusted, using a square-wave voltage of about 5000 Hz. The form of the output voltage of the amplifier is simultaneously checked with an oscilloscope which immediately reveals any discrepancy in the adjustment. This is done in a way similar to the way we nowadays adjust our oscilloscope probes.
Owing to the finite time constants of the three RC couplings *(C1-R1, C2-R2 and C3-R3)*, the gain is smaller in the low frequencies than in the middle of the range; to compensate this, the feedback network is so designed that the feedback is reduced with decreasing frequency. When the frequency is reduced, the capacitor C8 (figure 5) increases the impedance of the branch *R8-C8* and hence also of Z2 so that the ratio of $Z1 / (Z1 + Z2)$ decreases.

This compensation is not perfect, however; to ensure that there will not be too little compensation in any given frequency range, some over-compensation must be permitted in another range. This is the reason why the solid curve figure 6 rises slightly at frequencies below 100 Hz, to reach a maximum at 2 Hz, which on average over a number of these amplifiers is roughly 12% above the nominal value of the amplification. Consequently, a perfectly square wave

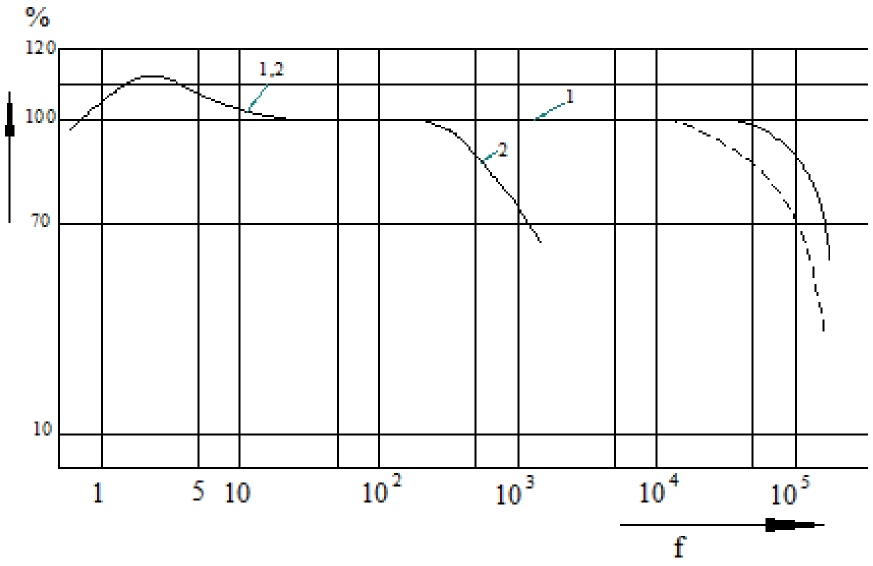

Figure 6. Amplification as a function of frequency.

of 12.5 Hz will be slightly distorted; at 25 Hz this distortion is almost imperceptible, and at 50 Hz it cannot be detected at all. Without the compensation, even a 50-Hz square-wave voltage would be badly distorted, and the compensation therefore ensures a useful increase in the range of frequencies for which the amplifier can be employed.

With a response curve of this shape (curve 1 in figure 6), obtained by means of the compensation mentioned, the unit is suitable for amplifying sinusoidal frequencies of from 1 to 150,000 Hz; with a square wave voltage the frequency range is 10 to 10,000 Hz. Even when all the battery voltages have dropped to half their rated values, the response curve retains the form shown, with the exception of the extreme right-hand end, i.e., at the higher frequencies, where the drop becomes slightly steeper (dashed line in figure 6).

Where amplification of very small voltages within a limited range of frequencies is required, it is useful to be able to reduce the background noise at the expense of the bandwidth. Such conditions will often occur in investigations of mechanical phenomena, which are concerned with very low frequencies; the high-frequency end of the range can then be safely suppressed, thus eliminating the noise attributable to the higher frequencies. This is effectuated very simply by placing a capacitor in circuit (C9 in figure 3). The noise voltage, referred to the input is less than $10\ \mu V$ without the capacitor C9, but is less than $5\ \mu V$ with this capacitor in circuit. In this case the response curve of the amplifier is as shown by curve 2 in figure 6, this being suitable for the amplification of sinusoidal voltages at frequencies of 1 to 1000 Hz, and square-wave or pulse voltages of from 10 to 50 Hz.

Additional design objectives

In the original article two more issues are discussed: forming of the electrolytic capacitors and microphony.

When looking at figure 1, two special positions are available on the main switch. These have to do with forming of the capacitors, a mechanism which will not be discussed here in detail. The reader is referred to the original publication. Microphony is the (mechanic) influence by vibrations (sound) on the position of the grids in the DL67. These vibrations may results in varying anode currents. In order to avoid possible trouble due to microphony when very low voltages are to be amplified, the amplifier chassis is flexibly mounted in the case.

Conclusion

This description of the Philips GM4574 pre-amplifier clearly shows a number of interesting design choices made during the design of this piece of equipment such as feedback, frequency characteristic and noise behavior.

[1] http://www.extra.research.philips.com/hera/people/aarts/_PhilipsBoundArchive/PTechReview/PTechReview-15-1953_54-169.pdf Philips Tech Review 17, 164-174, 1953; Volume 15 No 6
[2] http://www.extra.research.philips.com/hera/people/aarts/_PhilipsBoundArchive/PTechReview/PTechReview-15-1953_54-037.pdf Philips Tech review 15, 37 – 48, 1953 (no. 2), An electronic hearing aid; P. Blom
[3] https://en.wikipedia.org/wiki/Pentode
[4] https://en.wikipedia.org/wiki/Hot_cathode
[5] https://en.wikipedia.org/wiki/Transconductance