RADIOTRONICS

AMALGAMATED WIRELESS VALVE CO. PTY. LTD.

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In this issue:—

POWER OUTPUT AND EFFICIENCY IN TRIODES, PENTODES AND TETRODES

Many a time has one looked with interest at the positive-grid region of triode valve characteristics where higher output and better efficiency may be obtained apparently for nothing, but the distortion and complications due to the power requirements of the grid have acted as a deterrent. This article shows how a pentode or beam tetrode provides equally high output and efficiency due to the positive accelerating voltage on a subsidiary grid (the screen) without the necessity for grid driving power but at the same time it produces a high plate resistance resulting in poor fidelity on a loudspeaker load. By the use of negative feedback this latter defect is overcome while the high efficiency is retained.

In the numerous amplifier designs which have been described from time to time in these pages, the aim of fidelity has been stressed. We have always striven to make clear the three important factors namely linearity, frequency response, and loudspeaker damping, which contribute to faithful reproduction. It has been shown that it is desirable, for the sake of frequency response and damping, to have an output resistance as small as possible compared with the normal load resistance, and negative feedback has been used in order to reduce the output resistance of pentode and tetrode valves.

There are, however, three factors apart from fidelity, to be considered in the design of most amplifiers, particularly those required for large audio output. They are respectively, power efficiency, power sensitivity and cost.

Power Efficiency

The power efficiency is the ratio of audio power output (maximum) to the power taken from the supply. The heater power requirements for output valves of similar power output are generally similar, but the ratio of output power to D.C. input to the plate circuit varies within wide limits. It is found that a single class "A" triode is usually about 20% efficient, while a pair of Class AB_1 tetrodes give a figure of 58% and Class B triode stages 68%.

For any particular power output, the efficiency is a measure of D.C. power input, and, both for economy of operation and first cost of power supply units, it is wise to select an output system of high efficiency. When a single class A triode is used, its efficiency varies with load, as may be seen from Fig. 1.

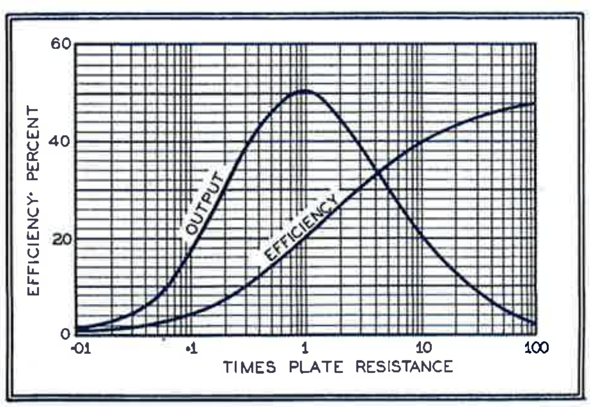

Fig. 1. *The effect of variation of load resistance on the output and efficiency of a typical power triode.*

The plate characteristic of a typical triode is shown in Fig. 2. The loadline of the valve is represented by *YXe, X* being the working point, *Y* the zero grid bias point and *e* the point of peak voltage swing. If distortion is assumed to be zero, *X* will be midway along *Ye.*

The D.C. plate current *I* is the current at the point *X*, while the D.C. plate voltage at the point *X* is *E*. The D.C. input power is therefore *IE* and is graphically represented by the area of the rectangle *OIXE*. The peak A.F. voltage is (*e-E*) and the peak A.F. current is *I* and therefore the power output is $\frac{1}{2}I(e\text{-}E)$ which is the area of the triangle *XEe*. The efficiency is therefore the area of the triangle *XEe* divided by the area of the rectangle *OIXE*. The efficiency may be increased by tilting the curve OY^1Y so as to be more nearly vertical and in the limiting case *Y* will be at zero plate voltage. Under these conditions *Oe* will be equal to *Ee* and the efficiency will reach 50% since the area of the triangle will be half that of the rectangle.

It may therefore be stated that the maximum efficiency which can be obtained with a valve having an operating point midway along the load-line is 50%.

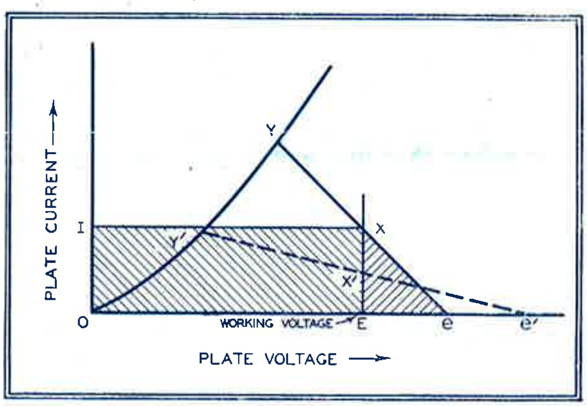

Fig. 2. *Graphical examination of variation of load resistance in a triode valve.*

In a practical valve is it never possible for *Y* to be at zero plate voltage. For a Class A1 triode OY^1Y is the zero grid bias line and, as may be shown from the discussion in Radiotronics 79, maximum power output occurs when $(e\text{-}E) = 0.2\ e$ or $e = 1.25E$. Under these conditions the power output, being the area of the triangle *XEe* will be $\frac{1}{2} \times 0.2\ eI$ which is equal to $\frac{1}{2} \times 0.2\ (1.25E)I$ or $0.125EI$. The D.C. power input is *EI* and therefore the efficiency is 12.5%.

It may therefore be stated that the efficiency which is obtained when a valve is adjusted for maximum power output and when the operating point is midway along the load-line is 12.5%.

In actual practice such a condition of operation is not used since the distortion is intolerably high for a single valve. In push-pull operation the distortion is reduced and the operating point may be adjusted to give a lower D.C. current and higher efficiency. However the purpose of the foregoing treatment is to demonstrate that the efficiency of a triode, in which the operating point is halfway along the loadline, is always between 12.5% and 50%. A normal power triode operating with plate voltages in the vicinity of 250 volts is usually arranged with a load resistance of about twice the plate resistance of the valve in order to limit the distortion to 5% total, and under these conditions the efficiency is about 20%. Care should be taken not to apply too rigorously this rule of load resistance being twice the plate resistance at the operating point, since it is affected by many factors such as the mutual conductance, plate voltage and shape of the characteristics.

It is obvious that if an attempt is made to increase the efficiency by increasing the plate load resistance, the power output will fall as the load resistance is increased, as shown by the loadline *Y'X'e'* in Fig. 2. It is to be understood that in any change of load resistance the point *e, e'* always remains at zero plate current, and the working point is adjusted to suit.

There is yet one way of increasing the efficiency without decreasing the power output, and that is to extend the load line beyond *Y*. This involves running into the positive grid region with consequent grid current, but the efficiency rises as *Y* approaches zero plate voltage. A typical plate family is shown in Fig. 3 in which a Class A loadline is shown extending to zero bias, and a Class B loadline extending well into the grid current region. The limit of excursion in the Class B case is the **Diode Line,** where the grid loses control. When the loadline extends almost to the diode line, the efficiency approaches 50% so long as the working point is the midpoint of the loadline. Such operation is technically known as Class A2, that is Class A with grid current, but is not normally used since the plate dissipation is too high. Class AB2 operation may be used with the same

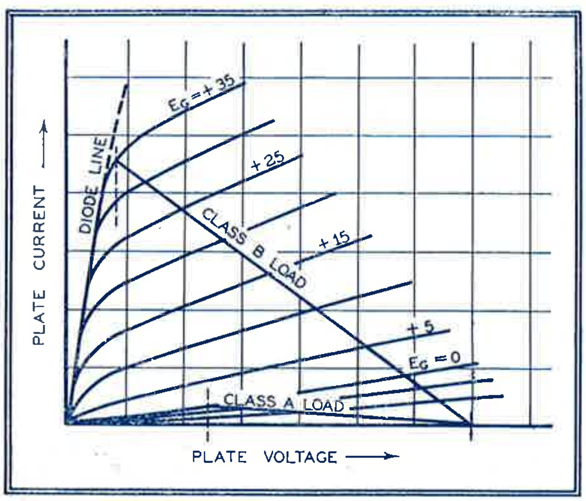

Fig. 3. *Comparison between Class A and Class B loadlines on a triode valve.*

loadline by choosing a working point to give a small standing plate current. However all these methods of increasing the efficiency involve running into grid current, thereby causing complications in the grid circuit.

Efficiency without Grid Current

Fortunately there is a way of extending the loadline without running into grid current. If the control grid is maintained at cathode potential, and the voltage on a second or outer grid (the screen grid of a pentode valve) is varied, a set of curves is obtained as in Fig. 4.

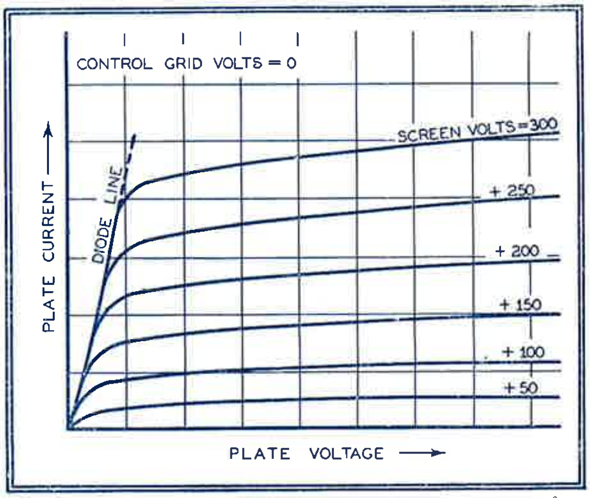

Fig. 4. *Plate voltage—plate current curves for zero control grid voltage on a beam tetrode power valve.*

These resemble, as regards diode line, the triode curves of Fig. 3, but show the output plate resistance to be higher over the working range. This is due to the screening of the plate from the cathode by the additional grid. By combining the accelerating field of this grid with the field of the usual control grid, the diode line can, by proper adjustment of the screen voltage, be reached on any given load line, without the control grid passing beyond zero bias, and the characteristics of Fig. 5 are obtained. In practice the screen grid is operated at a fixed D.C. potential. However if secondary emission currents are to be avoided, the plate must be far enough away, or sufficiently well screened from the region of the positive screen grid for there to be no backward flow of electrons. The last mentioned further increases the plate resistance, so that little change in plate current results from wide variations in plate voltage.

The negative grid need never be operated at potentials above the cathode voltage, and the pentode with its three grids (control, accelerating, and suppressor) is well known to be more sensitive and more efficient than a triode. In beam power valves of the 6L6G Class, the efficiency is even better, on account of the sharp "knees" in the curves, at the diode line, as seen in Fig. 5.

Operation similar to Class B or Class AB_2 is thus possible in pentodes and tetrodes without the flow of current at the inner grid. The efficiency is high, and the power output is limited chiefly by the permissible dissipation of the valve. Power is still supplied to a grid, but it is steady power with no A.F. component, fed to the accelerating grid (Grid No. 2). No A.F. power is required at Grid No. 1.

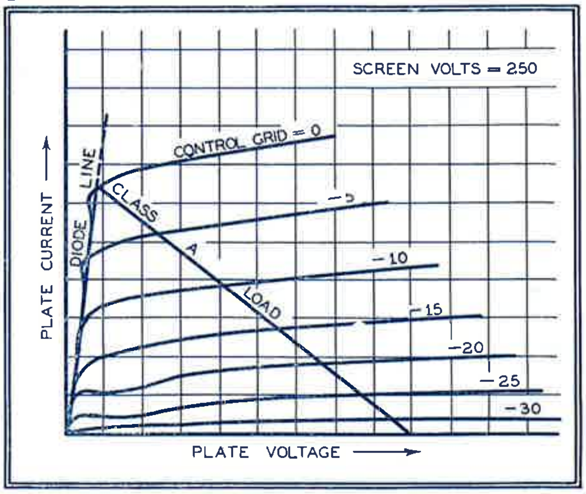

Fig. 5. *Plate voltage—plate current curves for constant screen voltage on a beam tetrode power valve.*

Reduction of Plate Resistance

Having found a means of higher efficiency, the plate resistances of pentode and beam valves have to be reduced to provide fidelity with varying values of load resistance. When one remembers that the chief cause of the high plate resistance is the screening between plate and cathode, a method which suggests itself for reduction of R_p, is the simple scheme of feeding some of the plate voltage externally back into the grid circuit. Because the plate voltage is out of phase with the grid input voltage the feedback is negative, and it is obvious that the greater the ratio of feedback, the lower will be the output resistance. Of course, extra voltage must be supplied across the input circuit to make up the difference between grid and feedback voltages. In fact, the valve assumes a new set of characteristics, similar to those of a triode having the same mutual conductance as the pentode or tetrode, excepting that the zero bias line coincides with the diode line of the valve up to the knee of the curve. The amplification factor is calculable from the expression:

$$\mu' = 1/(\beta + 1/\mu)$$

Where μ' = apparent amplification factor.
$\beta = e_g/e_p$, the numerical value of the feedback ratio.
μ = tetrode or pentode amplification factor.

As $1/\mu$ is usually small compared to β, the function μ' may be taken as approximately $1/\beta$, and the plate resistance as $1/g_m\beta$: As β is independent of e_p, the tetrode or pentode with feedback may be pictured as an ideal triode, having a constant amplification factor. Fig. 6 shows a family of I_pE_p curves for a 6L6G having (up to the grid current point) 16.6% feedback. The similarity to triode characteristics is evident.

Power Sensitivity

The power sensitivity of any valve is defined as the ratio of power output to the square of the required grid input voltage (R.M.S.). Without feedback, the cut-off grid voltage of a pentode or tetrode is determined by the screen voltage and grid-to-screen amplification factor (triode μ). When the load resistance is correct, the grid voltage of the valve is varied from near cut-off to near zero bias. The peak plate current is fixed by the knee of the I_pE_p curve at zero bias, and is dependent upon the triode μ and mutual conductance of the valve, while the peak plate voltage depends upon the applied plate voltage. The output is thus a function of the mutual conductance, the triode μ, the plate load resistance, and the voltages applied to plate and screen. When the power output is divided by the square of the input voltage, it is found that the sensitivity varies with the product of the mutual conductance and the triode μ.

In a triode, the power sensitivity is more easily calculable from the expression:

$$\sigma = G_m \ \mu/(R_L/R_p + R_p/R_L + 2)$$

Where σ = power sensitivity

G_m = mutual conductance

μ = amplification factor.

The ratio R_L/R_p is fixed, usually to compromise between output and distortion, and σ becomes a definite fraction of the product μG_m (the Barkhausen figure). When feedback is applied to a pentode stage, to reduce the ratio R_p/R_L to the same order as that with a triode, the same formula may be used to calculate sensitivity. It should be observed that where R_p/R_L is fixed, the power sensitivity depends almost entirely upon the mutual conductance, G_m, and that for a given figure for R_p/R_L, a triode has no less gain than its equivalent pentode (with feedback), if the mutual conductances are of the same order.

Having decided that R_p/R_L should equal 0.5, the feedback factor may be found to be 0.126, in the case of a 6L6G, the effective amplification factor is 7.5, and the sensitivity becomes 9.6mW/V^2.

Cost

In the matter of cost, it may be stated that negative feedback networks may be simple or complicated, but as it is essential, for the sake of speaker damping, for changes in plate voltage to be felt at the cathode **immediately,** it is wise, in output systems, generally to use the simplest possible feedback circuits. The extra cost over a "straight" pentode or tetrode amplifier, is very small, and as the bias and supply voltages are smaller than those for triodes there is distinct economy in using a pentode or tetrode with negative feedback. As the efficiency is better, the plate current for the same output is generally less than that for a triode, and the power supply unit is less costly in consequence.

Conclusion

In conclusion, it may be stated that two inherent advantages which the tetrode stage has over the triode output stage have been demonstrated. They are efficiency and cost of installation. When feedback is used correctly the tetrode loses neither of its advantages, but

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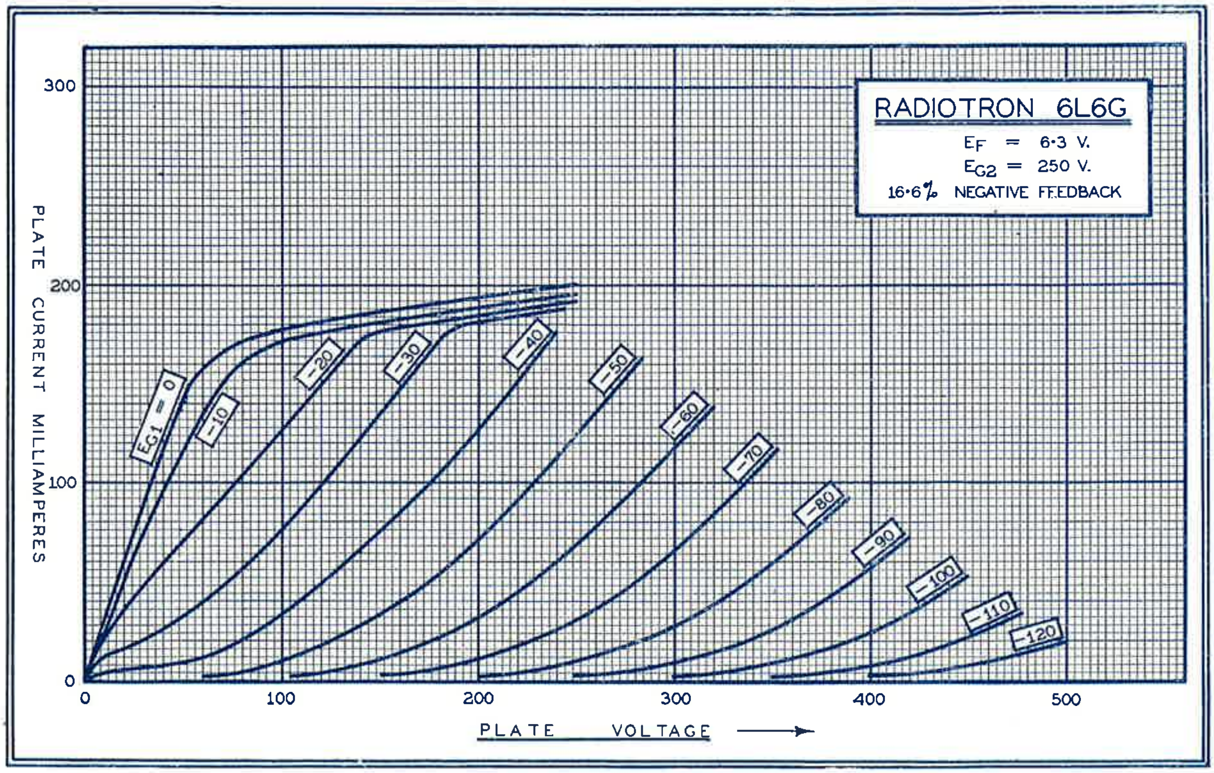


Fig. 6. *Plate voltage—plate current curves for Radiotron 6L6G beam tetrode with 16.6% negative feedback at full output.*

PUSH-PULL AMPLIFIERS WITH NEGATIVE FEEDBACK

FEEDBACK OVER THREE STAGES

To gain full benefit of the high efficiency of beam tetrode output valves, they should be operated in push-pull. When negative feedback has been applied to push-pull amplifiers, there has been, in many cases, a pronounced tendency for the phase of the feedback to change sufficiently to become positive and cause free oscillation at some supersonic frequency. One solution to the problem appeared in Radiotronics 79, in which a specially designed transformer was described.

Due to the difficulties in the production of such a transformer, Radiotron engineers have given further attention to the problem, and are now able to recommend very simple, yet perfectly stable circuits using both 6V6G's and 6L6G's in push-pull output stages.

Most of the troubles attending feedback over more than one stage have been due to phase shifts in various parts of the circuit. By using a feedback network with negligible phase shift it is possible to feed back more voltage without risk of instability.

Screen Injection

It has been found that the screen grid of a resistance coupled pentode stage is a very useful point at which to inject a feedback voltage. The effect of screen voltage variation on the I_pE_p curve of a valve is almost identical to a change in control grid voltage of $1/\mu'$ times the value, where μ' is the triode μ of the valve. Thus, if the stage uses Radiotron 6J7G with a gain of 150 times at grid No. 1, and with $\mu' = 20$, the gain between grid No. 2 and plate is 150/20 or 7.5 times. Because a positive increment in screen voltage results in an increase in plate current with a consequent negative change of plate voltage, there is a phase reversal in the feedback over the valve itself. When the feedback voltage is taken from the load of the output valve, there must be another phase reversal between the plate of the pentode voltage amplifier and the grid of the output stage, in order that the feedback voltage be out of phase with the input. This phase reversal may well be provided by a phase-splitting stage where push-pull output is employed.

As there is some gain between the screen and plate of the resistance coupled stage, and a loss (represented by a fractional gain) from grid to plate in the phase splitter, the actual feedback factor at the grid of the output valve must be divided by the resultant gain over the two stages in order to find the fraction of the output voltage which is fed to the screen. The amplifier arrangement is therefore a first stage consisting of a resistance coupled pentode, a second stage triode phase splitter, and a final push-pull stage, feedback being taken from the plate circuit of the final stage to the screen grid of the first stage. Since the screen grid of the first stage has a linear voltage relationship with the control grid, the feedback may be considered as having been injected with suitable phase relationship into the control grid circuit. On this basis **the feedback is external to the amplifier proper and does not result in any decrease of gain inside the amplifier nor in any increase of voltage output from any stage.** The initial distortion is therefore not increased through the addition of negative feedback, and the full reduction of distortion is obtained in proportion to the gain reduction factor.

Design of Practical Amplifiers

If the first stage is Radiotron 6J7G with a screen to plate gain of 7.5, followed by a 6J7G triode phase splitter with a stage gain of 0.9, the total gain between 6J7G screen and grid of output valve will be $7.5 \times 0.9 = 6.75$. If the output valves are 6V6G's, requiring a plate to plate load of 10,000 ohms and representing 5000 ohms per valve at the working point (See Radiotronics 79), and the output resistance is to have half this value, then the term $\beta.G_m$

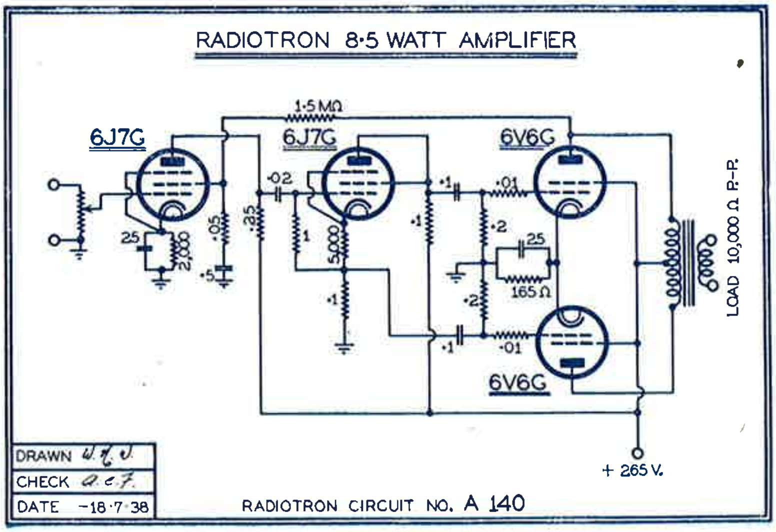


Fig. 7. *Radiotron 8.5 Watt 6V6G Amplifier with feedback over three stages, giving a gain reduction of 3.98 and requiring an input voltage of 0.31 volt RMS.*

must be 1/2500. In a 6V6G, the mutual conductance is 3900×10^{-6} amps/volt at $I_p = 35$ mA., and β, the feedback factor, becomes $10^6/(2500 \times 3900) = 0.103$ or 10%, approximately. This is the percentage of feedback on to the grid of one 6V6G valve to give an output resistance half the value of the load resistance. Since there is a gain of 6.75 times from the screen of the first valve to the grid of the 6V6G, the feedback to this screen will be 10.3/6.75 or 1.5% for an equivalent effect. The simplest possible circuit to arrange the screen feed (A.F. and D.C.) without upsetting the self adjusting characteristic of series screen feed, seems to be that shown in Figs. 7 and 9 in which a small resistance is inserted between screen and screen by-pass condenser, and the screen dropping resistance is fed from the plate of the appropriate output valve. The two resistors form a divider for the audio voltage. If the feedback factor is 1.5% and the screen dropping resister is 1.5 megohm the extra resistance must be $1.5 \times 1.5/98.5 = .0228$ megohm.

The gain of the amplifier has been reduced by a factor $(1 + M\beta)$ where M is the gain from the point at which feedback is applied. The gain of the 6V6G may be calculated from the voltage developed at maximum output, which is $\sqrt{5000 \times 4.25}$ or 146 volts RMS equivalent to 206.5 volts peak per plate, and the peak grid input voltage, which is 15 volts. The ratio volts-output/volts-input $= 206.5/15 = 13.8$ in stage gain. The total gain between screen and 6V6G plate is then $13.8 \times 6.75 = 93$, and the gain reduction is $1 + 93 \times .015 = 2.40$.

Without feedback, it would have been necessary to provide $15/(150 \times 0.9) = .111$ volts peak, or .0785 volts RMS at the grid of the first 6J7G for maximum output. Feedback increases the figure to 0.189 volts RMS which is still unnecessarily small. By increasing the feedback resistance to .05 megohm, β becomes 3.2%, making the gain reduction 3.98, and the required input voltage 0.31 volts RMS for full output. The latter figure is well within the output capabilities of most ordinary high resistance pick-ups, and the amplifier has then better regulation than is possible with the average triode.

The complete 6V6G amplifier has a maximum output of 8.5 watts, with less than 3% second harmonic and negligible higher order harmonic distortion over a frequency range from 30 to 10,000 c/s (Fig. 8). It should make a cheap substitute for the 7 watt Radiotron amplifier A115 described in Radiotronics 77. The power supply is required to deliver 265 volts, 77 to 93 mA, and since extremely good regulation is not essential any ordinary rectifier and filter arrangement may be used. The rectifier may be Radiotron 5V4G (83V) with a 385-385 volt transformer and condenser input and a total resistance of 1500 ohms distributed between the two filter chokes (see Radiotron Circuit A.130, Radiotronics 83 Page 100).

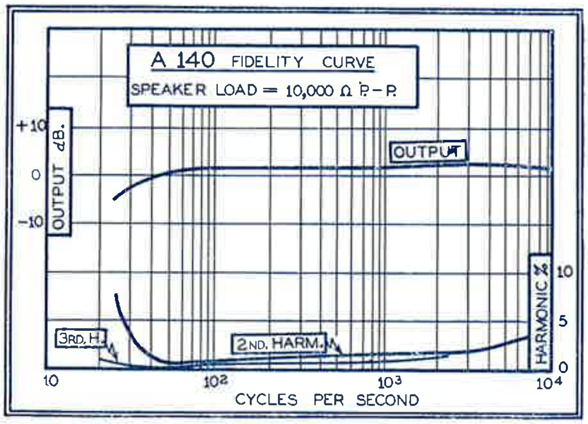


Fig. 8. *Fidelity curves of 8.5 Watt 6V6G Amplifier A140 on a loudspeaker load at full output.*

For higher outputs, 6L6G's may be used in the circuit of Fig. 9 to provide 32 watts output with less than 4% second harmonic and less than 2% third harmonic distortion from 40 to 10,000 c/s (Fig. 10). This amplifier employs a gain reduction of 2.88 and requires an input voltage of 0.43 volts RMS for full output.

The power supply is required to deliver 425 volts, 186-211 mA and any rectifier and filter

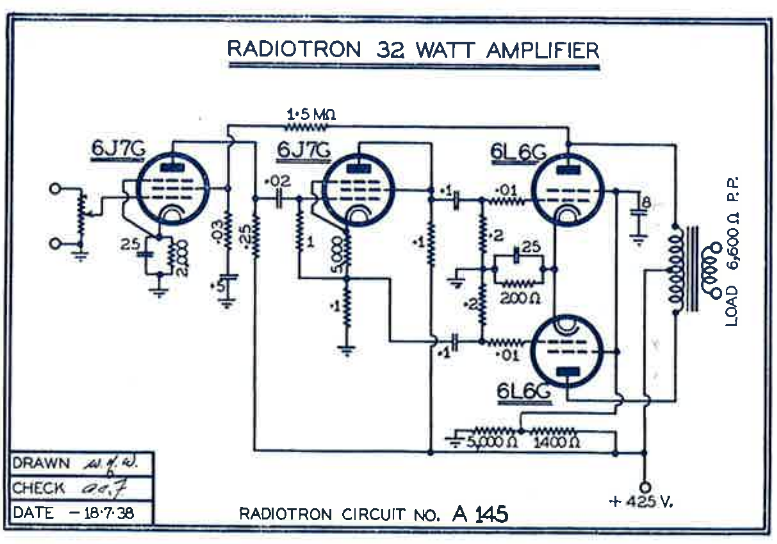


Fig. 9. *Radiotron 32 Watt 6L6G Amplifier with feedback over three stages, giving a gain reduction of 2.88 and requiring an input voltage of 0.43 volt RMS.*

giving reasonably good regulation may be used. Radiotron 83 mercury vapour rectifier with choke input filter operating from a 500-500 volt transformer would provide about 435 volts D.C. at the input to the filter. Radiotron 5V4G (83V) is limited to 200 mA and is, therefore, liable to be overloaded, while type 5U4G (5Z3) with condenser input gives rather poor regulation which will result in a slight decrease in power output.

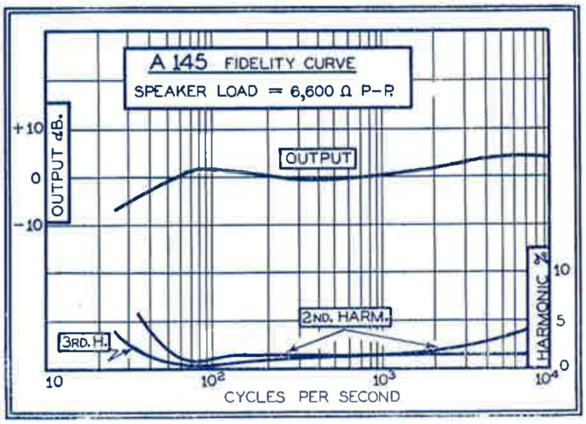


Fig. 10. *Fidelity curves of 32 Watt 6L6G Amplifier A145 on a loudspeaker load at full output.*

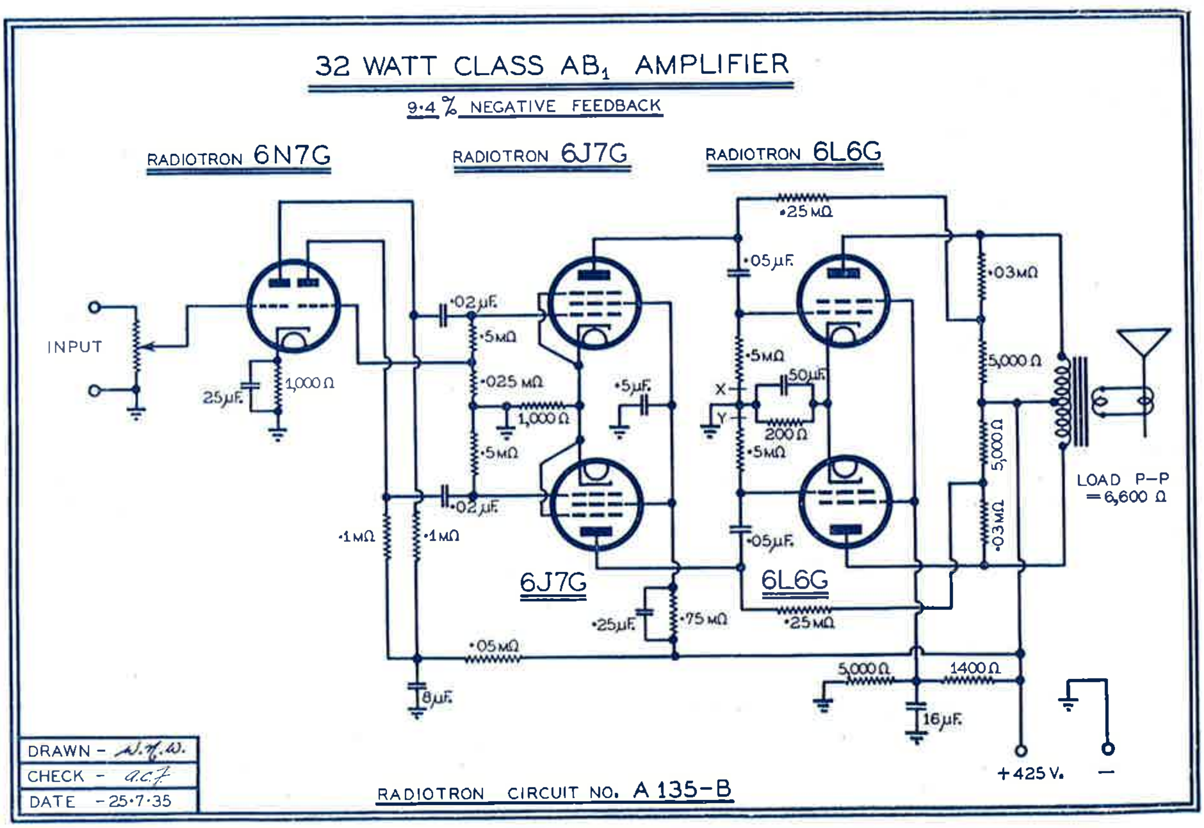
Although this feedback circuit arrangement appears to be free from instability under normal operating conditions with any output stage, a word of caution appears desirable since it is not impossible for certain variations to prove unstable. Consequently we recommend strict adherence to the published circuit diagrams which represent amplifiers which have been constructed and tested in our laboratory.

It will be noted in Circuit A140 that self-bias is used on the 6V6G valves although previously published data covered fixed bias operation only. This is quite satisfactory for 250 volt operation with a cathode resistor of 165 ohms, but is not permissible with 300 volt operation unless the operating conditions are chosen so as to avoid excessive dissipation under no-signal conditions.

32 WATT 6L6G AMPLIFIER

Modifications to Circuit A135

Radiotron Circuit A135 for a 32 Watt 6L6G Amplifier, described in Radiotronics 86, has been found to require decoupling between the first and second stages. A modified circuit (A135B) incorporating this addition, is given on this page, although the alternative circuit (A145) given elsewhere in this issue provides the same output with one valve less and will probably be preferred for this reason.



RCA APPLICATION NOTE ON RECEIVER DESIGN

This Note discusses briefly a variety of topics that relate to radio-receiver design. The material contains information on the characteristics of valves and circuits and also offers suggestions for improving receiver performance. In most instances, suggested changes correct peculiar behaviour, and do not require alteration in the basic design of the receiver.

Use of Pentagrid Converter with Separate Oscillator

When a pentagrid converter type of valve is used with a separate oscillator, oscillator voltage is usually connected to the No. 1 grid of the pentagrid converter; its anode-grid may be grounded or connected to screen. With anode-grid grounded, a peculiar form of oscillation, which is evidenced by tunable noise in the receiver, may be generated. The remedy is to connect anode-grid to screen, because the oscillation and, hence, the noise are not present with this connection.

Grid-Resistor Value for Partial Self-Bias Operation

Two recommended maximum values of grid resistors for an output valve are usually specified one for fixed-bias operation and one for self-bias operation. For operation involving partial self-bias, it is suggested that a proportional relation be used:

$$R = R_{fb} + P_{sb} (R_{sb} - R_{fb}),$$

where R is the value of grid resistor for the per cent. self-bias (P_{sb}) of interest, R_{sb} is the recommended maximum value of grid resistor for self-bias operation, and R_{fb} is the recommended maximum value of grid resistor for fixed-bias operation. P_{sb} is defined as the ratio of the output valve's cathode current to the total current flowing through the bias resistor.

Power Sensitivity of A-F Amplifier in Radio Receivers

Experience indicates that microphonic or hum problems may become serious when the gain of the A.F. section of a radio receiver is high. Measurements on a number of receivers of average design indicate that a good value of maximum audio-frequency power sensitivity for battery receivers is 50 mhos and for A.C. operated receivers, 200 mhos. Power sensitivity in mhos is defined as the ratio of the power output in watts to the square of the input signal in volts (rms). Values of power sensitivity in excess of these figures may be used when better than average precautions are taken to reduce hum and microphonics.

Hum-Reducing Precaution in Type 6C8-G

When using the type 6C8-G in a high-gain A.F. amplifier in which one side of the heater is grounded, it is advisable to ground heater terminal No. 7 to reduce hum. A further reduction in hum may be obtained by connecting a 100- to 500-ohm potentiometer across the heater terminals and grounding the adjustable arm. Another suggestion is to use the lowest practical value of resistor in each grid circuit of the 6C8-G. In this type, hum is produced at the grids by capacitance coupling between the grids and the heater lead connecting to pin No. 7.

RADIOTRON NEWS

Radiotron 6V6G, 4.25 Watt Beam Power Tetrode, is now being manufactured in Australia. This type has already proved popular owing to its high grid sensitivity, high plate efficiency and high power output and is expected to be adopted very widely during the coming season.

Radiotron types 1A4, 1D5G and 6B7 have also been added to the list of Australian made valves during the past few months.

Radiotron 902, 2 in. Cathode Ray Tube, has proved a valuable addition to the range and is particularly suitable for portable equipment. Supplies are available from stock at £2:15:0 each nett (Australian price).

In addition to Radiotron 1851, television amplifier pentode with a mutual conductance of 9,000, two additional types have been announced. Radiotrons 1852 and 1853 have mutual conductances of 9,000 and 5,000 respectively, but are not yet available from stock. Further information will be given in the next issue.

Radiotron 832, Push-Pull Beam Tetrode Power Amplifier for ultra-high frequencies is designed for operation at maximum ratings on a wavelength of 2 metres. Further information will be given in the next issue.

Radiotron 6AF6G, twin indicator Magic Eye without any amplifying units, to be described in the next issue, will shortly be available in limited quantities from stock.

Radiotron 1G5G, Power Pentode with 2 volt 0.12 amp. filament and up to 750 m.W. output at 135 volts, is available in limited quantities from stock.

POWER OUTPUT AND EFFICIENCY

(Continued from page 148)

becomes an ideal low impedance output valve, provided that the time constant of the feedback network is small. The power sensitivity is not inherently better in either type of valve, though the mutual conductances of most power tetrodes are higher than those of power triodes, thus providing the modified tetrodes with higher sensitivity.

Where negative feedback is used with push-pull amplifiers, the added advantage of higher efficiency due to Class AB^1 operation may be realised, without sacrifice of fidelity.

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