RADIOTRONICS

AMALGAMATED WIRELESS VALVE COMPANY LIMITED

BOX No. 2516 BB G.P.O., SYDNEY

TECHNICAL BULLETIN No. 76 **26th MAY, 1937**

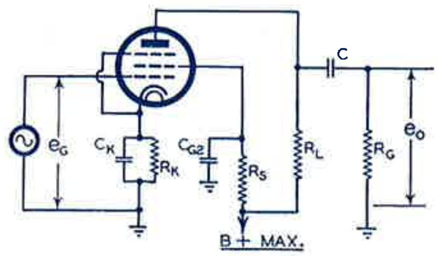
In this issue:—

RESISTANCE COUPLED PENTODE AMPLIFIERS

Summary:

Resistance coupled pentodes have considerable advantages over triodes in the same application, and are superior with regard to stage gain, high frequency response, low frequency response, low distortion, and high output voltage. The operation of pentodes is dealt with fully in this article, and formulae giving their frequency response for various circuit constants are given. Distortion and voltage output are also dealt with in full.

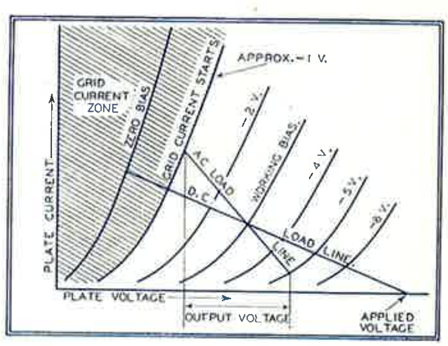
Fig. 1



It has only recently been realised that pentodes as resistance coupled amplifiers have many advantages over triodes. In the past there has been very meagre information available, and many of the operating conditions which have been published, have applied only to a limited field. Their extension to other conditions has not been very widely understood and as a consequence the advantages gained through the use of pentodes have not all been realised. It has been shown in recent issues of Radiotronics that resistance coupled pentodes are capable of giving very high gain per stage and a very low degree of distortion. It has also been stated that the frequency response with pentodes extends both to higher and to lower frequencies than with triodes under the same conditions. The purpose of this article is to investigate these matters more fully so that the performance of pentode amplifiers can be predicted with a very high degree of accuracy.

Since the plate to grid capacities of pentodes such as the 6C6 are very low when compared with triodes, it seems obvious that they have advantages for high audio frequencies. It is not so obvious that their characteristics also result in an improved low frequency response. Investigations which have been conducted in the laboratory of Amalgamated Wireless Valve Company Ltd. have shown that it is possible to calculate the performance of pentodes as resistance coupled amplifiers to a very high degree of accuracy and these results have opened the way to a fuller understanding of the factors concerned. Although the calculations may seem to be rather involved, the results obtained are of the greatest interest and are worthy of detailed consideration. In order that the radio engineer may readily apply the results obtained in this manner, tables of recommended operated conditions are given which can be applied with a minimum of difficulty.

Fig. 2.



MATHEMATICAL INVESTIGATION

Stage Gain

The stage gain (m) of a resistance capacity coupled stage may be expressed[1] for all frequencies

$$m = \frac{gm}{\frac{1}{R_p} + \frac{1}{R_L} + \frac{1}{R_g} + \frac{C_o}{CR_g} + \frac{C_i}{C}\left(\frac{1}{R_p} + \frac{1}{R_L}\right) + j\left[\omega(C_o + C_i + \frac{C_oC_i}{C} - \frac{1}{\omega CR_g}\left(\frac{1}{R_p} + \frac{1}{R_L}\right)\right]} \quad (1)$$

where m = stage gain.
R_p = plate resistance of valve *at operating plate current.*
R_L = plate load resistance.
R_g = grid resistor of following valve.
C_o = total output capacitance (including stray capacities).
C_i = total input capacitance of following stage (including stray capacities).
C = coupling capacitance.
gm = mutual conductance *at operating plate current.*
ω = 2π x frequency.
j = vector operator ($\sqrt{-1}$).

It may be seen that at a certain frequency, the coefficient of j in the denominator becomes zero, giving m its maximum value. When f is lower or higher than this frequency, the amplification is reduced. Further, it is evident that the reduction in gain is accompanied by a phase shift between input and output voltages, the output voltage leading at low and lagging at high frequencies. In both of these respects, the resistance capacity network between the plate of one stage and the grid of the next behaves much like a tuned transformer as used for R.F. coupling. In fact, it has been shown that the mathematical functions governing the operation of both are identical in form, but have different constants[2]. As most resistance coupled stages are required to amplify over a wide range of frequencies, it is fortunate that the maximum effective Q which is attainable is 0.5, and very much lower values are more general.

The Q factor of a tuned circuit may be found from the ratio of the resonance frequency to the difference between the two frequencies where the resistive and reactive components are equal in scalar value. When such equality holds, the response has fallen by a ratio $1/\sqrt{2}$, which represents about 3 db. In audio amplifier design, the upper and lower frequencies themselves are of more value than the selectivity of the stage. To find them, one must equate both sides of the denominator of the function for m and solve for ω.

High Note Loss:

As the reference points should occur at about 50~ or lower, and 10,000~ or higher, the reactance of the coupling condenser C at the high reference frequency will be at the most, 0.5% of its value at the lower reference point when it is equal the resistive component. For purposes of design, therefore, it is practicable to neglect its effect at high frequencies, and lump the capacities, C_o, C_i, into a total C_s, the shunt capacitance. It is also permissible to disregard the last three terms in the resistive component. Thus it is found, at 3DB down,

$$fh = \frac{1}{2\pi C_s R_t} \quad (2)$$

$$\text{and } R_t = \frac{1}{2\pi fh C_s} \quad (3)$$

Where $\frac{1}{R_t} = \frac{1}{R_p} + \frac{1}{R_L} + \frac{1}{R_g}$

and fh = high frequency where gain has dropped 3 db.
C_s = total shunt capacitance.

As the offending capacity is C_s, its nature should be understood. Besides the plate to cathode capacitance on one valve, the grid to cathode capacitance in the next, and the stray capacitance in the wiring, there is also the capacitance from plate to grid in the second valve. There are alternating voltages on both grid and plate, the plate voltage being approximately 180° out of phase with that at the grid, and much greater. A zone of minimum potential therefore exists between grid and plate, being nearest to the grid in valves giving high gain. There is, in effect, a virtual earth screen lying close to the grid, tending to increase the total input capacitance of the valve. Including that due to the "Miller" effect described, the total input capacitance of a valve may be taken as

$$Cgk + Cgp\ (m + 1)$$

where m = gain of next stage.
Cgk = grid-cathode capacitance.
and Cgp = grid-plate capacitance.

It should be obvious that in equipment where the upper frequency has to be very high, Cgp should be as low as possible. For some audio frequency work where stability is of prime importance, triodes are chosen. High mu types such as the 75 have fairly high grid-plate capacitance and also high gain, making the input capacitance very high. Low impedance types such as the 6C6 triode have lower gain figures, and, consequently, less "Miller effect" capacitance. Pentodes such as the 6C6 provide ample gain with very low input capacitance.

In broadcast receivers there are usually only two audio stages. The first should have low input capacitance, to minimise the loss of high frequencies in its grid circuit. In order to determine the gain of the first stage, the input capacitance of the output stage must be considered. Typical values for commonly used valves are:—

2A3 - 60$\mu\mu$F. 6L6 - 31$\mu\mu$F. 42 - 18$\mu\mu$F.

From the equation (3) it is evident that where f_h is high, R_t must be low, and the load, R_L, must be correspondingly small. With triode valves a limit is set by harmonic distortion which increases rapidly as the ratio R_L/R_p is reduced. Pentode valves stand more load reduction, and may be used in resistance coupled applications for frequencies up to 50,000~.

Low Note Loss:

It may be shown that at the low reference frequency, the reactance of the capacitances C_o and C_i are high enough to be negligible. The following relations thus hold:—

$$f_L = \frac{1}{2\pi C\left(R_g + \dfrac{1}{\dfrac{1}{R_p} + \dfrac{1}{R_L}}\right)} \quad \text{......} \quad (4)$$

$$C = \frac{1}{2\pi f_L\left(R_g + \dfrac{1}{\dfrac{1}{R_p} + \dfrac{1}{R_L}}\right)} \quad \text{......} \quad (5)$$

where f_L = low frequency where gain has dropped 3 db.

The terms R_g, R_p are set by the choice of valve. To keep harmonic distortion to a minimum, R_g/R_L should be large. It may also be seen from (4) that R_g should be large in order that f_L be low. A limit is set by the tendency of the grid to emit electrons (grid emission) generating a current which builds up across R_g a *positive* voltage that may endanger the emission of the cathode. Maximum values of Rg are given with the characteristics of each type of valve. For fidelity operation, it is wise to use the maximum resistance, but not to increase it beyond the value recommended. The plate resistance (R_p) has an effect on the bass response. As R_p is increased f_L becomes lower. Pentode valves having very high values of R_p therefore amplify better than triodes at low frequencies.

R_L is usually fixed by the upper frequency reference point, leaving the coupling capacity C the variable factor to determine the lower reference frequency. It should be as large as possible for fidelity, but in cases of severe instability it may be reduced to prevent low frequency oscillation.

There are two other factors influencing the low frequency response — the bypass condensers from cathode to earth and from screen grid to earth.

The stage gain, including loss due to the cathode bypass is expressed

$$m = \frac{1}{\dfrac{1}{m'} + \dfrac{1}{R_L\left(\dfrac{1}{R_k} + j\omega C\right) + 1}} \quad (6)$$

Where m′ = stage gain with A.C. short across bias resistor

R_k = cathode bias resistance

and C = bypass capacity.

For good response at low frequencies the expression ($R_L/R_k + R_L\omega C$) should be large. In triode stages the ratio R_L/R_k is usually much smaller than with pentodes, and a larger value of C is therefore required with triodes for a similar frequency response.

However, 25μF dry electrolytic condensers have sufficiently low reactance to cause only 0.1% loss in typical pentode stages and 1% in triode stages at 50~.

The loss from the screen bypass reactance is shown by the equation

$$m = m''\left[1 - \frac{1}{1 + \dfrac{\mu t}{g_m}\dfrac{i_p}{i_s}\left(\dfrac{1}{R_s} + j\omega C\right)}\right] \quad \text{......} \quad (7)$$

Where m″ = gain with infinite screen bypass capacitance.

μt = triode amplification factor.

gm = pentode mutual conductance.

$\dfrac{i_p}{i_s}$ = Ratio plate to screen currents.

R_s = Screen dropping resistor.

C = Screen bypass capacitance.

The term ωC must be large at low frequencies for efficient operation. A .1 μF condenser can reduce the gain of a single 6C6 pentode by 2.5 db at 50~. For fidelity operation, a .25 or .5 μF bypass is recommended.

Harmonic Distortion:

An amplifier may have an ideal frequency characteristic, and still distort the wave form of the output signal. It is not generally recognised that all stages in amplifying (and transmitting and receiving) equipment can introduce their share of distortion. In properly designed amplifiers the major part of the total harmonic distortion is due to the output stage, and the earlier stages are operated well within their limits.

Power triodes and pentodes are usually rated to provide certain figures for power output at a predetermined percentage of harmonic distortion, generally 5%. Voltage amplifiers (resistance or transformer coupled) may be rated by the voltages they are able to deliver with set factors of distortion. It follows naturally that the valve which has the greatest voltage output, introduces the least distortion for any required voltage.

From fig. 2 the output voltage of a triode is seen to depend on three variables—the plate load resistance, the grid leak resistance of the following stage, and the plate resistance of the valve. The D.C. load line is drawn through the applied voltage on the plate voltage axis, and at a slope equal to $-1/R_L$. The operating point is determined by the bias. Earlier in this article it has been shown that the load resistance very nearly approximates $1/(1/R_L + 1/R_g)$ throughout the working range of frequencies. Thus the A.C. load line is plotted through the operating point with a slope of $-(1/R_L + 1/R_g)$. The lower limit of plate voltage is set then by the tendency of the grid to draw positive grid current, and the upper limit is set by plate current cut-off. It is obvious that as R_L is increased so the lower limit is reduced, as the load line becomes more nearly horizontal. It may also be seen that the smaller the difference between the D.C. and A.C. loads (i.e., the larger the grid resistor) the higher will be the upper limit.

The slope of the characteristic curves is equal to $1/R_p$. Where R_p is small, the curves tend to become more nearly vertical, allowing larger output voltages. Where R_p is large, as in the type 75, the amplification factor is high, and the grid current commencement voltage is very nearly equal to the plate current cut off voltage for applied voltages of less than 200 volts. The output in such cases is severely restricted, and type 75 is prone to distort badly before providing complete excitation for an output triode such as type 2A3.

Where possible, it is wise to increase the applied voltage above 250 volts. It is safe to use supply voltages up to 400, because the actual plate voltage is reduced by the load resistance.

Triode valves have plate resistances ranging from very low to high values, and their performance as resistance coupled amplifiers is largely dependent on their plate resistance. Pentode valves used in resistance coupled applications are of the high plate resistance type, and the effect of any change in R_p is comparatively small. The total output voltage varies little with changes in plate load resistance until the latter is reduced below about 50,000 ohms.

In Radiotronics No. 69 a method was described for the graphical determination of operating conditions for resistance coupled pentodes. It may further be simplified by finding from the triode curves the screen voltage at which the cathode current,

$$I_k = \frac{i_p + i_{g2}}{i_p} \times \frac{E_s}{R_L} \times 0.55$$

where i_p, i_{g2} are plate and screen currents under standard conditions (published figures).

E_s = supply voltage

and R_L = plate load resistance.

By making the bias great enough, an operating curve may be selected to avoid grid current and still combine high gain with high output voltage.

The output may still be restricted, however, by the grid resistor, R_g. Voltage output from resistance coupled pentodes is reduced in the ratio $1/\left(1 + \frac{R_L}{R_g}\right)$ by the grid resistor, which should be kept as large as is safely allowable.

Summary:

(a) To minimise harmonic distortion:—
- R_L should be made large.
- R_g must be much larger than R_L.
- R_p (in triodes) should be low.

(b) Pentodes give greater voltage outputs than triodes under similar conditions.

(c) To calculate stage gain at middle frequencies

$$m = \frac{gm}{\frac{1}{R_p} + \frac{1}{R_L} + \frac{1}{R_g}}$$

(d) At high frequencies, m is 3DB down when

$$f_h = \frac{1}{2\pi C_s R_t}$$

$$\text{or } R_t = \frac{1}{2\pi f_L C_s}$$

where $C_s = C_{pk} + C_{gk} + C_{gp}(m + 1) + C_w$

and C_w = stray capacitance in wiring, etc.

(e) At low frequencies, m is 3DB down when

$$f_L = \frac{1}{2\pi C\left[R_g + \frac{1}{\frac{1}{R_p} + \frac{1}{R_L}}\right]}$$

$$C = \frac{1}{2\pi f_L\left[R_g + \frac{1}{\frac{1}{R_p} + \frac{1}{R_L}}\right]}$$

(f) The cathode bypass condenser, C_k should be large — 25μF is sufficient in most cases.

(g) The screen bypass condenser should be at least 0.1μF in pentode stages, and a higher capacitance is preferable.

(h) The cathode current, I_k of a pentode stage should be

$$I_k = \frac{i_p + i_{g2}}{i_p} \times \frac{E_s}{R_L} \times 0.55.$$

RESISTANCE COUPLED PENTODES

(See references at foot for meaning of symbols).

GROUP I.

Type	E_{max}	E_{g_1}	R_s	R_k	R_L	R_g	m	db	E_{op}
6C6 / 6J7 / 57	135	—	1.5	2,000	0.25	1	116	41.3	36
						0.5	96	39.6	31
	250	—	1.5	2,000	0.25	1	150	43.5	72
						0.5	125	42.0	60
	400	—	1.5	2,000	0.25	1	175	45.0	115
						0.5	145	43.3	95
77	135	—	1.5	2,000	0.25	1	105	40.4	34
						0.5	88	38.9	29
	250	—	1.5	2,000	0.25	1	134	42.5	60
						0.5	110	40.8	50
	400	—	1.5	2,000	0.25	1	160	44.1	96
						0.5	133	42.5	80

GROUP II.

Type	E_{max}	E_{g_1}	R_s	R_k	R_L	R_g	m	db	E_{op}
6B7S	135	—	*	2,000	0.25	1	75	37.5	30
						0.5	63.5	36.0	25
	250	—	*	2,000	0.25	1	93	39.4	42
						0.5	77	37.7	35

* Voltage Divider 1.0 and 0.25 Megohm.

GROUP III.

Type	E_{max}	E_{g_1}	R_s	R_k	R_L	R_g	m	db	E_{op}
2B7 / 6B8	135	—	1.75	2,000	0.25	1	75	37.5	30
						0.5	63	36.0	25
	250	—	1.75	2,000	0.25	1	95	39.5	56
						0.5	80	38.1	46
	400	—	1.75	2,000	0.25	1	110	40.8	88
						0.5	92	39.3	72

GROUP IV.

Type	E_{max}	E_{g_1}	R_s	R_k	R_L	R_g	m	db	E_{op}
1K4	90	–1.5	0.75	—	0.25	1	59	35.4	25
						0.5	48	33.6	20
	135	–1.5	0.75	—	0.25	1	75	37.5	36
						0.5	62.5	35.9	30
	180	–1.5	1.0	—	0.25	1	88.5	39.0	48
						0.5	74	37.4	40
1K6	90	–1.5	1.0	—	0.25	1	54	34.7	22
						0.5	45	33.1	18
	135	–1.5	1.0	—	0.25	1	76	37.6	34
						0.5	63	36.0	28
	180	–1.5	1.0	—	0.25	1	83	38.4	45
						0.5	69	36.8	38

GROUP V.

Type	E_{max}	E_{g_1}	R_s	R_k	R_L	R_g	m	db	E_{op}
6C6 / 6J7 / 57	250	—	0.3	2,000	0.1	1.0	98	39.8	85
						0.5	82	38.3	78
						0.25	70	36.9	67
	400	—	0.3	2,000	0.1	1.0	105	41.4	135
						0.5	92	39.3	124
						0.25	80	38.1	106

E_{max} = TOTAL SUPPLY VOLTAGE.
E_{g_1} = GRID BIAS VOLTS (BATTERY TYPES).
R_L = PLATE LOAD RESISTOR (Megohms).
R_g = FOLLOWING GRID RESISTOR (Megohms).
R_s = SCREEN DROPPING RESISTOR (Megohms).
R_k = CATHODE BIAS RESISTOR OHMS. (A.C. TYPES).
m = RATIO OUTPUT/INPUT VOLTAGES AT 400~ 0.25V. INPUT.
db = DECIBELS GAIN PER STAGE AT 400~.
E_{op} = PEAK VOLTAGE OUTPUT AT 3% DISTORTION.

Resistance Coupled Pentodes (continued)

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(2) W. F. Curtis:
"The limitations of Resistance Coupled Amplification."
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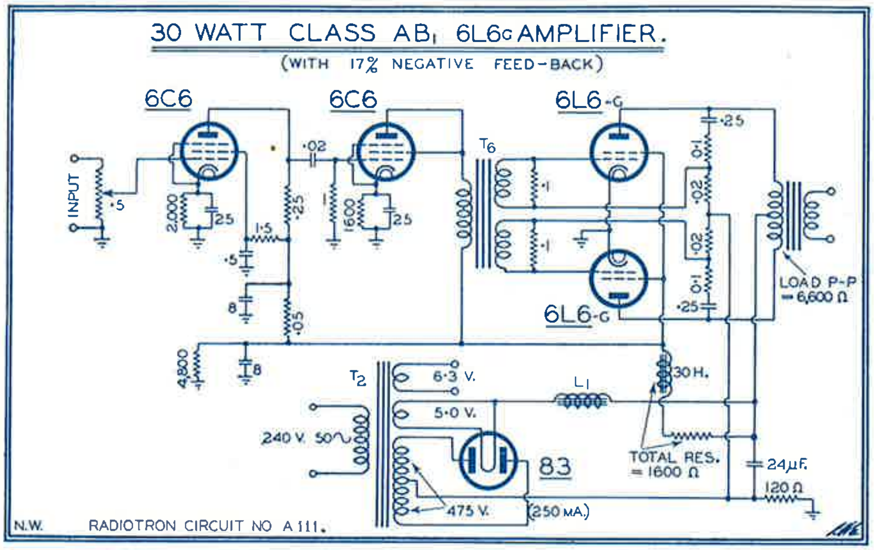
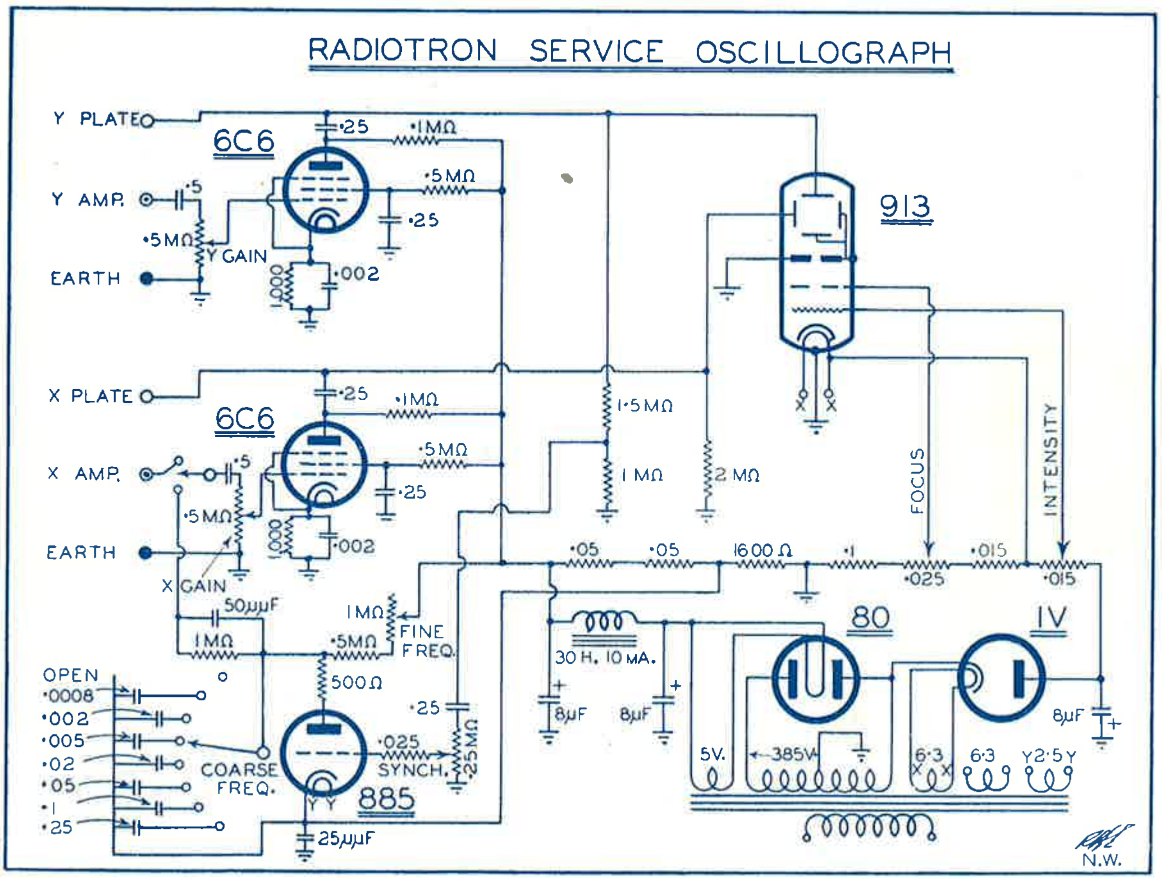
30 WATT 6L6G AMPLIFIER

FIG. 3 (for text, see Page 43).
Note: L_1 = 10 Henries (min.) at 200 mA.



RADIOTRON 913 OSCILLOGRAPH

In Radiotronics 75, page 36, the circuit for a Service Oscillograph using Radiotron 913 was shown. This circuit has been slightly amended and the correct circuit is shown below.



30 WATT 6L6G AMPLIFIER WITH NEGATIVE FEEDBACK

Circuits for the application of negative (inverse) feedback to resistance capacity coupled circuits have been described in previous Radiotronics Bulletins. There are, however, applications where resistance coupled stages have insufficient output completely to excite an output stage provided with feedback. In the case under consideration, it was decided to make use of sufficient feedback with a pair of 6L6G's in the 30 watt, class ABI condition, to provide the stage with regulation equal to that of a pair of 2A3's.

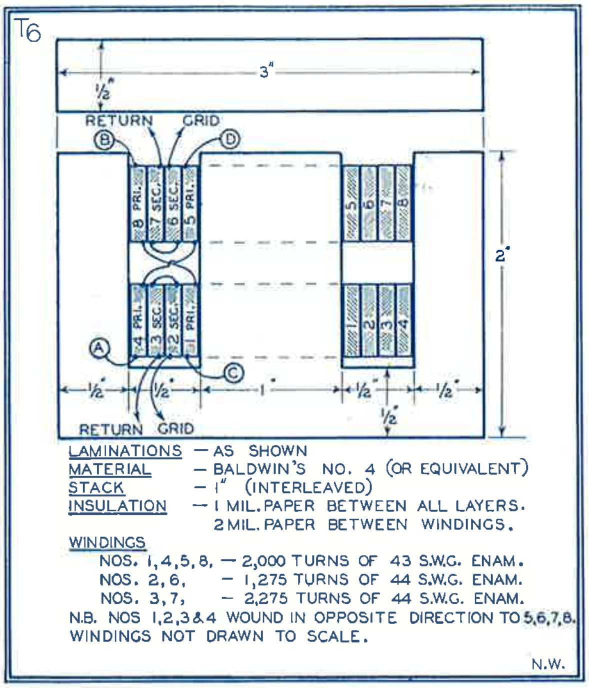


FIG. 4.

Leads A & C to be tied and taken to plate.
Leads B & D to be tied and taken to B+.

The regulation of any electrical equipment is defined as the ratio of output voltages under fully loaded and unloaded conditions. The no load output voltage of an amplifier

$$e_{max} = -\mu e_g$$

where μ = amplification factor of valve
and e_g = input voltage.

The loaded voltage

$$e_L = \frac{-\mu e_g}{1 + \dfrac{R_p}{R_L}}$$

where R_p = plate resistance of valve.
and R_L = plate load resistance of valve.

The regulation is thus expressed

$$1/\left(1 + \frac{R_p}{R_L}\right)$$

from which it is evident that the ratio $\frac{R_p}{R_L}$ is the criterion. For the regulation of 6L6G's to be as good that of the 2A3's.

$$R_o = \frac{R'_L R''_p}{R''_L}$$

where R_o = effective output resistance of 6L6G stage
R'_L = 6L6G load
R''_L = 2A3 load
and R''_p = 2A3 plate resistance.

The output impedance of a feedback stage is

$$R_o = 1/(1/R_p + gm.K)$$

where R_p = plate resistance of valve
gm = mutual conductance of valve
and K = feedback ratio.

whence

$$K = \frac{1}{gm}\left(\frac{R''_L}{R'_L R''_p} - \frac{1}{R'_p}\right)$$

For a 2A3,
R''_p = 800 ohms.
R''_L = 2500 ohms.

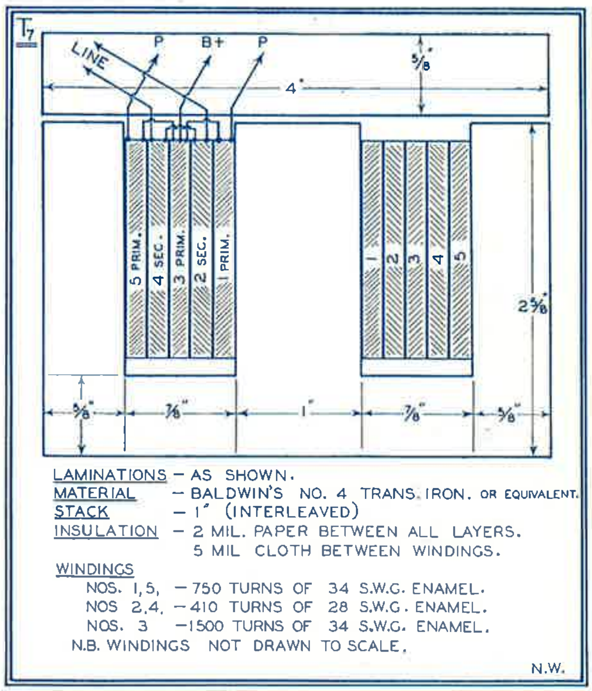


FIG. 5.

30 WATT OUTPUT TRANSFORMER
6600 TO 500 OHM LINE.

For a 6L6G,

$R'_p = 22500$ ohms.
$R'_L = 3300$ ohms.
and $gm = 6000\ \mu$mhos.

$$\text{making } K = \frac{10^6}{6000}\left(\frac{2500}{3300 \times 800} - \frac{1}{22500}\right)$$
$$= 0.15 \text{ (i.e., 15\% feedback).}$$

It should be noted that the values of R'_p and R'_L are those given for Class A operation, and do not hold exactly for the working point in Class AB1 operation. They are, however, a sufficiently close approximation as average values over a complete cycle.

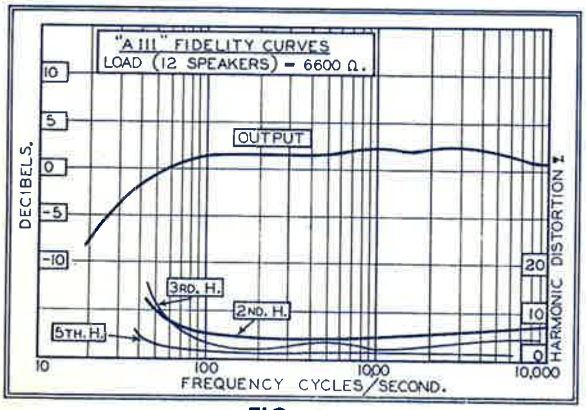


FIG. 6.

The peak output voltage of the 6L6G fully loaded is $\sqrt{2R_L.W}$, where W is the output power, and the feedback voltage is K times the output voltage.

Thus it is found:

$e_{fb} = K.\sqrt{2R_LW}$
where e_{fb} = peak feedback voltage
$= 0.15\ \sqrt{2 \times 3300 \times 15}$
$= 47$ volts, peak.

The required input voltage is the sum of the bias and feedback voltages, being 25 + 47 = 72 volts peak, for each valve, or 144 for the pair. Such a swing is beyond the capabilities of most high resistance pentodes applicable to feedback amplifiers, and the use of transformer coupling is justified.

From the curves of E_p, I_p, the 6C6 triode was found to provide satisfactory output using a turns ratio of 1:1 primary to half secondary. The transformer must be wound in sections, divided and connected in a method which reduces as much as possible the capacitance to earth of each end of each half-winding. This was found necessary in order to minimise resonant frequencies in the windings, when the feedback changed phase from negative to positive. The secondary windings should have their layers of maximum capacity to earth at the points of minimum potential, in this case at a point 25/72 from the grid end. The sections are wound in the ratio 2:1 (approximately) and connected as in fig. 4.

If oscillation occurs, its frequency most generally will be supersonic, and a cathode ray oscillograph connected across the output terminals will show its existence, nature, and frequency. However, if the transformer described is copied in its disposition and connections of windings, there should be no difficulty, and the amplifier should be stable at all frequencies.

Fig. 3 shows the circuit diagram for the complete amplifier; fig. 4 shows the winding details for the coupling transformer, and fig. 5 the output transformer. The experimental results of tests of gain and distortion versus frequency, and output and distortion versus input voltage, are given in figs. 6 and 7. In each case the load was a battery of 12 speakers, having typical characteristics. The curve of fidelity was taken with an input of 26.3 millivolts giving a maximum output of 29.3 watts at 400~.

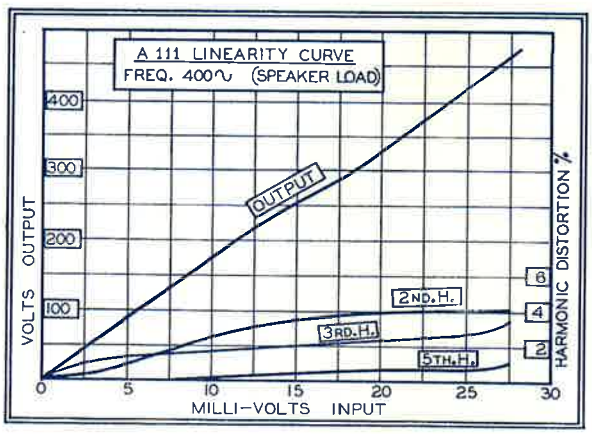


FIG. 7.