A Low Distortion Single-Ended Push-Pull Audio Amplifier

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Summary.

A new type of power output stage is described in which the normal limitations of conventional push pull amplifiers are absent. The circuit is of the single-ended push pull class with no output transformer and the valves connected in series for DC. The improved behaviour is due to the system of driving one of the output valves with a signal derived from the departure of the output waveform from the undistorted input.

Extremely low harmonic distortion (0.02% total) is obtained in class AB operation, right up to the point of clipping, without the use of overall feedback and the output impedance is less than 0.01 of the load impedance, which is not critical. Very wide frequency response is also obtained.

1. Introduction.

In conventional push-pull audio frequency power amplifiers, the most important single factor determining overall behaviour is the output transformer. Not only is the transformer an intrinsic part of the valve circuit but it is fed from an impedance which is large enough to allow the development of significant harmonic voltages due to the transformer itself. Using modern core materials and careful design[1], most of the objections to the transformer can be overcome but the expenditure on this one item can become as great as for the amplifier itself. Apart from this, the output stage develops considerable distortion in its own right—the actual amount depending upon balance between the two valves and their respective grid drives and also the operating conditions. The standard technique of applying a large amount of negative feedback around the whole amplifier can greatly reduce harmonic distortion but it is seldom that the required reduction in distortion is compatible with a really adequate margin of stability so that there is some doubt regarding the true benefit under transient and overload conditions[2]. Some of these factors are overcome in the single-ended push-pull amplifier[3, 4].

Basically, an immediate advantage is obtained in the single-ended amplifier as a transformer is not required for normal circuit operation. Even in the parallel-fed case where a transformer is used, the coupling between the two valves is unity so that design requirements of the transformer are simpler. In the series connected type of circuit, if the required load impedance is low enough, no transformer of any kind is necessary. Particularly in the case of larger amplifiers there is also an easing of power supply requirements as the same current flows through both valves in the series connected circuit. The major disadvantage associated with the single-ended push-pull type of circuit is that one of the output valves requires an extremely large grid drive which is difficult to obtain without excessive distortion in the driver stage. A number of circuits, showing different methods for ensuring balanced grid voltages for the output valves, have been published,[5, 6, 7] ranging from transformer coupling to combinations of negative and positive feedback. The circuit presented in this paper is a new approach to this problem. In this case, negative feedback is used around only one of the output valves in

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Presented at the 1959 I.R.E. Radio Engineering Convention, Melbourne, May, 1959.

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Manuscript received by The Institution May 25, 1959.
U.D.C. number 621.375.2.

1. Crowhurst, N. H., "Output transformer design", *Audio*, 40, Sept. 1956, 20.
2. Ketchledge, R. W., "Distortion in feedback amplifiers", *B.S.T.J.* xxxiv, Nov. 1955, pp. 1265-1285.
3. Peterson, A. and Sinclair, D. B., "A single-ended push-pull audio amplifier". *Proc. IRE*, 40, Jan. 1952, 7-11.
4. Chai, Yeh, "Analysis of a single-ended push-pull audio amplifier", *Proc. IRE*, 41, June 1953, 743-747.
5. Amemiya, H., "An output-transformerless amplifier", *J. Audio Eng. Soc.*, 4, April 1956, 72-75.
6. Review. "Output transformerless amplifiers", *Wireless World*, 63, Feb. 1957, 58-62.
7. De Miranda, J. R. and Van Zeist, J. J. Z., "New developments in output-transformerless amplifiers", *J. Audio Eng Soc.*, 6, Oct. 1958, 244-250.

order to introduce the correct amount of distortion in its grid signal to ensure no distortion in the output of the amplifier. No other feedback loop is required, even when a transformer is used for impedance matching to the load.

2. Description of Circuit.

The basic amplifier circuit is shown in Figure 1. The two output valves V_1, V_2 are connected in series for DC and the load is fed through the capacitor C_1. The input signal e_s is fed directly to the grid of V_1 and the drive to V_2 is provided by V_3. The good performance of this circuit is due to the manner in which the input to V_3 is obtained. In operation V_2 and V_3 behave like a "see-saw" inverter or "anode follower". A fraction of the undistorted input signal is added to the required fraction of the output voltage, so that the sum of these two voltages, after amplification in V_3, provides correct drive for V_2. By sampling the output voltage in this manner a continuous comparison is made between the input signal and the distorted output from the power amplifier, constraining V_2 to oppose the distortion produced by V_1.

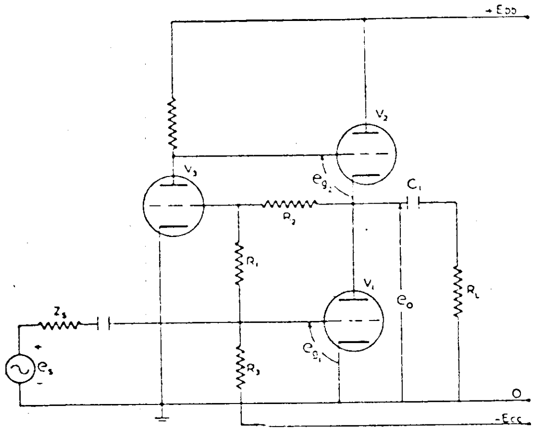

Figure 1.—Basic circuit diagram of low distortion power amplifier.

The ratio of R_1 to R_2 determines the exact grid signal to V_3 so that the input to V_2 contains the correct amount of distortion, out of phase with that produced by V_1. If the gain of V_3 is high, the effective feedback from cathode to grid around V_2 is sufficient to reduce distortion to an extremely low value and so make the complete amplifier behave as though V_1 and V_2 together provided a linear transfer characteristic. A second result of this system of drive is that the output impedance of the amplifier is considerably reduced in accordance with normal feedback behaviour. As far as V_1 is concerned, the magnitudes of R_1, R_2, R_3 and Z_s are such that any direct negative feedback in this part of the circuit is negligible.

3. Circuit Analysis.

Figure 2 shows the equivalent circuit of the amplifier, assuming small signal linear operation. In general, $R_1 \gg Z_s$ and $R_2 \gg Z_o$, the output impedance of the amplifier, so that the following equations may be written:

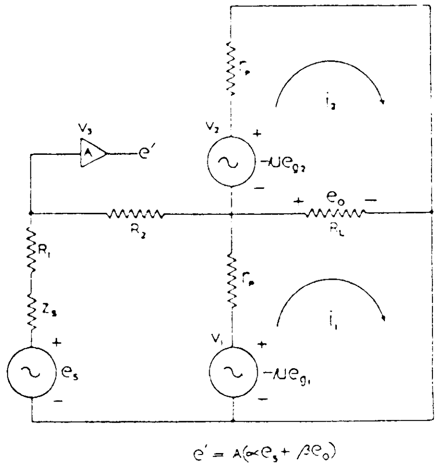

Figure 2.—Equivalent circuit of the low distortion amplifier.

$$e_{g1} = e_s$$
$$e_{g2} = A(\alpha e_s + \beta e_o) - e_o$$

where A is the voltage gain of V_3, $\alpha = R_2/(R_1 + R_2)$ and $\beta = R_1/(R_1 + R_2)$; $(\alpha + \beta = 1)$.

Then $\quad -i_1(r_p + R_L) + i_2 R_L = \mu e_s$
and $\quad i_1 R_L - i_2(r_p + R_L) = \mu[A\alpha e_s - e_o(1 - A\beta)]$.

The current flowing through the load resistance R_L is then given by

$$i_o = i_1 - i_2 = \frac{-\mu e_s(1 - A\alpha)}{r_p + 2R_L + \mu R_L(1 - A\beta)} \tag{1}$$

and voltage gain

$$A_V = \frac{-\mu(1 - A\alpha)}{r_p/R_L + 2 + \mu(1 - A\beta)} \tag{2}$$

Power sensitivity is given by $i_o{}^2 R_L/E_s{}^2$, that is

$$\frac{P_o}{E_s{}^2} = \left[\frac{-\mu(1 - A\alpha)}{r_p + 2R_L + \mu R_L(1 - A\beta)}\right]^2 R_L \tag{3}$$

It may also be shown that the output impedance of the amplifier is given by

$$Z_o = r_p/[2 + \mu(1 - A\beta)] \tag{4}$$

For correct push-pull behaviour we require $i_1 = -i_2$. Equating these two currents gives,

$$\beta = \frac{1}{A} + \frac{1}{1 + 2\mu R_L/(r_p + 2R_L)} \tag{5}$$

If equation (5) is satisfied the previous general equations become:

$$i_o = -2\mu e_s/(r_p + 2R_L) \tag{6}$$
$$A_V = -2\mu R_L/(r_p + 2R_L) \tag{7}$$
$$P_o = [-2\mu E_s/(r_p + 2R_L)]^2 R_L \tag{8}$$
$$R_L = \tfrac{1}{2} r_p \text{ for maximum } P_o \tag{9}$$

and output impedance remains unchanged at

$$Z_o = r_p/[2 + \mu(1 - A\beta)] \tag{10}$$

It must be remembered that the above expressions represent a small-signal analysis and therefore need not apply directly to the design of an amplifier. However, they do indicate in general terms what may be expected.

It is seen from (5) that for a particular load, not necessarily optimum, the value of β to give correct push-pull behaviour may be determined. From β the output impedance can be calculated using (10). Expressions (6),

(7) and (8) show the behaviour of the amplifier for the chosen R_L, assuming linear characteristics.

Of greater interest is the use of the earlier part of the analysis. Expressions (1), (2) and (3) indicate the expected behaviour as R_L is varied for a fixed value of β and hence α. For example, (2) may be rewritten as output voltage,

$$e_o = -g_m(1 - A\alpha)e_s \, . \, Z_o R_L/(Z_o + R_L) \qquad (11)$$

This suggests the familiar constant current equivalent circuit with R_L in parallel with Z_o. However, if β is fixed so also is Z_o, which under normal conditions has a very small value. Hence, within current overload limits, the output voltage should be almost independent of R_L.

Finally, the voltage gain of V_3 is normally large enough so that $A\alpha$ and $A\beta \gg 1$. Then

$$A_F \simeq -\alpha/\beta$$

and
$$Z_o \simeq \frac{r_p}{-\mu A\beta} \text{ (A is negative).}$$

4. Practical Considerations.

In the design of an amplifier using this type of circuit there are several factors to be considered. The choice of output valve depends upon power output required, plate supply and load to be driven. If ordinary output valves are used—triodes or triode connected pentodes—a very large supply voltage is necessary and difficulties may be encountered regarding maximum ratings of components. As the output stage is series connected, current requirements are quite moderate and present no special problem. The most suitable choice is one of the recent high perveance valves such as EL81, 6CM5, 6CD6, which require a total supply voltage of approximately 500 volts. In order to drive low impedances such as a 15 ohm speaker a number of output valves may be connected in parallel to supply the required current, but it is felt that a matching transformer is a better solution.

As the load is coupled by means of a capacitor, the DC component in the load is negligible. A typical optimum load impedance is 500-600 ohms while the output impedance is around 1 to 5 ohms. Under these conditions the design of a matching transformer is greatly simplified. Using grain-oriented silicon cores the flux density may be run to as high as 10 kilogauss with negligible distortion, (0.05% at 30 cycles per second) due to the low source impedance (Z_o). Also, by disposing the windings in a number of layers, a leakage inductance of around 500 microhenrys, referred to the primary, is readily obtained.

The normal operating condition of the output stage is well into class AB. As the correction for distortion is confined to the upper valve, V_2, the only restriction on its operation is that it should never be driven past cut-off. A suitable operating bias would allow the direct current from the power supply to change by 2 : 1 from zero signal to full output. It is preferable to use a fixed bias supply rather than self bias as, with the latter, operating conditions vary with output level and also the plate supply voltage would have to be increased by the bias voltage—about 50 volts. The provision of a negative voltage is simple and not costly using modern solid state rectifiers and may be used as the reference voltage when operating from a regulated supply. In any amplifier where large changes in supply current occur the behaviour is improved by the use of a regulated plate supply. Also, problems associated with common supply impedance and decoupling stages are virtually non-existent. Using no choke in the regulated case, for the same performance, there is very little difference in overall cost of the two systems.

The provision of adequate drive to V_2 is simplified in this circuit. Distortion in the driver, V_3, does not directly appear as it is included within the comparison feedback loop. In order to ensure sufficient available anode excursion for V_3 the standard "boot-strap" anode load connection is desirable. Not only does this method ensure full drive voltage but it allows a voltage gain, A, of 1,000 to 2,000. The attendant reduction in high frequency response is not felt until 150-200 kc/s. This driver stage is direct coupled throughout and so provides correct bias for V_2. The DC and AC requirements for V_2 are not usually satisfied simultaneously. This may be rectified by bypassing a portion of R_2 or by the method shown in the typical amplifier of Figure 3, where the two conditions may be independently adjusted. Owing to the DC feedback setting of operating conditions, the DC potential at the output is unaffected by changes in supply voltage, which then result only in changes of available power output.

5. Low Distortion Amplifier (18 Watt).

A design based on the considerations presented in this paper is shown in Figure 3.

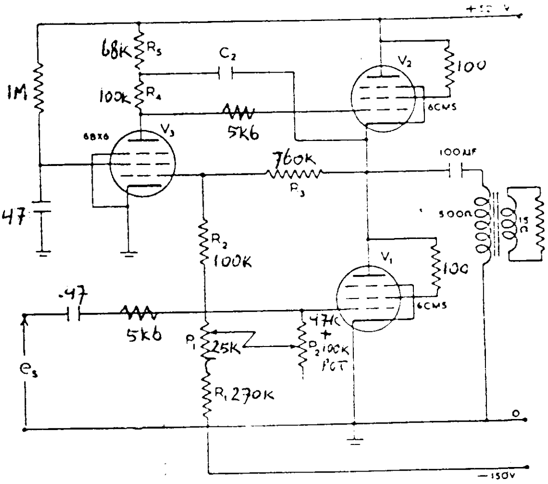

Figure 3.—Circuit of an 18 watt single-ended push-pull amplific

The output valves are triode connected 6CM5's an the driver stage a 6BX6. The output point of th amplifier has a DC potential of 260 volts with a tot plate supply of 520 volts at a zero signal current of 65 m rising to approximately 130 mA at full output. T bootstrap connection for V_3 is provided by C_2 and bootstrap giving a voltage gain A of 1,200. The potential at t cathode of V_2 is determined by the ratio of R_3 to R_2 $P_1 + R_1$, current through V_1 and V_2 adjusted by and the exact value of β is set by P_2. The input sign for full output is approximately 35 volts rms.

The performance figures shown in Table 1 were obtained with a matching transformer, 500 ohms to 16 ohms (resistive load) with a primary inductance of 25 henrys and a leakage inductance, referred to the primary, of 600 microhenrys.

Table 1.

18 watt amplifier characteristics.

Rated Power Output	18 watts
Maximum Power Output—sine wave ...	20 watts
Maximum Power Output—square wave	40 watts
Measured output impedance, amplifier only (approximate)	3 ohms
Load impedance, amplifier only ...	500 ohms
Damping factor, 15 c/s-10 kc/s at any power level, with transformer ...	16
Rise time, any level	8 μs
Overshoot and ringing	zero
Frequency response—3 db points :	
At 1 watt	2 c/s—50 kc/s
At 18 watt	13 c/s—50 kc/s
(Below 13 c/s power output is limited by the power supply)	
Power output : 18 watts into 16 ohms from 15 c/s to 20 kc/s falling to 14 watts at 50 kc/s.	

The trend of harmonic distortion is shown in Figure 4. Owing to equipment limitations the distortion at 50 c/s could not be measured accurately, but it appears to be less than 0.075%.

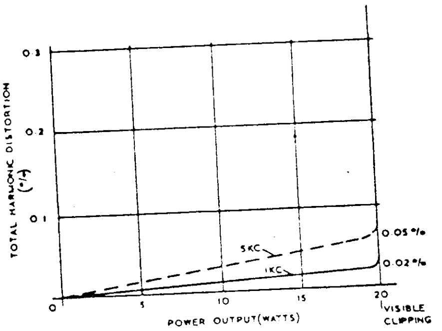

Figure 4.—Total harmonic distortion.

Intermodulation distortion was measured by feeding the amplifier with two frequencies, the lower at four times the amplitude of the higher, total amplitude corresponding to approximately full power output. Sidebands were measured and expressed as a percentage of the smaller signal component (Table 2).

Table 2.

Intermodulation distortion with 18 watts into 16 ohms at various frequencies.

f_1 c/s	f_2 c/s	Distortion %
40	1000	0.16
60	2000	0.16
100	4000	0.16
150	7000	0.08
400	12000	0.32

On heavy overload, the clipping of the output waveform is asymmetrical, due to the DC shift caused by grid current in V_1. However, on removal of overload, recovery is very rapid and there is no blocking. The asymmetry does not occur for brief overload.

Operating the amplifier into an open circuit has negligible effect on the harmonic distortion or output voltage. However, under this condition the current drawn by the output stage remains unchanged, output power being now dissipated in the valves which load each other. Thus, care should be taken that prolonged use, under a load of much higher value than the design load, does not cause excessive dissipation in the output valves.

6. Conclusion.

The new type of amplifier described in this pape achieves extremely low distortion as a result of its basi design. Feedback is used around only one output valv in order to provide grid drive depending on a compariso between the output and input waveform. Under class A operation distortion of less than 0.02% has been achieve without the use of any overall feedback. Extremely wid frequency response is obtained and the load impedanc is not critical.

While this amplifier finds its place as a piece of "Hig Fidelity" equipment, this type of circuit has as its maj field of application such uses as signal generators an modulators.

Acknowledgment.

The initial development of this circuit was carried o in conjunction with Mr. R. B. White of the Radio Researc Board.

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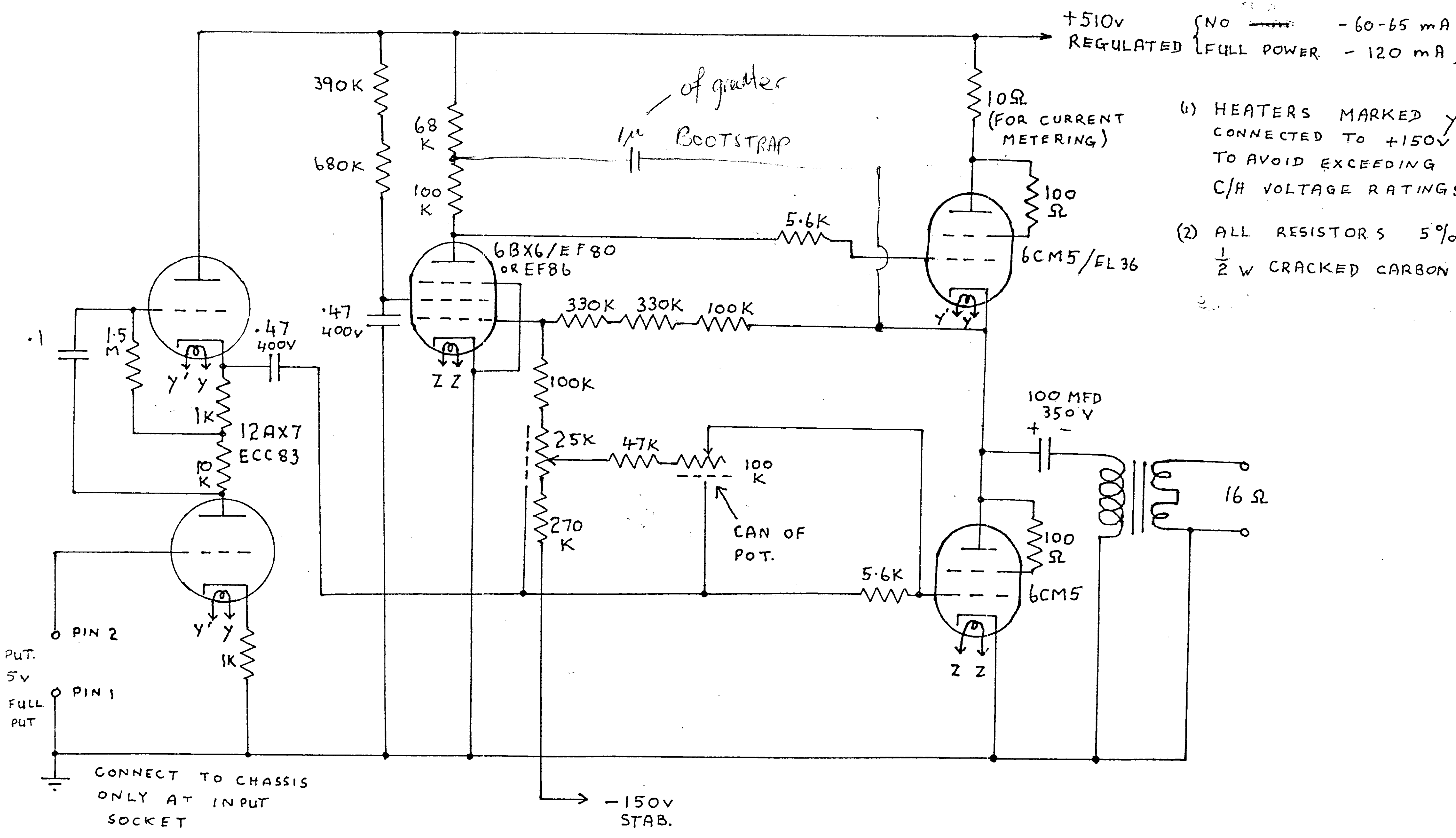
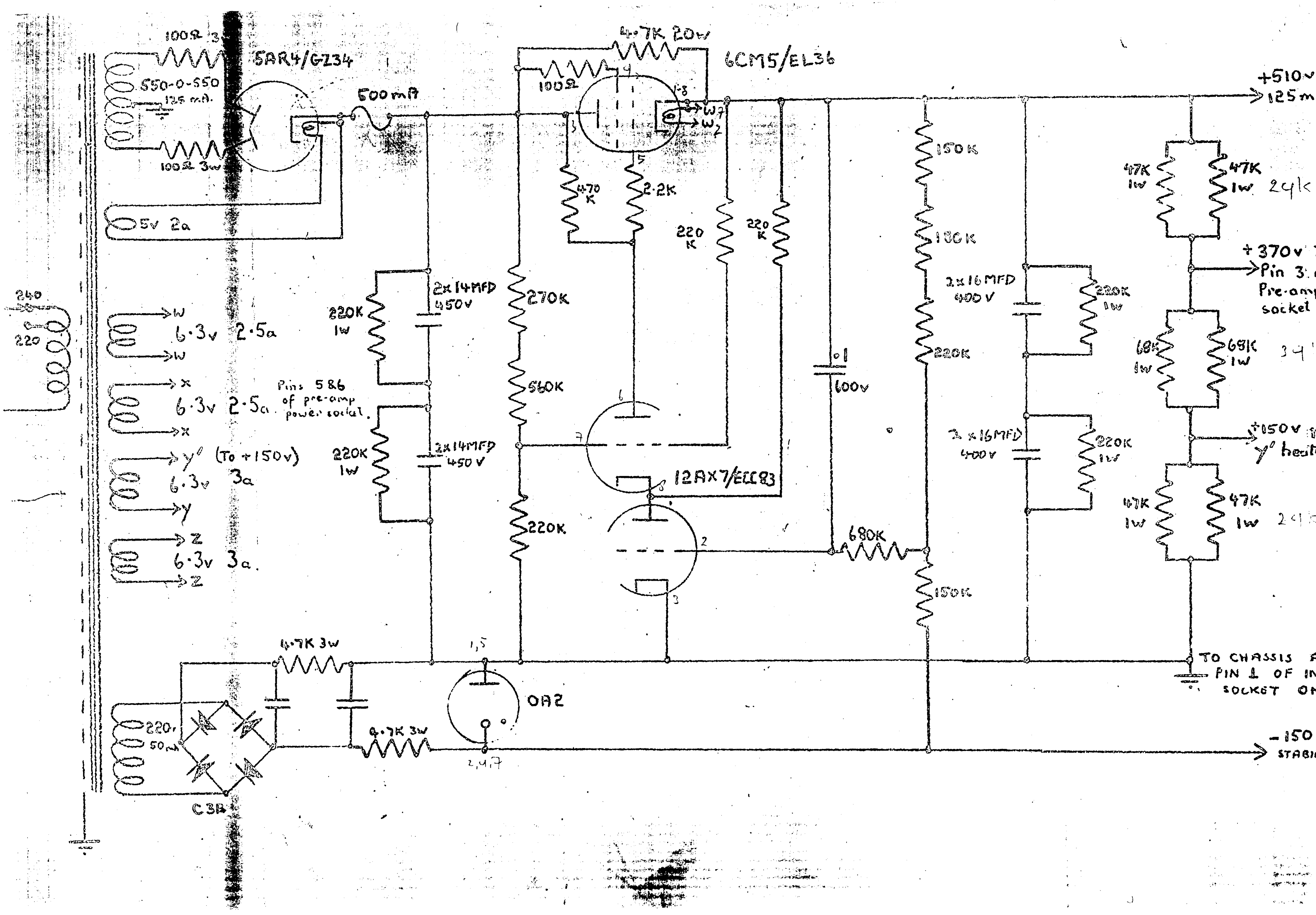


(1) HEATERS MARKED Y
CONNECTED TO +150v
TO AVOID EXCEEDING
C/H VOLTAGE RATINGS

(2) ALL RESISTORS 5%
$\frac{1}{2}$ W CRACKED CARBON


100Ω 3w
5AR4/GZ34
550-0-550
125 mA.
100Ω 3w
5v 2a
500 mA
4.7K 20w
100Ω
6CM5/EL36
+510v
125m
W1
W2
470 K
2.2K
220 K
220 K
150K
180K
220K
150K
47K 1w
47K 1w 24K
+370v
Pin 3
Pre-amp
socket
68K 1w
68K 1w 34
+150v
y' heat
47K 1w
47K 1w 24
240
220
W
6.3v 2.5a
W
X
6.3v 2.5a
X
Pins 5&6 of pre-amp power socket.
y' (To +150v)
6.3v 3a
y
Z
6.3v 3a
Z
220K 1w
2x14MFD 450v
220K 1w
2x14MFD 450v
270K
560K
220K
12AX7/ECC83
.01
600v
680K
2x16MFD 400V
220K 1w
2x16MFD 400V
220K 1w
TO CHASSIS
PIN 1 OF IN
SOCKET ON
4.7K 3w
4.7K 3w
1,5
2,4,7
OA2
220v
50mA
C3B
-150
STAB