

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 design¹, 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 conditions². 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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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

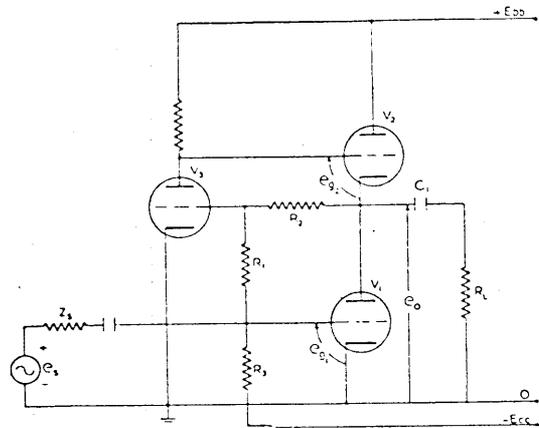


Figure 1.—Basic circuit diagram of low distortion power amplifier.

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 "seesaw" 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 .

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 :

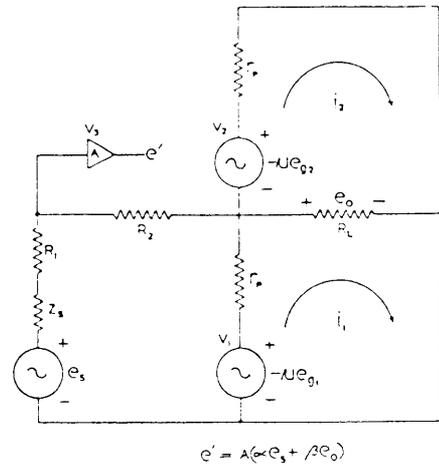


Figure 2.—Equivalent circuit of the low distortion amplifier.

$e_{g1} = e_s$
 $e_{g2} = A(\alpha e_s + \beta e_o) - e_o$
 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 $-i_1(r_p + R_L) + i_2 R_L = \mu e_s$
 and $i_1 R_L - i_2(r_p + R_L) = \mu[A\alpha e_s - e_o(1 - A\beta)]$.

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 :

$$i_o = -2\mu e_s / (r_p + 2R_L) \tag{6}$$

$$A_v = -2\mu R_L / (r_p + 2R_L) \tag{7}$$

$$P_o = [-2\mu E_s / (r_p + 2R_L)]^2 R_L \tag{8}$$

$$R_L = \frac{1}{2} r_p \text{ for maximum } P_o \tag{9}$$

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),

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 μ s
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%.

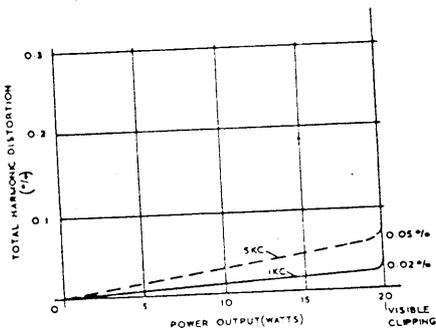


Figure 4.—Total harmonic distortion.

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.

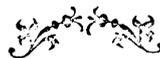
6. Conclusion.

The new type of amplifier described in this paper achieves extremely low distortion as a result of its basic design. Feedback is used around only one output valve in order to provide grid drive depending on a comparison between the output and input waveform. Under class A1 operation distortion of less than 0.02% has been achieved without the use of any overall feedback. Extremely wide frequency response is obtained and the load impedance is not critical.

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

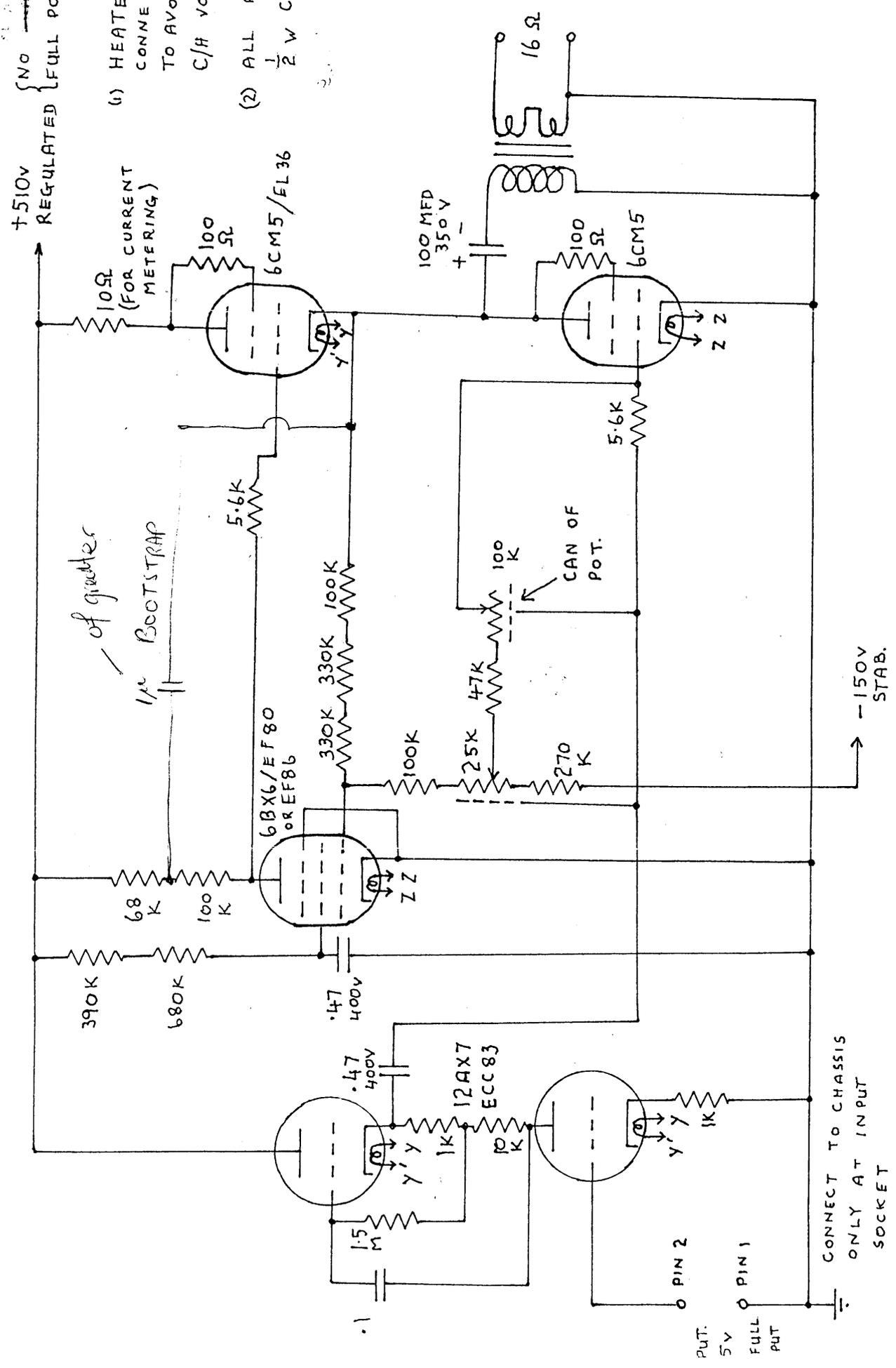
Acknowledgment.

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NO REGULATOR - 60-65 mA
 FULL POWER - 120 mA

- (1) HEATERS MARKED Y CONNECTED TO +150V TO AVOID EXCEEDING C/H VOLTAGE RATINGS
- (2) ALL RESISTORS 5% 1/2 W CRACKED CARBON



PUT.
 5V
 FULL
 PUT

