500kHz where the second pole of the output section starts to contribute excess phase shift. The choice of the position of the dominant compensation was a difficult one. If it was placed in the output section, as is normally the case, the gain of the input amplifier would have to be restricted at low frequencies, affecting the distortion performance of the amplifier.

Another choice was using the dominant lag to encompass the output section as well as part of the input amplifier. This would lead to instability internal to the loop enclosed by the dominant lag and thus an internal pole would have to be introduced to remedy this condition. The final choice (shown in Fig. 7) gives the single-pole compensation needed for unconditional stability coupled with minimal high-frequency distortion. The inherent pole in the output section is subdued by the feedback resistance R_3 (so far as the main loop is concerned) but gives the required unconditional stability of the output section.

The performance with reactive loads will be spoilt if the output impedance of the amplifier is controlled by the overall feedback loop, i.e

$$Z_{out} = \left(1 + j\frac{f_1}{f_2}\right) \Big/ g_m$$

where f_1 is the signal frequency and f_2 the open-loop -3dB frequency. This expression has a simple analogy with a series inductance and resistance, where $R = 1/g_m$ and $L = 1/2\,\pi\, g_m\, f_2$.

A little more work† shows that if a capacitive load is used the amplifier would have a response given by

$$G = \frac{1}{p^2T^2 + a\,pT + 1}$$

This is the equation of a second-order system, where a $(1/g_m)\sqrt{(C/L)}$, and the natural frequency of oscillation is $w_o = 1/T = 1/\sqrt{(LC)}$. If the amplifier has an overshoot it must be due to the overall amplifier having an a-value approaching zero. If we now assume typical values and examine the worst case condition, g_m = 10A/V, f_2 = 4kHz and a = 0.1 (20dB peak), then C = 4μF and w_o = 250kHz.

If this was a perfect model for the amplifier the overshoot would be excessive, but in practice the output impedance is not only a function of frequency but also of output current. Thus a gets larger (less overshoot) as the output current increases. The basic assumption of this simple analysis is that the output impedance is controlled by the main feedback loop, but in this amplifier resistor R_6 generates another loop which effectively places a damping resistance across the apparent output inductance (Fig. 8).

The only remaining improvement to the transient performance of the amplifier is by pole-zero cancellation using the feedback element. If this term seems somewhat academic, an alternative is to study the overshoot with a second-order system with various inputs. If the input is an ideal step the amplifier will give theoretical overshoots, but if the rate of rise of the input waveform is *decreased* the overshoot will reduce and eventually disappear. The capacitor (a zero) in the feedback loop is really reducing the maximum rate of change of the voltage across the load and hence the degree of excitation given to this inherently oscillatory system. By using this type of compensation excellent performance with reactive loads has been finally achieved (Fig. 9). The overshoot with capacitative loads, such as 4μF, is about 50% with an ideal step input and far less when fed via a preamplifier, thus no difficulties should be experienced with any normal load.

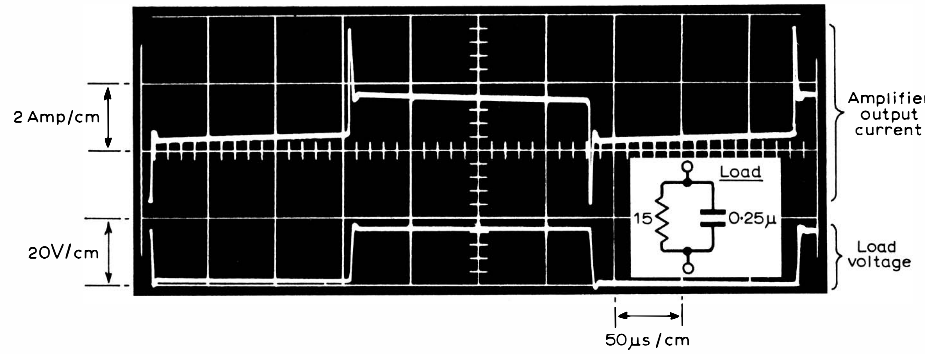


Fig. 9. Performance with a capacitative load. Capacitor in feedback loop effectively reduces maximum rate of change of voltage across load. Overshoot is much less when fed from a pre-amplifier.

Performance—with 60V regulated supply

output power	20 watts into 15 ohms
	30 watts into 8 ohms
power response	30Hz to 100kHz (−3dB)
output impedance	0.1 ohm at 1kHz
total harmonic distortion	< 0.01% throughout audio band and all power levels
intermodulate distortion	< 0.003%
voltage gain	100
noise level	−120dB below full power
maximum peak output current	±3 amps, approx.

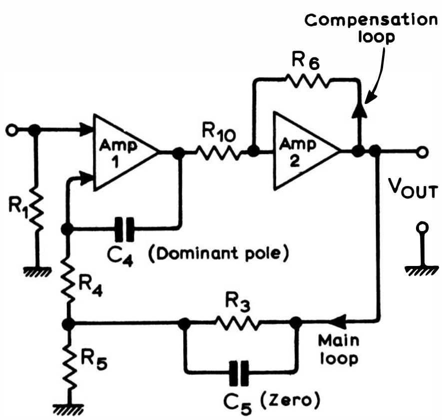
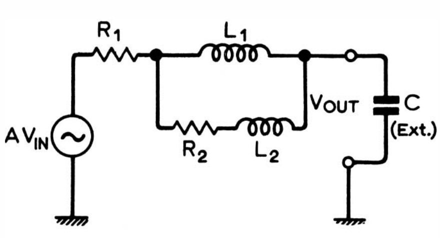


Fig. 7. Single-pole frequency compensation method used gives unconditional stability coupled with minimal h.f. distortion.



$$R_1 = \frac{1}{g_{m1}}\left(1 + \exp\left(K.\frac{I_{OUT}}{I_{MAX}}\right)\right)$$

$$L_1 = \frac{1}{2\pi f_2\, g_{m1}}$$

$$L_2 = \frac{1}{2\pi f_3\, g_{m2}}$$

$$R_2 = \frac{1}{g_{m2}}$$

Fig. 8. Power amplifier equivalent circuit. Simple analysis shows output impedance is controlled by main feedback loop, but in practice R_6 generates another loop effectively placing a damping resistance across the apparent output inductance.

Electrostatic loads. The distortion characteristic with this type of load was still insignificant below 10kHz and gave a gradual rise up to 20kHz where it was still less than 0.05% at maximum output‡. Square-wave performance is shown in Fig. 10 at maximum ‡output. The ringing is due to the finite output impedance converting the ringing current in the inductance and capacitance of the load into ripples in the output, plus the overshoot of the amplifier itself.

Future developments

The amplifier design is hopefully only a source of ideas which may encourage further research into the whole approach to design. So that the trend may be continued, future proposals are outlined in Fig. 11. Here, the main difference is that

† See for instance "Active filters" F. E. J. Girling and E. F. Good, *Wireless World*, vol. 75, Sept. 1969, pp. 403-8.

‡ Maximum output is dictated by peak current output capability.