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Ultra-Linear Amplifiers

In recent years, and particularly in the U.S.A., the so-called ultra-linear amplifier has become popular among quality enthusiasts. A great deal has been written about it and a good many performance figures have been published which do seem to show some reduction of non-linearity distortion as compared with similar triode, tetrode or pentode amplifiers[1]. No serious attempt at explaining why this result should occur seems to have been made, however.

The arrangement is shown in Fig. 1 applied to a single output valve (a pair in push-pull is usually adopted) and it can be seen that it differs from a normal output stage only in that the screen grid is connected to a tapping on the output transformer primary. If this tapping were at the h.t. end of the winding, the screen-grid would be joined to h.t. and the stage would be an ordinary tetrode or pentode one. If it were at the anode end of the winding, the screen-grid would be joined to the anode, and the stage would be a normal triode one.

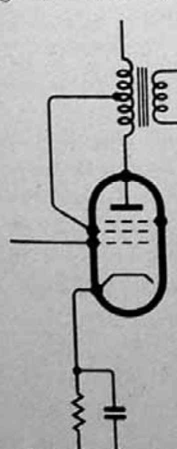

Fig. 1

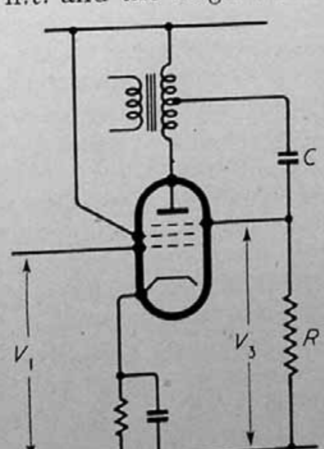

Fig. 2

What happens is that a portion of the alternating voltage developed on the anode is fed back to the screen grid and the amount of feedback depends on the position of the tapping on the winding. By varying the amount of feedback, a gradual transition between the limiting triode and tetrode conditions is obtainable. Now a triode is generally thought to be more linear than a pentode and it is sometimes said that this can be accounted for by the linearizing action of feedback. A triode can be regarded as merely a tetrode with 100% feedback to the screen-grid.

If this were all, the ultra-linear stage would represent an intermediate condition between the triode and the tetrode and one would expect it to be less linear than the triode and more linear than the tetrode. On this basis, there is nothing to account for its being more linear than either.

The flaw in this argument is the supposition that the ordinary ideas about negative feedback hold good when they are applied to this special case of feedback to an electrode other than the input electrode. The normal ideas have been developed on the basis of the feedback and the input being applied to a common electrode so that the feedback voltage and the input voltage are additive. It is well known that feedback then always tends to improve the linearity. When separate electrodes are used, however, it can be shown that feedback will introduce curvature into an otherwise straight characteristic.

[1] "Amplifiers and Superlatives" by D. T. N. Williamson and P. J. Walker, *Wireless World*, September 1952, p. 357.

A modified form of the ultra-linear amplifier is shown in Fig. 2; in this, a fraction β of the anode voltage is applied through the CR coupling to the suppressor grid. It is well known that in a pentode the cathode current is

$$i_k = a_1 + b_1 V_1$$

within the limits of a linear approximation. It is also well known that it is independent of V_3 which serves only to control the division of current between screen-grid and anode, so that

$$i_a = i_k (a_3 + b_3 V_3)$$

Therefore, we can write

$$i_a = (a_1 + b_1 V_1)(a_3 + b_3 V_3) \quad .. \quad .. \quad (1)$$

In Fig. 2, the anode voltage is $-i_a R_a$, where R_a is the anode load, and so $V_3 = -\beta i_a R_a$, and (1) becomes

$$i_a = \frac{a_3(a_1 + b_1 V_1)}{1 + \beta b_3 R_a (a_1 + b_1 V_1)}$$

$$= A [a_1 + b_1 (1 - a_1 B) V_1 - b_1^2 B (1 - a_1 B) V_1^2 + b_1^3 B^2 (1 - a_1 B) V_1^3 \ldots\ldots] \quad .. \quad (2)$$

where $A = a_3 / (1 + a_1 b_3 \beta R_a)$

and $B = b_3 \beta R_a / (1 + a_1 b_3 \beta R_a)$

Feedback to the suppressor grid thus introduces curvature into an otherwise linear characteristic. If the input V_1 is a sine wave, the anode current will contain all harmonics of it.

Feedback to the screen-grid of a valve is, of course, not quite the same thing as feedback to the suppressor grid. However, as is well known, the mutual conductance does depend upon the screen voltage and so the equation for this condition must be rather like (1); there must be a term involving the product of the control- and screen-grid voltages. If this product term is present, then the equation for screen-grid feedback will be of the same general form as (2).

It would thus appear that feedback to an electrode other than the input electrode is a bad thing. However, we have only so far shown that it makes an otherwise linear stage non-linear. There is the possibility that the kind of non-linearity which it introduces is inverse to that which occurs naturally in valves. If this possibility is a reality, then a critical degree of feedback to screen or suppressor grid would improve the linearity of a stage.

Let us suppose that the input grid has a non-linear action, but the feedback grid is still linear, so that the equation for anode current is

$$i_a = (a_1 + b_1 V_1 + c_1 V_1^2 + d_1 V_1^3)(a_3 + b_3 V_3)$$

and, as before, $V_3 = -\beta i_a R_a$. Then

$$i_a = \frac{a_3(a_1 + b_1 V_1 + c_1 V_1^2 + d_1 V_1^3)}{1 + \beta b_3 R_a (a_1 + b_1 V_1 + c_1 V_1^2 + d_1 V_1^3)}$$

$$= A \frac{a_1 + b_1 V_1 + c_1 V_1^2 + d_1 V_1^3}{1 + B(b_1 V_1 + c_1 V_1^2 + d_1 V_1^3)}$$

where A and B have the same values as before. This equation can be expanded to the form

$$i_a = A [a_1 + (b_1 - a_1 B) V_1 - (1 - a_1 B)(b_1^2 B - c_1) V_1^2 + \{B^2 b_1^3 (1 - a_1 B) - B b_1 c_1 (1 - 2 a_1 B) - B(a_1 d_1 + b_1 c_1) + d_1\} V_1^3 \ldots]$$

retaining terms only up to the cube.

It is at once evident that it may be possible to choose β so that the coefficient of V_1^3 is zero. It is not worth while to attempt to work out the condition for this. The equation would be complex and of little practical utility because we have assumed a linear control of anode current by the feedback grid and this is unlikely to be present in practice.

With feedback to a grid other than the signal grid, however, the possibility exists of being able so to adjust the amount of feedback that a particular harmonic can be eliminated from the output. In the ultra-linear amplifier, two valves are used in push-pull so that all even harmonics are, ideally, eliminated.

The third harmonic, which is normally the most important remaining one, can, again ideally, be eliminated by a critical adjustment of feedback to the screen-grids. The distortion present should thus be confined to odd-order harmonics higher than the third. Superficially, therefore, the ultra-linear amplifier would appear to be an improvement on ordinary types. We say superficially because we have not examined the amplitudes of the residual harmonics and the ability to eliminate a third harmonic would confer no benefit if it meant that the higher harmonics became of comparable amplitude.

There is no reason to suppose that this is the case, however, for the evidence of measurement does support the claims made for the ultra-linear amplifier. Our aim here has been merely to show the mechanism by which this improvement is achieved, for we have felt that it has remained too long unexplained.

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