Inherent Feedback in Triodes

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SUMMARY—*The triode is imagined to be replaced by an infinite-impedance pentode (with its simplified anode-current expression $g_m dV_c$) with a fictitious emf in the grid circuit to represent the "back action" of the anode on the field at the cathode It is shown how this transformation makes it possible to obtain practical triode circuit formulæ from conventional feedback theory.*

IN COMPARISON WITH A PENTODE, a triode has both strong and weak points. If, in mathematical analyses, the triode be considered as an infinite-impedance pentode with negative feedback, certain of its advantages appear as direct and expected results of negative-feedback theory and in some cases a simplified analysis can result. The method is of particular interest for control circuits and output stages utilizing low-μ triodes, since the back action from the anode on the emission-controlling field at the cathode is then appreciable. Fundamentally, *this electric field action is a form of negative feedback.*‡

Fig. 1a shows a conventional pentode representative of any screen-grid, multi-electrode valve. Fig. 1b shows a conventional triode. The dynamic mutual conductance g_{md} is, for the pentode circuit:

$$g_{md} = g_m = \frac{dI_b}{dV_c} \qquad (1)$$

and for the triode circuit:

$$g_{md} = \frac{r_a}{r_a + Z_b} g_m = \frac{dI_b}{dV_c} \qquad (2)$$

or

$$g_m = \frac{dI_b}{dV_{ce}} \qquad (3)$$

where the equivalent; control voltage, $dVce$, is:

$$dV_{ce} = dV_c + \frac{dV_b}{\mu} \qquad (4)$$

It is seen that Eqn. 1 becomes identical with Eqn. 3 when the term dV_b/μ in Eqn. 4 tends to zero. The presence of this term may then be considered as the result of the removal of one or more shielding or screening grids in the circuit Fig. 1a. Thus, it is logical to consider dV_b/μ as a feedback voltage injected in series with dV_c and thus added to dV_c because of lack of electric shielding between the anode and the cathode. (If dV_c is positive, dV_b produces a negative term hence $dV_{ce} < dV_c$).

Eqn. 2 represents a form of the Equivalent Anode Circuit theorem. This theorem also applies to the circuit in Fig. 1c where a fictitious screen grid has been inserted between the anode and cathode to justify the transfer of the voltage dV_b from the anode circuit to the grid circuit where it appears as the fictitious voltage $dV_f = dV_b/\mu$, as required by Eqn. 4. Equivalence is now established between the circuit

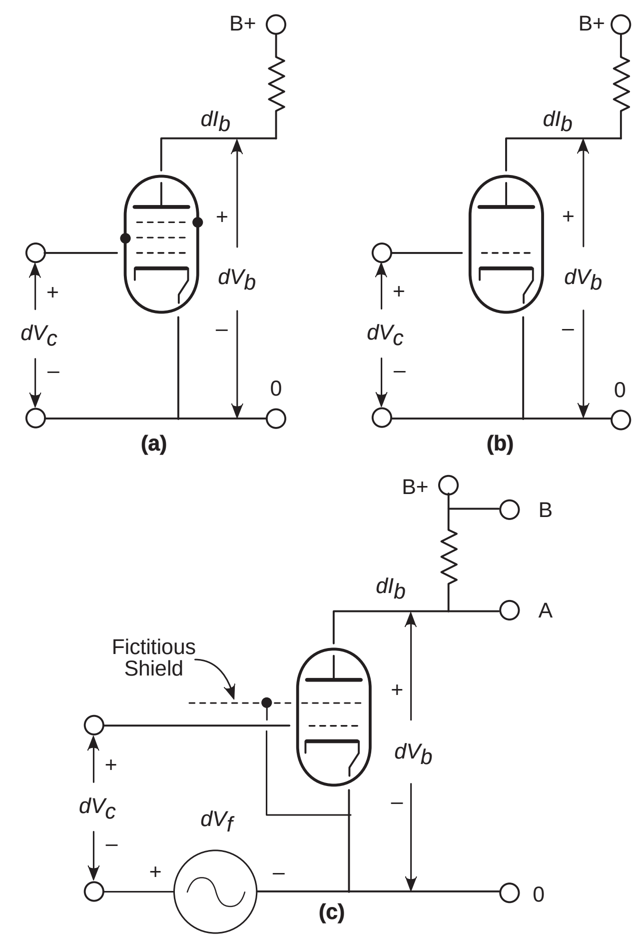

Fig. 1. Pentode and triode circuits (a) and (b) along with an equivalent (c) in which a voltage, dV_f, in the grid circuit produces the effect of a screen grid.

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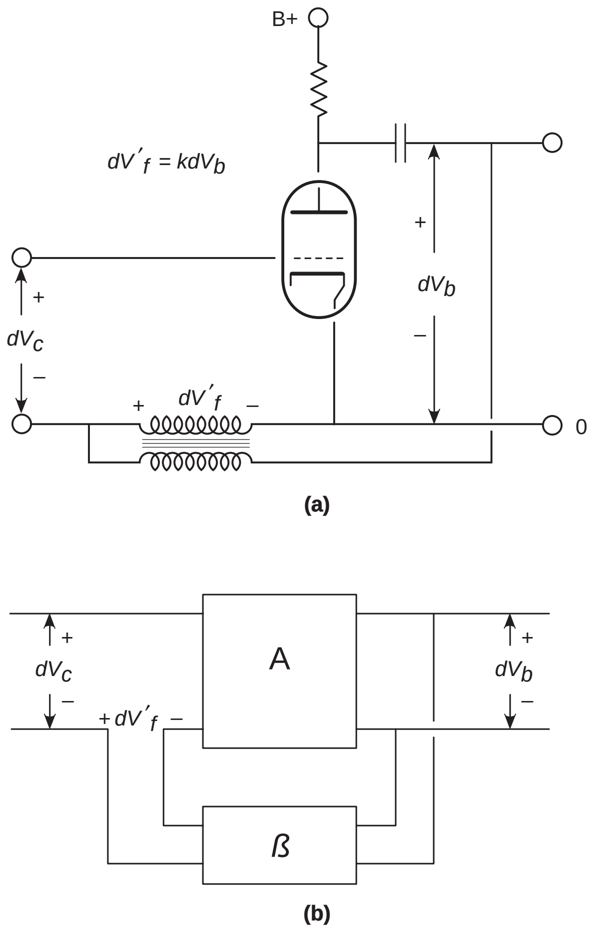

Fig. 2. (a) a circuit for obtaining the grid voltage of Fig. 1c by feedback and (b) its equivalent circuit.

in Fig. 1c and the basic circuit for voltage-controlled feedback, Fig. 2b, where A is the amplification of the triode functioning as a pentode; thus $A = -g_m Z_b$ and $ß$ is the feedback transmission coefficient $1/\mu$. The fundamental equation for a triode circuit can now be derived from conventional feedback theory. Thus, the actual amplification of the triode takes the well-known form:

$$A_a = \frac{A}{1 - \beta A} = \frac{-\mu Z_b}{r_a + Z_b} \qquad \text{.(5)}$$

The combination impedance Z_{AB} seen right to left between the output terminals A, B in Fig. 1(c) can be determined if, for $dV_c = 0$, a voltage source dV_0 is applied to these output terminals sending the current dI_0 into the parallel circuit, and has the obvious form

$$Z_{AB} = \frac{dV_o}{dI_o} = \frac{r_a Z_b}{\left(r_a + Z_b\right)} \qquad \text{.(6)}$$

This equation clearly expresses the reduction in output impedance due to the shunting of Z_b with the low r_a of a low-μ triode. The fictitious shield is insignificant for the above output impedance calculations; there is only one field change at the cathode, no degeneration, and $dV_f = 0$.

When external feedback is applied, it can be considered a logical addition to the already-present internal feedback, expressed by the method given above. This implies that the feedback transmission coefficient should be changed to include the externally-established coupling coefficient. As an example, a very simple external feedback circuit is shown in Fig. 2a, utilizing a transformer to inject the voltage $dV'_f = kdV_b$, where k is a constant, into the grid circuit, so that for increased negative feedback the resulting transmission coefficient becomes

$$\beta = \frac{1}{\mu} + k \qquad \text{.(7)}$$

Therefore the actual amplification in this example is

$$A_a = \frac{A}{1 - \beta A} = \frac{-\mu Z_b}{r_a + \left(\mu k + 1\right) Z_b} \qquad \text{.(8)}$$

Extending the example further, we may consider the transformer in the region of its upper cut-off frequency, with a peak response due to its leakage-reactance resonance. It is well known that this response curve flattens out when external negative feedback; is applied. Actually, before any external feedback is applied, *the response curve has already flattened out by the internal feedback*. If the internal feedback were removed, the response curve would be still more peaked. Thus the quality improvement due to internal feedback is of the same nature as the quality improvement due to external feedback. This line of thought pertaining to negative feedback might be useful in comparing the inferior frequency response of a pentode to the frequency response of a triode.

Considering the external application of positive feedback, it follows that we must apply a substantial amount of such feedback to a triode circuit before we have actually applied any feedback at all, in the true sense of the word. This is the feedback Eqn. 5, for if, $ßA = 0$, $A_a = A$; indicating no change due to feedback. Reversing the connections on one side of the transformer so as to provide positive feedback, it is seen that the feedback transmission is still represented by Eqn. 7, with reversed sign for k however, so that if we apply just enough positive feedback to make $k = 1/\mu$, there is no feedback at all in the circuit—$ß = 0$. The true status of feedback in a triode valve circuit is of importance when comparing different circuits with *the same amount of feedback* *applied to each circuit*. Thus, if a quantity such as reduction in noise is to be measured, first without feedback, then with specified amounts of feedback, and if the second term in Eqn. 4 is appreciable compared to the first one, it follows that equity obtains only if the "zero" feedback of the triode is compared with an amount of feedback in the pentode corresponding to the second term in Eqn. 4.

If (by changing the transformer ratio) we increase k further, the point of oscillation is reached for $ßA = 1$. Solving Eqn. 7 with $k = -k^*$ for this condition, and multiplying by A, we obtain the critical value for oscillation

$$k^* = \frac{1}{g_m Z_b} + \frac{1}{\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

This value of k is indicative of a negative resistance in the resulting loop-circuit equal to the positive loss resistance. The first term in Eqn. 7 represents the positive feedback which would be needed to make the tube oscillate if it were the equivalent of a pentode. The second term represents the additional feedback needed in a triode circuit to overcome the already-present negative feedback, which is due to back action from the anode on the electric field at the cathode.

As a mathematical criterion, $ßA = 1$ is considered a correct indication of oscillation in the above circuit. From a technical point of view, the formulæ resulting from $ßA = 1$ are not true, nor do they represent more than an approximation even when $ßA \neq 1$ or $ßA \approx 1$. The reason for this is the heavy regeneration that precedes oscillation as $ß$ is increased. The circuit is then no longer linear, and since the feedback formula is derived from Kirchoff's equations, the formula does not fully apply. While the above theory also applies to high-μ triodes, the second term of Eqn. 4 then becomes so small as to be negligible, and there is no further need to shield the anode from the cathode. Since high-μ valves are more likely to be used for high-frequency operation than low-μ valves, an entirely different shielding or screening, namely of the anode from the control grid, becomes significant. This shielding, to prevent circuit coupling (the oft-discussed Miller effect) is thoroughly treated in the literature and will not be discussed here. However, it should be noted that in cases where a low-μ triode is used at radio frequencies and if the transmission coefficient is properly modified to include the effective coupling between the anode and the grid circuits, the basic theory given above is naturally extended to include the Miller effect. Thus, one generalized feedback theory will cover both of the above-discussed gain controlling phenomena exhibited by triodes.

The original invention of the screen-grid valve in 1918 by W. Schottky, Germany, aimed at the removal of the second term in Eqn. 4 by shielding the DC field at the cathode from modulation by variations in the anode's field.[1,9] Theoretically, *a similar improvement can be obtained by applying positive feedback to cancel the inherent negative feedback.*‡ If there existed an ideal solution to this positive feedback proposition, low-μ triode valves might today be used in many applications now employing pentodes. So far there has been no invention aiming at the elimination of the second term in Eqn. 4 that has been of any significance compared to the simple and ingenious Schottky screen-grid invention (or later beam-tube solutions). Such a development is, however, not contradictory to the basic laws of physics and may be made in the future. This is said in view of the fact that future "grid-controlled" devices, competing with the low-frequency output valve, would make use of basic principles for magnetic amplification, dielectric (ferro-electric) amplification, transistor amplification, and other amplification, where the equivalent to the second term in Eqn. 4 is either virtually non-existent or can be eliminated by methods not applicable to a vacuum tube.

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‡ Indicates my conversion to *Italic*; bp.