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Inverse Feedback, Its Benefits and Its Limitations

By the Engineering Department, Aerovox Corporation

DEGENERATION, or inverse feedback has recently come in favor with design engineers and may soon be regular equipment in receivers and amplifiers. The serviceman as well as the set builder and the amateur will no doubt be interested in knowing the principles of this circuit as well as the limitations in its applications. This article is intended to explain the principles, how they can be applied, what to do and what not to do.

HISTORY

Contrary to popular opinion, the use of degeneration is not new. Its application was suggested as early as 1919

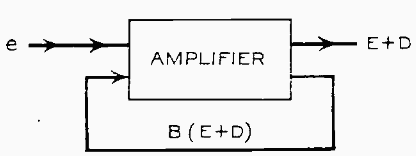

Fig. 1

and it was indeed used in scientific measuring instruments since that time. However, it was not applied on a large scale in receivers or amplifiers until recently. The reason is, no doubt, that the purpose of degeneration is to obtain better fidelity at the expense of gain. During the past years it was not considered economical to "throw away" gain. The new high-gain pentodes and new output tubes have made it relatively easy to obtain enough amplification to make up for the loss caused by degeneration and now the circuit can be usefully employed. One of the reference articles on the subject appeared in Electrical Engineering for January 1934; its title is Stabilized Feed-Back Amplifiers by H. S. Black. Some other articles on the subject are: Feedback Amplifier Design by F. E. Terman appearing in Electronics for January 1937, and Practical Feedback Amplifiers by J. R. Day and J. B. Russell in Electronics for April 1937. There are a considerable number of other articles in other periodicals and some data was supplied by the tube manufacturers. Some of these data are conflicting; we present the subject here according to the latest findings.

DISTORTION

There are three kinds of distortion which are now defined as follows in accordance with the recent standards set by the A. S. A.

Frequency distortion is that form of distortion in which the change is in the relative magnitudes of the different frequency components of a wave,

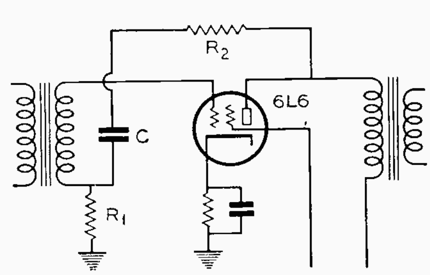

Fig. 2

provided that the change is not caused by nonlinear distortion.

Nonlinear distortion is that form of distortion which occurs when the ratio of voltage to current, using root-mean-square values, is a function of the magnitude of either.

Delay distortion is that form of distortion which occurs when the phase angle of the transfer impedance with respect to two chosen pairs of terminals is not linear with frequency within a desired range, thus making the time of transmission or delay vary with the frequency in that range.

The first type of distortion results in discrimination against certain fre-

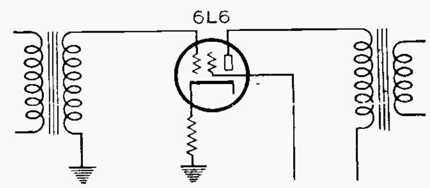

Fig. 3

quencies. The second type has usually been known as "harmonic distortion" it results in the creation of new frequencies which were not present in the input signal. These new frequencies may be harmonics of the input signal or they may be the sums and differences of the various frequencies in the input signal. When the wave to be amplified consists of many different frequencies there are many combinations of sums and differences which causes the familiar mushy background. The third type of distortion is also called "phase distortion." As we shall see, inverse feedback reduces all three types.

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PRINCIPLES OF INVERSE FEEDBACK

Referring to Figure 1, consider an amplifier consisting of one or more stages which has a voltage amplification of A times. Then the output voltage for an input voltage e would be $E_0 = Ae$ volts plus noise plus hum plus distortion. In order not to complicate the matter too much let us assume that there is only distortion. This consists of an additional signal

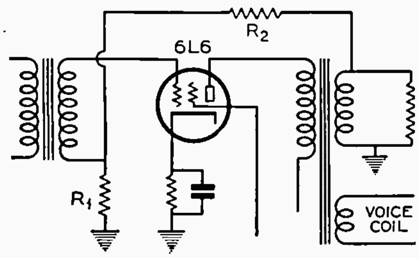

Fig. 4

which is a definite percentage of the output voltage and can be written dE_0 volts, where d x 100 is the percent nonlinear distortion. Thus we have without feedback:

$$E_0 = Ae + dE_0 \text{ volts} \qquad (1)$$

A portion of the output voltage is fed back in reverse phase. Call this proportion B (for negative feedback, B is negative), call the new output voltage E and the accompanying distortion voltage D. Since we know the relation between the net input voltage and the output voltage we can write

$$E + D = A \left\{ e + B\,(E + D) \right\} + dE$$

or: (2)

$$E\,(1 + AB) + D\,(1 - AB) = Ae + dE \qquad (3)$$

$$E = e\,\frac{A}{1 - AB} \qquad (4)$$

$$D = E\,\frac{d}{1 - AB} \qquad (5)$$

Comparing the result with equation (1) we see that the amplification has been divided by a factor (1 — AB) and that the percentage of distortion has also been divided by the same factor. By increasing the input signal it is possible to get the original output voltage back but the distortion remains less than it was without feedback since it is a definite percentage of the output voltage. By a similar proof it can be shown that the noise and hum are reduced in the same proportion.

In order to make this point clear let us substitute actual values. Consider an amplifier with a voltage gain of 100 while the percentage of nonlinear distortion is 5. Thus $A = 100$, $d = 0.05$; now let us feed back a voltage equal to the input signal or $B = -0.01$. Then we have for an input signal of 1 volt

E without feedback = 100 volts + 5 volts distortion

With feedback

$$E = 1\,\frac{100}{1 - 100\,(-0.01)} = 50 \text{ volts}$$

$$D = 50\,\frac{0.05}{1 - 100\,(-0.01)} = 1.25 \text{ volts}$$

In order to obtain full output again we may double the input voltage which will double both E and D. The result is now that the same output is obtained as without feedback but the distortion is only one half. Similarly, the noise and the hum are reduced to one half their previous value.

Both nonlinear distortion and delay distortion can be considered as consisting of the original signal plus an added new signal. Therefore, the above proof shows how these two types of distortion are reduced. It goes without saying that one may feed back considerably more voltage with a corresponding farther reduction of distortion and the same reduction of gain. So, for instance, by making $B = -0.09$, in the above example, the gain will be reduced ten times and the distortion cut to one half percent. Let us see what happens to frequency distortion.

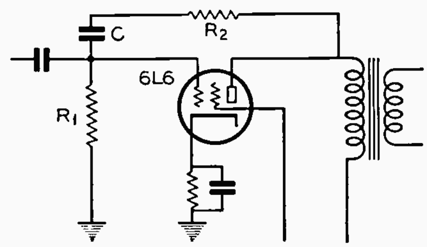

Fig. 5

Suppose the gain for 400 cycles is 100 but at 50 cycles the amplifier is 20 db. down which means that the gain is then only 10. Now by applying feedback ($B = -0.09$) we find that the output voltages at the two frequencies are (see equation 4)

$$E \text{ at 400 cycles} = e\,\frac{100}{1 - 100\,(-0.09)} = 10\,e \text{ volts}$$

$$E \text{ at 50 cycles} = e\,\frac{10}{1 - 10\,(-0.09)} = 5.26\,e \text{ volts}$$

While the ratio of output voltages for a given input voltage were 10 to 1 without feedback it is now approximately 2 to 1, or, the amplifier is now only 6 db. down at 50 cycles.

It is generally relatively easy to make up for the lost gain by employing an extra voltage amplifier stage before the amplifier in question.

Another very important advantage of inverse feedback is its improvement of response to transient signals. The average speaker, when fed from pentodes suffers from "hangover" which is especially noticeable on transients. The inverse feedback circuit reduces this effect because it acts as a "brake," damping the movement of the speaker cone. This may be visualized as follows: Any electrodynamic device is both a motor and a generator. Therefore, when the cone makes extra motion after a transient, the voltage induced in the voice coil is applied to the input of the amplifier and returns amplified and reversed in phase so that it stops the motion of the cone.

LIMITATIONS

The above equations assumed that the feedback voltage always arrived 180 degrees out of phase with the input signal. In practice this is never the case and the amount of lag or lead with respect to the correct phase relations may vary with frequency. Aside from the fact that this varies the amount of feedback for different frequencies, one must be careful to see that the lag or lead never amounts to 180 degrees for the feedback then becomes positive. In certain amplifiers, those where the voltage is fed back over three stages this may happen. Instability will still not occur if the gain of the amplifier has been reduced at this frequency to a point which makes AB less than 1. This fact, however, limits the total amount of feedback which can be used and therefore the maximum amount of reduction in distortion, hum and noise.

It is perhaps desirable to examine this matter of phase shift somewhat closer. It is generally considered that the phase is reversed in each amplifier stage and this is taken in consideration when determining the proper polarity of the feedback voltage. In addition to this 180 degree shift, each stage has another phase shift which is due to reactances in the coupling units

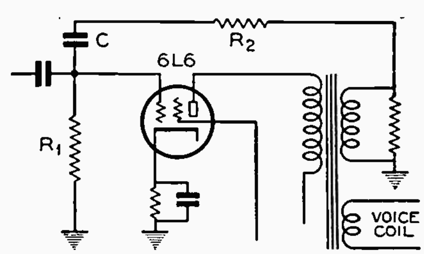

Fig. 6

and the capacitance of the tubes. This shift varies with frequency and is never more than 90 degrees for one stage. The effects of two or more stages add up however, which means that it is unlikely to have a 180 degree phase shift in a two stage amplifier but it may easily happen in a three stage amplifier. Therefore, feedback may readily be accomplished around one or two stages, but it becomes difficult over three stages and practically impossible when the number of stages is greater than three.

APPLICATIONS

When applying inverse feedback to a single stage, several circuits can be employed. It is at all times important to see that correct phase relations are maintained and that the feedback circuit itself has no frequency discrimination. Figure 2 shows an output stage with a part of the plate voltage fed back to the grid. Since the plate voltage decreases when the grid voltage increases this is the correct phase for negative feedback. In this case

$$B = -\frac{R_1}{\sqrt{(R_1 + R_2)^2 + X_c^2}}$$

or, if Xc is small compared to $R_1 + R_2$

$$B = -\frac{R_1}{R_1 + R_2}$$

In such a circuit the capacity between the transformer secondary and the core is in parallel with R_1 and may cause difficulties if the capacity is large enough. This circuit does not compensate for any distortion in the input or output transformer.

Figure 3 shows another way of accomplishing the same result. Here the feedback is obtained by removing the bypass condenser across the bias resistor. This scheme is less desirable because the amount of feedback cannot readily be regulated and there is a power loss.

Figure 4 illustrates another method where the feedback voltage is taken

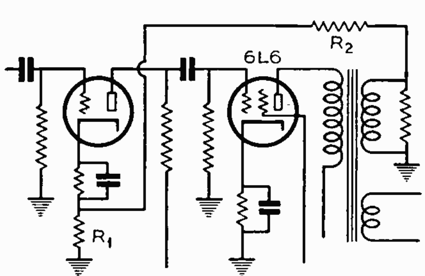

Fig. 7

from the secondary of the transformer. It is assumed that correct polarity of the secondary is used. This may be found by trial and error. The equations 4 and 5 can be used again; A is now the voltage gain between the grid of the tube and the secondary of the transformer. B is $-R_1/(R_1 + R_2)$. Whenever the feedback voltage is taken from the transformer the secondary in question must be loaded either by the voice coil or a resistor otherwise the leakage inductance of the transformer is in series with R_1 and R_2 thereby varying the amount of feedback for different frequencies. If a 500 ohm winding is used while the voice coil secondary connects to the speaker, the secondary should not be loaded with a 500 ohm resistor for this would cause too much power loss; a 10,000 ohm resistor will serve the purpose.

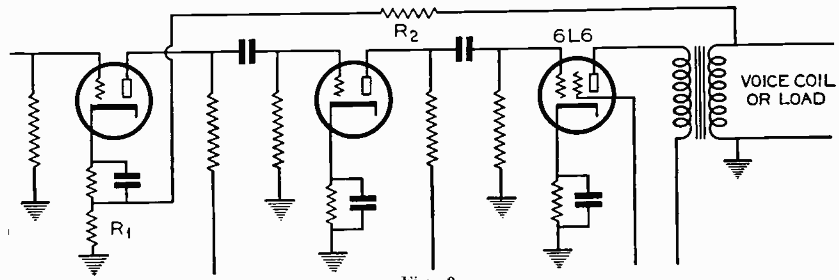

Fig. 9

When the input to the stage employs resistance coupling, circuits similar to Figure 2 and Figure 4 cannot be used because this would not place the feedback voltage in series with the input voltage. Instead, use Figures 5 and 6. In Figure 5 it is important that the condenser be placed at the grid end of R_2 and the foil should be connected to the grid. Stray capacity between the condenser and the chassis must be minimised.

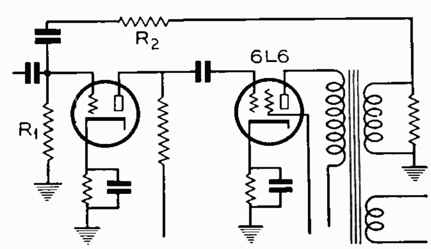

Fig. 8

Theoretically the proportion B can be any amount, or the feedback may be as large as desired. In practice, the transformer secondary will not deliver enough voltage to obtain enough feedback and the driver tube may not be able to supply the additional input voltage without adding much more distortion. In such cases it is better to bridge two stages by the feedback circuit.

Feedback across two stages may be introduced either in the cathode circuit as in Figure 7 or in the grid circuit as in Figure 8. If the input device is likely to be varied, the circuit of Figure 8 is less desirable because different input circuits will change the feedback ratio. The circuit of Figure 7 is recommended. Since R_1 can usually be quite small it will not introduce any difficulty due to its own degeneration. The feedback ratio is again $-R_1/(R_1 + R_2)$ and it can be taken from the primary or the secondary of the output transformer for the circuit of Figure 7, but for Figure 8 it must be taken from the secondary. It will generally not be difficult to obtain a reduction in gain of the order of 20 db. and a corresponding improvement in noise, hum and distortion.

When feedback is carried over three stages, the circuit of Figure 9 is recommended. It is also possible to feed from the plate of the output tube to the grid circuit of the input stage or from the secondary of the output transformer to the grid of the input stage. Difficulty is likely to be encountered unless the total phase shifts of the three stages can be kept down. Terman recommends that one of the stages be designed for minimum phase shift.

When wiring the amplifier it will be found necessary to shield any long leads in the cathode circuit. It will probably be best to have the resistor R_1 near the input tube rather than at the output transformer.

When using inverse feedback with push-pull stages it is practicable to feed back from the plate of each tube to its grid circuit and the two stages must then have a separate grid return calling for a split secondary. Do not try to feed back the voltage from the output transformer secondary to one side of the push pull stage, nor from one side of the push pull stage to a single ended preceding stage. It is however quite practical to bridge the feedback circuit over the push-pull stage from the output transformer secondary to the input of the single ended driver stage. Also, if resistance coupling and an inverter is used, the feedback may be arranged from the output transformer secondary across push-pull stage, phase inverter and one more stage. The phase inverter in this case consisting of two tubes.

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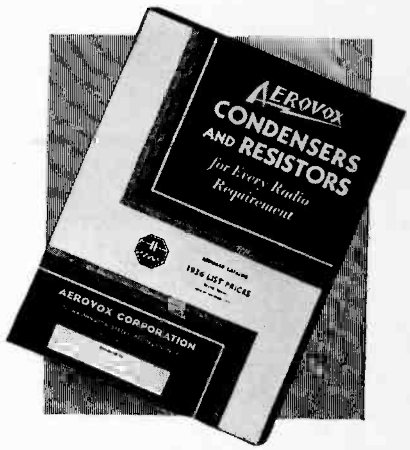

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