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INVERSE FEEDBACK

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INVERSE FEEDBACK

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PREFACE

Amplifier properties can be improved considerably by the deliberate use of inverse feedback to better response characteristics; to reduce hum, noise, or harmonic distortions; and to control gain. These, and many other circuit uses, involve the feeding of part of the output voltage back to the grid circuit out of phase with the incoming signal.

Inverse feedback may involve voltage feedback, current feedback, or a combination of both (bridge feedback). Each has its own effects on the amplifier input and output impedances and amplifier operation. This book is designed to give an explanation of these and other important aspects of inverse feedback. The subject matter is organized to give a comprehensive review of the essential topics and it is assumed that the reader has a knowledge of basic electronic circuit principles.

Where essential, sufficient mathematics have been included to permit the advanced student, technician, or practicing engineer to follow the development of the fundamental concepts. Descriptive analyses are given of the effects and advantages of negative feedback; the types of inverse feedback; general and specific considerations pertaining to feedback effects on output and input impedances; voltage feedback considerations; phase relationships, phase response, frequency response, and stability as affected by feedback; feedback loops; inverse feedback used in push-pull amplifiers; and typical feedback applications.

Since the small scale of this book precluded inclusion of all the many variations of circuit types, only a few of the more important common applications are given. These include the cathode follower, Williamson amplifier, avc, and a direct current vacuum tube voltmeter using inverse feedback.

Grateful acknowledgment is made to the staff of the New York Technical Institute for its assistance in the preparation of the manuscript of this book.

New York, N. Y.
August 1956 A. S.

CONTENTS

Chapter 1

THE HOW AND WHY OF FEEDBACK

1. Introduction

The term feedback as used in electronics describes a process for transferring energy from the output circuit of a device (such as an amplifier) to its input circuit. When this transfer is accomplished in such a manner that the energy produced at the output circuit when feedback is used exceeds the energy so produced when feedback is not used, this process is defined as "positive" or "regenerative" feedback. When this transfer takes place in a different manner so that the output energy in the presence of feedback is less than that produced in the absence of feedback, this process is defined as "negative," "degenerative," or "inverse" feedback.

Both types of feedback are of the utmost importance in modern electronic design. However, each type is a subject in itself, and this book is concerned only with *inverse* feedback.

2. Advantages of Negative Feedback

All electronic amplifiers develop a certain amount of hum or noise, or both. Further, the gain of any amplifier varies at least a small amount with the frequency of the signal it amplifies. In other words, no amplifier has a perfectly "flat" frequency response or complete freedom from noise. In addition, the amplifier behavior is likely to change as tubes are replaced, as circuit components change value, or as power supply voltages vary. As will be explained in detail in later portions of this text, these and other amplifier defects may be wholly or partly eliminated when inverse feedback is used.

The uses of feedback are numerous. As a rule, however, the principal effect underlying each use of inverse feedback is the control of gain. All other feedback effects are directly related to the effect on gain.

3. Effect of Negative Feedback on Gain

The gain control principle involved in the use of inverse feedback can best be understood from a study of the system shown in Fig. 1. An amplifier having a voltage gain denoted by the symbol A produces an output voltage, E_0. An incoming alternating signal, E_I, is supplied to the input of the amplifier.

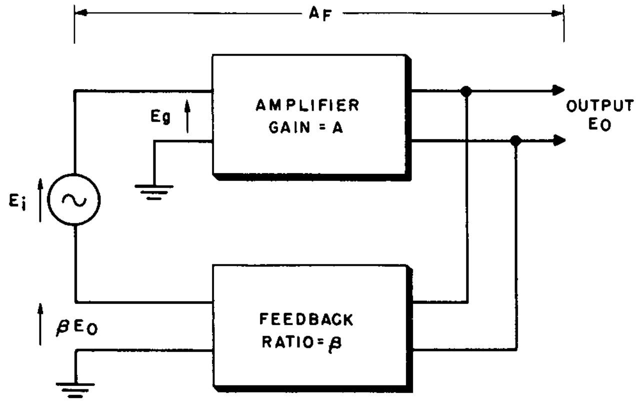

Fig. 1. Basic feedback arrangement.

A fraction, β (which is always less than 1), of the output voltage is fed back through a feedback network to the input of the amplifier as a feedback voltage, βE_o. When the feedback voltage is negative, β is negative. This ties in with the fact that when *inverse* (negative) feedback is used, the amplifier output energy in the presence of feedback is less than the output energy where no feedback is used. Consequently, to be negative, the feedback voltage must always act in oposition to the incoming signal.

At the point to which signal is fed back, the feedback voltage and the input signal voltage (from the previous stage) add together to produce the total effective input to the amplifier.

If feedback is negative, the feedback voltage opposes the signal voltage, so the net total amplifier input voltage is equal to the numerical difference between the signal input and feedback voltages.

This is illustrated in Fig. 1. The amplifier is assumed to have amplification A in the absence of feedback. The feedback network takes part of the amplifier output voltage (E_{o}) and transfers it to the input circuit. The fraction of E_o that is fed back is symbolized as β, sometimes called the "feedback ratio." For example, suppose the signal output of the amplifier is 100 volts, of which 50 volts is fed back to the input. Then

$$\beta = \frac{50}{100} = 0.5$$

From this it can be seen that the voltage (E_{fb}) fed back to the input is

$$E_{fb} = \beta E_o$$

Normally, we take the signal voltage at the point to which feedback is applied as a reference. Then E_o may be either positive or negative. For example, if there is one stage of amplification, a 180-degree phase shift is introduced, and E_o has a negative value. If there are two stages, E_o is positive. (In both cases it is assumed that input voltage is at the grid and output voltage is at the plate.)

If E_o is negative, some of it can be tapped off and applied directly to the input for negative feedback. In such a case β is said to be positive because it has not changed feedback phase. If E_o is positive, it must be inverted before application to the input. This inversion is accomplished in the feedback network when β is negative.

From the above it can be seen that for negative feedback, either E_o or β, but *not both,* must be negative. This will presently be checked mathematically.

We have now defined basic factors well enough to set down the fundamental relations applying to Fig. 1. We call the signal voltage obtained from the previous stage E_i and the total signal into the amplifier with feedback E_g.

Feedback signal βE_o *is* applied to the input so as to add to signal voltage E_i to produce input signal E_g. Expressing this mathematically:

$$E_g = E_i + \beta E_o \qquad (1)$$

Because the amplification of the amplifier (without feedback) is A,

$$E_o = AE_g \qquad (2)$$

Substituting (1) in (2):

$$E_o = AE_i + A\beta E_o$$

and

$$E_o(1 - A\beta) = AE_i$$

thus

$$\frac{E_o}{E_i} = \frac{A}{1 - A\beta} \qquad (3)$$

But the ratio E_o/E_i is the amplification with feedback applied, which we will designate A_F, so

$$A_F = \frac{A}{1 - A\beta} \text{ and } \frac{A_F}{A} = \frac{1}{1 - A\beta} \qquad (4)$$

Equation 4 is a basic universal relation, upon which most feedback theory is based. Most negative feedback networks do not have gain, so β is less than 1. Remembering this, it can be seen in Equation 4 that if A and β are both positive (no phase shift or phase shift a multiple of 360 degrees) or both negative (180-degree shift) the gain with feedback is greater than gain without feedback and feedback is *positive.* For negative feedback, either A or β must be negative, and the gain with feedback must be less than the gain without feedback.

An example of how negative feedback may be obtained in an actual circuit is shown in Fig. 2. This is a simple resistance-coupled amplifier, whose output signal voltage is E_o and whose input signal voltage is E_i. E_o is 180 degrees out of phase with E_i, as in any resistance-coupled amplifier. *C1* blocks plate d-c voltage $E\beta$ from the grid, but has enough capacitance to appear as a short circuit for signal voltages. E_o is coupled through *C1* to the voltage divider formed by *R1* and *R2*. The portion of this voltage appearing at the grid is the ratio of *R2* to *R1* + *R2*, so

$$E_{fb} = E_o \frac{R2}{R1 + R2}$$

Since E_o is in phase opposition to E_i, so is E_{fb}, and the feedback is negative.

Let us now see how we may apply Equation 4 to determine how much the gain of the stage of Fig. 2 is reduced by the addition of feedback network *R1C1*. First, assume that the gain without feedback *(A)* is 10. β is the portion of E_o fed back, so

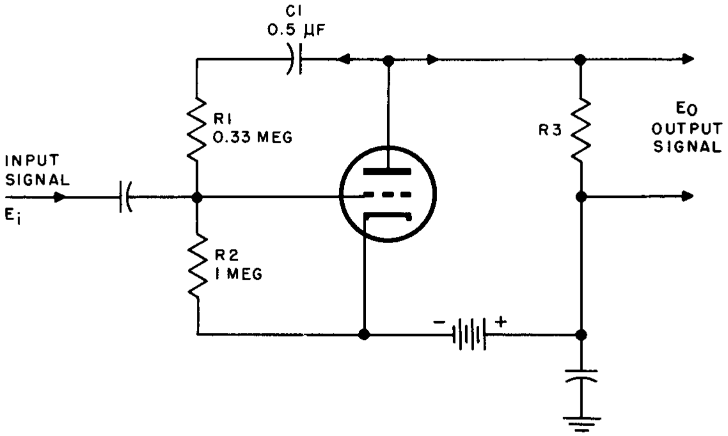

Fig. 2. Example of negative feedback arrangement.

$$\beta = \frac{R2}{R1 + R2} = \frac{1}{1 + 0.33} = \frac{1}{1.33} = 0.75$$

Because βE_o is direct feedback with no phase change from E_o, β is positive. Because E_o is opposite in phase to E_i, A is negative. We may now substitute in Equation (4):

$$\frac{A_F}{A} = \frac{1}{1 - A\beta} = \frac{1}{1 - (-10 \times 0.75)} = \frac{1}{1 + 7.5} = \frac{1}{8.5} = 0.118$$

In other words, the gain after feedback circuit *R1C1* has been added is 10 x 0.118 = 1.18. In this example there is a relatively large amount of feedback, hence the extreme reduction in gain.

The preceding example shows how inverse feedback has the effect of dividing the normal gain by the quantity $(1 - \beta A)$. This quantity is defined as the *feedback factor*. Large amounts of feedback are normally used, and βA becomes large compared to 1, so the quantity $(1 - \beta A)$ is approximately equal to the quantity $(-\beta A)$. For example, if $(1 - \beta A) = 100$, $(-\beta A) = 99$. The quantity $(-\beta A)$ is itself often referred to as the *feedback factor*, and the reader should take care not to become confused by identical use of $(1 - \beta A)$ *and* $(-\beta A)$.

When large amounts of feedback are used, the amplifier gain in the presence of feedback (A_F) is approximately equal to the quantity

$$\frac{A}{\beta A} \quad \text{or} \quad A_F = -\frac{1}{\beta}\,. \tag{5}$$

Thus the gain of an amplifier using large amounts of inverse feedback depends only upon β, and is unaffected by changes in the amplifier gain (A) when feedback is not used. This characteristic of feedback prevents the amplifier behavior from being sensitive to small changes in tube characteristics caused, for example, by aging of tubes, or to small variations in power supply voltages. Effectively, the amplifier behavior is held uniform over long periods of time. For this reason, inverse feedback amplifiers are widely used in vacuum tube voltmeter circuits, because accurate instrument calibration can thus be maintained despite tube changes or replacements. It will be noted that feedback can be used with either dc or ac amplifiers. In the dc amplifier, inverse feedback is obtained through the use of incoming signals and feedback voltages that are opposed in *polarity*; in the ac amplifier, the signals and feedback voltages are opposed in *phase*.

In electronic terminology, changes in power are often expressed in terms of decibels (db). Thus, if the output power of an amplifier changes from P_1 watts to P_2 watts, the change in power as expressed in decibels is equal to the quantity

$$10 \log_{10} \left(\frac{P_2}{P_1}\right) \tag{6}$$

The ratio of two voltages can also be expressed in db, by the expression

$$\text{db} = 20 \log_{10} \frac{E_2}{E_1} \tag{7}$$

where voltage changes from E_1 to E_2.

In a similar manner, changes in amounts of feedback are often expressed in decibels. The amount of feedback is actually indicated by the reduction in amplifier gain. Thus an amplifier with 20-db feedback is one in which the gain has been reduced 20 db by feedback.

As an example of expression of feedback in db, consider the previous example. The gain of the stage was reduced from 10 to 1.18. First express each gain in terms of db:

Without feedback $\text{db} = 20 \log_{10} (10) = 20 \times 1 = 20$ db

With feedback $\text{db} = 20 \log_{10} (1.18) = 20 \times .07 = 1.4$ db

The reduction of gain in db is $20 - 1.4 = 18.6$ db. Therefore, the circuit of Fig. 2 can be said to have 18.6 db of feedback.

4. Effect of Negative Feedback on Amplitude Distortion

No practical amplifier can amplify an incoming signal in such a manner that its amplified output signal is a perfect reproduction of the incoming signal. In particular, all amplifiers exhibit some degree of amplitude distortion; that is, the amplified output signal contains some frequency components not present in the incoming signal. Let the distortion voltage present in the output signal when feedback is not used be equal to D, and let D_f be the value of the distortion voltage present when inverse feedback is used. Then if the output signal in the presence of feedback is adjusted to the same level as when feedback is not used, a distortion voltage (βD_f) is fed back to the input of the amplifier. This distortion voltage is amplified to yield an output distortion voltage of $\beta A D_f$ where A is the gain of the amplifier without feedback. This output distortion voltage adds to the distortion (D) that would be present without feedback, so

$$D_f = D + \beta A D_f = \frac{\mathrm{D}}{(1 - \beta A)} \tag{8}$$

Thus the distortion when feedback is used is equal to the distortion when feedback is not used divided by the feedback factor.

5. Effect of negative feedback on Frequency Response

The gain of an amplifier varies at least a little with frequency. Assume that an amplifier that does not make use of feedback has a gain A_1 for one signal frequency and a second and different gain A_2 for another signal frequency. When inverse feedback is used, the gain for the first signal frequency A_{1F} will equal the quantity $A_1/(1 - \beta A_1)$. Similarly, the gain for the second frequency A_{2F} will equal $A_2/(1 - \beta A_2)$. Then the ratio of these two gains in the presence of feedback will be

$$\frac{A_{2F}}{A_{1F}} = \left(\frac{A_2}{(1 - \beta A_2)}\right)\left(\frac{(1 - \beta A_1)}{A_1}\right) = \frac{A_2}{A_1}\,\frac{(1 - \beta A_1)}{(1 - \beta A_2)} \qquad (9)$$

Thus the ratio of these two gains in the presence of feedback is equal to the ratio when feedback is not used multiplied by the factor $(1 - \beta A_1)/(1 - \beta A_2)$. The net result is that the gains at these two signal frequencies are more nearly the same when feedback is used.

As an example, consider an amplifier in which amplification at two different frequencies, without feedback, is

Amplification A_1 at $F_1 = -10$
Amplification A_2 at $F_2 = -1$

The ratio of gains at the two frequencies is 10:1. Now suppose feedback, with $\beta = 0.5$ is applied. Then

$$\frac{A_{2F}}{A_{1F}} = \frac{1 - \beta A_1}{1 - \beta A_2} = \frac{1 + 5}{1 + 0.5} = \frac{6}{1.5} = 4$$

Thus frequency components that without feedback had a gain ratio of 10 have a gain ratio of only 4 after feedback has been applied. The frequency response of the amplifier is thus improved.

6. Effect of Negative Feedback on Hum and Noise

Amplifier hum is caused by the amplification of undesirable alternating voltages (for example, alternating filament voltages supplied to the tubes in the amplifier). Amplifier noise is caused by tube microphonics, noisy resistors, and similar effects. When the incoming signal supplied to the amplifier contains hum or noise generated in earlier amplifier stages and extended to the amplifier itself, the output signal from the amplifier will contain the same percentage of hum or noise, whether or not inverse feedback is used. This result follows from the fact that, although the amplifier gain is reduced through action of inverse feedback, both the useful portion of the incoming signal and the hum or noise component of this signal are amplified to the same extent.

However, if the hum or noise generated *within* the amplifier is subjected to inverse feedback action, this internal hum or noise will be reduced in the same manner and to the same extent as the amplifier gain is reduced by feedback. Proof that this reduction in noise or hum is actually accomplished is somewhat complex mathematically and will not be discussed here.[1]

When noise is present in a low gain amplifier, (for example, in an audio preamplifier) there is little advantage in using feedback to reduce noise; the use of feedback diminishes the amplifier gain to such an extent that additional amplification is required. This additional amplification raises the noise level to substantially its original value.

7. Types of Inverse Feedback

Inverse feedback can involve current feedback, voltage feedback, or combined current and voltage feedback. Each type of inverse feedback has a characteristic effect on amplifier operation, particularly on amplifier output and input impedances, as will be shown in subsequent chapters. However, each type of feedback will first be defined.

8. Current Feedback

The circuit shown in Fig 3 illustrates *current feedback.* Here the feedback voltage is derived from the voltage appearing across resistor R_o. This voltage is equal to the quantity I_oR_o, where I_o is the amplifier output current flowing through resistor R_o. Therefore, the feedback voltage is proportional to the output current and is defined as *current feedback.*

When current feedback is used, if the load impedance connected to the amplifier increases, the output current will decrease. As a result, the feedback voltage will also decrease, causing the amplifier gain to increase and the output current to increase. Thus, if the input signal is held constant, the output current tends to remain constant despite changes in output impedance, and the circuit of Fig. 3 acts as a constant current generator.

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[1] For a detailed discussion of this reduction, see F. Langford-Smith (ed.), *Radiotron Designer's Handbook* (4th ed.; Sidney, Australia: Wireless Press, 1952).

9. Voltage Feedback

In the circuit shown in Fig 4, the feedback voltage is derived directly from the output voltage, E_0. Since the feedback voltage is proportional to the output voltage, this type of feedback is called *voltage feedback.*

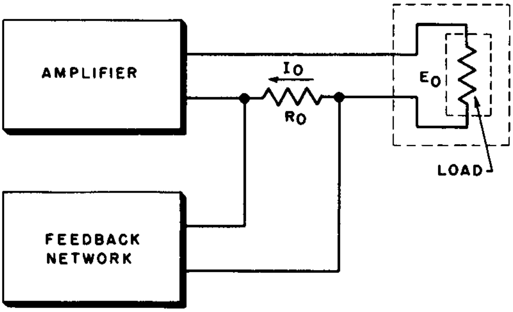


Fig. 3. Current feedback arrangement.

When the load impedance is increased in this arrangement, the output voltage increases, the feedback voltage increases and the amplifier gain is reduced. This reduction in gain acts to reduce the output voltage. Thus, if the input signal is held constant, the output voltage tends to remain constant despite changes in output impedances, and the circuit of Fig. 3 acts as a constant voltage source.

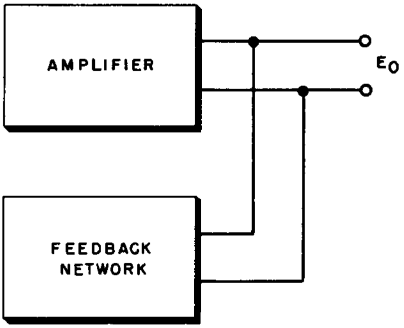


Fig. 4. Voltage feedback arrangement.

10. Combined Current and Voltage Feedback

Both current and voltage feedback can be combined in one circuit, as shown in Fig. 5. The output voltage (E_0) appears across potentiometer P_o, so that the potential appearing at the arm of potentiometer P_o is proportional to the output voltage. In addition, the output current flows through potentiometer P_i, and the potential appearing at the arm of potentiometer P_i is proportional to the output current.

The feedback voltage is proportional to the difference between these two potentials, and therefore represents a combination of current and voltage feedback. This combination of feedback is sometimes called "bridge" or "hybrid" feedback.

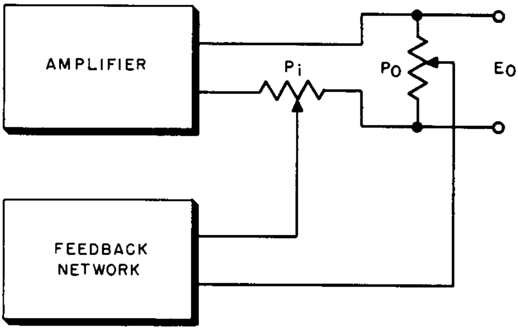


Fig. 5. Combined current and voltage feedback.

11. Review Questions

(1) What is feedback?
(2) Explain the difference between regenerative and inverse feedback.
(3) Why is feedback used?
(4) How does negative feedback affect amplifier gain?
(5) Explain the difference between current and voltage feedback.
(6) What is meant by the term 20-db feedback?
(7) When large amounts of feedback are used, what is the relationship between amplifier gain and the feedback fraction β?
(8) What is the effect of negative feedback on hum or noise?
(9) What is bridge feedback?
(10) What is the effect of negative feedback on amplitude disorton?

Chapter 2

EFFECT OF FEEDBACK ON OUTPUT AND INPUT IMPEDANCE

When the output energy from one electronic device is to be supplied as input energy to a second device, the output impedance of the first device must be matched to the input impedance of the second device; if it is not, there will be an excessive loss of power. For example, audio power amplifier tubes have high plate impedance, yet they must supply power to one of more loudspeakers, which are low impedance devices. If these two devices were to be connected directly together, the impedance mismatch would be so great that the speaker would not receive enough power to produce the desired sound level. Impedance mismatch can also have other undesirable effects, such as increasing distortion. Therefore, an output transformer is used as an impedance matching device.

When inverse feedback is used, both the input and output impedances of the device are affected. Therefore, in order to prevent impedance mismatch, it is necessary to understand the nature and degree of changes in impedance caused by the use of inverse feedback.

12. General Considerations

Before proceeding to a consideration of more specific situations, let us examine some of the general factors involved in the influence of feedback on input and output impedance.

Without feedback, the impedances of the amplifier are determined by the impedance values of components in the circuit. The change of impedance caused by feedback results from modifications feedback makes in the *way currents vary with voltages.* Thus, if a signal voltage swing is upward, but there is negative feedback, the resulting current may swing upward more slowly than without feedback. In such a case the impedance has been *raised,* because the current response has been lowered as though more component impedance had been added.

Input impedance change due to feedback is influenced only by the currents and voltages in the input circuit in virtually all practical circuits. Similarly, output impedance is affected by the currents and voltages in the output circuit. Thus input impedance is substantially independent of the way in which feedback voltage is obtained from the output circuit, and output impedance is independent of the way in which the feedback voltage is applied to the input.

We shall consider the application of feedback both in series and in parallel with input voltage. Since the output circuit does not affect the impedance of the input circuit, the effect of feedback on input impedance is the same for either voltage feedback or current feedback.

For output circuits we shall also consider voltage feedback and current feedback. The effect of feedback on output impedance is the same whether the feedback is applied in parallel or in series with the input voltage.

Another factor of importance is the relative impedance of the feedback circuit itself; this impedance should usually be negligible. To insure this, certain relationships must be maintained. First, if feedback is applied in series with the input voltage, its effective impedance must be negligibly low in order not to disturb the circuit. Second, if the feedback is applied in parallel with the input circuit, the feedback circuit impedance must be relatively high, so that the feedback circuit acts as a constant-current device, and the input signal voltage is not affected by feedback. With the series connection, the input and feedback voltages add to produce the amplifier input voltage; with the parallel connection, the input currents add.

13. Feedback Voltage in Series with Input Signal

Figure 6 shows a current feedback arrangement in which the feedback voltage is in series with the input signal. The amplifier, when no feedback is used, will have an input impedance Z_i because of coupling capacitors, grid resistors, stray grid-to-ground capacitance, and so forth. Then, if the input signal is E_i, the current through this impedance (I_{Zi}) will be E_i/Z_i.

It will be assumed, as is normally the case, that the impedance of a series connected feedback network (as in Fig. 6) is much smaller than the amplifier input impedance. Thus the network impedance need not be considered in this discussion.

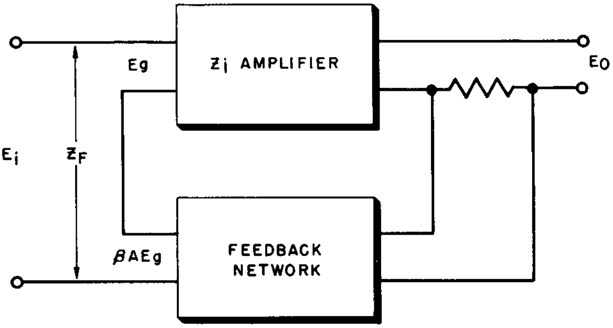


Fig. 6. Feedback voltage in series with input signal.

In this situation, it is desirable to assume that E_o is kept at the same value for feedback and non-feedback conditions. In other words, without feedback the input voltage is E_g. Then, with feedback, the input voltage must be raised to a higher value of E_i to restore the same E_o. Z_i is the input impedance of the amplifier in the absence of feedback; Z_F is the input impedance with feedback.

$$E_g = E_i + \beta A E_g \tag{1}$$

$$E_i = E_g \ (1 - \beta A) \tag{10}$$

$$Z_i = \frac{E_g}{I_i}$$

$$Z_F = \frac{E_i}{I_i} = \frac{E_g \ (1 - \beta A)}{I_i}$$

$$\frac{Z_F}{Z_i} = \frac{E_g \ (1 - \beta A)}{I_i} \times \frac{I_i}{E_g} = 1 - \beta A$$

$$Z_F = Z_i \ (1 - \beta A) \tag{11}$$

This says that the input impedance is increased by the feedback factor when feedback is added to a series-connected circuit.

EXAMPLE: An amplifier has an input impedance of 20,000 ohms without feedback, and its gain is −10. What is the input impedance if feedback with $\beta = 0.1$ is added?

$$\begin{aligned} Z_F = Z_i\ (1 - \beta A) &= 20{,}000\ [1 - 0.1\ (-10)\,] = 20{,}000 \times 2 \\ &= 40{,}000 \text{ ohms} \end{aligned}$$

14. Feedback Voltage in Parallel with Input Signal

Sometimes the feedback is connected in parallel with the input signal, as indicated in Fig. 7 (A). As previously explained, with such a connection the feedback circuit impedance must be relatively high, and the feedback source becomes a constant-current generator. To visualize this properly, consider the input circuit itself, illustrated at (B) of Fig. 7.

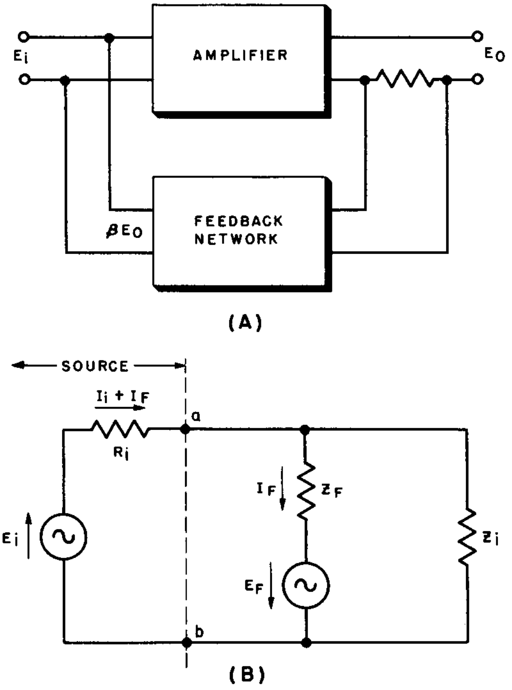
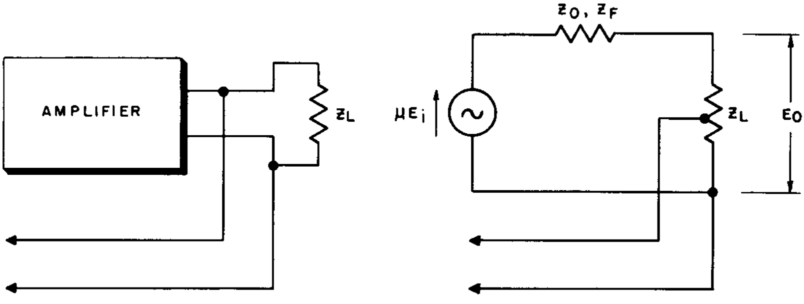


Fig. 7. Feedback voltage in parallel with input signal.

The incoming signal "sees" the impedance between points *a* and *b* "looking" from the left. The feedback voltage (E_F) is connected through its impedance (Z_F) to the input terminals. *If* E_F *is connected for negative feedback, so as to oppose* E_i *across* Z_i, *it aids the current around the loop* E_F—E_i—R_i—Z_F. Thus the current feeding into the circuit at *a-b* is greater than the same current without feedback, and the input impedance is effectively *lowered.*

Let us neglect Z_i, since it has the effect merely of further lowering the impedance, and consider the remainder of the input circuit.



(A) (B)

Fig. 8. Output circuit with voltage feedback.

The voltage remains E_i whether or not there is feedback; only the current changes. Since impedance is inversely proportional to current at a given voltage:

$$\frac{Z_F}{Z_i} = \frac{I_i}{I_i + I_F}$$

$$Z_F = Z_i \frac{I_i}{I_i + I_F} \qquad (12)$$

With negative feedback the currents are additive, hence input impedance with feedback is lower than input impedance without feedback for the shunt connection.

Because the feedback and signal currents depend upon source and feedback impedances, and these are rather complex, a complete solution in terms of β and A is beyond the scope of this book. However, Equation 12 shows the important fact that feedback lowers input impedance in this arrangement.

15. Output Impedance with Voltage Feedback

To demonstrate the effect of voltage feedback on output impedance, as in the arrangement of Fig. 8 (A) we must consider an equivalent circuit as shown at (B) in Fig. 8. The output impedance is the output voltage source impedance, and is equivalent in the no-feedback case to plate resistance r_p. In the folowing derivations, these symbols are employed:

μ = amplification factor of output stage without feedback
μ_F = amplification factor of output stage with feedback
A = amplification without feedback
A_F = amplification with feedback
E_i = input signal voltage without feedback
E_F = input signal voltage with feedback
Z_o = output impedance without feedback (r_p) (normally resistive)
Z_F = output impedance with feedback (normally resistive)
Z_L = load impedance (normally resistive)
E_o = output signal voltage without feedback
E_{oF} = output signal voltage with feedback

Without feedback, by voltage divider action:

$$E_o = \mu E_i \left[\frac{Z_L}{Z_o + Z_L}\right] \tag{13}$$

and

$$A = \mu \left[\frac{Z_L}{Z_o + Z_L}\right] \tag{14}$$

With feedback:

$$E_{oF} = A_F E_F = \frac{A}{1 - \beta A} E_F = \frac{E_F}{\frac{1}{A} - \beta} \tag{15}$$

substituting (14) in (15):

$$E_{oF} = \frac{E_F}{\frac{Z_o + Z_L}{\mu Z_L} - \beta} = \frac{\mu Z_L E_F}{Z_o + Z_L - \mu Z_L \beta}$$

$$= \frac{\mu Z_L E_F}{\frac{Z_o\ (1 - \mu\beta)}{1 - \mu\beta} + Z_L\ (1 - \mu\beta)} = \frac{\mu Z_L E_F}{(1 - \mu\beta)\left[\frac{Z_o}{1 - \mu\beta} + Z_L\right]}$$

$$= \frac{\mu E_F}{1 - \mu\beta} \times \frac{Z_L}{\frac{Z_o}{1 - \mu\beta} + Z_L} \tag{16}$$

This expression for E_0 with feedback is the same as the equation for E_0 without feedback, except that:

$$\mu_F = \frac{\mu}{1 - \mu\beta} \quad \text{and} \quad Z_{oF} = \frac{Z_0}{1 - \mu\beta} \tag{17}$$

Thus, with voltage feedback, output impedance is reduced in proportion to the feedback factor increase, using amplification factor μ instead of A. If the feedback extends around more than the output stage, μ is replaced by μA, where A is the amplification between the feedback application and the final stage. This modification is necessary because the output stage is a power (rather than voltage) stage.

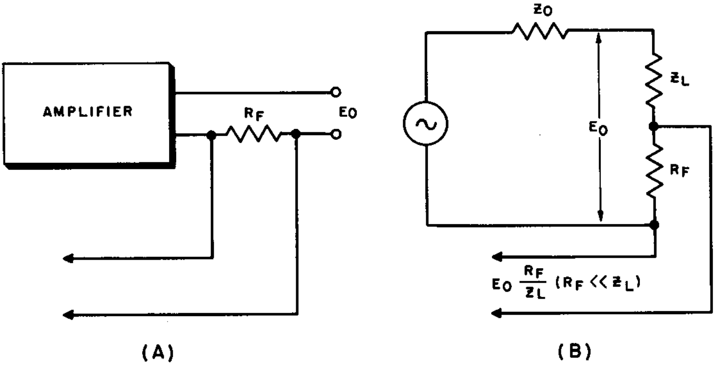


Fig. 9. Output circuit with current feedback.

EXAMPLE: Negative feedback with $\beta = 0.2$ is provided around a power stage whose amplification factor is -20 and whose plate impedance is 6000 ohms in the absence of feedback. What is the effective output impedance with feedback? What is the new effective amplification factor?

$$Z_{oF} = \frac{Z_0}{1 - \mu\beta} = \frac{6000}{1 - (-20 \times 0.2)} = \frac{6000}{1 + 4} = 1200 \text{ ohms}$$

$$\mu_F = \frac{\mu}{1 - \mu\beta} = \frac{-20}{5} = -4$$

16. Output Voltage with Current Feedback

In current feedback, the output circuit conditions are changed by the addition of series resistor R_F, illustrated in Fig. 9 (B). R_F

must be small compared to Z_L. Otherwise, the same symbols will be used here as in the previous discussion of voltage feedback impedance. With no feedback in this circuit:

$$A = \frac{E_o}{E_i} = \frac{-\mu Z_L}{Z_o + R_F + Z_L} \tag{18}$$

With current feedback:

$$A_F = \frac{E_o}{E_F} = \frac{E_o}{E_i + \frac{R_F}{Z_L} E_o} = \frac{1}{\frac{E_i}{E_o} + \frac{R_F}{Z_L}}$$

$$= \frac{1}{\frac{Z_o + R_F + Z_L}{-\mu Z_L} + \frac{R_F}{Z_L}} = \frac{-\mu Z_L}{Z_o + R_F + Z_L + \mu R_F}$$

$$= \frac{-\mu Z_L}{(Z_o - \mu R_F) + R_F + Z_L} \tag{19}$$

This expression is the same as the expression for gain without feedback (Equation 18), except that the output impedance has changed from Z_o to $Z_o - \mu R_F$. Since no allowance is made in this arrangement for inversion in the feedback network, μ must be negative for negative feedback. Thus output impedance is effectively *increased* by negative current feedback.

EXAMPLE: An output stage with an amplification factor of -10 has a plate resistance of 10,000 ohms. What is the effective plate resistance after negative current feedback is added, using a 100-ohm feedback resistor?

$$Z_F = Z_o - \mu R_F = 10{,}000 - (-10 \times 100) = 11{,}000 \text{ ohms}$$

17. Combined Current and Voltage Feedback (Bridge Feedback)

In certain electronic applications (for example, when an amplifier is to supply energy to a transmission line), the output impedance must have a value lower than that obtainable through current feedback but higher than that obtainable through voltage feedback. In this event, the circuit shown in Fig. 5 can be used. By varying the positions of both potentiometer arms, the ratio of the amount of current feedback to the amount of voltage feedback can be adjusted to any value between 0 and 1, and thus the output impedance can be adjusted to have any value between the maximum value determined by the use of current feedback alone and the minimum value obtained by the use of voltage feedback alone. The combination of current and voltage feedback is often referred to as *bridge feedback.*

18. Use of Inverse Feedback in Preventing Impedance Mismatch

Assume that the input circuit of an amplifier without feedback has an input impedance (R_i) on the order of 25,000 ohms and is to receive an input voltage of 5 volts as developed across resistor *R2* in the circuit shown in Fig. 10. When the amplifier is not connected in the circuit, it will be seen that 10 volts is applied across the two series resistors (*R1* and *R2*) to ground. Since the value of each resistor is 100,000 ohms, the voltage developed across $R2 = 10[R2/(R1 + R2)] = 10[10^5/(10^5 + 10^5)] = 5$ volts, which is the desired value.

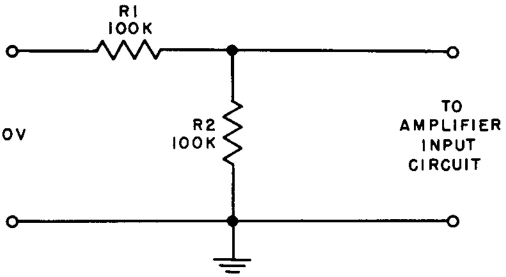


Fig. 10. Simple input voltage divider.

However, when the amplifier input circuit is connected across resistor *R2,* this resistor is shunted by the amplifier input impedance, and the effective resistance (R_e) of these parallel resistors is equal to $R_iR2/(R_i + R2) = (10^5)(2.5 \times 10^4)/(10^5 + 2.5 \times 10^4) =$ 20,000 ohms. Under these conditions the voltage developed across this effective resistance (which is the voltage supplied to the amplifier input circuit) is no longer 5 volts, but is reduced to $10[R_e/(R1 + R_e)] = (2 \times 10^5)/(10^5 + 2 \times 10^4) = 1.67$ volts. This is often an unacceptably low value.

However, when inverse feedback is used in such a manner that the feedback voltage is in series with the input voltage, and the feedback factor is chosen to have a value of 100, the input impedance in the presence of feedback (which, as indicated previously, is equal to the input impedance in the absence of feedback multiplied by the feedback factor), will be equal to 25,000 (100) or 2.5 megohms. The effective resistance under these conditions is equal to $(10^5)(2.5 \times 10^6)/(10^5 + 2.5 \times 10^6)$ or approximately 96,000 ohms. As a result, the input voltage will be $(9.6 \times 10^4)/(10^5 + 9.6 \times 10^4)$ or approximately .49 volt. Thus the input voltage is maintained very close to its proper value.

As a further example, assume that an amplifier is coupled at its output circuit to a long transmission line, and that the output impedance of the amplifier without feedback is 35,000 ohms, while the input impedance of the transmission line is 350 ohms.

In order to hold power losses to a minimum, the output impedance of the amplifier should be approximately equal to the input impedance of the transmission line. Here there is a 100-to-1 ratio between the amplifier output impedance and the transmission line input impedance and, obviously, there will be a substantial power loss.

If inverse feedback is used in the manner shown in Fig. 8, and a feedback factor of 100 is used, the amplifier output impedance will be 35,000/100 or 350 ohms, and the desired impedance relations are established.

19. Review Questions

(1) What is meant by impedance matching?

(2) What is the effect on amplifier input impedance when the feedback voltage is in series with the input signal?

(3) What is the effect on amplifier input impedance when the feedback voltage is in parallel with the input signal?

(4) What is the effect on amplifier output impedance when current feedback is used?

(5) What is the effect on amplifier output impedance when voltage feedback is used?

(6) How is the amplifier output impedance affected by the use of bridge feedback?

(7) Explain the effect when the feedback voltage is in parallel with the input signal.

(8) Explain the effect when the feedback voltage is in series with the input signal.

(9) In what manner does bridge feedback modify the amplifier input impedance as compared to current and voltage feedback?

(10) When the output of an amplifier is connected to a transmission line, what is the advantage in using negative feedback?

Chapter 3

EFFECT OF FEEDBACK ON PHASE RESPONSE, FREQUENCY RESPONSE, AND STABILITY

20. Phase Relations in the Absence of Feedback

The gain of any amplifier varies at least a little with the frequency of the incoming signal. This variation of gain with frequency is due to the presence of inductive and capacitive reactances in the amplifier. These reactances not only alter the amplitude of the output signal and voltage with frequency (when a constant amplitude signal of variable frequency is used as an input signal), but also shift the *phase* of this voltage. As we shall see, this phase shift is extremely important in inverse feedback applications. However, in order to understand the action of amplifier phase shift in the presence of feedback, it is necessary to understand the action of amplifier phase shift when no feedback is present.

One of the simplest and most common cases of phase shift occurs with the circuit shown in Fig. 11. When an incoming a-c voltage is applied between the left hand terminal of the resistor and ground, an output voltage will be produced across the capacitor. For a given value of resistance and a given value of capacitance, the reactance of the capacitor will decrease as the frequency of the incoming voltage increases. (It will be recalled that the capacitor reactance is equal to $1/2\pi fC$ when f is the frequency of the incoming voltage and C is the capacitance of the capacitor.) Thus, as the frequency is increased, a point will be reached at which the capacitor reactance approximates zero, and virtually no voltage will be developed across the capacitor. Thus this circuit acts as a low pass filter that cuts off at frequencies high enough to cause the capacitor reactance to approach zero.

This circuit also shifts the phase of the voltage developed across the capacitor with respect to that of the incoming voltage. This effect can best be understood by analyzing the circuit behavior as the frequency of the incoming voltage is varied. When this voltage has zero frequency (that is, the voltage is steady d-c), the capacitor charges to the steady dc value after a time fixed by the ratio of the resistance to the capacitance. As frequency increases, the capacitor charges to its maximum value at a later time than that at which the incoming voltage attains its maximum value, and the capacitor voltage lags the incoming voltage. Thus a lagging phase shift is produced.

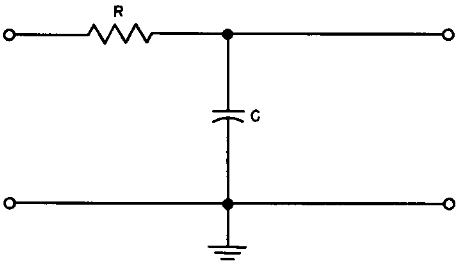


Fig. 11. A circuit that causes phase shift (low pass filter).

As the frequency of the incoming signal is further increased, the amount of phase shift increases and approaches 90 degrees as a theoretical limit. A plot of this shift against frequency for a practical circuit with typical component values is shown in Fig. 12. For those interested, the mathematical expression for the phase angle (Φ_0) is given in this figure.

The circuit shown in Fig. 13 also acts as a low pass filter. The reactance of the coil is equal to $2\pi fL$, where f is the frequency of the incoming signal and L is the inductance of the coil. Thus, as the frequency of the incoming signal increases to relatively high values, the reactance of the coil becomes so large relative to the resistance of the resistor that the voltage developed across the resistor becomes negligible. At this point, of course, there is virtually no output voltage.

It will be recalled that the voltage across an inductance leads the current flowing through it by 90 degrees. For high frequencies,

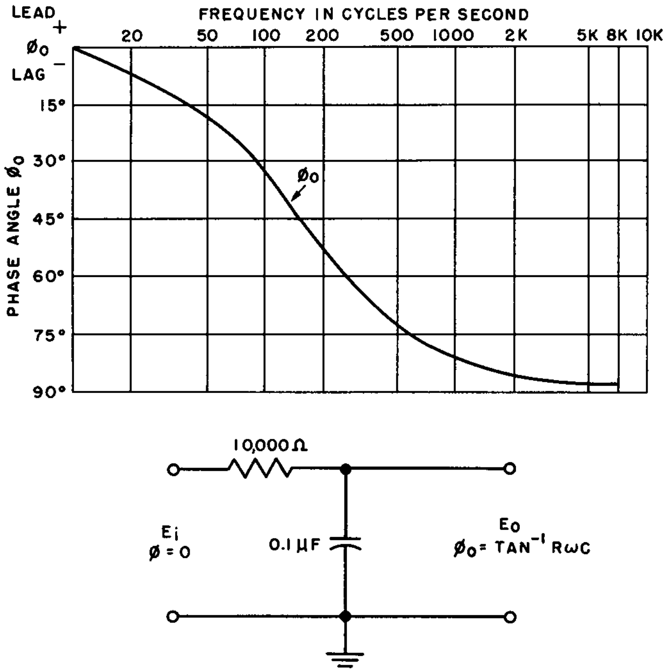


Fig. 12. Phase shift characteristic of a typical low pass filter circuit.

substantially all of the impedance appears across the coil. The current through the combination therefore lags the applied voltage by almost 90 degrees. Thus, the small output voltage developed across the resistor must also lag the input voltage by almost 90 degrees (assuming that the load has no effect). As the signal frequency decreases, this lagging phase shift decreases. In other words, the circuits of Fig. 11 and Fig. 13 behave in similar fashion.

Consider the circuit shown in Fig. 14. When an incoming voltage is applied between the left hand terminal of the capacitor and ground, an output voltage will be produced across the resistor. As the frequency of the incoming signal is decreased, the resistor and capacitor having fixed values, the reactance of the capacitor will increase. Consequently, a point will be reached at which virtually all the incoming voltage will be applied across the capacitor, and virtually no voltage will be applied across the resistor. Thus this circuit acts as a high pass filter; it will not pass frequencies low enough to cause the voltage across the resistor to approach zero.

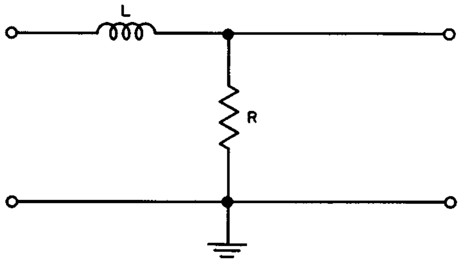


Fig. 13. Another phase shifting circuit, also a low pass filter.

It will be recalled that the current flowing through a capacitor leads the voltage produced across it by 90 degrees. Thus, in the circuit shown in Fig. 14, if d-c (zero-frequency) voltage is suddenly applied at the input, the voltage across the resistor is initially a maximum and decreases toward zero as the capacitor charges to its maximum value. Thus the voltage across the resistor leads the incoming voltage by nearly 90 degrees. As the frequency of the incoming voltage increases, this phase shift decreases, but it remains a leading phase shift. A plot of this shift against frequency

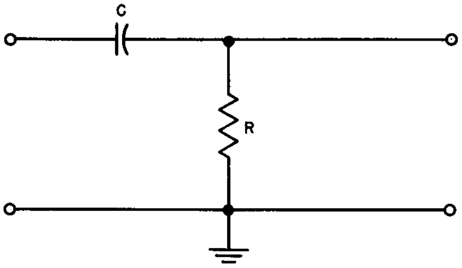


Fig. 14. High pass filter phase shifter.

is shown in Fig. 15. Note that the shape of the curve is exactly like that of Fig. 12, but here the phase is leading and starts at 90 degrees, falling off to near zero at high frequencies.

A resistance-inductance network can also be used as a high pass filter, as shown in Fig. 16. As the signal frequency decreases, the reactance of the coil decreases until, at low frequencies, most of the voltage of the circuit is developed across the resistor. There is very little voltage produced across the coil; hence there is no output voltage.

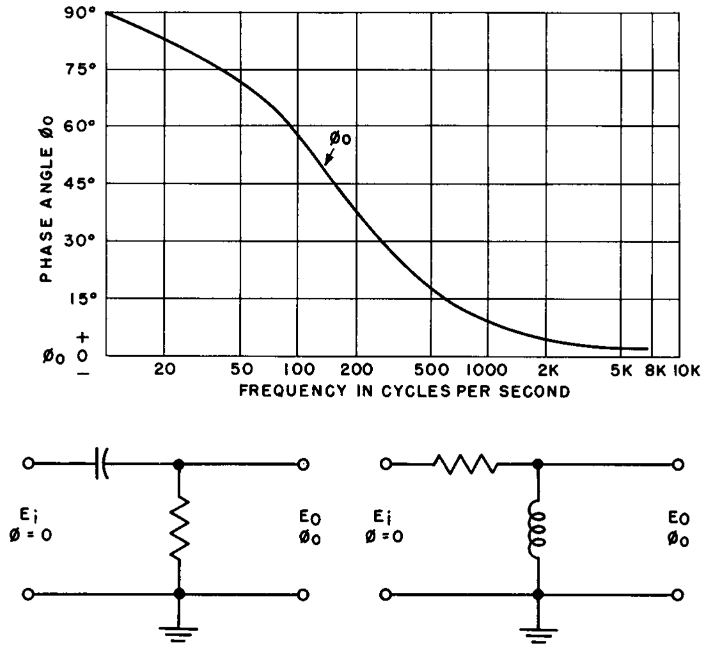


Fig. 15. Leading phase shift produced by high pass filter.

The current in the coil lags behind the voltage developed across it, and the voltage across the resistor is in phase with the current flowing through it. At low frequencies virtually all the input voltage appears across the resistor, and the current flowing through the resistor is in phase with the input voltage. This same current flows through the coil, and therefore the very small voltage developed across the coil leads the current by almost 90 degrees.

Consequently, this small voltage leads the input signal by the same approximate 90-degree phase shift. As the signal frequency increases, the amount of shift decreases, but it remains a phase lead.

Thus the circuits of Figs. 14 and 16 function in the same manner, and both develop a leading phase shift.

To summarize, in a low pass filter, high frequency cutoff causes a phase *lag* in the output voltage relative to the input voltage, while in a high pass filter, low frequency cutoff causes a phase *advance* in the output voltage relative to the input voltage. The amplitude and phase relations in the four simple filter circuits discussed are summarized in Fig. 17.

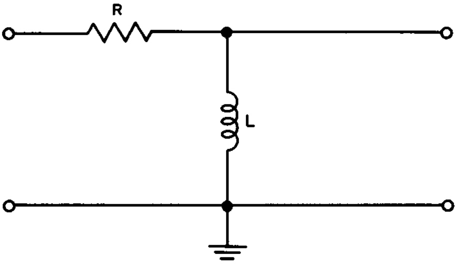


Fig. 16. An inductive high pass filter.

Since almost every amplifier contains one or more high pass and low pass filters (even though not always referred to as such), it will be seen that a phase shift between amplifier input and output voltage can readily be produced, and further that the amount of phase shift can vary with frequency.

21. Frequency Response in the Absence of Feedback

Amplifiers having one or more of these filters will not respond well to signals of frequencies beyond cutoff. When an amplifier will not respond to frequencies above and below a certain range, while passing all frequencies falling within the range, it is said to have a frequency bandwidth or frequency bandpass characteristic defined by the lowest and highest frequencies that can be passed.

When an incoming signal of a fixed amplitude is supplied to an amplifier having a given bandwidth, and the signal frequency is varied within this band, it will be found that (as indicated in the previous section) the gain of the amplifier is not fixed, but varies with frequency. This variation is called its frequency re-

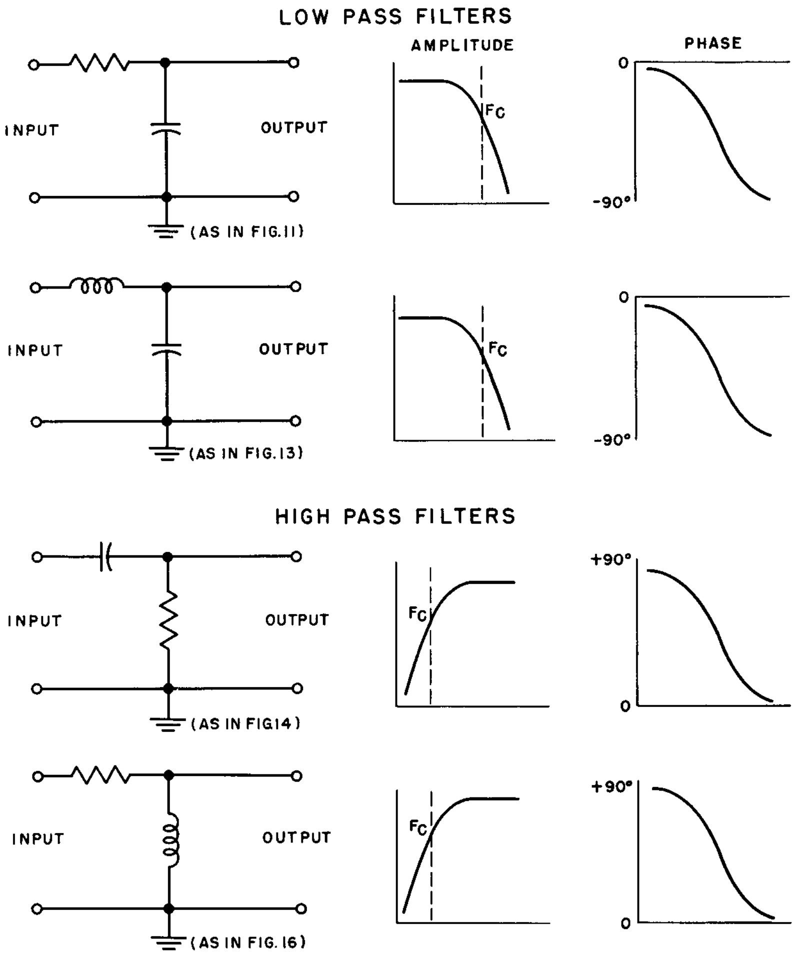


Fig. 17. Summary of characteristics of simple high and low pass filters.

sponse. Figure 18 is a graph of the frequency response of a typical audio frequency amplifier.

22. Effect of Feedback on Phase and Frequency

In inverse feedback the incoming signal and the feedback voltage always oppose each other. For a-c signals, this is equivalent to stating that the incoming signal and the feedback voltage are always opposite in phase. In the case of d-c signals, they are opposed in polarity. However, because of the phase shifts between amplifier input and output voltages caused by frequency cutoff characteristics, it will be seen that the feedback voltages can also shift in phase. This is the same as saying β has a phase angle other than zero, or A has a phase angle other than zero or 180 degrees. This shift can be so great as to convert inverse feedback into positive feedback (in which case the feedback voltage will act in phase with the incoming signal). At this point, the gain of the amplifier with feedback will be in excess of the gain without feedback and the amplifier may even oscillate. Consequently, inverse feedback is not always a cure-all, and careful analysis of the circuitry in which it is to be used is necessary before inverse feedback can be used successfully.

The discussion thus far has indicated that, for a given value of the input signal and a given amplifier gain, the feedback voltage will have a fixed value. As indicated previously, however, the gain of an amplifier varies with frequency so that, when the amplitude of the incoming signal is held constant but its frequency is varied, the amplitude of the feedback signal will vary with frequency. The net result is that the gain of an amplifier employing inverse feedback is not necessarily held constant over a given frequency range.

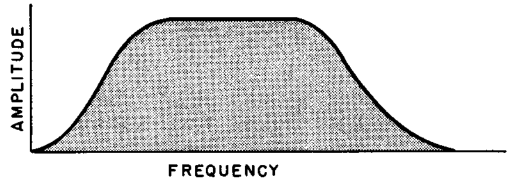


Fig. 18. Shape of frequency response characteristic of typical a-f amplifier.

One aproach to overcoming these phase and frequency limitations in inverse feedback is to design the feedback network to adjust its phase and frequency response with respect to the phase and frequency response of the amplifier in such a manner that the feedback voltage is automatically adjusted to have the proper phase and amplitude relative to the incoming signal.

For example, suppose that at a given frequency, the amplifier output voltage lags the amplifier input signal by 45 degrees, so that the feedback voltage would be shifted 135 degrees with respect to the input signal instead of the desired 180-degree shift. If the feedback network is designed at this frequency to cause the feedback voltage yielded by the network to lead the amplifier output voltage by 45 degrees, the desired 180-degree shift in feedback voltage can be obtained.

Similarly, if the amplifier gain is reduced at a particular frequency, the feedback network can be designed to have a like increase at this frequency, so that the feedback voltage can be maintained at its proper value.[1]

The bandwidth of an amplifier is normally defined as the number of frequency units between the points at which the response characteristic falls below 0.707 times the response (gain) in the middle-frequency range. The response above and below these points does not drop sharply below the 0.707 value, but tapers off. In the amplifier with feedback, the feedback voltage is greatest whenever the gain is greatest, which is the value in the middle portion of the response characteristic. Therefore, in this range, the full effect of feedback in lowering the gain is experienced. However, at frequencies just beyond the 0.707 points, feedback falls off with gain, so the overall gain is not lowered as much. The lower the amplifier gain, the less reduction it suffers from feedback. There is thus a marked "flattening effect" on the response, and the 0.707 response points are pushed further apart. Accordingly, the bandwidth of the amplifier is substantially increased.

Through the use of feedback, the gain of the amplifier can be limited to small values over substantially the entire bandwidth. Thus the effective bandwidth can be extended to conform substantially to the bandwidth defined by the high and low cutoff frequencies of the amplifier.

23. Effect of Feedback on Stability

When an amplifier oscillates or tends to oscillate at one or more frequencies, it is said to be unstable at these frequencies. An amplifier without feedback can be unstable, particularly when resonant circuits cause the amplifier gain to peak sharply at certain frequencies.

Consequently, when inverse feedback is properly used, the amplifier gain can be maintained at such a value that it is insuffi-

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[1] For detailed information on the design of feedback networks, see Hendrik W. Bode, *Network Analysis and Feedback amplifier Design* (New York: D. Van Nostrand Co., Inc., 1945).

cient to cause oscillation. In this manner, use of inverse feedback can improve the stability of an amplifier.

As described previously, however, phase shifts can convert inverse feedback into positive feedback, thus making an amplifier less stable than without feedback. A designer, if he so chooses, can make a series of calculations and determine what phase shifts are developed in an amplifier for each signal frequency under consideration, and thus design his amplifier circuitry so that inverse feedback will serve its proper purpose over the frequency range desired. Such calculations are extremely tedious and time consuming, so that other more rapid methods are normally used. One such method is called a Nyquist diagram. This method is highly mathematical and will not be described in detail here. However, the Nyquist diagram is a graph on which the quantity $-\beta A$ is plotted against frequency in such a manner that it is possible to determine amplifier stability at any particular frequency by reading values off the graph.

24. Review Questions

(1) Why does the gain of an amplifier vary with frequency?

(2) What is high frequency cutoff? A low pass filter?

(3) What is low frequency cutoff? A high pass filter?

(4) What is the effect of high frequency cutoff on the direction and magnitude of phase shift?

(5) What is the effect of low frequency cutoff on the direction and magnitude of phase shift?

(6) What is meant by the term "frequency bandpass characteristic?"

(7) Why is phase shift important in inverse feedback applications?

(8) Can the band width of an amplifier be broadened through the use of feedback?

(9) What is meant by amplifier instability?

(10) What is a Nyquist diagram?

Chapter 4

MULTI-LOOP AND MULTI-STAGE APPLICATIONS

25. Feedback Loops

The combined amplifier and feedback circuit shown in Fig. 1, which extends from the amplifier input through the amplifier and feedback network back to the amplifier input, is called a *feedback loop*. Since one amplifier stage and one network are used, this arrangement is defined as a single-stage single-feedback loop.

When one amplifier stage is used in conjunction with two or more feedback networks in the manner described in more detail later in this chapter, the resulting circuit has as many feedback loops as there are feedback networks. Such an arrangement is termed a single-stage multi-loop feedback circuit.

When one feedback network is used in conjunction with two or more amplifier stages, again in a manner described in more detail later, the resulting circuit has as many stages as there are amplifier stages. Such an arrangement is termed a multi-stage single-loop feedback circuit.

In order to understand how multi-stage and multi-loop feedback circuits function, it is necessary to analyze single-stage single-leep feedback systems in more detail.

Figure 19 shows a typical triode amplifier circuit incorporating one stage of amplification and one voltage feedback network. An incoming alternating signal is applied through blocking capacitor *C1* between the grid of a single triode *V1* and ground. The plate of the tube is connected through a load resistor R_L to the positive terminal of a battery *(B1)*. The negative terminal of the battery is grounded. The cathode of the triode is connected to ground through a cathode resistor, R_k. The cathode resistor is shunted by a bypass capacitor, C_k. The plate of *V1* is connected through a blocking capacitor (C_f) and a feedback resistor (R_f) back to the grid. The cathode resistor and capacitor serve to produce cathode bias in the usual fashion.

This circuit operates in the following manner. As the alternating signal increases in amplitude, the current flow through the tube increases, the voltage drop across the load resistor increases, and the plate of the tube becomes less positive. As the plate potential decreases, this decrease is fed back through capacitor C_f and feedback resistor R_f to the grid as a feedback voltage in series with the incoming voltage. This voltage acts in opposition to the incoming signal, and hence is an inverse feedback voltage.

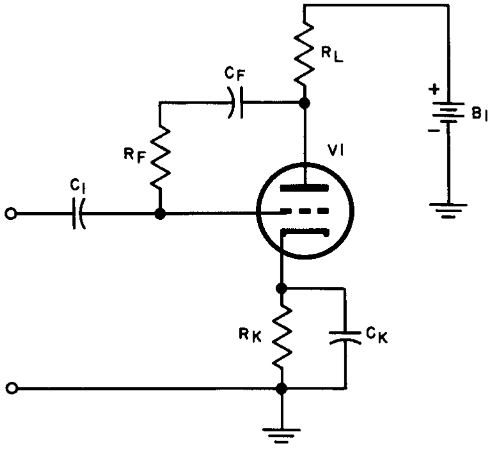

Fig. 19. One stage amplifier with single feedback loop.

Conversely, when the alternating signal decreases in amplitude, the current flow through the tube decreases, the voltage drop across the load resistor is decreased, and the plate of the tube becomes more positive. As the plate potential increases, this increase is fed back to the grid as an inverse feedback voltage in the same manner as before.

Now, if the circuit of Fig. 19 is modified by removing capacitors C_f and C_k and resistor R_f, as shown in Fig. 20, it will be seen that the resulting circuit incorporates one stage of amplification and one current feedback network.

Since the cathode bypass capacitor has been eliminated, all a-c voltages previously shunted around the cathode resistor by its bypass capacitor now flow through the cathode resistor. As the instantaneous voltage of the incoming signal increases, the instantaneous current through the cathode resistor increases and the positive cathode voltage increases. Similarly, when the instantaneous voltage of the incoming signal decreases, the instantaneous current through the cathode resistor decreases and the positive cathode voltage decreases. The positive voltage on the cathode with respect to ground (and thus also with respect to grid) is also a negative voltage on the grid with respect to cathode. Thus the changes in cathode voltage act in an inverse sense compared to the change in the incoming signal, so that an inverse current feedback effect has been developed.

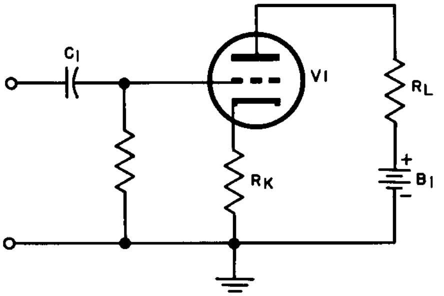

Fig. 20. One stage amplifier with one current feedback loop.

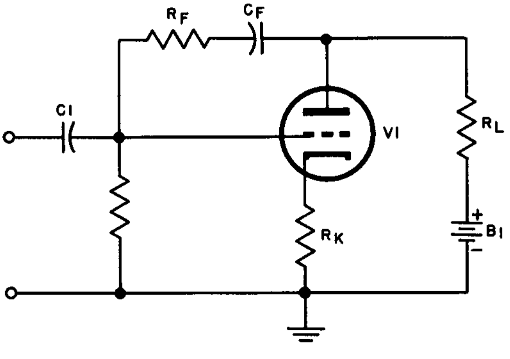

Fig. 21. Single stage, double loop circuit.

26. Single-Stage Multi-Loop Feedback Circuit

The inverse voltage and current feedback systems shown in Figs. 19 and 20 can be combined into a single-stage double-loop feedback circuit, as shown in Fig. 21.

Current feedback takes place in the same manner as indicated in Fig. 20, while voltage feedback takes place in the same manner as in Fig. 19. This arrangement is similar to the bridge feedback arrangement described in Chap. 1, and functions in the same manner.

27. Multi-Stage Single-Loop Feedback Circuit

In order to change the amount of feedback, the feedback factor must be changed. For example, if the amount of feedback is to be increased, either the feedback fraction *(β)* or the amplifier gain in the absence of feedback *(A)*, or both *A* and β must be increased. The feedback fraction can be changed by suitable design of the feedback network, but since this fraction is virtually always less than 1, the total change produced in this manner is limited. However, the amplifier gain can be increased either by increasing the gain in an amplifier stage or by using additional stages.

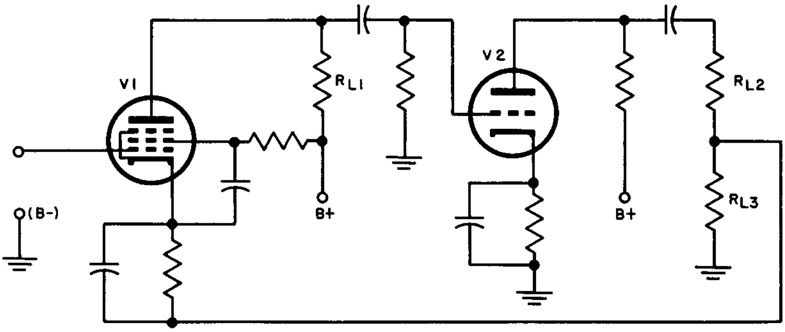

Fig. 22. Multi-stage, single loop arrangement.

When several stages of amplification are required, circuits similar to that shown in Fig. 22 can be used. This arrangement includes a pentode tube *(V1)* and a triode tube *(V2)*. When an incoming alternating signal is supplied to the grid circuit of the pentode, the signal is amplified in the pentode and appears in amplified form across the load resistor (R_{L1}) of this tube. The amplified signal is then supplied to the grid circuit of the triode (*V2*). This signal is further amplified in the triode and appears in amplified form across the load resistors (R_{L2} and R_{L3}) of tube *V2*. The portion of the amplified signal that appears across R_{L3} is returned as a feedback signal to the cathode of the pentode *V1*.

The midfrequency amplified signal appearing at the plate circuit of any ordinary resistance-coupled tube is 180 degrees out of phase with the signal applied to the input circuit of the tube. Since two successive tubes are used in this circuit, the signal supplied to the grid circuit of tube (*V1*) is shifted 180 degrees by the action of the tube *V1* and is shifted by the action of tube *V2* an additional 180 degrees. The total amplification (*A*) is thus positive. Consequently, the feedback voltage is in phase with the incoming signal. However, the incoming signal is supplied to the grid of tube *V1,* while the feedback voltage is supplied to the *cathode* of this tube.

Thus, as the instantaneous voltage of the incoming signal increases, the cathode voltage of tube *V1* is increased, and the action of the feedback voltage opposes that of the incoming signal to provide the desired inverse feedback relation.

If an additional amplifier tube is coupled to the output of tube *V2,* and the feedback voltage is derived from the plate circuit of the additional tube, the feedback voltage will be shifted an additional 180 degrees with respect to the incoming signal. In this event, the feedback voltage will be 180 degrees out of phase with the incoming signal, and to provide inverse feedback the feedback voltage and the incoming signal must both be applied to the grid of tube *V1*.

28. Inverse Feedback in Push-Pull Amplifiers

When a push-pull amplifier does not make use of inverse feedback, the two tubes that provide the push-pull operation must have matched characteristics and must be balanced in the circuit to provide identical amounts of gain. Otherwise, the amplifier output signal will not have the same waveshape and amplitude over each half of the signal cycle, and the amplifier output signal will be appreciably distorted. It is not always easy to provide such matched tubes. In addition, as the tubes age their characteristics can change in different ways so that the tubes will no longer be matched. Furthermore, as the circuit components age and change values, the circuit balance can be upset. The net result is impaired signal fidelity.

However, as indicated in Chap. 1, when large amounts of inverse feedback are used in an amplifier, the amplifier gain depends only on the feedback fraction and is substantially independent of the gain of the amplifier in the absence of feedback. Therefore, when large amounts of inverse feedback are used in a push-pull amplifier and the feedback factor is the same for both tubes, the gains provided by these tubes can be adjusted to the same value even though the tube characteristics vary and the circuit components change value.

Figure 23 shows a push-pull amplifier circuit in which inverse feedback is used. A feedback network, consisting of a blocking capacitor (C_f) and a resistor (R_f) in series, is connected between the plate of tube *V1* and the ungrounded end of grid resistor *R1*. The voltage produced at the plate of *V1* is 180 degrees out of phase with the incoming signal supplied to the grid of *V1*. Since a portion of this voltage is impressed as a feedback voltage across the grid resistor, the feedback voltage and the incoming signal are supplied in phase opposed to the signal voltage at the grid of tube *V1*, thus inverse feedback is developed.

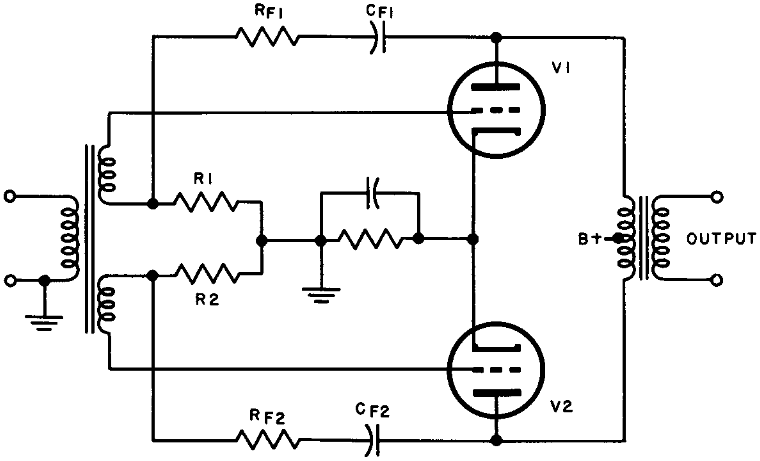

Fig. 23. Push pull circuit with inverse feedback.

An identical feedback network is connected in the same manner in the circuit of tube *V2*, and inverse feedback is developed in a similar fashion. By increasing the value of the grid resistor relative to that of the resistor in the feedback network, the magnitude of the feedback voltage produced across the grid resistor is increased; a suitable ratio of these two resistor values will provide a sufficiently large amount of feedback to cause the gain of each tube to be dependent only upon the feedback fraction.

Essentially, a push-pull amplifier using inverse feedback can be regarded as a single-stage double-loop feedback circuit.

29. Effect of Feedback upon the Stability of Multi-Loop and Multi-Stage Circuits

When a multi-loop single-stage amplifier is used, the phase and frequency relationships must be carefully analyzed for each feedback loop in the manner described in Chap. 3. However, this type of amplifier is normally more stable than a single-stage single-loop amplifier because, even if positive feedback is provided in one loop, the inverse feedback provided by the other loops is normally sufficient to hold the amplifier gain at a level below that required for oscillation.

The single-loop, multi-stage amplifier circuits, on the other hand, tend to be less stable than the single-stage single-loop circuit. Each amplifier stage, of course, contains high and low pass filters, which introduce phase shift. The shifts produced in each stage are added together to produce an overall phase shift in the particular multi-stage circuit used. Therefore, even though the phase shifts in any one stage may be insufficient to convert feedback to positive feedback, the cumulative effect of the shifts produced in each stage may do so.

Since the cumulative effect of phase shift increases as the number of stages is increased, negative feedback is normally not used around more than three stages. In most cases only two stages are used.

When inverse feedback is used in push-pull amplifiers, great care must be taken to insure that both feedback loops behave in an identical fashion. If the two loops are not adjusted properly, the halves of the circuit can become unbalanced, and the amplifier will not behave properly. As long as the phase shifts in each loop are analyzed properly, however, even though the tubes are unbalanced, the amplifier will not oscillate, and will remain stable.

30. Review Questions

(1) What is a feedback loop?

(2) What is a single-stage multi-loop feedback circuit?

(3) What is a multi-stage single loop feedback circuit?

(4) What is the special advantage of using inverse feedback in push-pull amplifier circuits?

(5) What is the effect of amplifier phase shift in multi-stage inverse feedback applications?

(6) How is current feedback produced in a single-stage amplifier circuit when no cathode bias capacitor is used?

(7) What is the advantage of using more than one stage in a feedback amplifier?

(8) What is the advantage of using more than one feedback loop?

(9) How does current feedback to an unbypassed cathode resistor produce an inverse feedback relation?

(10) Why is negative feedback normally used around a maximum of three stages?

Chapter 5

TYPICAL FEEDBACK APPLICATIONS

There are literally hundreds of different types of circuits in which inverse feedback is used. The circuits described in the remaining portion of this chapter are well known and widely used, but can represent only a few of the many applications of feedback.

31. Cathode Followers

The cathode follower is basically an amplifier in which inverse feedback is obtained by means of an unbypassed cathode resistor which also serves as an output load resistor. The output voltage is produced across this cathode resistor. The cathode follower has a high input impedance and a very low output impedance, and for this reason is often described as an impedance transformer. Its voltage gain is always less than one, but generally, the output power is at a much higher level than the power carried by the input signal.

One very important use of the cathode follower is found in highly complex electronic equipment where a signal must be transmitted along a transmission line for a considerable distance (often as much as 100 feet or more). A transmission line normally represents a low impedance, and thus the low impedance output of the cathode follower is ideally suited for supplying maximum power to such a line.

A conventional cathode follower circuit is shown in Fig. 24. It is a single-stage single-loop inverse feedback circuit in which the output voltage is taken across the cathode resistor, R_k. There is no cathode bypass capacitor. The plate of the tube, which in this example is a triode, is usually connected directly to B+. If a plate load resistor is used, this resistor is bypassed by a capacitor.

When a positive signal voltage swing is supplied to the grid, the plate current increases, and the voltage drop across the cathode resistor increases. Similarly, a negative signal voltage swing reduces the plate current and the voltage developed across the cathode resistor decreases. Thus the voltage across the cathode resistor "follows" the grid voltage. This tends to reduce the voltage difference between grid and cathode (and hence the amplifier gain) established by the input signal alone.

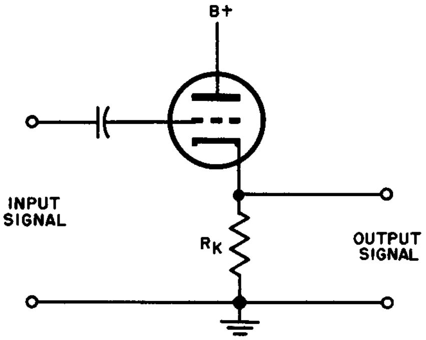

Fig. 24. Conventional cathode follower.

Because of the particular action just explained, the output voltage is in phase with the input signal. This, of course, is not the situation in a conventional amplifier when the output voltage is 180 degrees out of phase with the input signal.

32. The Williamson Amplifier

The Williamson amplifier is a well known high fidelity audio amplifier utilizing inverse feedback. It is essentially a multi-stage single-loop feedback circuit having a push-pull power amplifier stage.

As shown in Fig. 25, the incoming signal is successively amplified in the *V1* and *V2* triode sections of a 6SN7 dual triode. This amplified signal is then supplied to the *V3* and *V4* sections of a second 6SN7 dual triode. This second tube serves as a phase splitter to produce two amplified output signals that are opposed in phase.

These two signals are then supplied as push-pull input signals to a push-pull power amplifier stage employing two 1614 pentodes. A transformer couples the common output circuit of the 1614's to a loudspeaker. The feedback voltage is derived from the secondary winding of the transformer and is supplied to the cathode of the *V1* section of the first 6SN7 *dual* triode as an inverse feedback voltage.

The voltage developed across the secondary winding of the transformer is 180 degrees out of phase with the voltage supplied to the primary winding. By tracing through the circuit it will be found that the feedback voltage has the proper phase relation with respect to the incoming signal to provide the necessary inverse feedback relation. Of course, feedback can be obtained in either polarity, according to the winding sense of the output transformer and the choice of which end of the secondary is grounded.

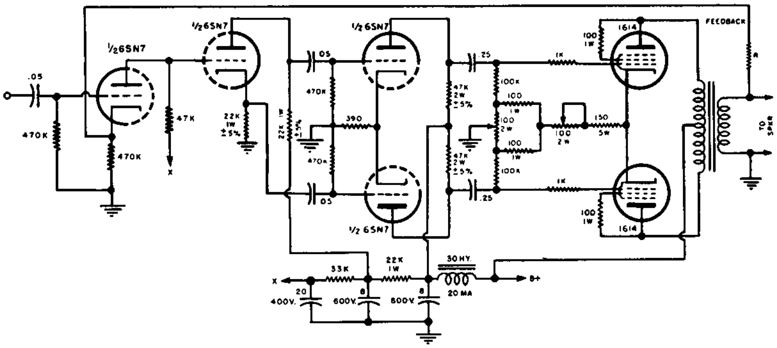

Fig. 25. The Williamson Amplifier circuit.

This action is similar to that described in the multi-stage single-loop circuits discussed in Chap. 4.

33. Bass Boost Feedback Amplifier

When a constant level input signal of variable frequency is supplied to a loudspeaker, it will be found that the sound power developed in the speaker at low frequencies is less than the power developed at higher (middle) frequencies. This is a result of limitations inherent in the speaker.

In order to compensate for this reduction in power at low frequencies, the amplifier supplying power to the loudspeaker is often designed to provide higher gain for low frequency signals than for mid-frequency signals. As a result, the low frequency loss in the speaker is overcome by the low frequency boost in the amplifier.

One popular method of adjusting amplifier gain in this fashion is to make use of inverse feedback. In this application, the amount of feedback used at low frequencies is less than the amount of feedback at higher frequencies. Thus the amplifier gain, though always reduced by inverse feedback, is reduced to a smaller degree for low signal frequencies than for higher frequencies.

A typical circuit of this type is shown in Fig. 26. This circuit is essentially a two-stage dual-loop feedback amplifier.

An incoming signal is amplified in tube *V1* and again in tube *V2*. The amplified output voltage appearing at the plate of tube *V2* is fed back through capacitor C_f and resistor R_f to the junction of resistors R_{K1} and R_{K2}. (The amplified voltage is an inverse feedback voltage because the feedback voltage is in phase with the incoming signal, and is fed to the cathode instead of the grid of tube *V2*. This relationship is discussed in more detail in Chap. 4.)

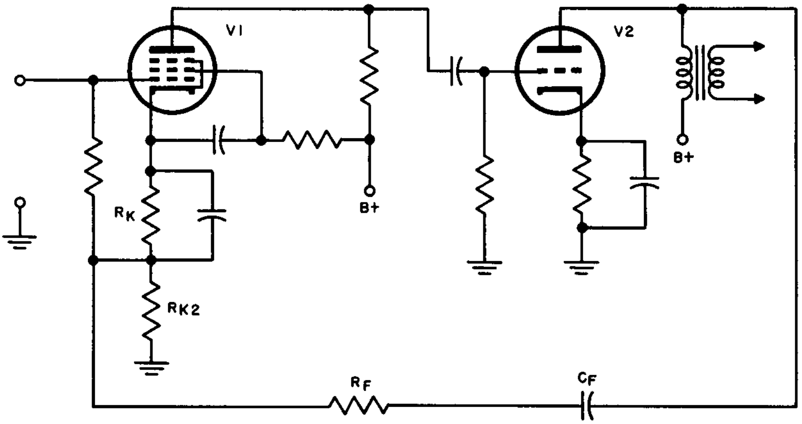

Fig. 26. Two stage dual feedback loop system.

Capacitor C_f has a high reactance at low frequencies and a low reactance at high frequencies. The portion of the output voltage that is supplied to the cathode of tube *V1* decreases as the frequency is lowered and capacitor reactance increases. Consequently, the feedback voltage reduces the low frequency gain of the amplifier to a smaller extent than the mid-frequency gain, and the desired amount of bass boost is obtained.

Since resistor R_{K2} is not bypassed by a capacitor, a small amount of negative current feedback is also present in the *V1* amplification stage. This current feedback, however, does not vary with frequency (except in proportion to gain) and serves only to provide an additional constant amount of inverse feedback, which tends to increase the stability of this circuit. However, as previously pointed out, even simple negative feedback tends to increase bandwidth.

34. Direct Current Vacuum Tube Voltmeter Using Inverse Feedback

The circuit shown in Fig. 27 is a d-c amplifier using current feedback. It is designed for a d-c measuring instrument and is somewhat unusual in that it utilizes almost 100 percent feedback. (In other words, the feedback factor is approximately 1.) The incoming d-c signal is amplified successively in three amplification stages, each stage using a 1B4 pentode. This type of tube has a directly-heated emitter. The output current flowing in the output amplifier stage passes through a parallel circuit consisting of a 10,000-ohm output resistor shunted by a voltmeter (V) and potentiometer (P) in series (a 1.5-volt battery is connected across the potentiometer) and is supplied thereafter to the emitters of the three paralleled 1B4's.

When the incoming signal becomes more positive, the amplified current in the output of the first 1B4 increases, causing the plate of the first 1B4 to become more negative. Thus the amplified current in the output of the second 1B4 decreases, and the amplified current in the output of the third 1B4 increases. This output current flows through voltmeter *V*, resulting in a voltage drop across *V*. This drop makes the cathodes of all the tubes more positive, thus decreasing the amplification for each stage and providing the necessary amount of inverse feedback.

The resistance of the voltmeter is on the order of 1000 ohms compared to the 10,000-ohm output resistor, so that very little current flows through the output resistor, and virtually all of the output current passes through the voltmeter to the cathodes as a feedback current.

In operating this voltmeter, the input terminals are short circuited and the potentiometer is adjusted until voltmeter *V* reads 0. These terminals are than opened and the input signal applied in the usual manner. The magnitude of the unknown d-c voltage applied to the input terminals is then given directly by the reading on the voltmeter.

This result is obtained because the voltmeter deflection measures the feedback signal and for large amounts of feedback, the feedback signal and the incoming signal are approximately equal. Thus, although gain is not much better than 1, the amplifier is a stable matching device between the high impedance input and the relatively low impedance meter.

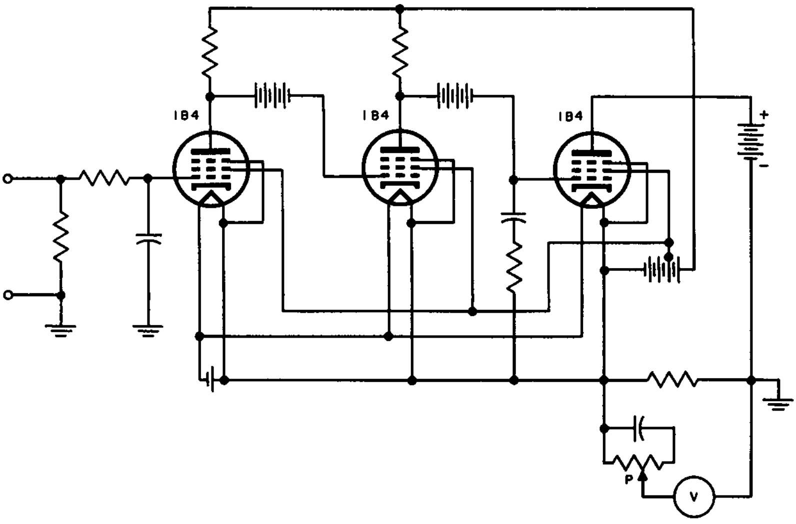

Fig. 27. A d-c amplifier circuit using current feedback for making d-c measurements.

35. Use of Feedback on Automatic Volume Control Circuits

It will be recalled that in a conventional a-m radio receiver an incoming carrier wave of given frequency, amplitude-modulated by an audio signal, is amplified, then heterodyned with a voltage from a local oscillator to produce a carrier of lower fixed (intermediate) frequency, but having the same modulation envelope as the incoming carrier wave. The carrier thus produced by the heterodyning operation is amplified in an intermediate frequency amplifier and then detected in a detector to recover the original audio signal. This audio signal is amplified and supplied to a loudspeaker.

Virtually all such receivers are provided with an automatic volume control circuit (avc) to maintain the carrier wave voltage supplied to the input of the detector at an approximately constant level. As a result, when the strength of the received signal varies due to fading, or when the receiver is tuned from weak to strong stations, the volume of the signal reproduced in the loudspeaker will not change appreciably. Accordingly, the volume control of the receiver does not have to be adjusted as frequently as in receivers without avc.

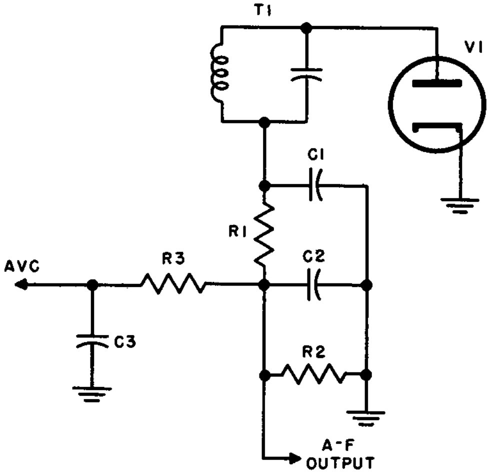

Fig. 28. Typical avc network.

The avc action is obtained by supplying a portion of the voltage produced at the output of the detector as an inverse feedback voltage to the input circuits of the various stages preceding the detector. In this manner, as the strength of the incoming carrier changes, the gain of these stages is changed in opposite sense and the carrier strength is held approximately constant. This action is sometimes called feedback. However, since the "signal" fed back is not in the same form as the input signal, it differs from types previously discussed.

There are many different types of avc circuit. Figure 28 shows one of the simplest of these.

The output signal from the intermediate frequency amplifier (developed across the primary winding of transformer *T1*) appears across the secondary winding of the transformer and is supplied to diode *V1*. This diode, together with an associated network composed of resistors *R1* and *R2* and capacitors *C1* and *C2*, serves to produce the detected signal, which appears across resistor *R2*. The d-c portion of the detected signal is then supplied through a low pass filter network containing resistor *R3* and capacitor *C3* back to the input circuits of the preceding stages in the manner indicated previously. (See Chap. 3 for further details on this type of network.)

The low pass filter network is required because the purpose of avc is to control the strength of the *carrier* and not the strength of the modulation signal riding on the carrier. The modulation signal is a low frequency (audio) signal. It appears across *R2* along with a d-c component, and this network removes most of the audio frequency components. The "feedback voltage" is the remaining d-c component. The low pass characteristic of *R3*-*C3* is such that the inverse feedback voltage follows slow changes in the strength of the incoming carrier, such as those which might result from fading and tuning stations of different signal strength.

36. Review Questions

(1) What is a "cathode follower?"

(2) Why is a cathode follower often referred to as an impedance transformer?

(3) Why is the output voltage produced by a cathode follower in phase with the input voltage supplied to it?

(4) How is inverse feedback developed in the Williamson amplifier?

(5) How can inverse feedback be used to vary amplifier gain as the frequency of the amplifier signal changes?

(6) What is meant by automatic volume control?

(7) Why is avc action like inverse feedback?

(8) Why does the avc feedback loop require a low pass filter?

(9) Why does the d-c measuring instrument shown in Fig. 27 use a feedback factor of approximately 1?

(10) What is the advantage of avc?

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