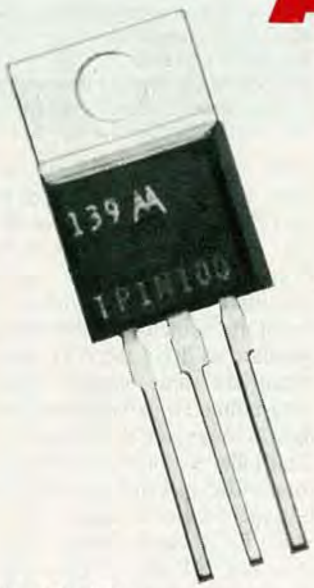
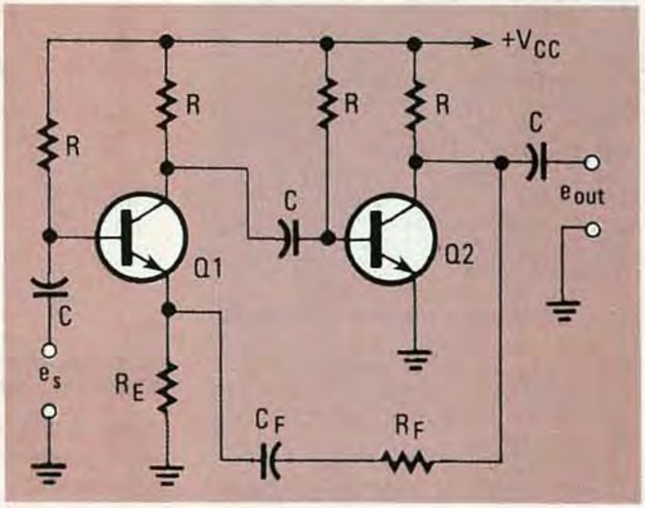
CIRCUITS

How to Design Analog Circuits
How to Use Feedback





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This month we turn our attention to an in-depth look at both positive and negative feedback. We will discuss both the advantages and disadvantages of feedback and how to properly design circuits that use feedback.

WE'VE TOUCHED UPON FEEDBACK IN some of our earlier discussions, particularly when we looked at op-amps. In those discussions we saw that feedback was important in establishing many circuit characteristics; this month we'll look more closely at that topic. Among the things we'll see are the different types of feedback, how feedback is established in an audio-amplifier circuit, and how the presence of feedback affects various circuit parameters including gain, bandwidth, and input and output impedances. We'll also see how feedback can cause circuit instability, a characteristic that is undesirable in an audio amplifier but vital in an oscillator.

Before we get too much farther, let's clarify two terms. A signal that is fed back from the output of a circuit to its input in such a way that the overall gain is reduced is called *negative* feedback. If, on the other hand, the signal is fed back in such a way that the overall gain is increased, or so that it causes the circuit to go into oscillation, it is called *positive* feedback.

Feedback characteristics

In any circuit that uses feedback, a portion of the signal at the output is fed back to the input. The ratio e_f/e_{out}, where e_f is the amount of signal that is fed back and e_{out} is the signal at the output, has been called β for many years. So as not to confuse that term with the I_C/I_B ratio of a bipolar transistor, which is also identified by the symbol β, we will use B when referring to the feedback ratio.

With that convention out of the way, let's now look at a basic circuit with feedback, such as the one shown in Fig. 1. In that circuit, a voltage e_s, is applied to the input. With no feedback, the voltage at the input to amplifier A, e_{in}, equals e_s. The gain of the overall circuit would then simply be $e_{out}/e_{in} = e_{out}/e_s$. When feedback is added, however, some of e_{out} appears at the input as e_f. Assuming that the feedback is positive, that is, that the signals are in phase and thus add, the input to the amplifier becomes $e_s + e_f$. When feedback is negative, the signals are 180° out-of-phase and the input to the amplifier equals $e_s - e_f$. Since e_f depends upon e_{out} and B, the gain of the circuit with feedback is:

$$A_F = \frac{A_v}{1 - BA_v} \qquad (1)$$

where A_V is the voltage gain of the amplifier without feedback, or e_{out}/e_{in}, and A_F is the gain of the overall circuit with feedback. The denominator of the equation, $1 - BA_V$, is known as the feedback factor. When negative feedback is used, the expression BA_V is negative; when positive feedback is used, that term is positive.

Assuming that the feedback is negative, and BA_V is much larger than 1, the gain of the amplifier is just about equal to 1/B. Negative feedback makes the gain of an amplifier less sensitive to variations in the circuit's parameters, such as the supply voltage. Positive feedback makes the gain more sensitive to such variations. We will see why that's important when we discuss oscillators.

Because the feedback in this circuit is

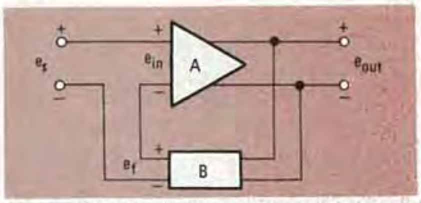

FIG. 1—AN AMPLIFIER with negative voltage feedback is shown in this block diagram.

applied in series with the input signal, the input impedance increases over what it would have been without any feedback; the amount it increases is directly proportional to the feedback factor. The output impedance, on the other hand, is reduced because the feedback signal is taken from across the load; the amount it decreases is indirectly proportional to the feedback factor. We'll see more about how input and output impedances are related to feedback later in this article.

Another effect of negative feedback is that distortion is reduced and the frequency response of an audio amplifier is improved. Distortion with feedback is equal to the distortion without feedback divided by the feedback factor. High-frequency response is extended from f_{OH}, the high-frequency limit without feedback to $f_{OH}(1 - BA_V)$, while the low-frequency response is extended from f_{OL}, the low-frequency limit without feedback, to $f_{OL}/(1 - BA_V)$. Remember here that since the feedback is negative the BA_V terms are negative and $1 - (-BA_V) = 1 + BA_V$.

Designing a circuit

When designing an amplifier with feedback, the first step is to determine the amount of overall gain that will be required. Let us say you need a circuit with a voltage gain of 40 dB, or 100. Assume that in this application about 20 dB of negative feedback is necessary around the circuit to reduce the distortion to about 10% of what it would have been without feedback. Then the gain of the overall circuit must be $100 \times 10 = 1000$ if it is to be adequate after feedback has been applied. The circuit shown in Fig. 2 should fulfill all the requirements. (That circuit, minus the feedback loop, was first covered in the December 1982 issue of **Radio-Electronics**; please see that issue for a more complete discussion of the circuit). Assume the load, R_L, is 10,000 ohms, $V_{CC} = 9$ volts, and the β of Q1 and Q2 are 100.

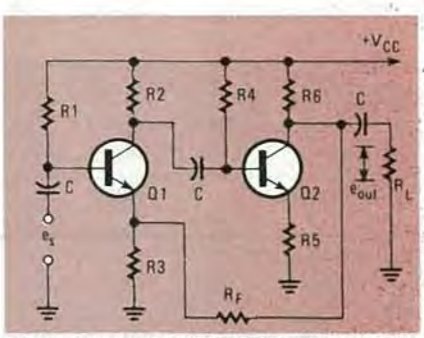

FIG. 2—IF THE FORWARD GAIN of this circuit is to be 100 after 20 dB of negative feedback is applied, the forward gain before the feedback is applied must be 1000. The circuit shown here uses series feedback.

Let's start by determining the values needed to get an overall gain of 1000 (before feedback is applied). The signal across the output load should be capable of an output voltage-swing of close to 9 volts, the voltage of the power supply. To accomplish that, the value of R6 should be less than one-fifth of R_L. Resistor R6 is chosen to be 1800 ohms.

The load in the collector circuit is equal to the resistance of R6 in parallel with R_L, or about 1500 ohms. Is is actually somewhat less because R_F is in parallel with the 1500 ohms. In this first step of the design, however, R_F can be ignored. For one thing, we have not yet determined what the value of R_F is. Also, it usually has only a minor effect on the load resistance as that of R_F is very small compared to that of R_L in parallel with R6. So we'll ignore R_F until after the feedback circuit has been designed.

The gain of the overall circuit should be divided between Q1 and Q2. If the overall gain without feedback is 1000, we can let the gain of each stage be about 35 so that the total gain will be 35×35, or 1225, which, of course, is somewhat more than 1000. As the gain around Q2 is just about equal to the ratio of the load in the collector circuit to the load in the emitter circuit (assuming that the load in the emitter circuit is much greater than the AC resistance of the emitter junction itself), by rearranging terms we can see that the value of R5 should equal 1500/35, or about 43 ohms.

The Q2 circuit presents an impedance of $\beta \times 43$ ohms $= 100 \times 43 = 4300$ ohms to the collector of Q1. If a 4300-ohm resistor is used for R2, the impedance in the collector circuit of Q1 is equal to 4300 ohms in parallel with 4300 ohms, or about 2150 ohms. If Q1 is to provide a gain of 35, the value of R3 should equal 2150/35, or about 61.5 ohms; the closest standard value to that is 56 ohms.

Now, let's add feedback to the circuit. Resistor R_F and the 56-ohm emitter resistor, R3, are the components that determine the B term in the feedback factor. If gain is to be reduced by 20 dB and be equal to 10% of the gain without feedback, the gain with feedback, A_F, must be equal to:

$$A_F = 100 = \frac{A_v}{1 - BA_v}$$

$$A_F = \frac{1000}{1 + \left(\frac{56}{56 + R_F}\right)1000}$$

so that R_F must be about 6200 ohms. Note that since we are again applying negative feedback, the BA_V term here is also negative and $1 - (-BA_V) = 1 + BA_V$.

When R_F is 6200 ohms, it reduces the load in the collector of Q2 to a substantial degree. It was originally calculated to be at about 1500 ohms. With the additional 6200 ohms across it, the collector load becomes about 1200 ohms. With the 43 ohms in the emitter of Q2, its forward gain is now reduced to about 29. To re-establish a gain of 35 for that circuit, R5 must be changed from 43 ohms to 1200/35 = 34 ohms. Use a standard 33-ohm resistor.

In the preceding analysis and example, the circuit discussed used series feedback. The next circuit we'll discuss uses parallel feedback; in it, the fed-back signal is applied in parallel with the input. That circuit is shown in Fig. 3.

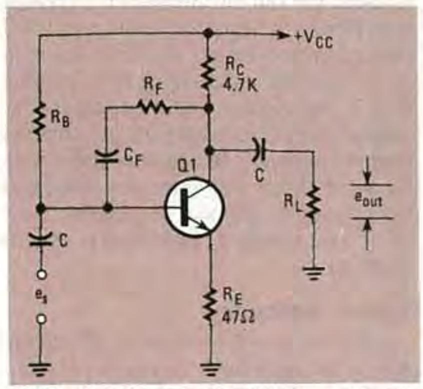

FIG. 3—PARALLEL FEEDBACK is used in this circuit.

Let's assume that we want to use that circuit in an application where the gain must be 10. If the β of the transistor is 100, the impedance at the base of the transistor due to R_E, the 47-ohm emitter resistor, is 4700 ohms. Now assume that all other impedances at the input of the transistor are high when compared to the 4700-ohm input impedance. As for the the output impedance, if R_L were 47,000 ohms, the output impedance would be 47,000 ohms in parallel with R_C, the 4700 ohm collector resistor, or about 4200 ohms.

Ignoring feedback resistor R_F, the voltage gain of the circuit is the output impedance divided by the value of R_E; that is 4200/47, or about 90. In order to get a gain of 10, the feedback factor, $1 + BA_V$, must equal 9. If $A_V = 90$, B is just about equal to 8/90. Because B is equal to the input resistance divided by R_F, $8/90 = 4700/R_F$. So R_F must be about 49,000 ohms. Make the impedance of capacitor C_F very small with respect to R_F at the lowest frequency to be reproduced by the circuit so that the capacitor does not affect the feedback.

While the input impedance of a circuit with series feedback is its impedance without feedback multiplied by the feedback factor, in parallel-feedback circuits the input impedance without feedback must be divided by the feedback factor to determine the input impedance. The output impedance is likewise reduced by that same feedback factor, just as it was in the series-feedback circuit. That is because the feedback signal in both instances is taken from across the load at the output.

In all of our discussion thus far, the feedback has been a function of the voltage at the output and hence is called voltage feedback. The feedback could, however, be a function of the current at the output instead. In that case, the signal is not fed back from across the load but from across a resistor or other device connected in series with it. That is referred to as current feedback because the the voltage generated across that device depends upon the current flowing through it as well as the load. When that configuration is used, the output impedance increases with feedback. Input impedance will still depend upon whether the feedback is in series with the input signal or in parallel with it. As always, input impedance increases in circuits where the information from the output is fed back in series with the input signal and decreases when that information is fed back in parallel. Now we'll want to take a closer look at current feedback.

Current feedback

When the current sensed at the output of a circuit determines the amount of voltage fed back to its input, the circuit is called a current-feedback amplifier. Such a circuit is shown in Fig. 4. As was the case with the circuit in Fig. 1, the fedback voltage is applied in series with the input signal.

In Fig. 4, voltage e_s is amplified and appears at the + and − output terminals of amplifier A. The total output is applied across the two series-connected resistors, R_L and R_S. The output voltage across R_L, as well as the voltage developed across R_S, varies with the current flowing through the two resistors. Because the signal voltage developed across R_S depends upon the amount of current flowing through it, all or a portion of that voltage can be used to supply the required feedback information. Voltage gain of the overall circuit, with feedback, is:

$$A_F = \frac{A_v}{1 - BA_v\left(\frac{R_S}{R_L}\right)} \qquad (2)$$

The values of resistors R_L and R_S can usually be adjusted so that there will be no need to further reduce the signal fed back through use of additional B networks. If that is done, equation 2 can then be simplified by setting B equal to 1.

Although the circuit in Fig. 3 was treated as if it used voltage feedback, it can also be thought of as an amplifier with current feedback (affecting current rather than voltage gain). To see that more clearly, remove R_B and C1 from the circuit and connect R_F directly from the collector of Q1 to the base. The value of R_F must be larger than was found in our original analysis of that circuit so that it can do the dual job of establishing the feedback and setting the DC bias of the amplifier. As collector current divides between R_F and R_C, the portion of the current fed back to the input is $4700/R_F$. If the current gain of the amplifier without feedback is A_I, the current gain with feedback, A_{IF}, becomes:

$$A_{IF} = \frac{A_I}{1 + \left(\frac{4700}{R_F}\right)A_I}$$

Note that while one requirement in establishing a substantial amount of voltage feedback was to make R_F small, its magnitude here has been greatly increased. If R_F is large, voltage gain with feedback is affected slightly by its presence while current gain is reduced considerably.

In practical circuits, current feedback can radically affect voltage gain. Consider the circuit shown in Fig. 5. Here, current in the base circuit due to the input signal voltage is amplified by the transistor. The amplified current flows through both R_C and R_E in the transistor's output circuit. Voltage e_f developed across R_E due to the signal current in the emitter circuit is subtracted from e_s (because the voltages are 180° out-of-phase with each other e_f bucks e_s) and applied to the base-emitter circuit of the transistor. Because $e_s - e_f$ is less than e_s, the gain of the overall circuit is less with feedback than without feedback.

Gain may be reduced further by increasing the size of R_E. Now a larger voltage will be developed across that resistor. That larger voltage is subtracted from e_s so that less voltage is applied to the base-emitter circuit, reducing the gain further. Hence the gain of the overall circuit is inversely related to the value of R_E. That was noted earlier when we indicated that voltage gain of a circuit similar to the one in Fig. 5, is equal to about R_C/R_E. That is true because of the presence of current feedback.

It was pointed out that for this circuit, the fed-back voltage is in series with the input signal voltage. From our discussion of feedback characteristics, we can conclude that the input impedance of that circuit should increase with the amount of voltage fed back. That amount depends upon the value of R_E. When basic amplifiers were discussed, we noted that the input impedance of that type of circuit is βR_E in parallel with R_B. That effect of R_E on the input impedance also holds in circuits were feedback is used.

In order to minimize the affect of R_B on the input impedance, a bootstrapping circuit may be used. An example of that type of circuit is shown in Fig. 6. Capacitor C1 has a large value and it acts as a short circuit to input signal voltage e_s. Without C1, the input impedance seen by e_s is $\beta R_E + R_{IN}$ in parallel with R_B; the combination is in parallel with R_X. (As far as the signal is concerned, V_{CC} and ground are at the same potential.) By adding C1 to the circuit, R_X and R_B are, signal-wise, across R_E while R_{IN} is connected from the base to the emitter of Q1. Now the input impedance of the circuit is equal to the parallel combination of R_B, R_X, and R_E, multiplied by beta. Resistor R_{IN} does not come into the picture for it is directly across the low impedance base-emitter junction; it is negligible when compared to that impedance. Because R_B and R_X have been shifted to be across R_E, the input impedance of the circuit is increased many times over what it would have been if C1 were not present.

Feedback in audio circuits

It was pointed out in a previous article

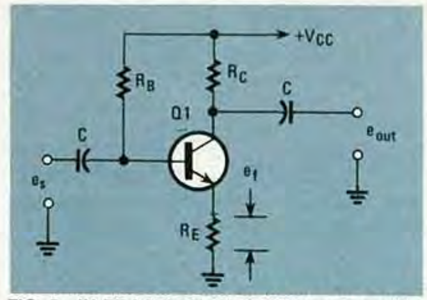

FIG. 5—IN PRACTICAL CIRCUITS such as this one, current feedback can greatly affect the circuit's voltage gain.

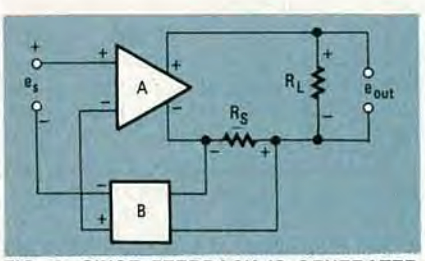

FIG. 4—SINCE FEEDBACK IS GENERATED across a resistor, R_F, that is in series with the load, this amplifier is said to use current feedback. That's because the same current that flows through the load must flow through that resistor

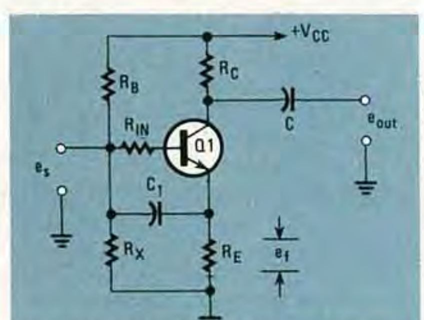

FIG. 6—TO MINIMIZE THE EFFECT of R_B on input impedance, a bootstrap circuit such as this one can be used.

that negative feedback is used around power amplifiers, small-signal audio amplifiers, op-amps, and so on. Its primary function is to reduce distortion, broaden the bandwidth of the amplifier, and reduce the output impedance. If a resistor-capacitor network is included in a feedback loop, the feedback network can also be designed to alter the frequency-response characteristics of the circuit.

Let's take a look at an audio amplifier. An example of an amplifier that can be used to reproduce the output from a tape player is shown in Fig. 7; an approximate curve that shows the desirable frequency characteristics of such an amplifier is shown in Fig. 8. The curve shows that the amplifier's output should remain at a maximum at frequencies below 50 Hz, should drop at the rate of 6-dB-per-octave from 50 Hz to 3000 Hz, and then become level once again at all frequencies above 3000 Hz. To establish that frequency characteristic, only a series resistor-capacitor circuit is required in the feedback loop. That is shown as C_F and R_F in the circuit.

The circuit to accomplish that goal can be designed through use of an R-C impedance equation and equation 1. The impedance of the series circuit consisting of C_F and R_F is $Z_F = (R_F + j/6.28fC_F) = (j + 6.28fC_FR_F)/6.28fC_F$. (For those unfamiliar with the topic, the impedance of a resistor and a capacitor in series is equal to the resistance of the resistor plus the reactance of the capacitor, where the capacitive reactance, X_C, equals $1/2\pi fC$. However, those two quantities can not simply be summed, as the voltages across the components are out of phase. Hence the introduction of the j operator, where $j = \sqrt{-1}$. That of course is an imaginary number and the reactive portion of the impedance is the imaginary component; the resistive part of the impedance is called the real component.) Plugging the impedance equation into equation 1, the voltage gain with feedback is:

$$A_{VF} = \frac{A_v}{1 + BA_v}$$

$$A_{VF} = \frac{A_v}{1 + A_v\left(\frac{R_E}{R_E + Z_F}\right)}$$

The portion of the output voltage that appears across resistor R_E is $R_E/(R_E + Z_F) = B$. That is the B that should be used in the equation. Should R_F be much larger than R_E, B simplifies to being equal to R_E/Z_F. The entire equation may be simplified farther if the voltage gain is very large. When $A_V(R_E/Z_F)$ is much greater than 1, the equation simplifies to:

$$A_{VF} = \frac{Z_F}{R_E} = \frac{j + 2\pi f C_F R_F}{2\pi f C_F R_F}$$

The above equation is the equation of the curve shown in Fig. 8. From the curve, we see that there are two break

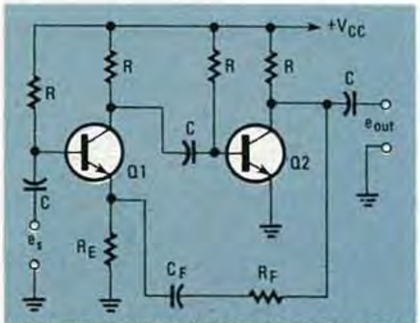

FIG. 7—A TAPE PLAYBACK PREAMPLIFIER is shown here; its simplified frequency-characteristic curve is shown in Fig. 8.

points, or corner frequencies, where rolloff begins and ends. The lower break-point occurs at a frequency such that the denominator of equation 2 is equal to zero. The upper break-point occurs at a frequency such that the numerator of equation 2 is equal to j + 1.

Let's first find the frequency where the denominator is equal to zero. That is, of

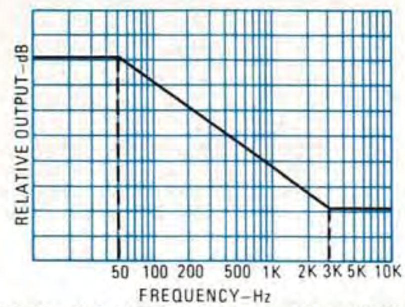

FIG. 8—THE SLOPE between the 50- and 3000-Hz points is 6-dB-per-octave.

course, at $f = 0$. Thus, at $f = 0$ rolloff begins. It will keep rolling off indefinitely unless there is some frequency where gain due to feedback begins to rise to compensate for that initial rolloff. That happens when the numerator in equation 2 is equal to j + 1, or when $f = 1/6.28C_FR_F$. Since the curve calls for a corner frequency of 3000 Hz, choose values of R_F and C_F that satisfy that condition.

Getting back to the frequency where rolloff starts, it was determined from our calculations that for this circuit it begins at 0 Hz. Actually, the curve calls for it to start at 50 Hz. That is taken care of by coupling capacitor C1. In an actual circuit, the value of the capacitor would be selected so that the corner frequency would fall as close to 50 Hz as possible. In a more accurate circuit, a resistor would be placed across C1 so that the corner frequency could be made precisely 50 Hz.

The curve in Fig. 8 is shown with sharp points at the corner frequencies. In the "real world" that never happens—the changes in the curve are never sharp at the corner frequencies and the rolloff and the flat-response sections do not follow the exact contours shown in the drawing. The curve in Fig. 8 is only an approximation of the actual curve required to satisfy the requirements of the circuit, and is used as shown here to simplify the design problem. When designing an actual circuit, most designers follow that procedure.

Stability

Even when only resistors are used in a feedback circuit, the feedback is not uniform over the entire band. It varies with the overall gain of the circuit as well as with the capacitance, inductance, and resistance inherent in the different sections of the circuit.

To check for stability, plot the frequency response of the circuit before feedback is applied. Note the response at the extreme high and low ends of the band. If a circuit is to be stable, the rolloff, when feedback is applied, should be less than 12-dB-per-octave. That can be shown with the help of Fig. 9.

That figure shows the frequency response of a circuit. Two feedback lines have also been plotted—one at −10 dB and one at −20 dB. At the points where the −10-dB feedback line crosses the frequency-response curve, the rolloff is 6-dB-per-octave. At the points where the −20-dB feedback line crosses the frequency-response curve, the rolloff is 12-dB-per-octave. Thus if 10 dB of feedback is added to the amplifier, the circuit is stable, but if 20 dB of feedback is added, the amplifier will be only marginally stable—it may have a tendency to oscillate because the line indicating the −20-dB feedback level crosses the frequency-response curve at a point where the rolloff is 12-dB-per-octave. At that point, feedback has a tendency to turn positive.

If the rolloff should exceed 12-dB-per-octave at the extreme high or low ends of the band, anything more than 20 dB of negative feedback at mid-frequency will turn the circuit into an oscillator.

Oscillators

Getting back to equation 1, if feedback is positive, the BA_V factor is positive. If BA_V is made equal to +1, the denominator of equation 1 becomes zero and the gain with feedback becomes infinite. A circuit with in-phase positive

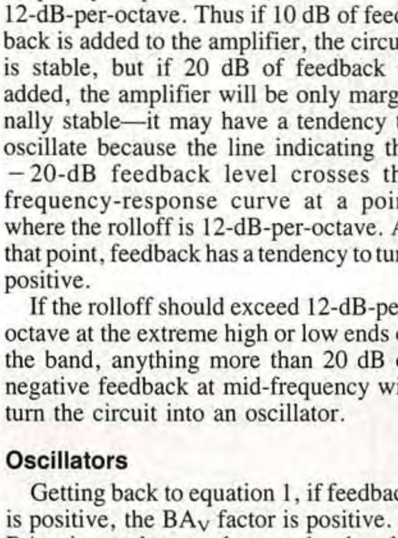

FIG. 9—TO CHECK AN AMPLIFIER FOR STABILITY, first plot its frequency response and then the feedback. At the points where the curves intersect, the rolloff should be less than 12-dB-per-octave to insure stable operation.

feedback and a gain of 1 or more after feedback has been applied will oscillate—there is an output even though no input signal is applied.

A conventional feedback arrangement is shown in Fig. 10. A resonant circuit is formed by L1 and C1. All feedback oscillators are resonant at a frequency of about $1/2\pi\sqrt{LC}$ Hz. Oscillation occurs because of the following sequence of events: When the supply voltage is applied to the oscillator circuit, a pulse reaches the L-C circuit. The L-C circuit turns the pulse into a waveform at its resonant frequency. It is coupled from L1 to L_F and from there to the base-emitter circuit of the transistor. That signal is amplified by the transistor and applied to the resonant circuit. If the signal across L1 and L_F is in the proper relative phase, it keeps on being fed back and amplified until the overall circuit remains in oscillation.

Oscillators have many shapes and forms—three are shown in Fig. 11. The oscillator shown in Fig. 11-a is known as a Colpitts oscillator. When calculating its resonant frequency, use C1C2/(C1 + C2) for the total capacitance of the L-C circuit. Another popular oscillator is the Hartley, shown in Fig. 11-b; its resonant frequency is simply $1/2\pi\sqrt{L1C1}$. A feedback oscillator circuit using only resistors and capacitors is shown in Fig. 11-c. It oscillates because the transistor shifts the phase of the signal 180° from the base to the collector. Each of the R-C networks in the circuit is designed to shift the phase 60° at the frequency of oscillation, for a total of 180°. The appropriate values of R and C for each network is found from $f = 1/(2\sqrt{3}\pi RC)$; that equation allows for the 60° phase shift required by the design.

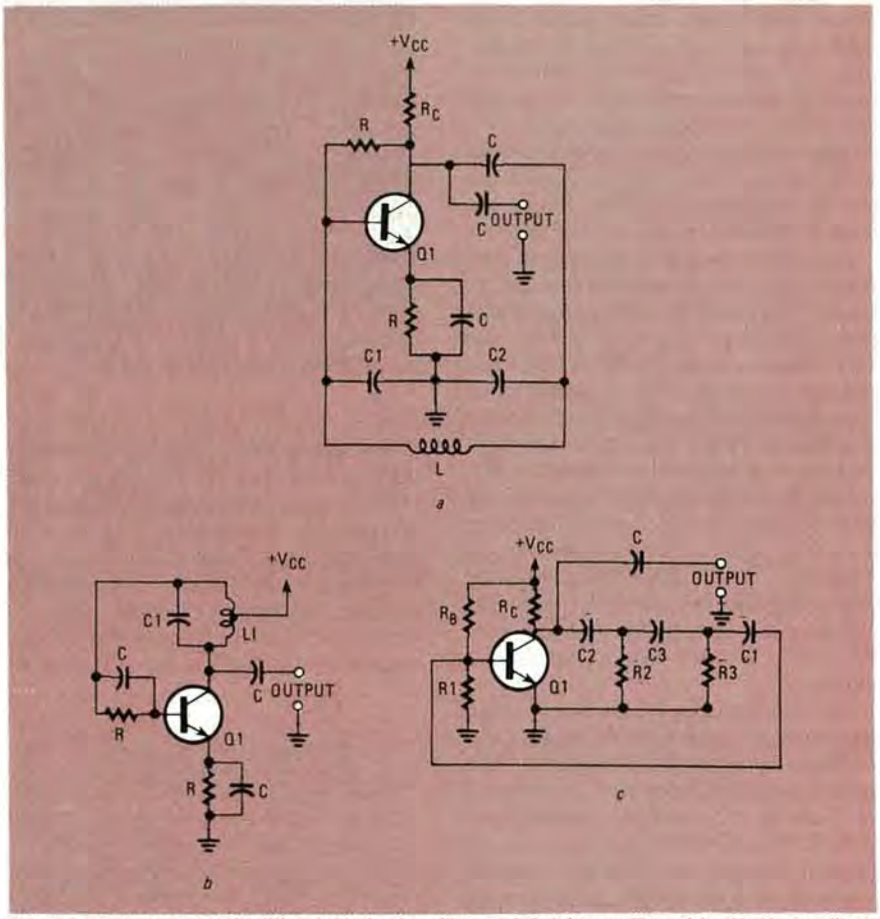

FIG. 11—THERE ARE MANY different kinds of oscillators. A Colpitts oscillator (*a*), a Hartley oscillator (*b*), and a phase-shift oscillator (*c*) are shown here.

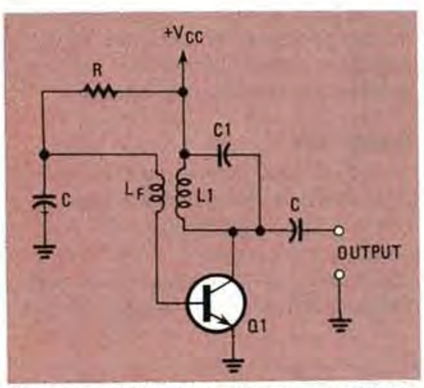

FIG. 10—A CONVENTIONAL FEEDBACK OSCILLATOR. The values of L1 and C1 determines the frequency of oscillation.

Adding the phase shift due to the transistor and the phase shift due to the R-C circuits, the overall phase shift from the input to the output is 360°. Signal from the output is fed back to the base in a positive feedback arrangement (due to the 360° phase shift), to reinforce the signal present at the base. That signal at the base was initiated by a random pulse when power was applied to the circuit, it was amplified, the phase shifted 360°, and fed back. The oscillator frequency will be about:

$$f = \frac{1}{2\pi(C1)}\sqrt{4(R1)R_C + 6(R1)^2}$$

if R_B is considerably larger than R1. Should R1 be omitted from the base circuit, the input resistance of the base circuit, when combined in parallel with R_B, must be chosen so that the combination is equal to R2 or R3 (note that R1, R2, and R3 are all equal).

Oscillators can be built around op-amps. The output of the circuit shown in Fig. 12 is a squarewave; let's see why. Negative feedback is established through R_{F1}, while there is positive feedback through R_{F2}. For that circuit, as well as for circuits described below, assume that the positive saturation voltage at the output of the op-amp is $+V_{CC}$ and that the negative saturation voltage at the output is $-V_{CC}$. The voltage at the non-inverting input depends upon the voltage at the output. It is positive when the saturation voltage is at $+V_{CC}$, and negative when it is at $-V_{CC}$.

Assume the oscillation starts when the output is at $+V_{CC}$. At that time, C1 gets charged to a positive level through R_{F1}. When that voltage exceeds the positive voltage at the non-inverting input, voltage at the output drops to $-V_{CC}$. When that happens, the voltage across C1 begins to drop and become negative because its charging voltage is now being supplied by the negative voltage at the output of the op-amp. Once it drops to below the voltage at the non-inverting input, the voltage at the output returns to $+V_{CC}$. The process keeps repeating itself. Consequently, the output is a squarewave. The frequency of oscillation is $1/2R_{F1}C$, provided that B = 0.462. Since B = $R1/(R1 + R_{F2})$, that condition will hold true if R_{F2} is made equal to 1.16R1.

A sawtooth generator is composed of

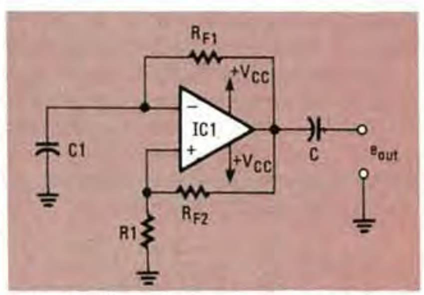

FIG. 12—OP-AMPS are commonly found in oscillator circuits. The output of this circuit is a squarewave.

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complex passive- and active-circuits around an op-amp. A triangular wave can be formed by adding the op-amp integrator shown in Fig. 13 to the output terminals of a squarewave generator like the one shown in Fig. 12.

Among the most popular oscillator circuits is the Wien bridge. A basic transistor circuit using the Wien bridge is shown in Fig. 14. Here, the Wien bridge circuit is placed around a single-ended differential amplifier; it consists of the series and parallel-connected R-C networks. Current is fed back through that filter network from the output to the input. Oscillation occurs if the forward gain of the amplifier is greater than 3 because the output at the junction of the series and parallel R-C circuits is ⅓ of that at the collector of Q2. The frequency of oscillation is $1/2\pi R1C1$, assuming that $R1 = R2$ and $C1 = C2$.

A similar circuit can be built around an op-amp, as shown in Fig. 15. Positive feedback is applied through the R-C Wien bridge to the non-inverting input of the op-amp. Negative feedback is applied through a resistor divider to the inverting input. The frequency of oscillation is found exactly as it was in the previous example. Two Zener diodes are included in the circuit to keep the output voltage, when at a peak, from putting the op-amp circuit into saturation. If it did go into saturation, the circuit would remain in that state and oscillation would no longer take place.

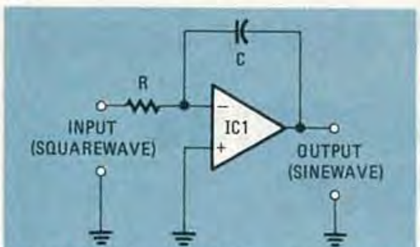

FIG. 13—AN INTEGRATOR, such as the one shown here, can be used to change a squarewave into a triangular wave.

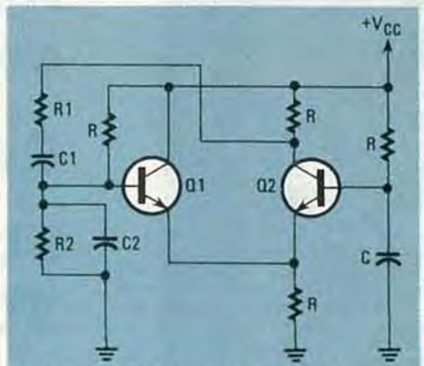

FIG. 14—ONE OF THE MOST POPULAR sinewave generators, the Wien-bridge circuit has been around since the days of vacuum tubes.

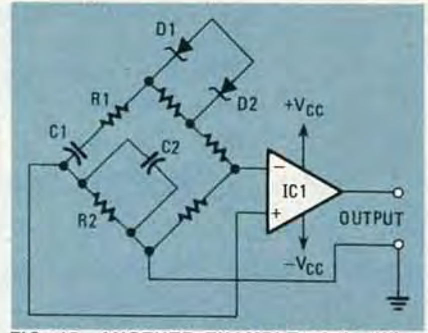

FIG. 15—ANOTHER EXAMPLE of the Wien bridge, this one is built around an op-amp.

High frequency

Unwanted feedback is quite likely to occur in high-frequency circuits. It has many causes: To give just one example, signal at an output can be coupled back to the input through adjacent wiring or through stray capacitances in a circuit. In the next article in this series, we will explore and determine just what its effects are and how to handle them in transistor circuits. **R-E**