STABILIZING FEEDBACK AMPLIFIERS

Types of oscillation, conditions producing them, the stability criterion

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TO AVOID confusion between kinds of instability let's start by defining the different things that can constitute instability. The one most evident is continuous oscillation. In feedback amplifiers, particularly, this usually occurs outside the audio spectrum, either at a very high or very low frequency.

If the high-frequency oscillation is of sufficient amplitude to load fully some or all amplifier stages, it results in *high-frequency blocking*. This is characterized by the output of the amplifier seeming exceptionally quiet until one tries to pass an audio signal through it. Then the audio signal breaks through in varying degrees, according to the strength of the high-frequency blocking, in an extremely distorted form. The sound resembles what one would imagine it to be like if the audio voltages had to break down a spark gap before they got through. Low-intensity sounds don't get through at all, but large ones break the gap down and manage to carry some other small ones through with them. Then, when the level drops, everything becomes quiet again. The waveform, as seen on a scope, is shown in Fig. 1.

Low-frequency oscillation results either in audible motorboating (since the oscillation is not sinusoidal), the variety most easily recognized, or in an approximately sinusoidal low-frequency waveform which is inaudible because it is subsonic.

However, the latter may result in intermodulation distortion because it carries peaks of the true audio signal beyond the output limit of the amplifier, as shown at Fig. 2. If you use an ac input to a scope, the real cause may not be evident because the blocking capacitor may stop the low-frequency component from registering on the scope displacement. It may just be noted that the clipping point on the top and bottom of the wave seems to fluctuate in some erratic manner.

A way in which this form of instability can be spotted, sometimes, is by taking dc readings at various points in the amplifier: plate, cathode, etc. The dc readings will go up and down with a slow fluctuation at the same rate as the low-frequency instability. And instead of moving with a ticking or sawtooth waveform, which is responsible for motorboating, the instrument pointer will wave up and down sinusoidally.

So much for the continuous types of instability. They are more definite than the others. The remaining kinds are parasitic and conditional oscillation.

Parasitic oscillation

This occurs at some point on a waveform and may be hard to detect as an entity audibly because the parasitic frequency is inaudible—it does not show up audibly on a sinusoidal wave. However, it may well interfere with some of the higher frequencies on the same wave and produce a form of intermodulation distortion that sounds muddy. The waveform for sine-wave input looks on the scope like Fig. 3. The amplifier generally breaks into oscillation at one point on a large-amplitude waveform and then dies out.

Conditional oscillation

The third variety of instability can be called conditional oscillation. There are two ways this can be caused and the results can be slightly different—although there may be cases where this difference is so marginal that it cannot be used to discover which kind of instability is occurring.

One way is to run into overload. This means that the amplifier behaves normally all the while the program level stays inside the clipping point. But as soon as the program runs into clipping, the amplifier bursts into oscillation and nothing will stop it except turning the unit off and starting over again.

The second way usually differs in the means by which it is initiated—not by going up to the clipping level, but by a somewhat smaller signal (but not a very low one). This means that the amplifier may be all right while playing very quietly. But as soon as a slightly louder program is passed through it, oscillation begins.

Superfically there is not much difference between these forms and in practical cases also the margin may be narrow. *But in cause there are two different cases here!* To explain these forms of instability in feedback amplifiers and find ways and means of curing them, we need to understand why they occur.

Stability criterion

A feedback amplifier is stable provided that the feedback does not get to being positive and of sufficient amplitude to cause oscillation at any frequency within the range of the amplifier. Considering the overall gain around the feedback loop, rolloffs are bound to occur at the end of the response—in direct-coupled amplifiers at the high-frequency end only; in the

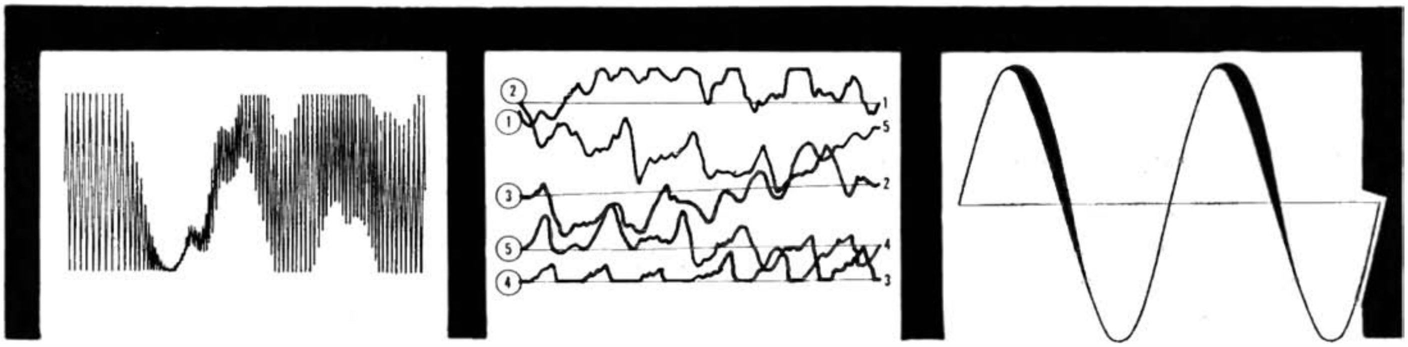


Fig. 1, left—High-frequency blocking. Fig. 2, center—Scope display when an amplifier oscillates inaudibly at a very low frequency. Circled numbers show start of trace and corresponding uncircled numbers show the trace ends. Fig. 3, right—sine-wave input produced by parasitic oscillation.

more usual R-C-coupled amplifiers at both ends of the response. Associated with the progressive attenuation that these rolloffs introduce is a phase delay at the high-frequency end and a phase advance at the low-frequency end.

The problem in achieving stability is one of insuring that the attenuation around the loop—that is, through the amplifier and back through the feedback to the input point again—becomes sufficient so that the fed-back signal is less than the input signal before the phase shift reaches 180°.

When the phase shift reaches 180°, the feedback has changed from negative completely over to positive so that, if the fed-back signal is equal to the input signal, we have the condition necessary to maintain oscillation. To determine whether this happens at any frequency we can draw the gain and phase characteristics of the amplifier loops (Fig. 4) and spot the point where the gain has dropped to unity, then check on the lower diagram to see that the phase is less than 180°. Or else, we can spot the point where the phase reaches 180° and check to see that the overall gain has dropped to less than unity. (A margin of about 30°, at unity gain, as shown, is desirable for excellent stability.) This entails looking at two curves, so the Nyquist diagram is a convenient way of presenting this information on a single picture.

Nyquist diagram

This consists of plotting a polar curve of the response so that the distance of a point on the curve from the origin represents the gain around the loop at any particular frequency and the angle of this line from the origin represents the phase shift. This presentation is illustrated in Fig. 5.

Using this form of presentation the condition for stability can be expressed simply by stating that the curve must pass inside the point representing a gain of unity in the negative direction, as shown at Fig. 5-a. (Note that gain in Fig. 5 is a straight voltage ratio, whereas it is expressed in decibels in Fig. 4.)

If the curve passes outside this point, as at Fig. 5-b, the amplifier is unstable because the amount of feedback at 180° phase shift is greater than unity. Hence the amplifier will oscillate good and hard at the frequency represented by this point on the curve.

There are advantages to each method of presenting this information, but we will not go into a discussion of this right here or we will not fulfill the purpose of this article. More detail on the Nyquist diagram appears in *High-Fidelity Circuit Design* (see footnote) if any reader wishes to pursue the subject further. What we want to see is how the loop gain presented in either of these methods is controlled and in what way practical parameters in the amplifier brings about such conditions.

As was explained in the series of articles by George Fletcher Cooper on

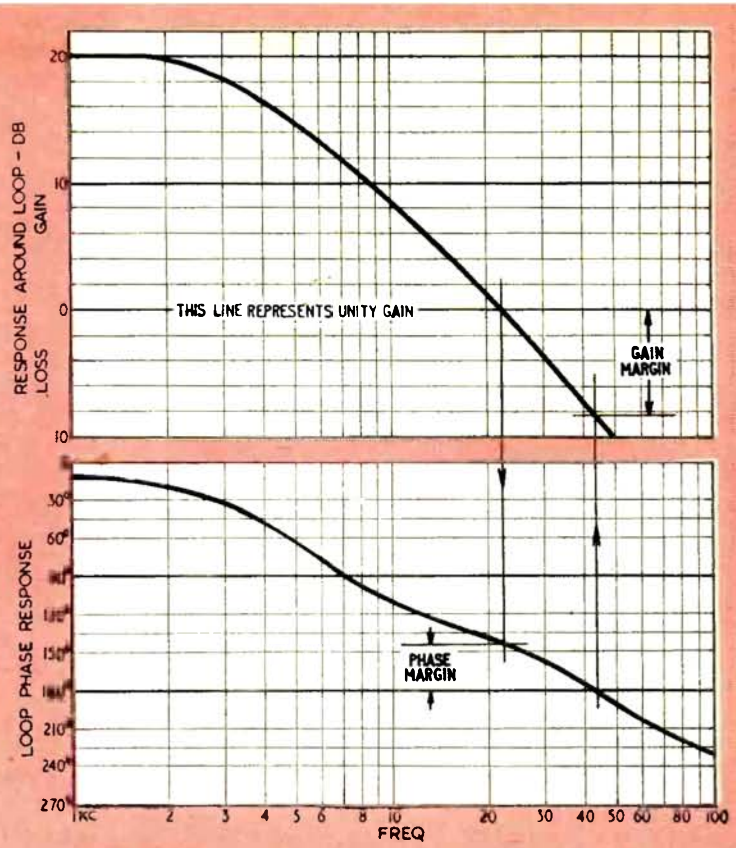
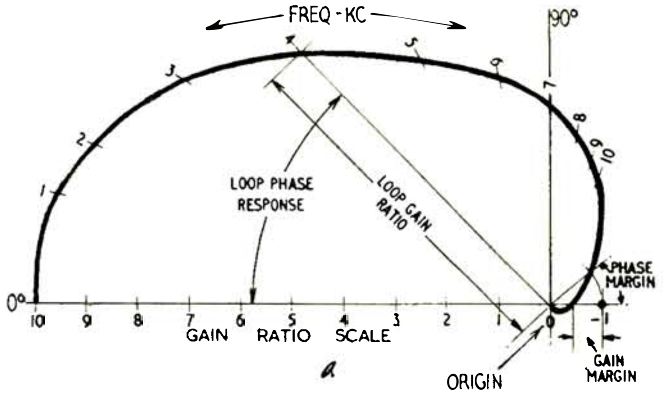


Fig. 4—Typical gain and phase response of an amplifier.



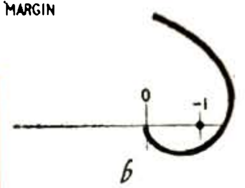


Fig. 5—Nyquist diagrams: a representation of information in Fig. 4; b. curve encircles the critical point, signifying instability. For simplicity, only response above 1 kc is shown.

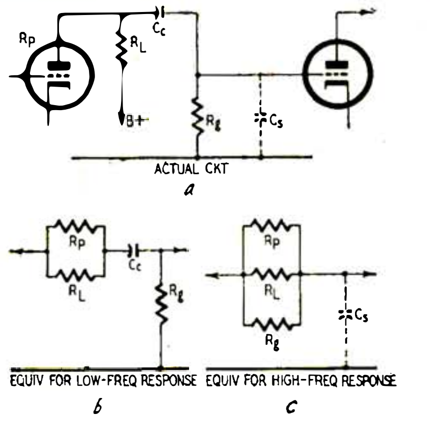


Fig. 6—Typical interstage coupling.

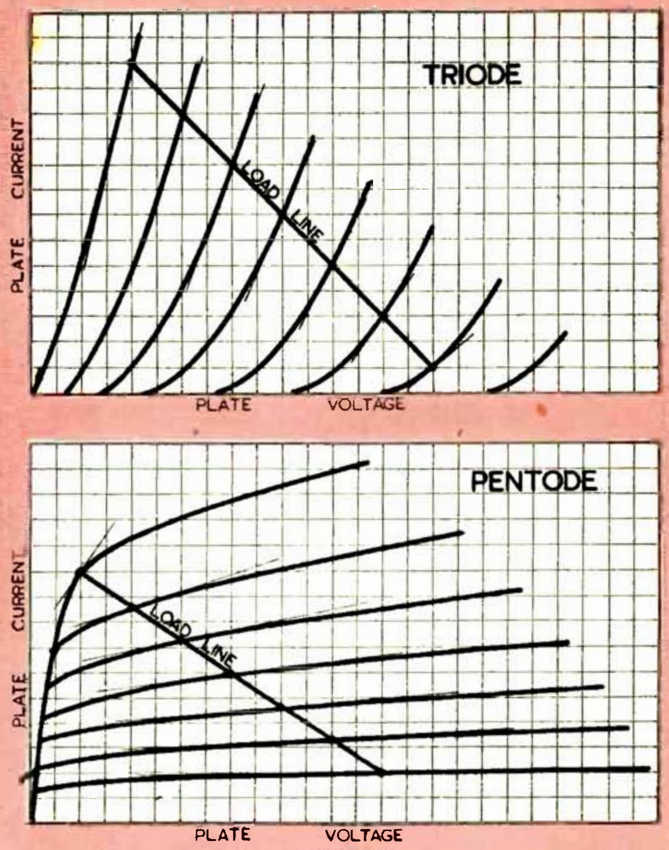


Fig. 7—Plate-current, plate-voltage curves for typical triode and pentode.

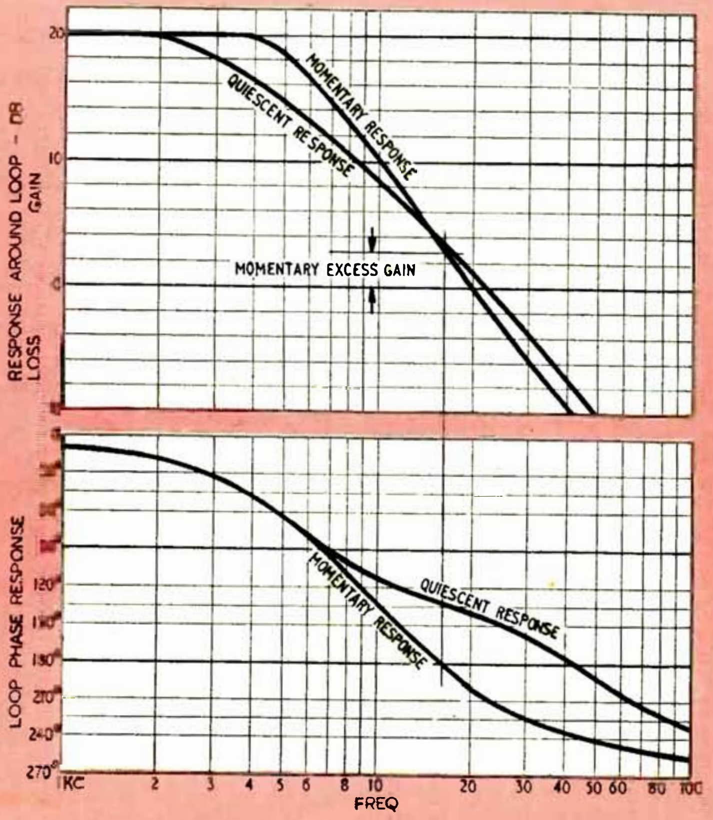


Fig. 8—With small signals response follows *quiescent response*. With large signals response changes *at one point in waveform* to position indicated as *momentary response*.

"Feedback Amplifier Design"*, the roll-off response at each end of the spectrum is contributed to by each of the coupling networks in the amplifier and also by various subsidiary circuitry such as decoupling arrangements. What has not been too clearly explained is how the quantities so contributed can vary with the character of the signal passed through the amplifier in such a manner as to produce some of the kinds of oscillation described.

Take the simple coupling arrangement of Fig. 6-a. Here the relevant quantities are the plate resistance R_p, the plate load resistor R_L, the coupling capacitance C_c and the grid resistor R_g of a following stage. The high-frequency response is controlled by the total stray capacitance C_s.

The low-frequency response is controlled by the relation of the reactance C_c to the total resistance with which it appears to be in series. This consists of R_g on one side and the parallel combination of R_p and R_L on the other side. This is shown at Fig. 6-b.

The high-frequency response is controlled by the relation of the reactance of total stray capacitance C_s to the total circuit resistance with which it appears in parallel. This consists of R_p, R_L and R_g all in parallel (Fig 6-c).

If the amplifier has been designed for minimum distortion, the amplification at all points on a waveform is uniform. Hence the stray capacitance due to Miller effect will be constant so one can regard the reactance component C_s for the high-frequency roll-off as remaining constant under all conditions. The reactance C_c for the low-frequency is naturally constant.

The quantity that varies is R_p. This is illustrated in Fig. 7 for both the pentode and triode. At different points along a load line the value of R_p is represented by the slope at which the characteristics, representing plate current and plate voltage variation for different fixed values of grid voltage, cross the load line. Although the load line has been chosen for minimum distortion in such a way that the intersection points along it representing equal steps in grid voltage are at uniform intervals—which is the condition for minimizing distortion—very often the angle at which the curves cross the load line is not uniform.

This means that the value of R_p in the computation of frequency response will vary *at different points on the audio waveform* although the overall gain does not vary. Multiply this effect by the number of stages in the amplifier and the result is that the amplitude phase characteristic can vary considerably at different points on the audio waveform. This is illustrated in Fig. 8 and the corresponding effect on the Nyquist diagram is shown in Fig. 9.

Another factor that can vary with different points on the waveform is

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* RADIO-ELECTRONICS, Oct., 1950 Nov., 1951. Included in *High-Fidelity Circuit Design*. Gernsback Library, Book 56.

the primary inductance of a transformer since it is not constant as the current through it varies. This particularly applies to an output transformer where the instantaneous values of inductance may change throughout an audio waveform.

From cause to effect

Now how does this explain the different phenomena that we have listed? First the case of the parasitic oscillation shown in Fig. 3.

This is usually caused by the change of plate resistance that occurs in some single-ended part of the amplifier. It will shift the time constants of the high-frequency rolloff at various points in the waveform and the response will go beyond the stability criterion in one direction of the audio signal fluctuation. This causes oscillation at a high frequency to appear at this point on the waveform, the frequency being controlled by the point at which the Nyquist diagram goes beyond the stability criterion. As the waveform causing this variation in transfer response returns toward the quiescent zero of the system, the loop gain characteristic returns to the stable side of the stability criterion and the oscillation dies.

The next case is the amplifier that oscillates when more than a small signal is passed through it.

This can happen in an amplifier that uses tetrodes and pentodes in class-AB push-pull for the output stage. Here the plate resistance, during the quiescent condition, is very much higher than when a signal passes through, causing the plate currents to swing up into the working range of each tube. This means that, not only does the value of R_p change during the waveform, but its *average value* throughout the entire waveform falls. Thus the average response throughout the waveform changes. This may well result in the overall loop gain curve moving over to an average condition where it encircles the critical point at which instability begins. Once this happens the high-frequency oscillation maintains this operating condition within the amplifier and the oscillation continues indefinitely or until the amplifier is switched off.

The other form of oscillation caused in this way is one that has been described before and is ascribed to a condition demonstrated with the Nyquist diagram as being conditional stability. If the attenuation and phase characteristics are such (Fig. 10) that the response goes around the point *without enclosing it*, the amplifier, while operating under this condition, cannot oscillate. But if the gain is reduced by any cause so the amplitude of the whole curve drops, the curve will then enclose the critical point for stability and oscillation starts.

Once oscillation commences there is sufficient gain in this amplifier to set up a saturating oscillation. This produces something like square waves and the gain during the whole period of the square-wave oscillation averages out so as to keep the Nyquist curve in a position to maintain oscillation.

Viewed otherwise, the gain changes during this square-wave oscillation, being at a maximum during the steep side and falling away at the top because of the saturation condition. This fluctuation of gain throughout the waveform maintains the peculiar form of oscillation that results.

However you explain it, the result is that the amplifier breaks into oscillation as soon as clipping occurs because, during the instant of clipping, the gain of the amplifier momentarily disappears and this is all that is needed to initiate this kind of instability.

The cure

The remedy for all these kinds of instability is much the same as for the continuous kind: Attention to the different circuits of the amplifier to produce a condition where the whole system is *inherently* stable. Any kind of conditional or parasitic oscillation is really a marginal condition that does not quite succeed in being continuously unstable. What is needed is a safer working margin.

The approach to this is to change the circuit values so as to obtain a greater spread in the time constants contributed by all the components that cause the rolloff attenuation and phase shift. This makes the rolloff more gradual so that a greater degree of attenuation can occur before the phase shift becomes as big.

There are a variety of ways to tackle this. But unless we want to get into a complete design problem the simplest way is to just try changing various values and see which ones appear critical and which do not seem to help appreciably. The ones that appear critical are the best bets to proceed with to find a value that gives a good margin of safety.

The high-frequency blocking form of oscillation may not be due to instability around the complete loop. It can often happen just in the output stage or in any single stage of the amplifier, due to a tuned-plate tuned-grid effect. This occurs at some very high frequency, the inductance of the plate lead with the plate capacitance forming one tuned circuit while the inductance of the grid lead with its effective capacitance to ground forms the other.

This is particularly liable to happen with many of the high-efficiency tubes, and the best remedy is a well known one: inserting suitable antiparasitic resistors in the grid and plate circuits. Suitable values are from 5,000 to 50,000 ohms in the grid circuit and from 100 to 500 ohms in the plate circuit. Similar resistors sometimes help in the screen circuit.

The important thing is that the resistors be connected as close as possible to the tube pins themselves—it is the actual lead that forms the inductance of the tuned circuit and the resistance must be placed between the tube and the inductance that causes the trouble. The capacitance is built into the tube so it cannot be isolated.

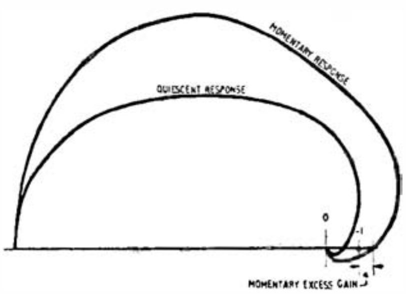

Fig. 9—Information of Fig. 8 converted into Nyquist diagram form.

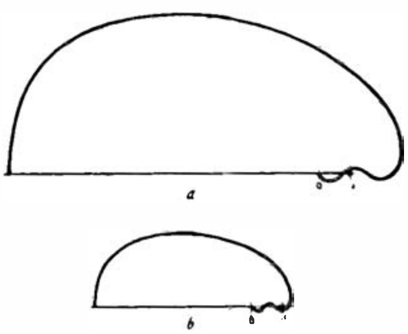

Fig. 10—Nyquist diagram illustrates form of conditional stability: a, amplifier is stable because loop goes inside –1 point; b, reducing gain of amplifier to one-half makes it unstable.

Motorboating usually is due to decoupling circuits. The inaudible type of motorboating, however, may be due to a bad choice of coupling components which can cause an almost perfect sine wave at a very low frequency due to the amplifier's becoming unstable. This is not uncommon in feedback amplifiers. The cure for this is changing various coupling capacitor values until a suitable combination is found that gives sufficient spread to get rid of the gain before the phase shift gets too big.

The audible variety of motorboating that goes plop, plop is more often due to bad decoupling arrangements somewhere. The best cure is to try various decoupling capacitor values. If this does not correct the trouble, try a different decoupling arrangement.

Remember that two stages together cannot be unstable by themselves. Instability of this kind occurs due to the fluctuations in the third-stage plate circuit feeding back to the plate circuit of the first stage, or some similar arrangement. This means that, combining the decoupling of the second and third stages of a three-stage amplifier, or maybe operating them both without decoupling and using decoupling just for the first stage, may give the best cure for this kind of instability.

Sometimes the more elaborate the precautions taken to safeguard the situation, the more unexpectedly oscillation turns up. The simplest circuit is usually the best circuit. END