

Stability Analysis of Voltage-Feedback Op Amps

Including Compensation Techniques

Application Report

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Stability Analysis of Voltage-Feedback Op Amps Including Compensation Techniques

Ron Mancini

ABSTRACT

This report presents an analysis of the stability of voltage-feedback operational amplifiers (op amps) using circuit performance as the criteria to attain a successful design. It discusses several compensation techniques for op amps with and without internal compensation.

1 Introduction

Voltage-feedback amplifiers (VFA) have been with us for about 60 years, and they have been a problem for circuit designers since the first day. You see, the feedback that makes them versatile and accurate, also has a tendency to make them unstable. The operational-amplifier (op amp) circuit configuration uses a high-gain amplifier whose parameters are determined by external feedback components. The amplifier gain is so high, that without these external feedback components, the slightest input signal would saturate the amplifier output. The op amp is in common usage, so this configuration is examined in detail, but the results are applicable to many other voltage feedback circuits. Current feedback amplifiers (CFA) are similar to VFAs, but the differences are important enough to warrant CFAs being handled in a separate application note.

Stability, as used in electronic circuit terminology, is often defined as achieving a nonoscillatory state. This is a poor, inaccurate definition of the word. Stability is a relative term, and this situation makes people uneasy because relative judgments are exhaustive. It is easy to draw the line between a circuit that oscillates and one that does not oscillate, so we can understand why some people believe that oscillation is a natural boundary between stability and instability.

Feedback circuits exhibit poor phase response, overshoot, and ringing long before oscillation occurs, and these effects are considered undesirable by circuit designers. This application note is not concerned with oscillators; thus, relative stability is defined in terms of performance. By definition, when designers decide what tradeoffs are acceptable they determine what the relative stability of the circuit is. A relative-stability measurement is the damping ratio (ζ) and the damping ratio is discussed in detail in Reference 1. The damping ratio is related to phase margin, hence, phase margin is another measure of relative stability. The most stable circuits have the longest response times, lowest bandwidth, highest accuracy, and least overshoot. The least stable circuits have the fastest response times, highest bandwidth, lowest accuracy, and some overshoot.

Amplifiers are built with active components such as transistors. Pertinent transistor parameters like transistor gain are subject to drift and initial inaccuracies from many sources. So, amplifiers being built from these components are subject to drift and inaccuracies. The drift and inaccuracy is minimized or eliminated by using negative feedback. The op-amp circuit configuration employs feedback to make the transfer equation of the circuit independent of the amplifier parameters (well almost), and while doing this, the circuit transfer function is made dependent on external passive components. The external passive components can be purchased to meet almost any drift or accuracy specification; only the cost and size of the passive components limit their use.

Once feedback is applied to the op amp, it is possible for the op-amp circuit to become unstable. Certain amplifiers belong to a family called internally compensated op amps; they contain internal capacitors which are sometimes advertised as precluding instabilities. Although internally compensated op amps should not oscillate when operated under specified conditions, many have relative stability problems that manifest themselves as poor phase response, ringing, and overshoot. The only absolutely stable internally compensated op amp is the one lying on the workbench without power applied! All other internally compensated op amps oscillate under some external circuit conditions.

Noninternally compensated or *externally* compensated op amps are unstable without the addition of external stabilizing components. This situation is a disadvantage in many cases because they require additional components, but the lack of internal compensation enables the top-drawer circuit designer to squeeze the last drop of performance from the op amp. You have two options: op amps internally compensated by the IC manufacturer, or op amps externally compensated by you. Compensation, except that done by the op amp manufacturer, must be done external to the IC. Surprisingly enough, internally compensated op amps require external compensation for demanding applications.

Compensation is achieved by adding external components that modify the circuit transfer function so that it becomes unconditionally stable. There are several different methods of compensating an op amp, and as you might suspect, there are pros and cons associated with each method of compensation. Teaching you how to compensate and how to evaluate the results of compensation is the intent of this application note. After the op-amp circuit is compensated, it must be analyzed to determine the effects of compensation. The modifications that compensation have on the closed-loop transfer function often determine which compensation scheme is most profitably employed.

2 Development of the Circuit Equations

A block diagram for a generalized feedback system is shown in Figure 1. This simple block diagram is sufficient to determine the stability status of any system.

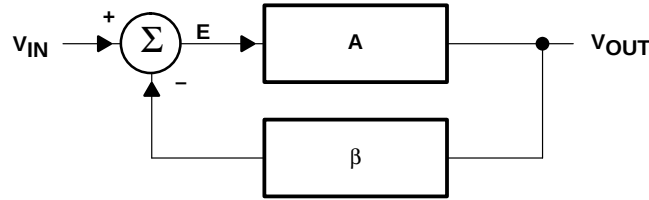


Figure 1. Feedback System Block Diagram

The output and error equations are written below.

$$V_{OUT} = EA \quad (1)$$

$$E = V_{IN} - \beta V_{OUT} \quad (2)$$

Combining equations 1 and 2 yields equation 3:

$$\frac{V_{OUT}}{A} = V_{IN} - \beta V_{OUT} \quad (3)$$

Collecting terms yields equation 4:

$$V_{OUT} \left(\frac{1}{A} + \beta \right) = V_{IN} \quad (4)$$

Rearranging terms yields the classic form of the feedback equation.

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \quad (5)$$

Notice that equation 5 reduces to equation 6 when the term $A\beta$ in equation 5 becomes very large with respect to one. Equation 6 is called the ideal feedback equation because it depends on the assumption that $A\beta \gg 1$, and it finds extensive use when amplifiers are assumed to have ideal qualities. Under the conditions that $A\beta \gg 1$, the system gain is determined by the feedback factor β . Stable-passive circuit components are used to implement the feedback factor, thus, the ideal closed-loop gain is predictable and stable because β is predictable and stable.

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{\beta} \quad (6)$$

The quantity $A\beta$ is so important that it has been given a special name, loop gain. Consider Figure 2; when the voltage inputs are grounded (current inputs are opened) and the loop is broken, the calculated gain is the loop gain, $A\beta$. Now, keep in mind that this is mathematics of complex numbers which have magnitude and direction. When the loop gain approaches minus one, or to express it mathematically $1 \angle 180^\circ$, equation 5 approaches infinity because $1/0 \Rightarrow \infty$. The circuit output heads for infinity as fast as it can using the equation of a straight line. If the output were not energy limited, the circuit would explode the world, but it is energy limited by the power supplies so the world stays intact.

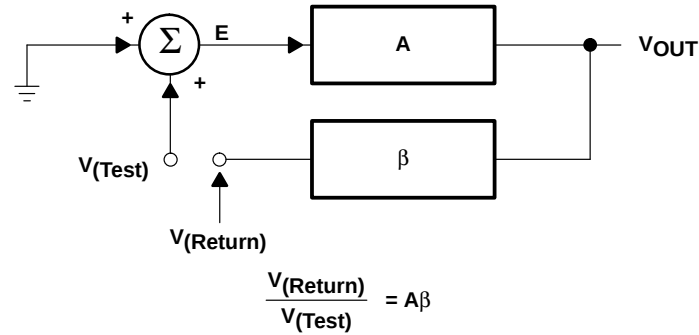


Figure 2. Feedback Loop Broken to Calculate Loop Gain

Active devices in electronic circuits exhibit nonlinear behavior when their output approaches a power supply rail, and the nonlinearity reduces the amplifier gain until the loop gain no longer equals $1\angle 180^\circ$. Now the circuit can do two things: first, it could become stable at the power supply limit, or second, it can reverse direction (because stored charge keeps the output voltage changing) and head for the negative power supply rail.

The first state where the circuit becomes stable at a power supply limit is named lockup; the circuit will remain in the locked up state until power is removed. The second state where the circuit bounces between power supply limits is named oscillatory. Remember, the loop gain, $A\beta$, is the sole factor that determines stability for a circuit or system. Inputs are grounded or disconnected when the loop gain is calculated, so they have no effect on stability. The loop-gain criteria is analyzed in depth later.

Equations 1 and 2 are combined and rearranged to yield equation 7 which gives an indication of system or circuit error.

$$E = \frac{V_{IN}}{1 + A\beta} \quad (7)$$

First, notice that the error is proportional to the input signal. This is the expected result because a bigger input signal results in a bigger output signal, and bigger output signals require more drive voltage. Second, the loop gain is inversely proportional to the error. As the loop gain increases the error decreases, thus large loop gains are attractive for minimizing errors. Large loop gains also decrease stability, thus, there is always a tradeoff between error and stability.

A noninverting op amp is shown in Figure 3.

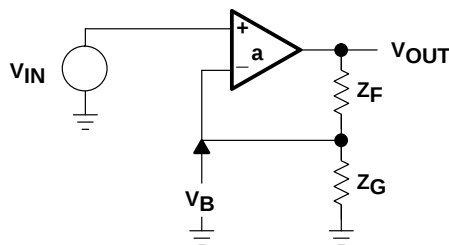


Figure 3. Noninverting Op Amp

Equation 8 is the amplifier transfer equation:

$$V_{OUT} = a(V_{IN} - V_B) \quad (8)$$

Equation 9 is the output equation:

$$V_B = \frac{V_{OUT}Z_G}{Z_F + Z_G} \text{ for } I_B = 0 \quad (9)$$

Combining equations 8 and 9 yields equation 10:

$$V_{OUT} = aV_{IN} - \frac{aZ_G V_{OUT}}{Z_G + Z_F} \quad (10)$$

Rearranging terms in equation 10 yields equation 11, which describes the transfer function of the circuit:

$$\frac{V_{OUT}}{V_{IN}} = \frac{a}{1 + \frac{aZ_G}{Z_G + Z_F}} \quad (11)$$

Equation 5 is repeated as equation 12 to make a term by term comparison of the equations easy.

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \quad (12)$$

By virtue of the comparison we get equation 13, which is the loop-gain equation for the noninverting op amp. The loop-gain equation determines the stability of the circuit.

$$A\beta = \frac{aZ_G}{Z_G + Z_F} \quad (13)$$

Equation 13 could have been derived by breaking the op amp feedback loop, say at point B, and calculating the loop gain. This procedure is used later to derive the inverting loop gain. Also, by comparison the direct gain A is seen to be $A = a$, or the direct gain for the noninverting op amp is the same as the op amp gain. The inverting, op-amp circuit is shown in Figure 4.

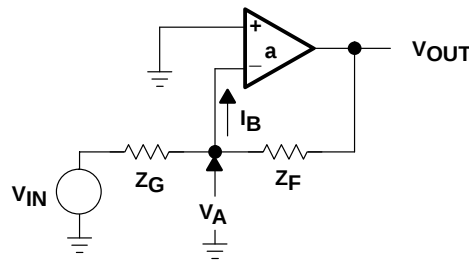


Figure 4. Inverting Op Amp

The transfer equation is given in equation 14:

$$V_{OUT} = -aV_A \quad (14)$$

The node voltage is described by equation 15, and equation 16 is obtained by combining equations 14 and 15.

$$V_A = \frac{V_{IN} Z_F}{Z_G + Z_F} + \frac{V_{OUT} Z_G}{Z_G + Z_F} \quad \text{for } I_B = 0 \quad (15)$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{\frac{-aZ_F}{Z_G + Z_F}}{1 + \frac{aZ_G}{Z_G + Z_F}} \quad (16)$$

Equation 16 is the transfer function of the inverting op amp. The direct gain garnered by the comparison method is $a - Z_G/(Z_G + Z_F)$. The inverting op amp with the feedback loop broken is shown in Figure 5, and this circuit is used to calculate the loop gain given in equation 17.

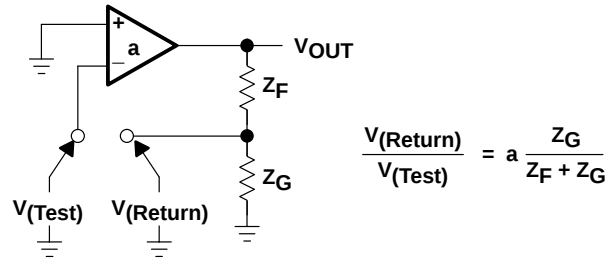


Figure 5. Inverting Op Amp: Feedback Loop Broken for Loop Gain Calculation

$$\frac{V_{RETURN}}{V_{TEST}} = \frac{aZ_G}{Z_G + Z_F} = A\beta \quad (17)$$

Several things must be mentioned at this point in the analysis. First, the transfer functions for the noninverting and inverting equations, 11 and 16, are different. For a common set of Z_G and Z_F values, the magnitude and polarity of the gains are different. Second, the loop gain of both circuits, as given by equations 13 and 17, is identical. Thus, the stability performance of both circuits is identical although their transfer equations are different. This makes the important point that *stability is not dependent on the circuit inputs*. Third, the A gain block shown in Figure 1 is different for each op-amp circuit. By comparison of equations 5, 11, and 16 we see that $A_{NON-INV} = a$ and $A_{INV} = aZ_F / (Z_G + Z_F)$. Equation 7 shows that the error is inversely proportional to the loop gain; thus, the accuracy of identical closed-loop gain inverting and noninverting op-amp circuits is different.

Equation 17 is used to compensate all op amp circuits. First, we determine what compensation method to use. Second, we derive the compensation equations. Third, we analyze the closed-loop transfer function to determine how it is modified by the compensation. The effect of the compensation on the closed-loop transfer function often determines which compensation technique will be used.

3 Internal Compensation

Op amps are internally compensated to save external components and to enable their use by less knowledgeable people. It takes some measure of analog knowledge to compensate an analog circuit. Internally compensated op amps normally are stable when they are used in accordance with the applications instructions. Internally compensated op amps are not unconditionally stable. They are multiple pole systems, but they are internally compensated such that they appear as a single pole system over much of the frequency range. The cost of internal compensation is that it severely decreases the closed-loop bandwidth of the op amp.

Internal compensation is accomplished in several ways, but the most common method is to connect a capacitor across the collector-base junction of a voltage gain transistor (see Figure 6). The Miller effect multiplies the capacitor value by an amount approximately equal to the stage gain, thus, the Miller effect uses small value capacitors for compensation. Figure 7 shows the gain/phase diagram for an older op amp (TL03X). When the gain crosses the 0-dB axis (gain equal to one) the phase shift is about 100° , thus, the op amp must be modeled as a second order system because the phase shift is more than 90° .

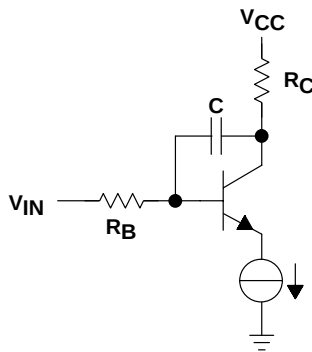


Figure 6. Miller Effect Compensation

This yields a phase margin of $\phi = 180^\circ - 100^\circ = 80^\circ$, thus the circuit should be very stable (Reference 1 explains feedback analysis tools). Referring to Figure 8, the damping ratio is one and the expected overshoot is zero. Figure 7 shows approximately 10% overshoot which is unexpected, but inspecting Figure 7 further reveals that the loading capacitance for the two plots is different. The pulse response is loaded with 100 pF rather than 25 pF shown for the gain/phase plot, and this extra loading capacitance accounts for the loss of phase margin.

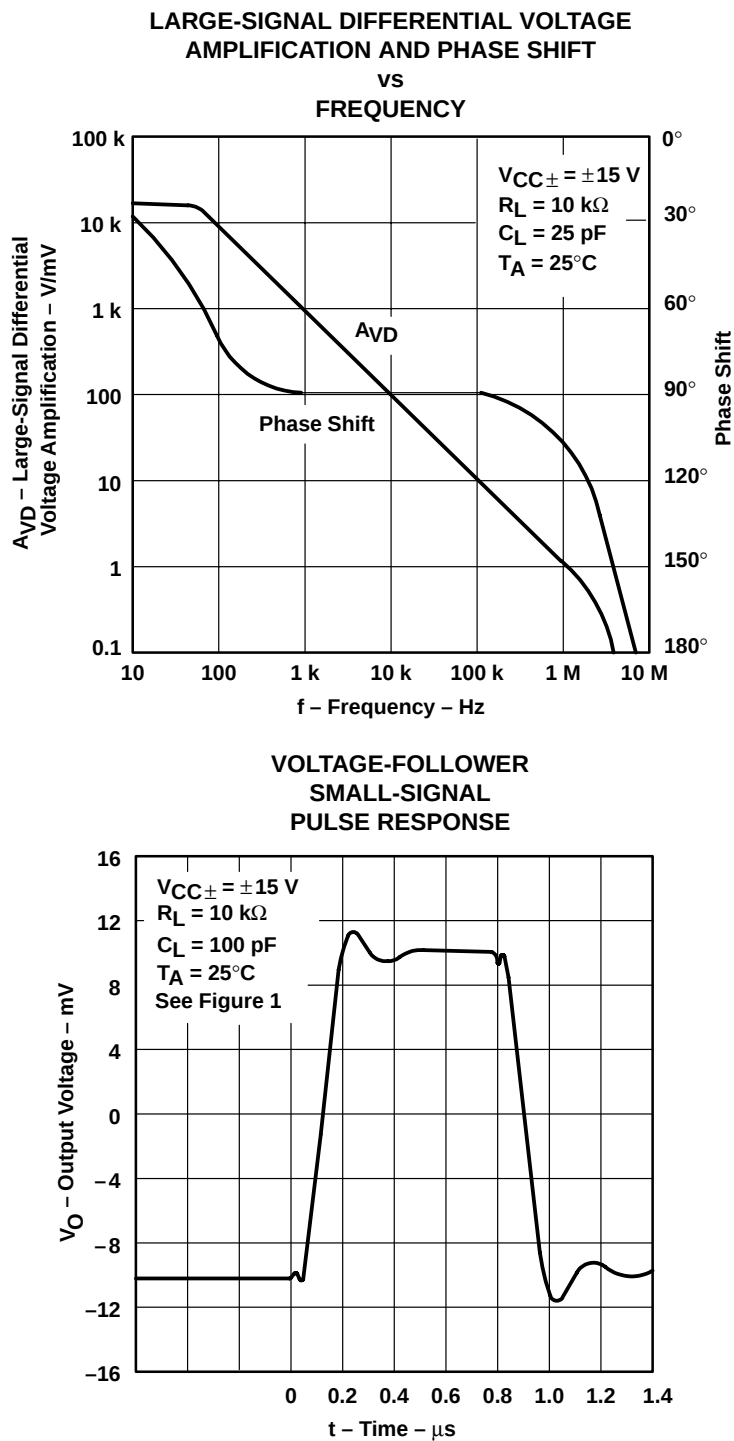


Figure 7. TL03X Frequency and Time Response Plots

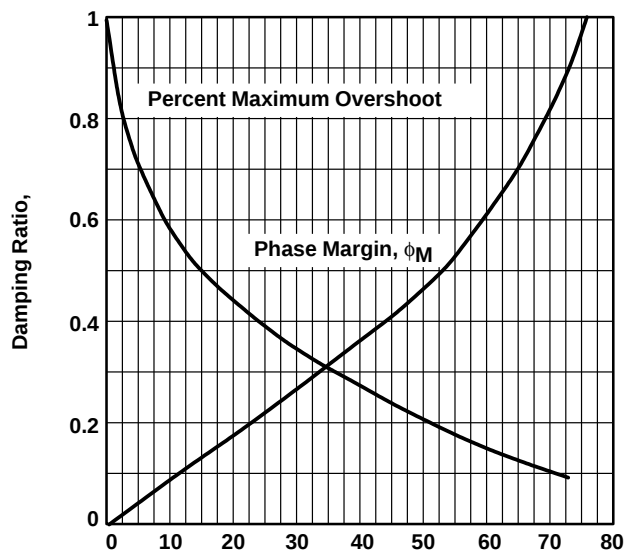
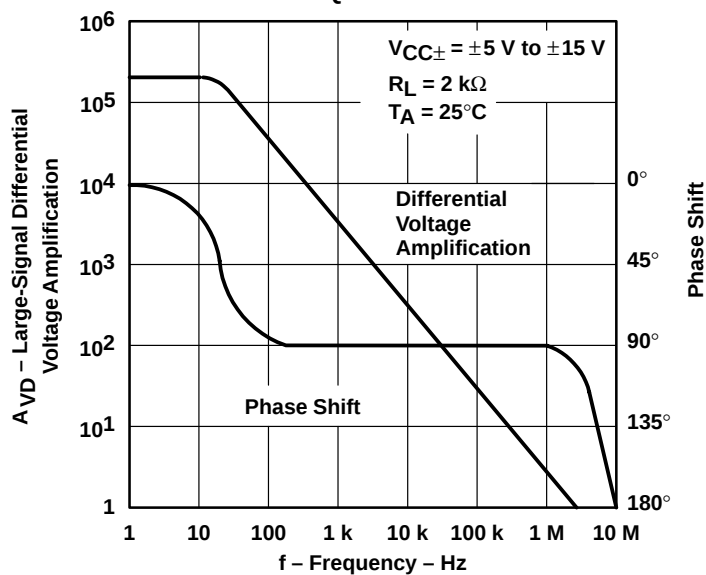


Figure 8. Phase Margin and Percent Overshoot Versus Damping Ratio

Why does the loading capacitance make the op amp unstable? Look closely at the gain/phase response between 1 MHz and 9 MHz, and observe that the gain curve changes slope drastically while the rate of phase change approaches $120^\circ/\text{decade}$. The radical gain/phase slope change proves that several poles are located in this area. The loading capacitance works with the op-amp output impedance to form another pole, and the new pole reacts with the internal op-amp poles. As the loading capacitor value is increased, its pole migrates down in frequency, causing more phase shift at the 0-dB crossover frequency. The proof of this is given in the TL03X data sheet where plots of ringing and oscillation versus loading capacitance are shown.

Figure 9 shows similar plots for the TL07X which is the newer family of op amps. Notice that the phase shift is 100° when the gain crosses the 0-dB axis. This yields a phase margin of 80° , which is close to being unconditionally stable. The slope of the phase curve changes to $180^\circ/\text{decade}$ about one decade from the 0-dB crossover point. The radical slope change causes suspicion about the 90° phase margin. Furthermore, the gain curve must be changing radically when the phase is changing radically. The gain/phase plot may not be totally false, but it sure is overly optimistic.

LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION AND PHASE SHIFT vs FREQUENCY



OUTPUT VOLTAGE vs ELAPSED TIME

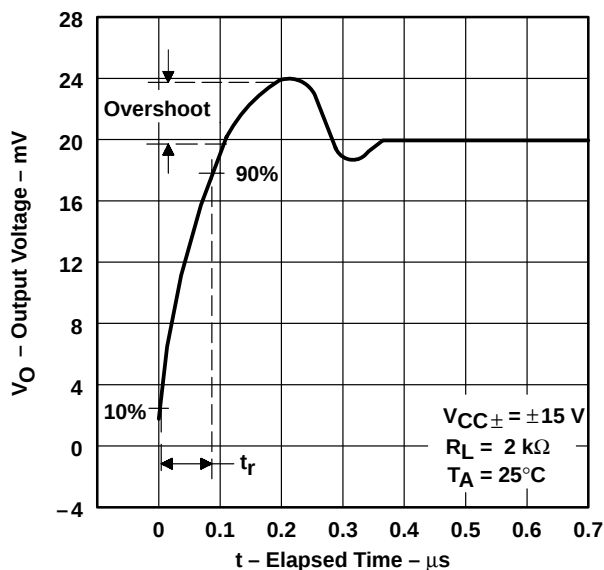
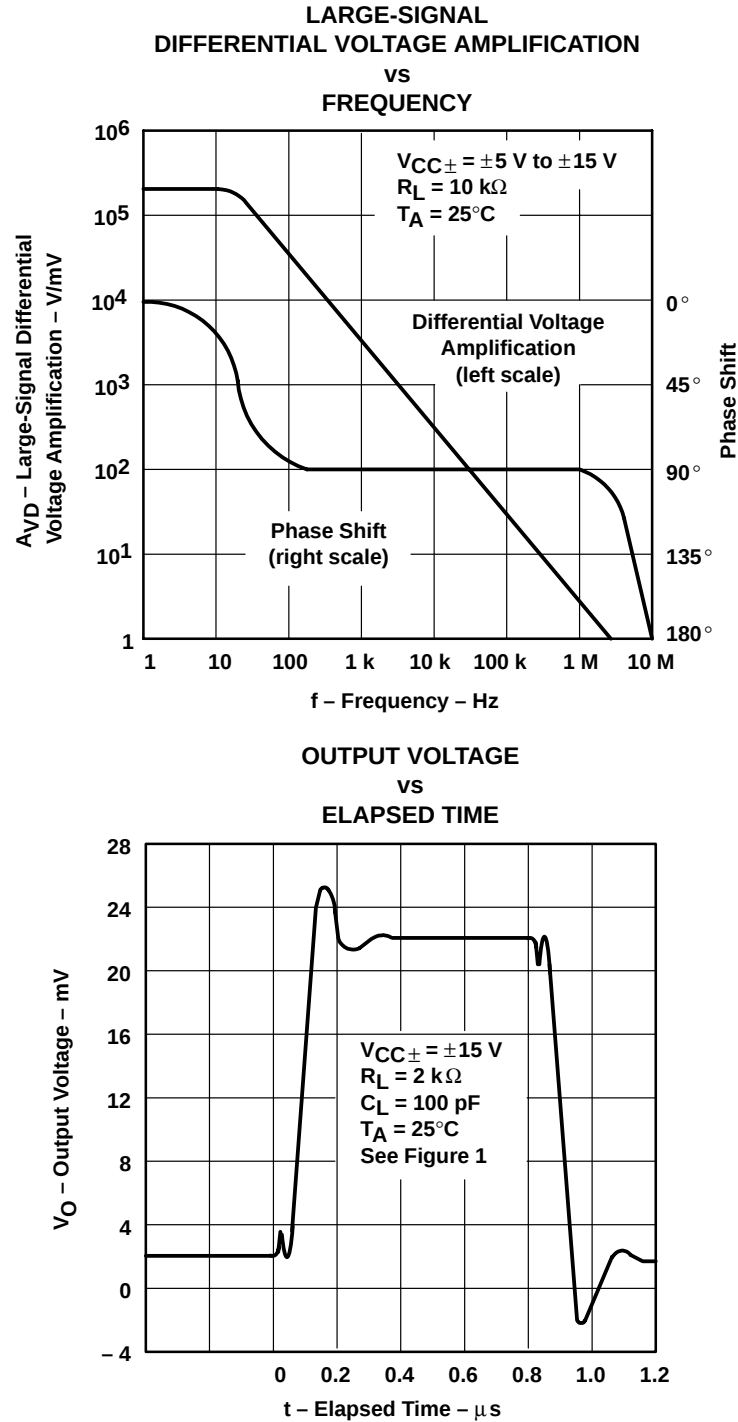


Figure 9. TL07X Frequency and Time Response Plots

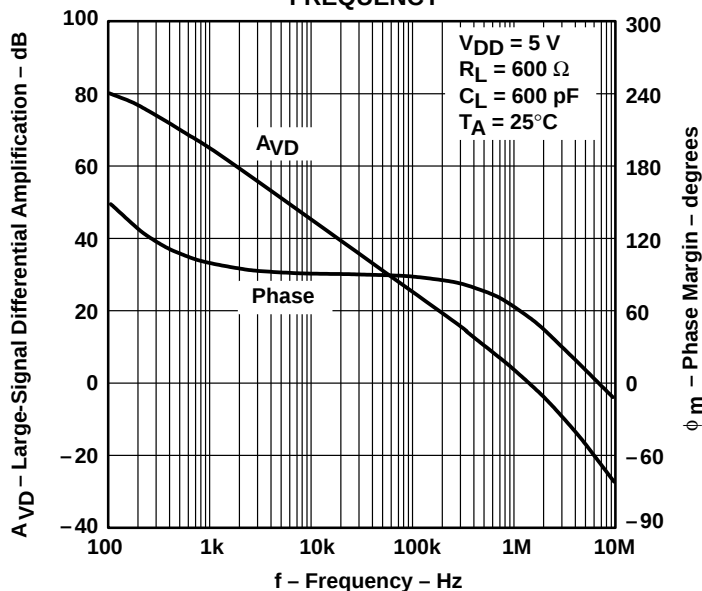
The TL07X pulse response plot shows approximately 20% overshoot. There is no loading capacitance indicated on the plot to account for a seemingly unconditionally stable op amp exhibiting this large an overshoot. Something is wrong here: the analysis is wrong, the plots are wrong, or the parameters are wrong. Figure 10 shows the plots for the TL08X family of op amps which are sisters to the TL07X family. The gain/phase curve and pulse response is virtually

identical, but the pulse response lists a 100-pF loading capacitor. This little exercise illustrates three valuable points: first, if the data seems wrong it probably is wrong, second, even the factory people make mistakes, and third, the loading capacitor makes op amps ring, overshoot, or oscillate.



The frequency and time-response plots for the TLV277X family of op amps is shown in Figures 11 and 12. First, notice that the information is more sophisticated because the phase response is given in degrees of phase margin; second, both gain/phase plots are done with substantial loading capacitors (600 pF), so they have some practical value; and third, the phase margin is a function of power supply voltage.

**LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION
AND PHASE MARGIN
vs
FREQUENCY**



**LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION
AND PHASE MARGIN
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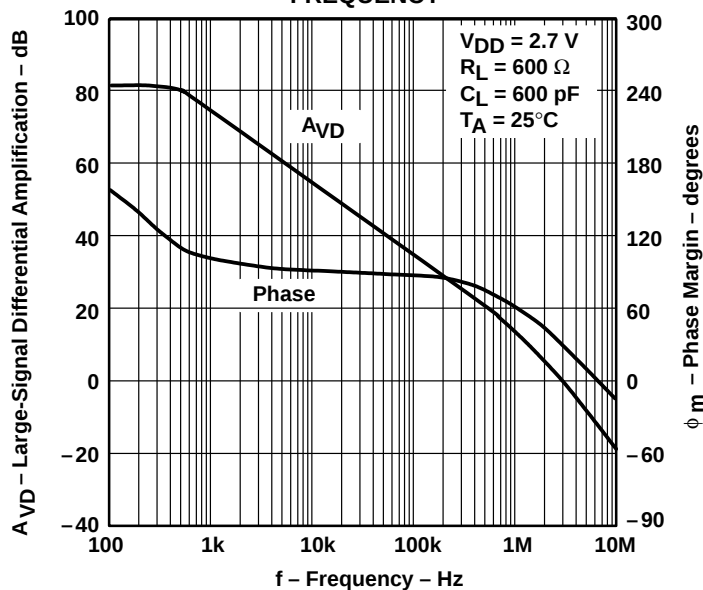


Figure 11. TLV277X Frequency Response Plots

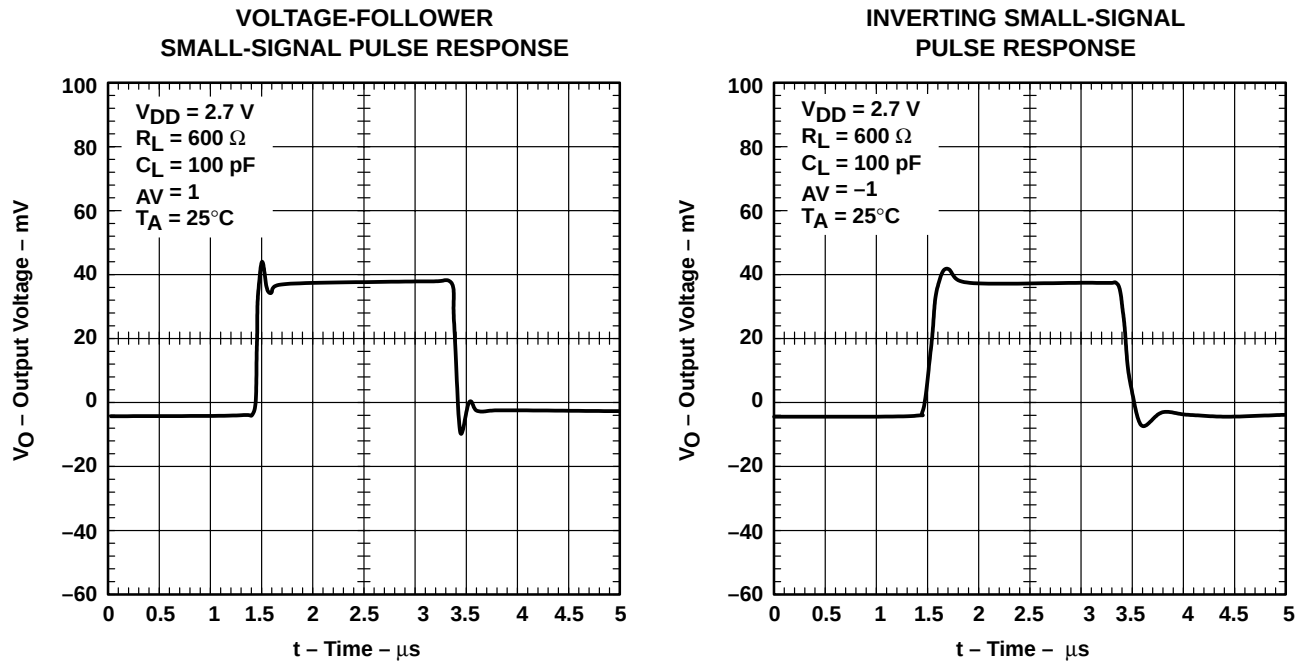


Figure 12. TLV227X Time Response Plots

At $V_{CC} = 5\text{ V}$, the phase margin at the 0-dB crossover point is 60° , while it is 30° at $V_{CC} = 2.7\text{ V}$. This translates into an expected overshoot of 18% at $V_{CC} = 5\text{ V}$, and 28% at $V_{CC} = 2.7\text{ V}$. Unfortunately, the time response plots are done with 100-pF loading capacitance, hence we can not check our figures very well. The $V_{CC} = 2.7\text{-V}$ overshoot is approximately 2%, and it is almost impossible to figure out what the overshoot would have been with a 600-pF loading capacitor. The small-signal pulse response is done with mV-signals, and that is a more realistic measurement than using the full-signal swing.

Internally compensated op amps are very desirable because they are easy to use, and they do not require external compensation components. Their drawback is that the bandwidth is limited by the internal compensation scheme. The op-amp open-loop gain eventually (when it shows up in the loop gain) determines the error in an op-amp circuit. In a noninverting buffer configuration, the TL277X is limited to 1% error at 50 kHz ($V_{CC} = 2.7\text{ V}$) because the op amp gain is 40 dB at that point. Circuit designers can play tricks such as bypassing the op amp with a capacitor to emphasize the high-frequency gain, but the error is still 1%. Keep equation 7 in mind because it defines the error. If the TL277X were not internally compensated, it could be externally compensated for a lower error at 50 kHz because the gain would be much higher.

4 External Compensation, Stability, and Performance

This section is approached on a compensation type basis. Nobody compensates an op amp because it is there; they have a reason to compensate the op amp, and that reason is usually stability. They want the op amp to perform a function in a circuit where it is potentially unstable. Internally and noninternally compensated op amps are compensated externally because certain circuit configurations do cause oscillations. Several potentially unstable circuit configurations are analyzed in this section, and the reader can extend the external compensation techniques as required.

Other reasons for externally compensating op amps are noise reduction, flat amplitude response, and obtaining the highest bandwidth possible from an op amp. An op amp generates noise, and noise is generated by the system. The noise contains many frequency components, and when a high-pass filter is incorporated in the signal path, it reduces high-frequency noise. Compensation can be employed to roll off the op amp's high-frequency, closed-loop response, thus, causing the op amp to act as a noise filter. Internally compensated op amps are modeled with a second order equation, and this means that the output voltage can overshoot in response to a step input. When this overshoot (or peaking) is undesirable, external compensation can increase the phase margin to 90° where there is no peaking. An uncompensated op amp has the highest bandwidth possible. External compensation is required to stabilize uncompensated op amps, but the compensation can be tailored to the specific circuit, thus yielding the highest possible bandwidth consistent with the pulse response requirements.

5 Dominant-Pole Compensation

We saw that capacitive loading caused potential instabilities, thus, an op amp loaded with an output capacitor is a circuit configuration that must be analyzed. This circuit is called dominant pole compensation because if the pole formed by the op amp output impedance and the loading capacitor is located close to the zero frequency axis, it becomes dominant. The op-amp circuit is shown in Figure 13, and the open-loop circuit used to calculate the loop gain ($A\beta$) is shown in Figure 14.

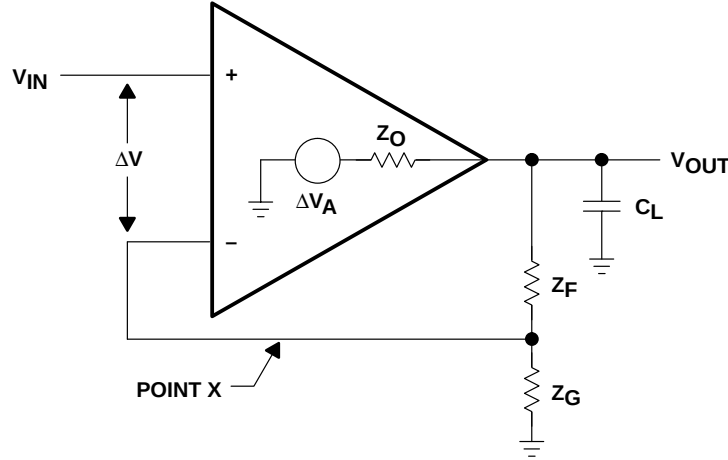


Figure 13. Capacitively-Loaded Op Amp

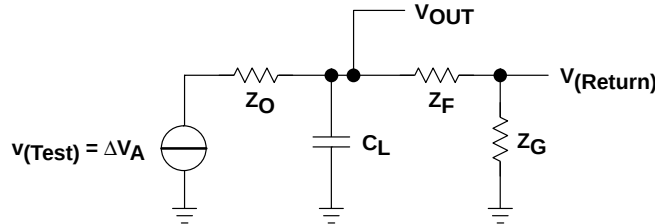


Figure 14. Capacitively-Loaded Op Amp With Loop Broken for Loop-Gain ($A\beta$) Calculation

The analysis starts by looking into the capacitor and taking the Thevenin equivalent circuit.

$$V_{TH} = \frac{\Delta V_a}{Z_O C_L s + 1} \quad (18)$$

$$Z_{TH} = \frac{Z_O}{Z_O C_L s + 1} \quad (19)$$

Then the output equation is written:

$$V_{RETURN} = \frac{V_{TH} Z_G}{Z_G + Z_F + Z_{TH}} = \frac{\Delta V_a}{Z_O C_L s + 1} \left[\frac{Z_G}{Z_F + Z_G + \frac{Z_O}{Z_O C_L s + 1}} \right] \quad (20)$$

Rearranging terms yields equation 21:

$$\frac{V_{RETURN}}{V_{TEST}} = A\beta = \frac{\frac{aZ_G}{Z_F + Z_G + Z_O}}{\frac{(Z_F + Z_G)Z_OC_Ls}{Z_F + Z_G + Z_O} + 1} \quad (21)$$

When the assumption is made that $(Z_F + Z_G) \gg Z_O$, equation 21 reduces to equation 22:

$$A\beta = \frac{aZ_G}{Z_F + Z_G} \left(\frac{1}{Z_OC_Ls + 1} \right) \quad (22)$$

Equation 23 models the op amp as a second-order system. Hence, substituting the second-order model for a in equation 22 yields equation 24 which is the stability equation for the dominant-pole compensation circuit:

$$a = \frac{K}{(s + \tau_1)(s + \tau_2)} \quad (23)$$

$$A\beta = \frac{K}{(s + \tau_1)(s + \tau_2)} \frac{Z_G}{Z_F + Z_G} \frac{1}{Z_OC_Ls + 1} \quad (24)$$

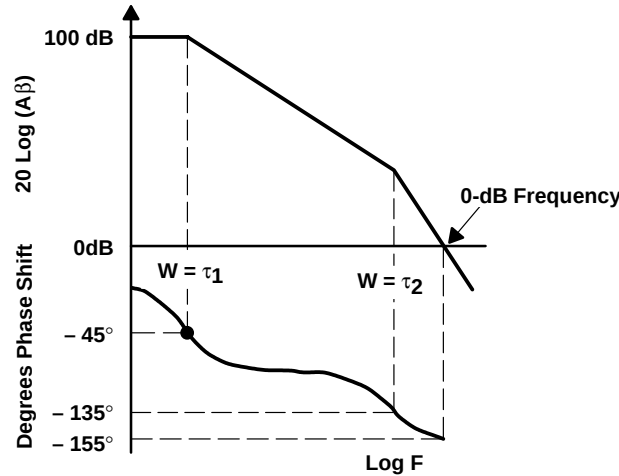


Figure 15. Possible Bode Plot of the Op Amp Described in Equation 23

Several conclusions can be drawn from equation 24 depending on the location of the poles. If the Bode plot of equation 23, the op amp transfer function, looks like that shown in Figure 15, it only has 25° phase margin, and there is approximately 48% overshoot. When the pole introduced by Z_O and C_L moves towards the zero frequency axis it comes close to the τ_2 pole, and it adds phase shift to the system. Increased phase shift increases peaking and decreases stability. In the real world, many loads, especially cables, are capacitive, and an op amp like the one pictured in Figure 15 would ring while driving a capacitive load. The load capacitance causes peaking and instability in internally compensated op amps when the op amps do not have enough phase margin to allow for the phase shift introduced by the load.

Prior to compensation, the Bode plot of an uncompensated op amp looks like that shown in Figure 16. Notice that the break points are located close together thus accumulating about 180° of phase shift before the 0 dB crossover point; the op amp is not usable and probably unstable. Dominant pole compensation is often used to stabilize these op amps. If a dominant pole, in this case ω_D , is properly placed it rolls off the gain so that τ_1 introduces 45° phase at the 0 dB crossover point. After the dominant pole is introduced the op amp is stable with 45° phase margin, but the op-amp gain is drastically reduced for frequencies higher than ω_D . This procedure works well for internally compensated op amps, but is seldom used for externally compensated op amps because inexpensive discrete capacitors are readily available.

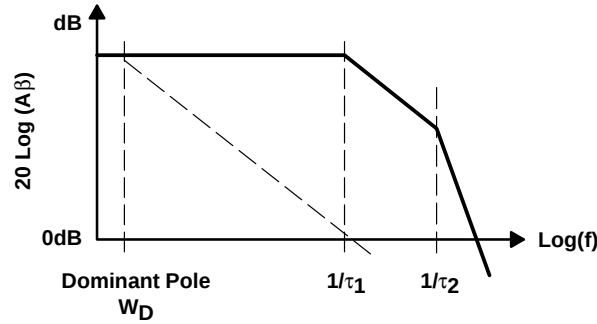


Figure 16. Dominant-Pole Compensation Plot

Assuming that $Z_O \ll Z_F$, the closed-loop transfer function, is easy to calculate because C_L is enclosed in the feedback loop. The ideal closed-loop transfer equation is the same as equation 11 for the noninverting op amp, and is repeated below as equation 25:

$$\frac{V_{OUT}}{V_{IN}} = \frac{a}{1 + \frac{aZ_G}{Z_G + Z_F}} \quad (25)$$

When $a \Rightarrow \infty$ equation 25 reduces to equation 26:

$$\frac{V_{OUT}}{V_{IN}} = \frac{Z_F + Z_G}{Z_G} \quad (26)$$

As long as the op amp has enough compliance and current to drive the capacitive load, and Z_O is small, the circuit functions as though the capacitor was not there. When the capacitor becomes large enough, its pole interacts with the op amp pole causing instability. When the capacitor is huge, it completely kills the op amp's bandwidth, thus lowering the noise while retaining a large, low-frequency gain.

6 Gain Compensation

When the closed-loop gain of an op-amp circuit is related to the loop gain, as it is in voltage feedback op amps, the gain can be used to stabilize the circuit. This type of compensation can not be used in current feedback op amps because the mathematical relationship between the loop gain and ideal closed-loop gain does not exist. The loop gain equation is repeated as equation 27. Notice that the closed-loop gain parameters Z_G and Z_F are contained in equation 27, hence the stability can be controlled by manipulating the closed-loop gain parameters.

$$A\beta = \frac{aZ_G}{Z_G + Z_F} \quad (27)$$

The original loop-gain curve for a closed-loop gain of one is shown in Figure 17, and it is or comes very close to being unstable. If the closed-loop noninverting gain is changed to 9, then K changes from $K/2$ to $K/10$. The loop-gain intercept on the Bode plot (see Figure 17) moves down 14 dB, and the circuit is stabilized.

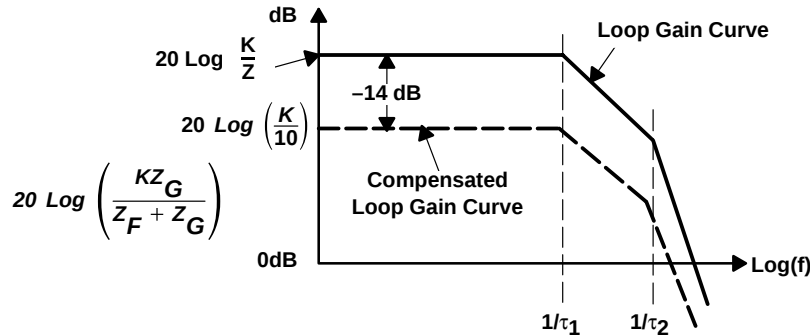


Figure 17. Gain Compensation

Gain compensation works for inverting or noninverting op-amp circuits because the loop gain equation contains the closed-loop gain parameters in both cases. When the closed-loop gain is increased, the accuracy and the bandwidth decrease. As long as the application can stand the higher gain, gain compensation is the best type of compensation to use. Uncompensated versions of normally internally compensated op amps are offered for sale as stable op amps with minimum gain restrictions. As long as the gain in the circuit you design exceeds the gain specified, this is economical and a safe mode of operation.

7 Lead Compensation

Sometimes lead compensation is forced on the circuit designer because of the parasitic capacitance associated with packaging and wiring op amps. Figure 18 shows the circuit for lead compensation; notice the capacitor in parallel with R_F . That capacitor is often made by parasitic wiring and the ground plane, and high frequency circuit designers go to great lengths to minimize or eliminate it. What is good in one sense is bad in another, because adding the parallel capacitor is a good way to stabilize the op amp and reduce noise. Let us analyze the stability first, and then we will analyze the closed-loop performance.

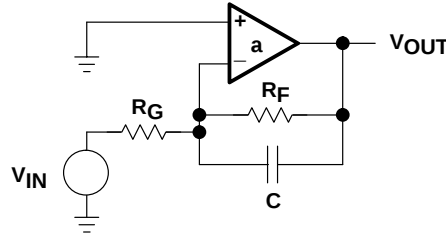


Figure 18. Lead-Compensation Circuit

The loop equation for the lead-compensation circuit is given by equation 28:

$$A\beta = \left(\frac{R_G}{R_G + R_F} \right) \left(\frac{R_F C s + 1}{R_G \parallel R_F C s + 1} \right) \left(\frac{K}{(s + \tau_1)(s + \tau_2)} \right) \quad (28)$$

The compensation capacitor introduces a pole and zero into the loop equation. The zero always occurs before the pole because $R_F > R_F \parallel R_G$. When the zero is properly placed it cancels out the τ_2 pole along with its associated phase shift. The original transfer function is shown in Figure 19, drawn as solid lines. When the $R_F C$ zero is placed at $\omega = 1/\tau_2$, it cancels out the τ_2 pole causing the Bode plot to continue on a slope of -20 dB/decade. When the frequency gets to $\omega = 1/(R_F \parallel R_G)C$, this pole changes the slope to -40 dB/decade. Properly placed, the capacitor aids stability, but what does it do to the closed-loop transfer function? The equation for the inverting op amp closed-loop gain is repeated below.

$$\frac{V_{OUT}}{V_{IN}} = \frac{\frac{-aZ_F}{Z_G + Z_F}}{1 + \frac{aZ_G}{Z_G + Z_F}} \quad (29)$$

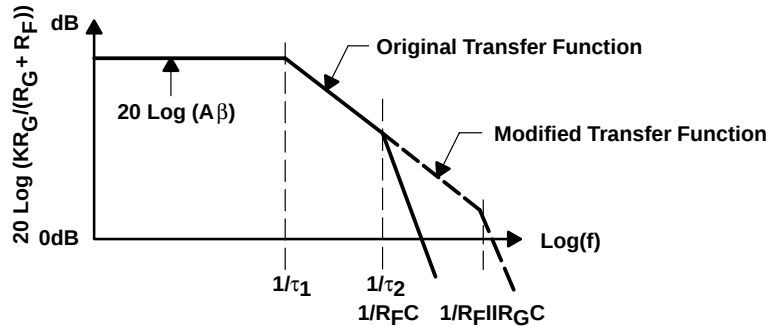


Figure 19. Lead-Compensation Bode Plot

When a approaches infinity, equation 29 reduces to equation 30:

$$\frac{V_{OUT}}{V_{IN}} = - \frac{Z_F}{Z_G} \quad (30)$$

Substituting $R_F \parallel C$ for Z_F and R_G for Z_G in equation 30 yields equation 31, which is the ideal closed-loop gain equation for the lead compensation circuit:

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_F}{R_G} \left(\frac{1}{R_F C s + 1} \right) \quad (31)$$

The forward gain for the inverting amplifier is given by equation 32. Compare equation 29 with equation 5 to determine A.

$$A = \frac{aZ_F}{Z_G + Z_F} = \left(\frac{R_F}{R_G + R_F} \right) \left(\frac{1}{R_F \parallel R_G C s + 1} \right) \quad (32)$$

The op-amp gain (a) the forward gain (A) and the ideal closed-loop gain are plotted in Figure 20. The op-amp gain is plotted for reference only. The forward gain for the inverting op amp is not the op-amp gain. Notice that the forward gain is reduced by the factor $R_F/(R_G + R_F)$, and it contains a high-frequency pole. The ideal closed-loop gain follows the ideal curve until the $1/R_F C$ breakpoint (same location as $1/\tau_2$ breakpoint), and then it slopes down at -20 dB/decade. Lead compensation sacrifices the bandwidth between the $1/R_F C$ breakpoint and the forward gain curve. The location of the $1/R_F C$ pole determines the bandwidth sacrifice, and it can be much greater than shown here. The pole caused by R_F , R_G , and C does not appear until the op amp's gain has crossed the 0 dB axis, thus, it does not effect the ideal closed-loop transfer function.

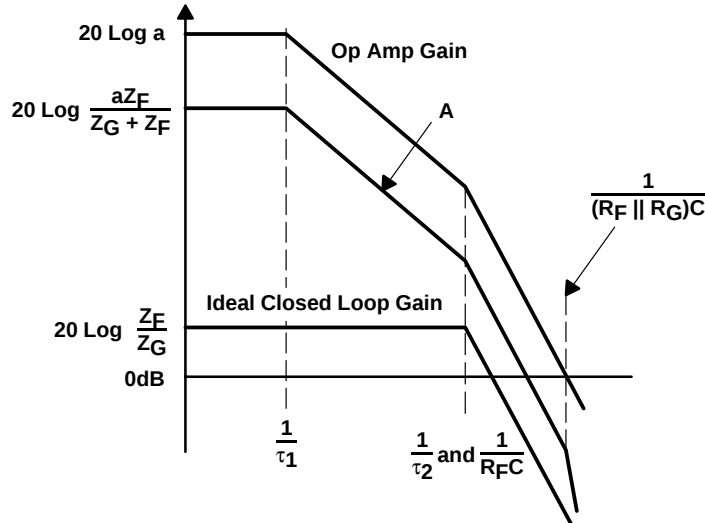


Figure 20. Inverting Op Amp With Lead Compensation

The forward gain for the noninverting op amp is a; compare equation 11 to equation 5. The ideal closed-loop gain is given by equation 33:

$$\frac{V_{OUT}}{V_{IN}} = \frac{Z_F + Z_G}{Z_G} = \left(\frac{R_F + R_G}{R_G} \right) \left(\frac{R_F \parallel R_G C s + 1}{R_F C s + 1} \right) \quad (33)$$

The plot of the noninverting op amp with lead compensation is shown in Figure 21. There is only one plot for both the op-amp gain (a) and the forward gain (A), because they are identical in the noninverting circuit configuration. The ideal starts out as a flat line, but it slopes down because its closed-loop gain contains a pole and a zero. The pole always occurs closer to the low-frequency axis because $R_F > R_F \parallel R_G$. The zero flattens the ideal closed-loop gain curve, but it never does any good because it can not fall on the pole. The pole causes a loss in the closed-loop bandwidth by the amount separating the closed-loop and forward-gain curves.

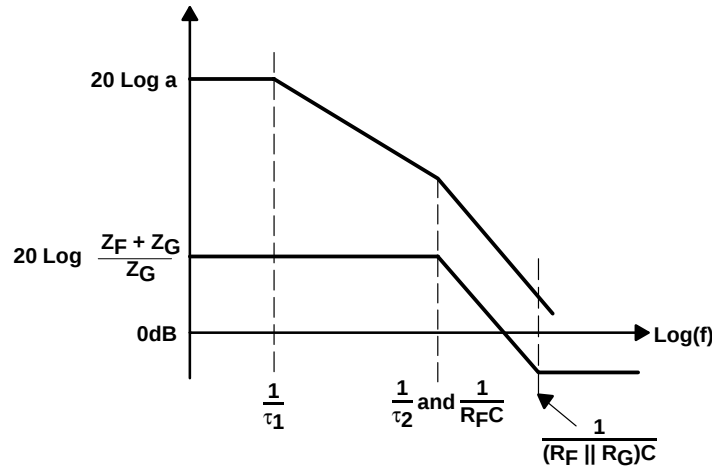


Figure 21. Noninverting Op Amp With Lead Compensation

Although the forward gain is different in the inverting and noninverting circuits, the closed-loop transfer functions take very similar shapes. This becomes truer as the closed-loop gain increases because the noninverting forward gain approaches the op-amp gain. This relationship can not be relied on in every situation, and each circuit must be checked to determine the closed-loop effects of the compensation scheme.

8 Compensated Attenuator Applied to Op Amp

Stray capacitance on op-amp inputs is a problem that circuit designers are always trying to get away from because it decreases closed-loop frequency response or causes peaking. The circuit shown in Figure 22 has some stray capacitance (C_G) connected from the inverting input to ground. Equation 34 is the loop-gain equation for the circuit with input capacitance.

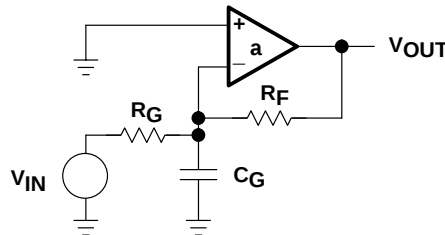


Figure 22. Op Amp With Stray Capacitance on the Inverting Input

$$A\beta = \left(\frac{R_G}{R_G + R_F} \right) \left(\frac{1}{R_G \parallel R_F C_S + 1} \right) \left(\frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)} \right) \quad (34)$$

Op amps having high input and feedback resistors are subject to instability caused by stray capacitance on the inverting input. Referring to equation 34, when the $1/(R_F \parallel R_G C_G)$ pole moves close to τ_2 the stage is set for instability. Reasonable component values for a CMOS op amp are $R_F = 1 \text{ M}\Omega$, $R_G = 1 \text{ M}\Omega$, and $C_G = 10 \text{ pF}$. The resulting pole occurs at 318 kHz, and this frequency is lower than the breakpoint of τ_2 for many op amps. There is 90° phase shift resulting from τ_1 , the $1/(R_F \parallel R_G C)$ pole adds 45° phase shift at 318 kHz, and τ_2 adds another 45° phase shift at about 600 kHz. This circuit is unstable because of the stray input capacitance. The circuit is compensated by adding a feedback capacitor as shown in Figure 23.

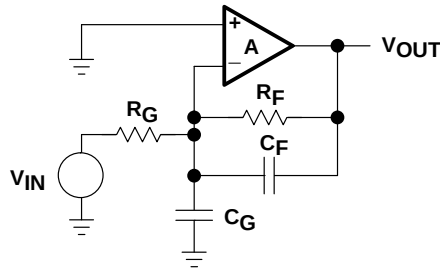


Figure 23. Compensated Attenuator Circuit

The loop gain with C_F added is given by equation 35:

$$A\beta = \left[\frac{\frac{R_G}{R_G C_G s + 1}}{\frac{R_G}{R_G C_G s + 1} + \frac{R_F}{R_F C_F s + 1}} \right] \left(\frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)} \right) \quad (35)$$

If $R_G C_G = R_F C_F$ equation 35 reduces to equation 36:

$$A\beta = \left(\frac{R_G}{R_G + R_F} \right) \left(\frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)} \right) \quad (36)$$

The compensated attenuator Bode plot is shown in Figure 24. Adding the correct $1/R_F C_F$ breakpoint cancels out the $1/R_G C_G$ breakpoint, the loop gain is independent of the capacitors. Now is the time to take advantage of the stray capacitance. C_F can be formed by running a wide copper strip from the output of the op amp over the ground plane under R_F ; do not connect the other end of this copper strip. The circuit is tuned by removing some copper (a razor works well) until all peaking is eliminated. Then measure the copper, and have an identical trace put on the printed-circuit board.

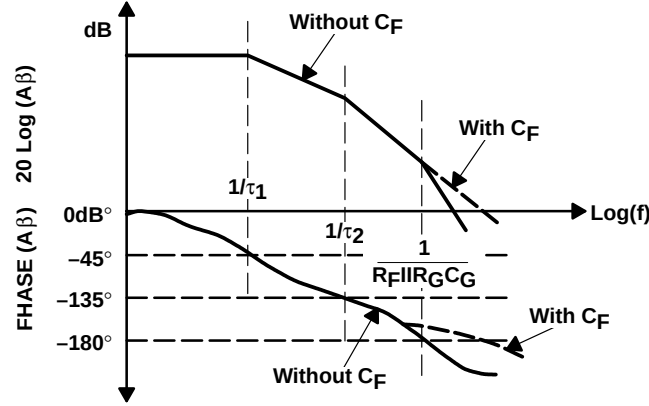


Figure 24. Compensated Attenuator Bode Plot

The inverting and noninverting closed-loop gain equations are a function of frequency. Equation 37 is the closed-loop gain equation for the inverting op amp. When $R_F C_F = R_G C_G$ equation 37 reduces to equation 38 which is independent of the breakpoint. This also happens to the noninverting op-amp circuit. This is one of the few occasions when the compensation does not affect the closed-loop gain frequency response.

$$\frac{V_{OUT}}{V_{IN}} = - \frac{\frac{R_F}{R_F C_F s + 1}}{\frac{R_G}{R_G C_G s + 1}} \quad (37)$$

$$\text{When } R_F C_F = R_G C_G \quad \frac{V_{OUT}}{V_{IN}} = - \left(\frac{R_F}{R_G} \right) \quad (38)$$

9 Lead-Lag Compensation

Lead-lag compensation stabilizes the circuit without sacrificing the closed-loop gain performance. It is often used with uncompensated op amps. This type of compensation leads to excellent high-frequency performance. The circuit schematic is shown in Figure 25, and the loop gain is given by equation 39.

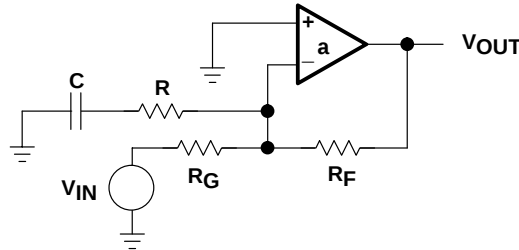


Figure 25. Lead-Lag Compensated Op Amp

$$A\beta = \frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)} \frac{R_G}{R_G + R_F} \frac{RCs + 1}{\frac{(RR_G + RR_F + R_G R_F)}{(R_G + R_F)} Cs + 1} \quad (39)$$

Referring to Figure 26, a pole is introduced at $\omega = 1/RC$, and this pole reduces the gain 3 dB at the breakpoint. When the zero occurs prior to the first op-amp pole it cancels out the phase shift caused by the $\omega = 1/RC$ pole. The phase shift is completely canceled before the second op-amp pole occurs, and the circuit reacts as if the pole was never introduced. Nevertheless, $A\beta$ is reduced by 3 dB or more, so the loop gain crosses the 0-dB axis at a lower frequency. The beauty of lead-lag compensation is that the closed-loop ideal gain is not affected as is shown below. The Thevenin equivalent of the input circuit is calculated in equation 40, the circuit gain in terms of Thevenin equivalents is calculated in equation 41, and the ideal closed-loop gain is calculated in equation 42.

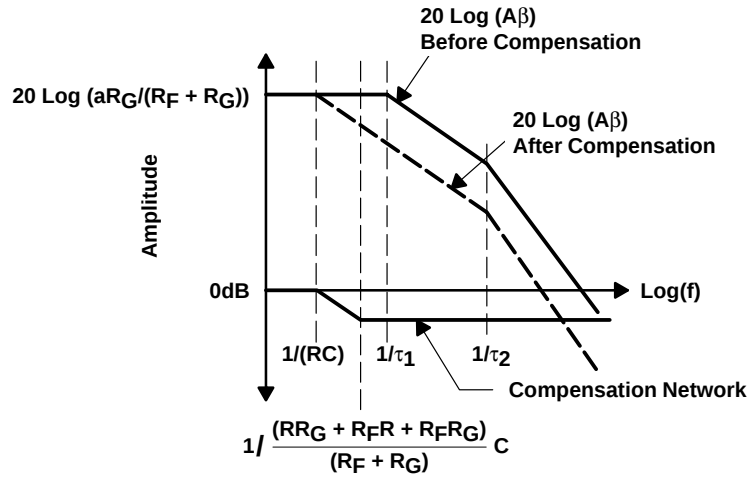


Figure 26. Bode Plot of Lead-Lag Compensated Op Amp

$$V_{TH} = V_{IN} \frac{R + \frac{1}{Cs}}{R + R_G + \frac{1}{Cs}} \quad R_{TH} = \frac{R_G \left(R + \frac{1}{Cs} \right)}{R + R_G + \frac{1}{Cs}} \quad (40)$$

$$V_{OUT} = - V_{TH} \frac{R_F}{R_{TH}} \quad (41)$$

$$- \frac{V_{OUT}}{V_{IN}} = \frac{R + \frac{1}{Cs}}{R + R_G + \frac{1}{Cs}} \frac{R_F}{\frac{R_G \left(R + \frac{1}{Cs} \right)}{R + R_G + \frac{1}{Cs}}} = \frac{R_F}{R_G} \quad (42)$$

Equation 42 is intuitively obvious because the RC network is placed across a virtual ground. As long as the loop gain ($A\beta$) is large, the feedback will null out the closed-loop effect of RC, and the circuit will function as if it weren't there. The closed-loop log plot of the lead-lag compensated op amp is given in Figure 27. Notice that the pole and zero resulting from the compensation occur and are gone before the first amplifier poles come on the scene. This prevents interaction, but it is not required for stability.

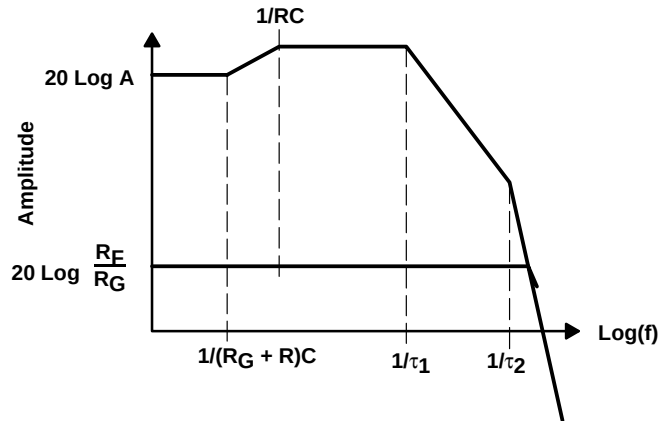


Figure 27. Closed-Loop Plot of Lead-Lag Compensated Op Amp

10 Comparison of Compensation Schemes

Internally compensated op amps can, and often do, oscillate under some circuit conditions. Internally compensated op amps need an external pole to get the oscillation or ringing started, and circuit stray capacitances often supply the phase shift required for instability. Loads, such as cables, often cause internally compensated op amps to ring severely.

Dominant pole compensation is often used in IC design because it is easy to implement. It rolls off the closed-loop gain early; thus, it is seldom used as an external form of compensation unless filtering is required. Load capacitance, depending on its pole location, usually causes the op amp to ring. Large load capacitance can stabilize the op amp because it acts as dominant pole compensation.

The simplest form of compensation is gain compensation. High, closed-loop gains are reflected in lower-loop gains, and in turn, lower-loop gains increase stability. If an op-amp circuit can be stabilized by increasing the closed-loop gain, do it.

Stray capacitance across the feedback resistor tends to stabilize the op amp because it is a form of lead compensation. This compensation scheme is useful for limiting the circuit bandwidth, but it decreases the closed-loop gain.

Stray capacitance on the inverting input works with the parallel combination of the feedback and gain setting resistors to form a pole in the Bode plot, and this pole decreases the circuit's stability. This effect is normally observed in high-impedance circuits built with CMOS op amps. Adding a feedback capacitor forms a compensated attenuator scheme which cancels out the input pole. The cancellation occurs when the input and feedback RC time constants are equal. Under the conditions of equal time constants, the op amp functions as though the stray input capacitance was not there. An excellent method of implementing a compensated attenuator is to build a stray feedback capacitor using the ground plane and a trace off the output node.

Lead-lag compensation stabilizes the op amp, and it yields the best closed-loop frequency performance. Contrary to some published opinions, no compensation scheme will increase the bandwidth beyond that of the op amp. Lead-lag compensation just gives the best bandwidth for the compensation.

11 Conclusion

The stability criteria often is not oscillation, rather, it is circuit performance as exhibited by peaking and ringing.

The circuit bandwidth can often be increased by connecting an external capacitor in parallel with the op amp. Some op amps have hooks which enable a parallel capacitor to be connected in parallel with a portion of the input stages. This increases bandwidth because it shunts high frequencies past the low bandwidth g_m stages, but this method of compensation depends on the op amp type and manufacturer.

The compensation techniques given here are adequate for the majority of applications. When the new and challenging application presents itself, use the procedure outline here to invent your own compensation technique.

12 Reference

1. Mancini, Ron, *Feedback Amplifier Analysis Tools*, SLVA058, Texas Instruments, 1999.