

Analyzing feedback loops containing secondary amplifiers

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Introduction

An op amp circuit contains a feedback loop, and sometimes it is advantageous to include a second amplifier within the op amp's feedback loop to modify closed-loop performance. For example, there is a limited selection of precision input/high-drive capability op amps. Because few such op amps exist, many designers connect a power amplifier in a precision op amp's feedback loop to obtain output-drive capability. Current amplifiers, linear-power amplifiers, switching-power amplifiers, summing amplifiers, nonlinear amplifiers, high-voltage amplifiers, and other amplifier variations are included in an op amp's feedback loop to obtain the desired closed-loop performance.

Sometimes the secondary amplifiers don't cause problems; but, more often than not, overshoot, ringing, or oscillation occurs when secondary amplifiers are added. Ringing and overshoot are the first signs of instability (with oscillation being the final sign). This article explains how the secondary op amp causes instability and how that instability can be cured.

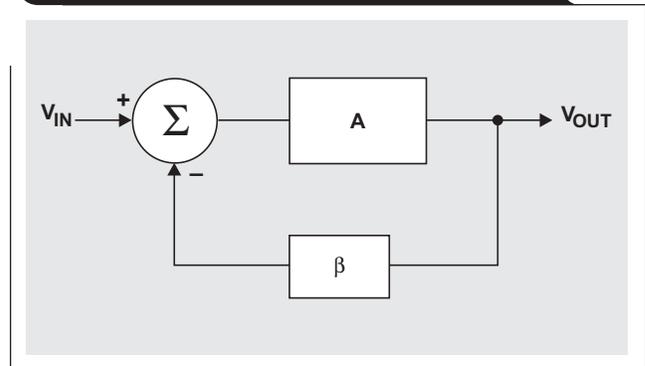
Feedback theory

Feedback theory and its application to op amps are discussed in Reference 1. The classic feedback loop is shown in Figure 1.

The block labeled "A" is the gain block, the block labeled "β" is the feedback block, and the condition for oscillation is $A\beta = -1 = |1| \angle -180^\circ$. To achieve oscillation, the gain magnitude must equal 1 when the loop phase shift equals 0. It seems almost impossible to keep the gain magnitude equal to 1 in an active circuit (especially when the phase angle must be exact), but the op amp output stage introduces nonlinearities that automatically do that.

When an op amp starts to saturate, its output stage becomes nonlinear, thus reducing the overall gain and satisfying the condition for oscillation. This situation enables

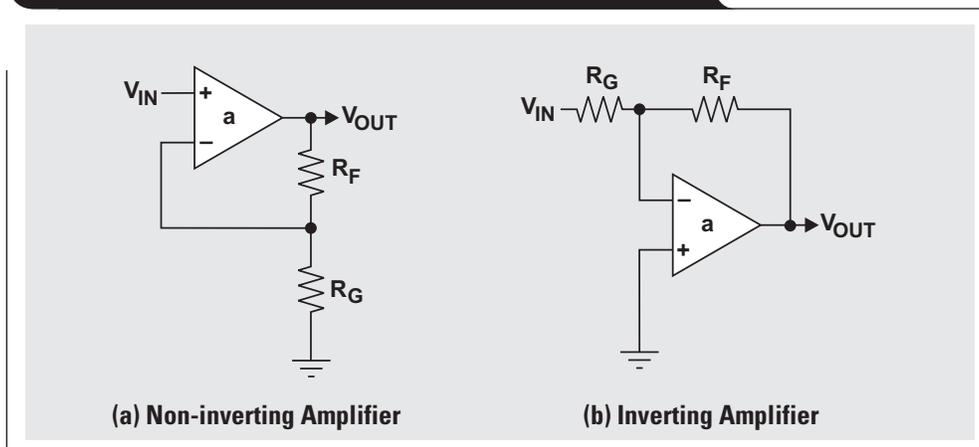
Figure 1. Classic feedback loop with gain block, A, and feedback block, β



the oscillation criteria to be written as $A\beta \geq 1 \angle -180^\circ$; hence, if the gain magnitude is greater than 1, the circuit oscillates when the amplifier phase shift is -180° because nonlinearities force the gain magnitude to 1. The greater the gain magnitude, the greater the nonlinearity required to achieve oscillation; consequently, the output voltage waveform becomes distorted rather than sinusoidal.

The classic feedback loop and op amp circuits have an inverting amplifier in the feedback loop. These circuits always oscillate at the frequency that yields -180° phase shift (when the gain ≥ 1) because this is the frequency where the feedback is in phase. Amplifier stability is evaluated at the point where the gain crosses the 0-dB axis (gain = 1). When the gain crosses over the axis, note the frequency and find the phase shift by following that frequency vertically to the phase curve. A measure of stability is phase margin, ϕ , which is calculated by subtracting the accumulated loop phase shift from 180° .

Figure 2. The two most common op amp configurations



Real op amps and data sheets

Figure 2 shows the typical schematic for op amp circuits.

The loop gain, $A\beta$, is given in the following equation, which is identical for inverting, non-inverting, and differential circuits.

$$A\beta = \frac{aR_G}{R_G + R_F}$$

Parameter “a” in Figure 2 is the op amp open-loop gain (shown in Figure 3 for a TLC27Lx op amp). As the maximum loop gain or the vertical gain intercept (800,000) decreases, a circuit becomes more stable because it accumulates less phase shift before the gain curve crosses 0 dB. When the TLC27Lx’s open-loop gain equals 1, rising vertically on a constant frequency line shows that the op amp’s phase shift is approximately 145°. If $R_G = R_F$, the vertical intercept curve for the gain, a (A_{VD} in Figure 3), drops 6 dB from 800,000 to 400,000; thus the phase shift changes from 145° to 130°. This results in a circuit phase margin of $\phi = 180^\circ - 130^\circ = 50^\circ$.

We should note several things at this point: Increasing phase margin increases stability, inverting and non-inverting op amp circuits have the same loop gain, and increasing the closed-loop gain increases stability. If a second TLC27Lx op amp configured as a non-inverting amplifier with a gain of 2 (see Figure 4) is included in the feedback loop, is the circuit stable?

The answer depends on the phase shift of the secondary op amp. With $R_F = R_G = 10\text{ k}\Omega$, the secondary op amp (TLC27Lx) has a measured phase shift of 90° at $f = 73\text{ kHz}$. Figure 3 shows that the primary op amp has 100° phase shift at 73 kHz with a gain of 15, so the complete circuit with the secondary op amp can easily achieve the criteria for oscillation. Actually, the circuit oscillates at 22.7 kHz; the exact frequency of oscillation is extremely hard to predict because there are two op amps contributing phase shift, and the phase/frequency transfer function is nonlinear.

There are three solutions to this problem. First, the loop gain can be reduced by inserting an attenuator in the feedback loop. The reduced loop gain causes a reduced accumulated phase shift at the 0-dB crossover point, and some value of loop gain can be found that yields a phase

Figure 3. Gain/phase curves for the TLC27Lx

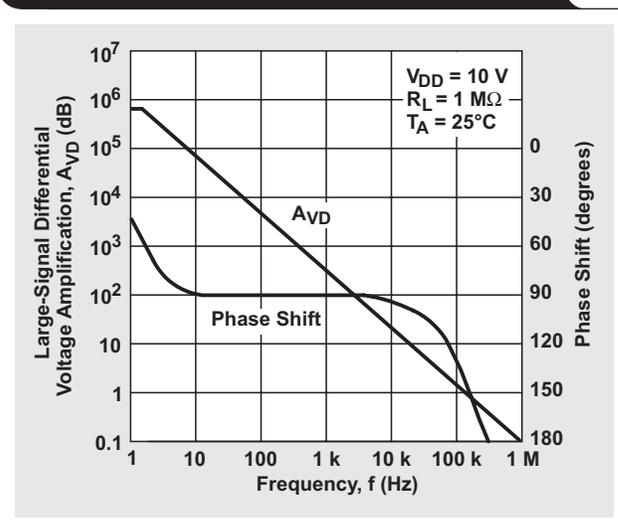
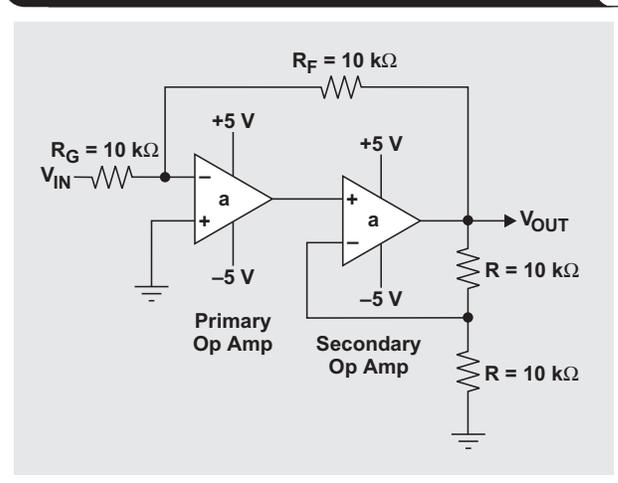


Figure 4. A secondary op amp in the feedback loop can cause oscillations

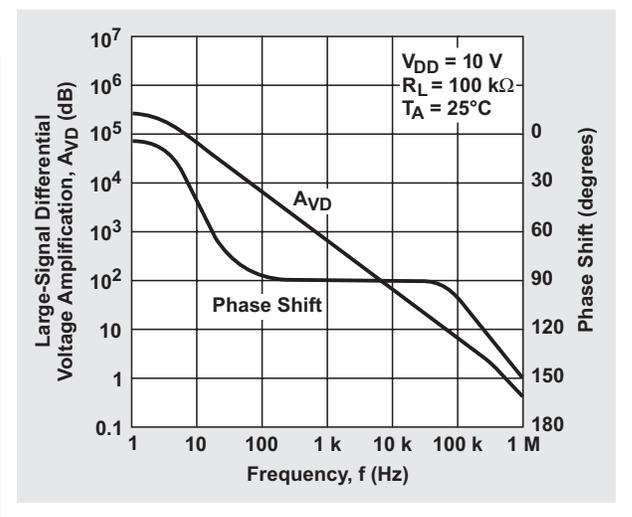


shift of less than -180° . Reduced loop gain reduces the closed-loop accuracy, so this solution is generally not acceptable. Second, the closed-loop gain can be increased, causing a loop-gain reduction and consequent increase in stability. This solution is preferable if the input signal is small enough to restrict the output voltage swing to the secondary op amp's output voltage range. Third, a secondary op amp can be selected whose phase shift is close to 0 at the 0-dB crossover point.

The TLC27Mx's unity-gain bandwidth or 0-dB crossover frequency (see Figure 5) is 635 kHz compared to the TLC27Lx's unity-gain bandwidth of 110 kHz. The 5.77/1 ratio of unity-gain bandwidths indicates that TLC27Mx's phase-shift contribution should be too small to accumulate -180° phase shift when the TLC27Lx crosses the 0-dB point. The TLC27Mx has 31° phase shift at 266 kHz when it is configured as a non-inverting op amp. Figure 3 shows that the accumulated phase shift is 160° (130° from the primary op amp and 30° from the secondary op amp), so the circuit is stable with a TLC27Mx used as the secondary op amp. Any op amp with a higher unity-gain bandwidth will satisfy the stability criteria, but higher-speed op amps tend to burn more power.

The circuit oscillates at 266 kHz when the TLC27Mx is used as the primary and secondary op amps. The measured non-inverting amplifier phase shift of the TLC27Mx is 90° at a frequency of 500 kHz. Figure 5 shows that the TLC27Mx has accumulated approximately 110° phase shift at 500 kHz with a gain of approximately 5. This circuit meets the criteria for an oscillator, so we find no surprises here. If we select a secondary op amp with a unity-gain bandwidth of approximately five times the TLC27Mx unity-gain bandwidth of 635 kHz, the circuit should become stable. Let's select a TLC07x op amp (see Figure 6a) because it has a unity-gain bandwidth of 10 MHz. The ratio of unity-gain bandwidths is $10/0.635 = 15.7$, so the circuit should be

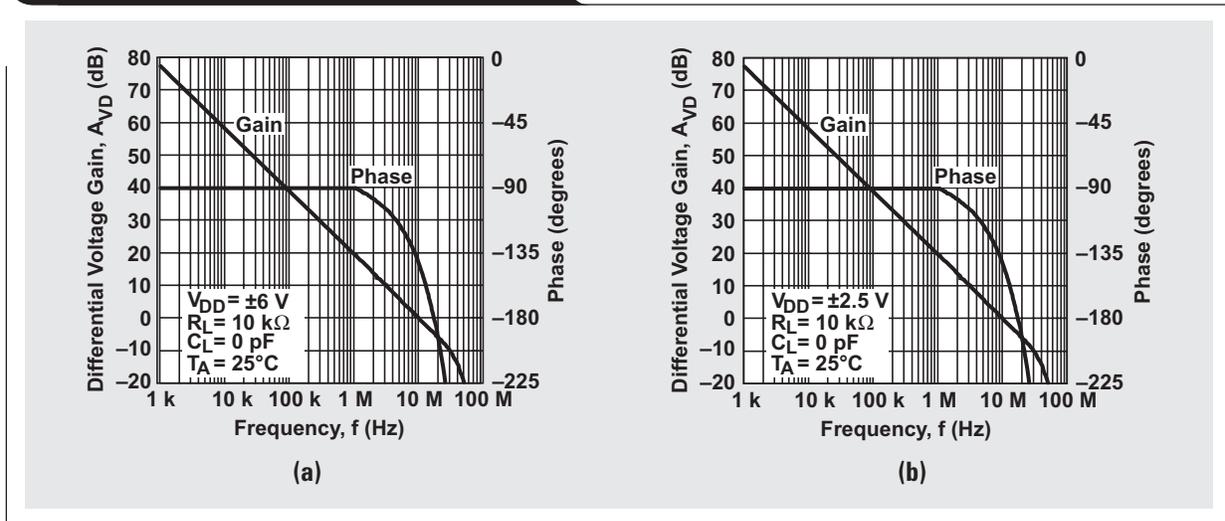
Figure 5. Gain/phase curves for the TLC27Mx



very stable; and measurements prove this statement to be accurate.

The measured non-inverting amplifier phase shift of the TLC07x is 15° at a frequency of 442 kHz. The TLC27Mx has a phase shift of 150° at the 0-dB crossover frequency; thus the theory agrees with the measurements because the accumulated phase shift is 165° . The circuit oscillates when the TLC07x is used for the primary and secondary amplifiers. The TLC07x's output-current capability is ± 50 mA, while the TLC27Mx's output current is limited to a few milliamps; so adding the TLC07x as the secondary amplifier has increased the loop's ability to drive high-current loads.

Figure 6. Gain/phase curves for the TLC07x



Conclusion

When two op amps with similar unity-gain bandwidths are included in a feedback loop, oscillations occur. The unity-gain bandwidth of the op amps must be separated by a factor of five (rule-of-thumb) to prevent oscillations.

Bandwidth data is not a guaranteed specification, and a phase-versus-frequency calculation is nonlinear; so the rule-of-thumb can't be relied upon for more than a mathematical starting point. All assumptions must be verified in the lab, and significant margins must be left to accommodate parameter changes.

Circuit stability is increased when the closed-loop gain is increased because the loop gain decreases. Circuit stability is decreased when the secondary amplifier gain is increased because the loop gain increases. The primary op amp is usually selected because it has precision or low-noise specifications. The secondary op amp is usually selected because it has excellent voltage/current-drive specifications.

The primary amplifier usually has the higher unity-gain bandwidth, but this is not a rigid criterion. A feedback

loop is a linear system; thus the gain blocks can be interchanged within the loop without affecting performance. High-power amplifiers may not be available with high bandwidth, so in that case the primary amplifier is selected as the high-unity-gain bandwidth amplifier to obtain the best speed performance.

Reference

For more information related to this article, you can download an Acrobat Reader file at www-s.ti.com/sc/techlit/litnumber and replace "litnumber" with the **TI Lit. #** for the materials listed below.

Document Title	TI Lit. #
1. Ron Mancini (ed.), <i>Op Amps for Everyone</i> , Design Referenceslod006

Related Web sites

analog.ti.com

www.ti.com/sc/device/partnumber

Replace *partnumber* with TLC07X, TLC27LX or TLC27MX

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