12. Why op amps oscillate: an intuitive look at two frequent causes

Bode plots are great analytical tools, but you may not find them intuitive. This is a purely qualitative look at frequently encountered causes for operational amplifier (op amp) instability and oscillations.

The perfectly damped response in **Figure 27** occurs with no delay in the feedback signal reaching the inverting input. The op amp responds by ramping toward the final value, gently slowing down as the feedback signal detects closure on the proper output voltage.

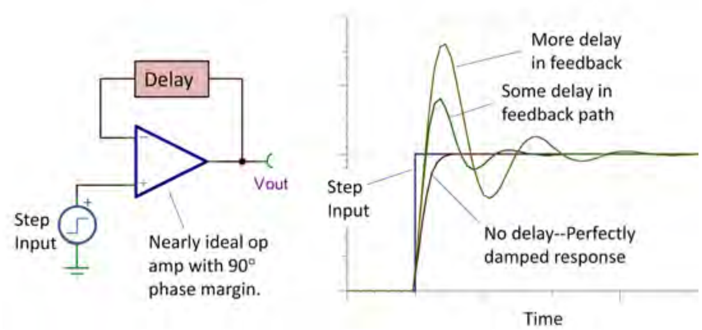

Figure 27: Op amp step response with varying delay inserted in the feedback path.

Problems develop when the feedback signal is delayed. With delay in the loop, the amplifier does not immediately detect its progress toward the final value. It overreacts by racing too quickly toward the proper output voltage. Note the faster initial ramp rate with delayed feedback. The inverting input fails to receive timely feedback that it indeed reached and passed the proper output voltage. It overshoots its mark and requires several successively smaller polarity corrections before finally settling.

A little delay and you merely get some overshoot and ringing. Too much delay and these polarity corrections continue indefinitely – an oscillation.

The source of delay is often a simple low-pass resistor-capacitor (RC) network. OK, it is not a constant delay for all frequencies, but the gradual phase shift of this network from 0° to 90 degrees produces a first-order approximation of time delay, $t_d = RC$.

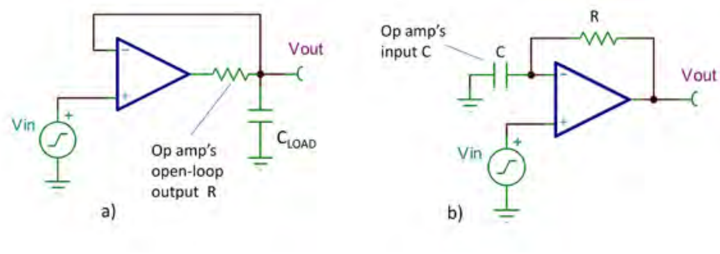

Figure 28: Phase shift (delayed feedback) commonly occurs in two ways: Due to capacitive load (a); or with capacitance at the inverting input terminal (b).

There are two commonly encountered situations where this RC network unintentionally sneaks into circuits. The first is with a capacitive load (**Figure 28a**). The resistor is the op amp's open-loop output resistance. The capacitor is, of course, the load capacitance.

In the second case (**Figure 28b**), the feedback resistance and the op amp's input capacitance form the RC network. Circuit-board connections also contribute to the capacitance at this sensitive circuit node. Note that the two circuits have identical feedback loops. The only difference is the node at which the output is taken. From a loop-stability standpoint, they can create the same issues. And these two causes of delayed feedback often occur in combination – a bit of both can be double trouble.

The second case needs a bit more comment: A feedback resistor is not necessary for the simple G = 1 buffer, so the more common situation is a gain configuration using a feedback resistor and resistor to ground (**Figure 29**). The parallel combination of these resistors forms the effective R in the RC circuit.

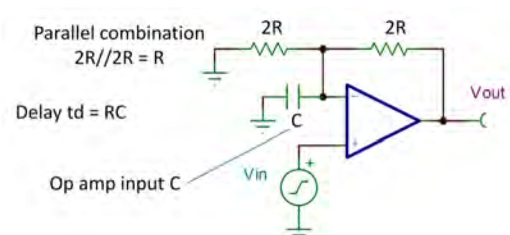

Figure 29: The parallel resistance of the feedback network form the R in an RC circuit.

There is more to learn with Bode analysis of feedback amplifiers. Still, this simple, intuitive view of how delay or phase shift in the feedback path affects stability can help you diagnose and solve the most common stability problems.

To see this original post with comments, click here.

13. Taming the oscillating op amp

In section 12, I looked at two very common reasons for oscillations or instability in operational amplifier (op amp) circuits. The ultimate cause of both was delay or phase shift in the feedback path.

A simple noninverting amplifier can be unstable or have excessive overshoot and ringing if the phase shift or delay created by the op amp's input capacitance (plus some stray capacitance) reacting with the feedback network resistance is too great (**Figure 30**). You may be able to make some improvements by reducing stray capacitance at this node, minimizing the circuit-board trace area of this connection. For a given op amp, input capacitance (differential plus common-mode capacitance) is a fixed value – you are stuck with it. You can, however, reduce the resistances of the feedback network proportionally to keep the gain identical.

Reducing the resistances moves the pole created by this capacitance to a higher frequency and decreases the delay time constant. Reducing the resistances to 5 kΩ and 10 kΩ in this example is a big improvement but still produces approximately 10-percent overshoot with ringing. It also creates additional load on the op amp, so you cannot take this solution too far. The sum of the two resistors is a load on the op amp, and you would not want it to be too low.

The better solution is likely to be a capacitor, Cc, connected in parallel with R2 (**Figure 31**). When R1×Cx = R2×Cc, the voltage divider is compensated and the impedance ratio is constant for all frequencies. There will be no phase shift or delay in the feedback network.

You can liken the feedback network to the compensated attenuator in a 10-times oscilloscope probe (**Figure 32**). It is the same concept. A variable capacitor in the probe allows adjustment to make the two time constants equal. Note that the response of this scope probe does not ever appear unstable, even when improperly adjusted. Why? Because it is not inside a feedback loop.

Just as you can adjust one of the capacitors in a scope probe to fine-tune the compensation, you may also need to adjust the value of Cc shown in **Figure 31**. You may not precisely know the capacitance, Cx, due to the uncertain effects of stray capacitance. Furthermore, you may want to tune the response of the circuit to meet your requirements, with a little bit of overshoot for improved speed and bandwidth.

Another common cause of instability is an op amp with capacitive load. Again, this situation produces phase shift in the loop (delayed feedback) that is the root of the problem. This one is tricky because open-loop output resistance is internal to the op amp. You cannot connect a compensating capacitor across this resistor. In fact, it is not really a resistor at all; it is an equivalent output resistance of the op amp circuitry.

Consider your last oscillating op amp. Can you explain the problem with delayed feedback?

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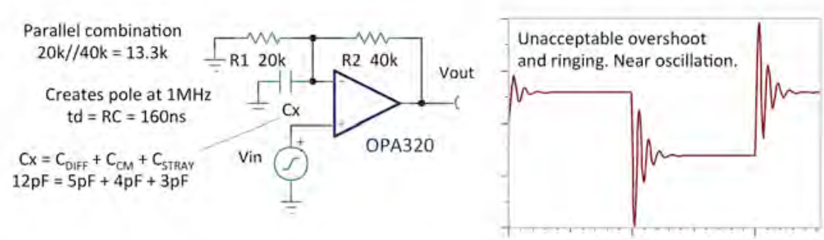

Figure 30: Excessive output overshoot and ringing indicates possible instability.

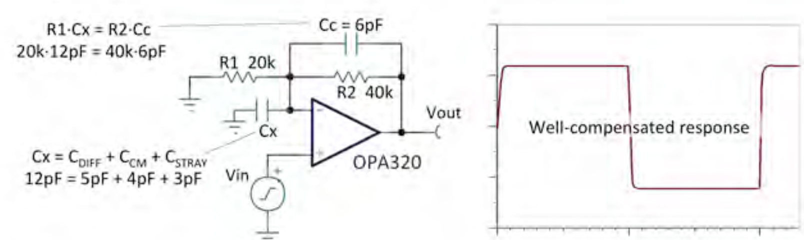

Figure 31: A capacitor, Cc, connected in parallel with R2 avoids phase shift in the feedback signal path.

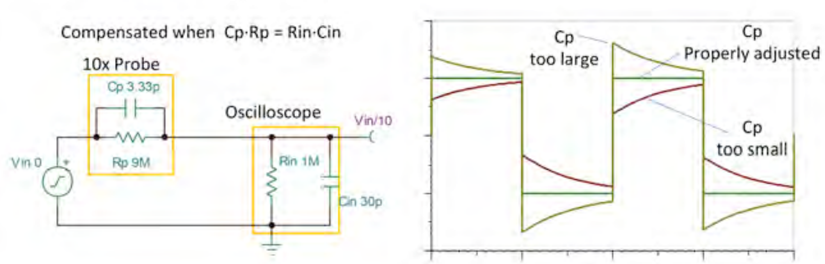

Figure 32: A feedback network is much like a compensated attenuator in a 10x oscilloscope probe.

14. Taming oscillations: the capacitive load problem

I have been looking at the stability of operational amplifiers (op amps), considering how phase shift (or call it delay) in the feedback path can cause problems. Picking up from section 12 and section 13, stability with a capacitive load is a tricky case.

The troublemaker, the open-loop output resistance (Ro) of the op amp, is not actually a resistor inside the op amp. It is an equivalent resistance dependent on the internal circuitry of the op amp. There is no chance to change it without changing the op amp. C_L is the load capacitance. If you want to drive a certain C_L, you are stuck with the pole created by Ro and C_L. A 1.8-MHz pole inside the feedback loop of a 20-MHz op amp in G = 1 spells trouble. Check it out in **Figure 33**.

Solutions to this issue have a common theme – they slow the amplifier down. Think about it: The loop has a fixed amount of delay, from Ro and C_L. To accommodate this delay, the amplifier must respond more slowly so that it does not speed past, overshooting a desired final value.

A good way to slow things down is to put the op amp in a higher gain. Higher gain decreases the bandwidth of the closed-loop amplifier. **Figure 34** shows the OPA320 driving the same 1-nF load but in a gain of 10. The response to a small step dramatically improves but is still marginal. Increase the gain to 25 or more, and it would look pretty good.

But here is another trick. **Figure 35** is still a gain of 10 but with Cc added, slowing things down a bit more in just the right way. Not enough Cc and the response looks more like **Figure 34.** Too much Cc and you are headed for trouble, more like **Figure 33**.

Getting this compensation just right is solving a "rate-of-closure" issue – Bode analysis. A bit of intuition is helpful with these problems, but if you want to advance to the next level of phase-compensation competence, you need Mr. Bode.

My colleagues, Pete Semig and Collin Wells, did a great job distilling the subject of op amp stability and Bode analysis to its essence.

To see this original post with comments, click here.

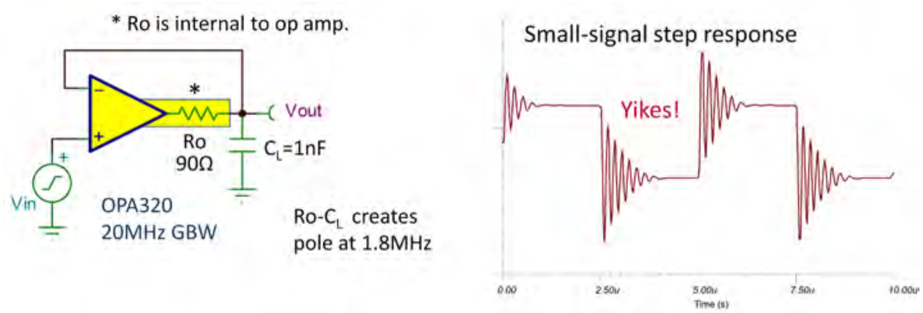

Figure 33: A 1.8-MHz pole inside the feedback loop of a 20-MHz op amp in G = 1 (left) can result in an undesirable small-signal step response (right).

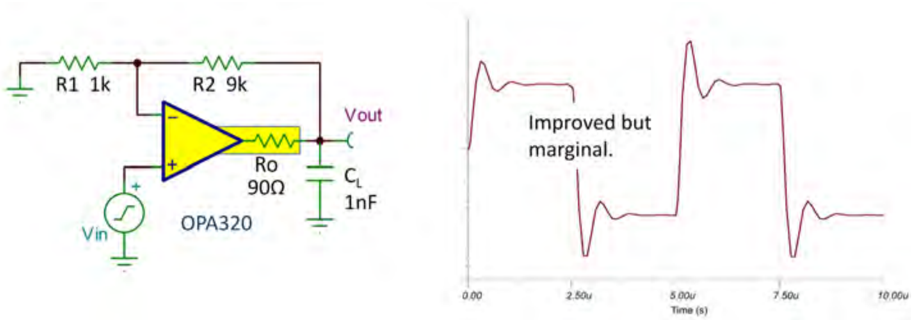

Figure 34: Using an op amp in a higher gain of 10 decreases the bandwidth of the closed-loop amplifier; however, the improvement is marginal.

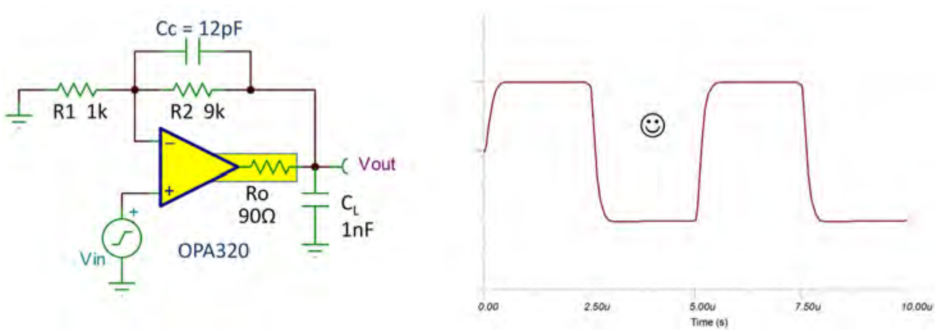

Figure 35: Using the same configuration, adding a Cc of 12 pF in parallel with the feedback resistor produces an ideal response.

15. SPICEing op amp stability

The simulation program with integrated circuit emphasis (SPICE) is a useful tool to help check for potential circuit-stability problems. Here is one simple way to do it.

Figure 36 shows a noninverting amplifier using the OPA211 with a couple of minor variations common in many applications. R3-C1 is an input filter. R4 is an output resistor to protect against abuse when connected to the outside world. C_L models a five-foot cable.

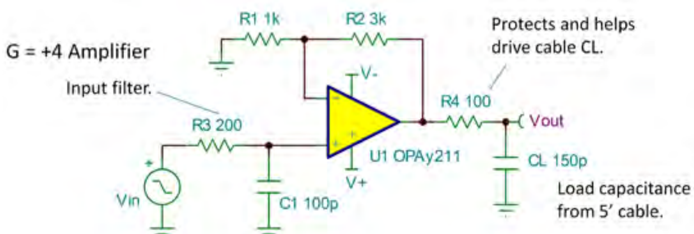

Figure 36: A noninverting amplifier with minor variations common to many applications.

Checking the response to a small-signal step function or square wave is the quickest and easiest way to look for possible stability problems. **Figure 37** shows the simulation circuit. Notice that the input terminal is connected to ground and the input test signal is connected directly to the noninverting input. The input filter would slow the input edge of a step function. If you want to know how a bell rings, hit it with a hammer, not a rubber mallet.

The response is probed at the output of the operational amplifier (op amp), not just the V_{OUT} node of the circuit. R4 and C_L filter the output response so that V_{OUT} will not show the true overshoot of the op amp. To check stability, you want to know what the op amp is doing.

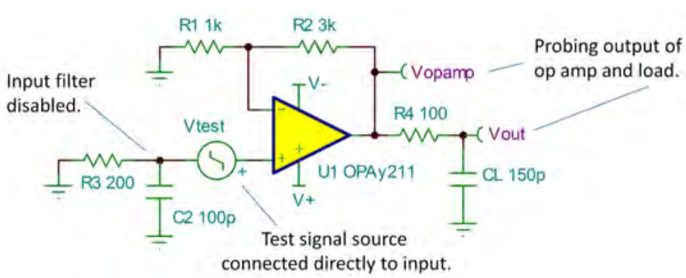

Figure 37: A simulation circuit with the input terminal connected to ground and the input test signal connected directly to the noninverting input.

Notice that the amplitude of the applied step is 1 mV (creating a 4-mV step at the output). You want the small-signal step response. A large input step that induces slewing will have less overshoot and will not clearly reveal potential instability.

The simulation shows approximately 27-percent overshoot at the op amp's output – too much for you to be comfortable that this circuit will be stable under all conditions (**Figure 38**).

Assuming a second-order stability system, this overshoot would indicate a phase margin of approximately 38 degrees. Also notice that the frequency response shows considerable amplitude peaking, another sign of potential instability. The peaking occurs at 14 MHz – the inverse of the period of the ringing in the time domain. A commonly accepted guideline for reasonable stability is a phase margin of 45 degrees (or greater), which translates to 20-percent (or less) overshoot (**Figure 39**).

Figure 39: A 20-percent overshoot indicates approximately 45º phase margin—often considered to be satisfactory for most circuits.

There are fancier analyses that you can do with SPICE – Bode analysis by breaking the loop, finding phase and gain margins. But for most relatively simple circuits (a feedback loop involving one op amp), this approach is a very good indicator of possible problems.

Of course, any SPICE simulation relies on the accuracy of the op amp's macromodel. Our best SPICE models are excellent but not perfect. Furthermore, circuit variation, nonideal components, circuit-board layout parasitics, poor supply bypassing – all can affect the circuit. That's why you build it, test it, compare with simulations and optimize. SPICE is a useful tool, valuable but not perfect.

The late Bob Pease, a true analog guru, wrote skeptically about the use of SPICE. Check out this blog on his opinions: SPICE It Up! … but does Bob Pease say no? To see this original post with comments, click here.

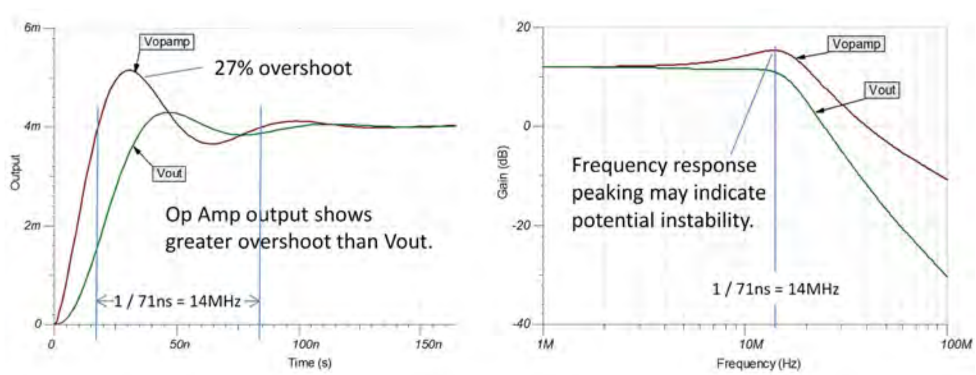

Figure 38: An op amp circuit with 27-percent overshoot may be marginally unstable.

16. Input capacitance: Common mode? Differential? Huh?

The input-capacitance specifications of operational amplifiers (op amps) are often confused or ignored. Let us clarify how to best use these specifications.

The input capacitance at the inverting input can affect the stability of an op amp circuit by causing phase shift – a delay of the feedback reaching the inverting input. The feedback network reacts with the input capacitance to create an unwanted pole. Scaling the impedance of the feedback network in relation to the input capacitance is an important step to assure a stable amplifier circuit. But which capacitance matters – differential? Common mode? Both?

The input capacitance of an op amp is generally found in an input-impedance specification showing both differential and common-mode capacitance (**Table 4**).

OPA1652

Input Impedance	Min	Typ	Max	Units
Differential	—	100 // 6	—	MΩ // pF
Common-Mode	—	6000 // 2	—	GΩ // pF

Table 4: Input-impedance specification showing both differential and common-mode capacitance.

Input capacitance is modeled as common-mode capacitance from each input to ground and differential capacitance between the inputs; see **Figure 40**. Though there is no ground connection on an op amp with dual supply voltages, consider the common-mode capacitances as being connected to the V– supply terminal, the alternating current (AC) equivalent of ground.

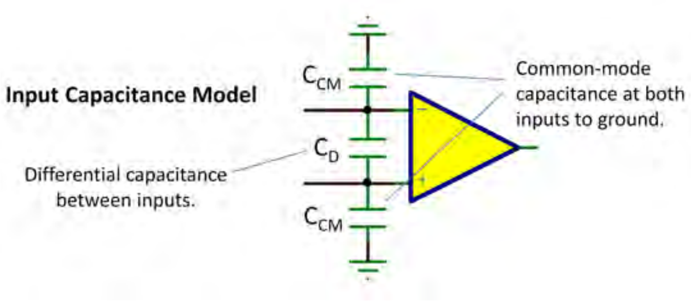

Figure 40: Input capacitance modeled as common-mode capacitance from each input to ground and differential capacitance between the inputs.

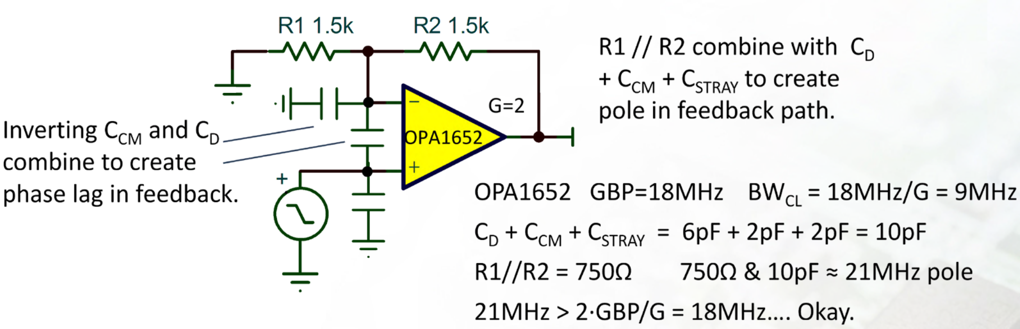

Figure 41: Calculation of pole due to input capacitance and feedback network.

At high frequencies where stability is a concern, the op amp has little open-loop gain, and substantial AC voltage exists between the two inputs. This causes the differential capacitance to combine with the inverting common-mode capacitance to alter the phase of the feedback signal. So add the two capacitances that connect to the inverting input. Include an estimate of stray wiring capacitance (perhaps around 2 pF). This total capacitance reacts with the parallel impedance of the feedback network (R1//R2) to create a pole (**Figure 41**).

A guideline: The frequency of this pole should be greater than two times the closed-loop bandwidth of the amplifier. A pole at two times the closed-loop bandwidth will reduce the phase margin of the circuit by approximately 27°. This is generally OK for most circuits in a closed-loop gain of two or greater. Applications with critical settling requirements or capacitive loads may require even greater margin. Reduce the feedback network impedance or consider adding a capacitor across the feedback capacitor, R2.

Today's general-purpose op amps often have wider bandwidths, from 5 MHz to 20 MHz and more. Feedback network resistances that may have been OK with 1-MHz op amps can now create problems – a reason to be diligent when checking the stability of your designs.

SPICE simulation is very helpful in checking sensitivities to input capacitance and feedback impedance, and good op amp macromodels accurately model input capacitances. A transient response check with a 1-mV input step should not cause excessive overshoot and ringing. But remember: Reality always trumps guidelines and simulations. This type of circuitry may require fine-tuning in a final circuit layout.

To see this original post with comments, click here.

17. Op amps ... G = 1 stable and decompensated

Unity-gain-stable operational amplifiers (op amps) are stable in the common G = +1 configuration, returning 100 percent of the output signal back to the inverting input. While it would be incorrect to call this truly a "worst case" for stability, you could reasonably call it a very common, testy case.

Decompensated op amps have smaller compensation capacitors that yield wider gain bandwidth (GBW) and faster slew rates. While higher speed normally demands more power, the same basic op amp can be significantly faster while operating on the same current. But they are not unity gain stable – they must be used in noise gains significantly greater than unity.

Figure 42 shows the critical portion of a gain vs. frequency graph for an idealized pair of unity-gain-stable and decompensated op amps. The decompensated version has five times the GBW – 10 MHz vs. 2 MHz. Slew rate gets the same boost. Note that the unity-gain bandwidth of the unity gain stable op amp is slightly less than its GBW, a common behavior. The unity-gain bandwidth of the decompensated amplifier is half its GBW. You have no business operating this amplifier with noise gain near the unity-gain bandwidth because a second pole at 3 MHz greatly affects the gain/phase behavior in this region. Phase margin would be poor or nonexistent.

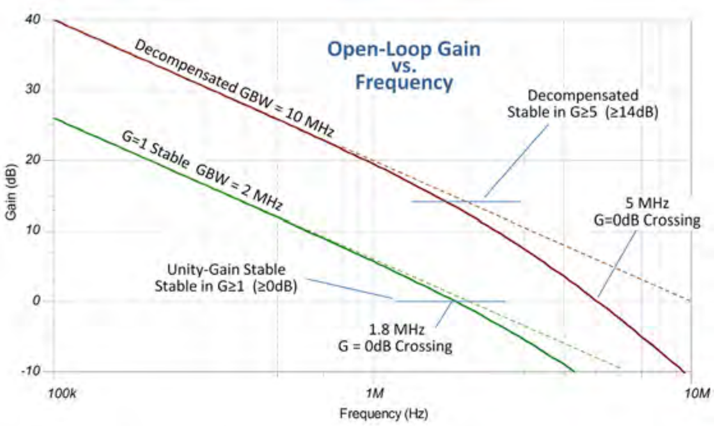

Figure 42: Graph of open-loop gain versus frequency for an idealized pair of unity-gain stable and decompensated op amps.

Decompensated op amps seem to hold a certain mystery, leaving some users uncertain about whether their circuits will be stable. **Figure 43a** shows a common misstep. Although this amplifier is connected in a signal gain of -10, a feedback capacitor rolls off the response at high frequency. This capacitor can be a virtual short circuit at high frequency where stability issues are a concern – unity gain. It is OK to use a small feedback capacitor to compensate the feedback network for flat gain, but a larger cap that rolls off response is sure to create problems.

Likewise, the multiple-feedback filter in **Figure 43b** invites trouble regardless of the low-frequency gain of the filter. The integrator (**Figure 43c**) is yet another application not suited to decompensated op amps.

TI has improved its op amp designs. We are smarter now and we have much better integrated circuit (IC) processes. With a few hundred microamperes, we can now make an amplifier that once required a couple of milliamperes. So sometimes a modern unity-gain-stable op amp may come very close to, or even beat, the speed/power of an older decompensated amp. Still, a decompensated op amp may be the best solution for a demanding application.

Let me be clear, I am not trying to urge you to select decompensated op amps over unity-gain-stable op amps. Each has merits, and you get to "vote" with your design choices. Whatever your selection, you should clearly understand the differences and issues. If you are unsure, help is available in the Precision Amplifiers forum on TI's E2E Community.

Here are some examples of decompensated and unity-gain-stable op amp pairs:

- OPA228 (OPA227 unity-gain-stable version) precision, low-noise, bipolar junction transistor (BJT) op amp.
- OPA637 (OPA627 unity-gain-stable version) precision, high-speed, junction FET (JFET) op amp.
- OPA345 (OPA344 unity-gain-stable version) rail-to-rail, CMOS op amp.
- LMP7717 (LMP7715 unity-gain-stable version) 88-MHz, CMOS op amp.

To see this original post with comments, click here.

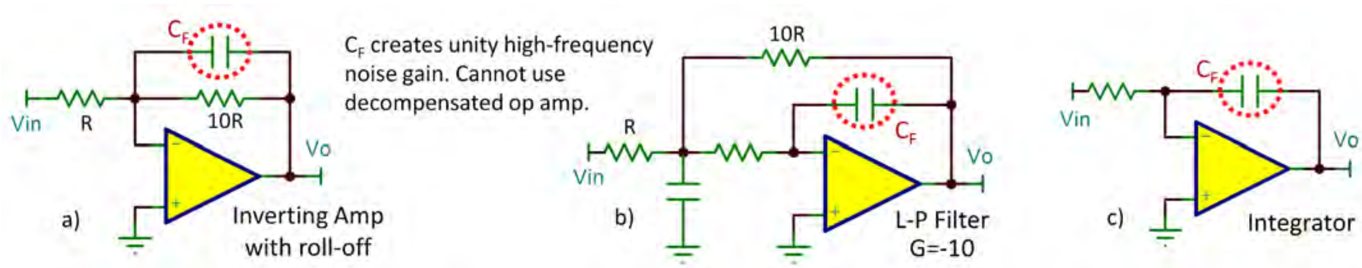

Figure 43: Using a decompensated op amp with a feedback capacitor to roll off the response at high frequency can lead instability (a); a multiple-feedback filter encounters problems irrespective of the filter's frequency gain (b); and an integrator is also unsuitable for decompensated op amps (c).

18. The inverting attenuator G = –0.1: is it unstable?

Unity-gain-stable operational amplifiers (op amps) are stable in a gain of one or greater, but not less, right? What to do (**Figure 44**)?

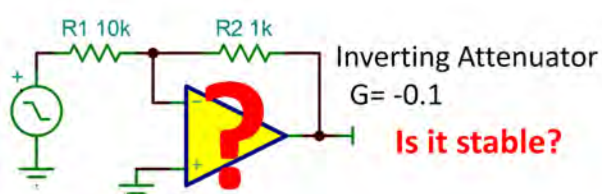

Figure 44: Example of an inverting attenuator.

OK, here is the short answer: an inverting attenuator is stable! You want to know why, right? There are a couple of ways to look at this issue, and a quick look may add clarity to general stability issues.

Consider this: If G = –0.1 were unstable, then even lower gain should be worse, right? Let us draw a circuit: a unity-gain amplifier with a 1-Ω feedback resistor, shown in **Figure 45**. Then consider possible circuit-board leakage forming an input resistor, R1 = 10 GΩ. This is a stray "input signal" amplified at very low inverting gain. Is it unstable? Certainly not! It is just a unity gain buffer with virtually no input. Stable.

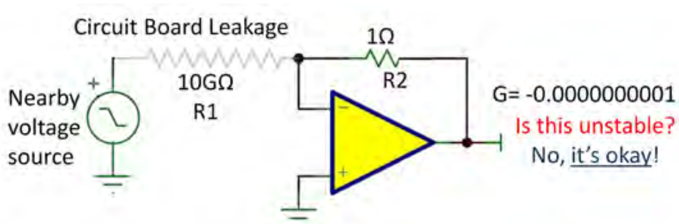

Figure 45: A unity-gain amplifier circuit with a 1-Ω feedback resistor is stable.

Think of the stability of an op amp as related to how much output signal is fed back to the inverting input. Stability experts refer to this feedback factor as beta (β). In unity gain, 100 percent of the output voltage is returned to the inverting input, so β is one. The example in **Figure 45** is essentially the same with nearly all of the output signal fed back to the inverting input.

Figure 46a shows an inverting amplifier and **Figure 46b** shows a noninverting amplifier. The circuits are the same; the input signal is just applied to different nodes. Both circuits return the same amount of output signal to the inverting input so their stability behavior is the same. β is the same.

Op amp wonks also use the term "noise gain" – so named because the op amp's voltage noise is amplified to the output by this factor. It is just another way to quantify the amount of feedback. An op amp circuit prone to oscillations or instability is incited by its own internal noise, amplified and fed back to the inverting input. The inverting amplifier, **Figure 46a**, has the same noise gain, β, and therefore the same stability behavior as its noninverting cousin, even though the input signal gain is different.

Are there circuits with noise gains less than one? Is β ever greater than one? Noise gains less than unity and β greater than one occur when gain is included in the feedback loop. Multiple amplifiers in a larger feedback loop, such as a control system, can face this issue. It also occurs when a transistor (common-emitter or common-source configuration) is included inside the feedback loop of an op amp. These circuits can have tricky stability problems.

Of course, there are other possible causes of oscillations or instability in an inverting attenuator. Capacitive load, excessively high resistor values or too much capacitance at the inverting input can cause instability – but these are unrelated to the basic inverting-attenuator configuration. Misconceptions about the "dangers" of the inverting attenuator persist. Relax. Simulate stability in TINA-TI software or your favorite SPICE program to confirm it. And if you have doubts or problems, check with the experts in the Precision Amplifiers forum on TI's E2E Community.

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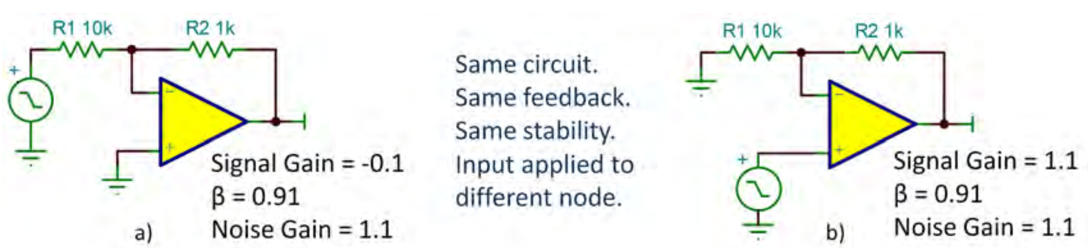

Figure 46: These two circuits, an inverting amplifier (a) and noninverting amplifier (b) have the same feedback factor and stability issues, but with the input signal are applied to different nodes.