Ask The Applications Engineer—25

by Grayson King

OP AMPS DRIVING CAPACITIVE LOADS

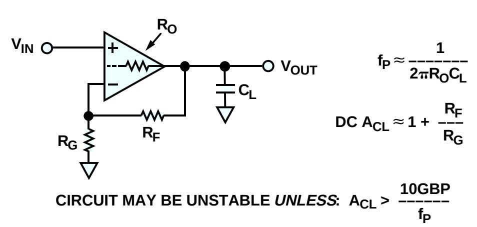
Q. *Why would I want to drive a capacitive load?*

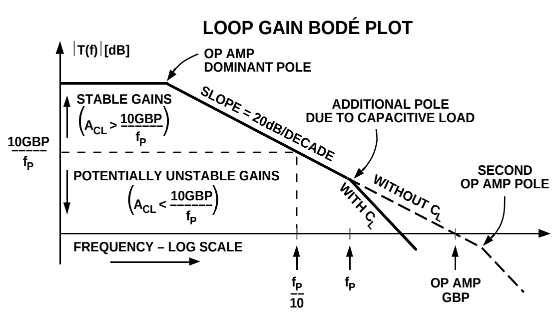
A. It's usually not a matter of choice. In most cases, the load capacitance is not from a capacitor you've added intentionally; most often it's an unwanted parasitic, such as the capacitance of a length of coaxial cable. However, situations do arise where it's desirable to decouple a dc voltage at the output of an op amp—for example, when an op amp is used to invert a reference voltage and drive a dynamic load. In this case, you might want to place bypass capacitors directly on the output of an op amp. Either way, a capacitive load affects the op amp's performance.

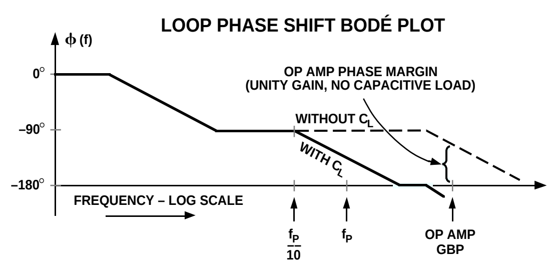
Q. *How does capacitive loading affect op amp performance?*

A. To put it simply, it can turn your amplifier into an oscillator. Here's how:

Op amps have an inherent output resistance, R_o, which, in conjunction with a capacitive load, forms an additional pole in the amplifier's transfer function. As the Bode plot shows, at each pole the amplitude slope becomes more negative by 20 dB/decade. Notice how each pole adds as much as –90° of phase shift. We can view instability from either of two perspectives. Looking at amplitude response on the log plot, circuit instability occurs when the sum of open-loop gain and feedback attenuation is greater than unity. Similarly, looking at phase response, an op amp will tend to oscillate at a frequency where loop phase shift exceeds –180°, if this frequency is below the closed-loop bandwidth. The closed-loop bandwidth of a voltage-feedback op amp circuit is equal to the op amp's gain-bandwidth product (GBP, or unity-gain frequency), divided by the circuit's closed loop gain (A_{CL}).







Phase margin of an op amp circuit can be thought of as the amount of additional phase shift at the closed loop bandwidth required to make the circuit unstable (i.e., phase shift + phase margin = –180°). As phase margin approaches zero, the loop phase shift approaches –180° and the op amp circuit approaches instability. Typically, values of phase margin much less than 45° can cause problems such as "peaking" in frequency response, and overshoot or "ringing" in step response. In order to maintain conservative phase margin, the pole generated by capacitive loading should be at least a decade above the circuit's closed loop bandwidth. When it is not, consider the possibility of instability.

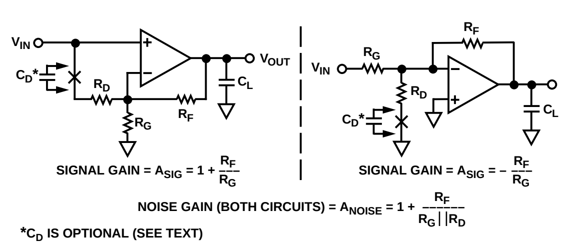
Q. *So how do I deal with a capacitive load?*

A. First of all you should determine whether the op amp can safely drive the load on its own. Many op amp data sheets specify a "capacitive load drive capability". Others provide typical data on "small-signal overshoot vs. capacitive load". In looking at these figures, you'll see that the overshoot increases exponentially with added load capacitance. As it approaches 100%, the op amp approaches instability. If possible, keep it well away from this limit. Also notice that this graph is for a specified gain. For a voltage feedback op amp, capacitive load drive capability increases proportionally with gain. So a VF op amp that can safely drive a 100-pF capacitance at unity gain should be able to drive a 1000-pF capacitance at a gain of 10.

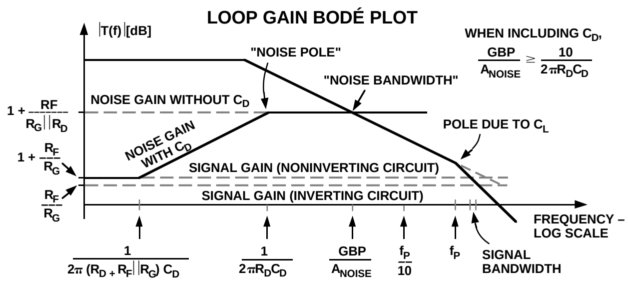
A few op amp data sheets specify the open loop output resistance (R_o), from which you can calculate the frequency of the added pole as described above. The circuit will be stable if the frequency of the added pole (f_P) is more than a decade above the circuit's bandwidth.

If the op amp's data sheet doesn't specify capacitive load drive or open loop output resistance, and has no graph of overshoot versus capacitive load, then to assure stability you must assume that any load capacitance will require some sort of compensation technique. There are many approaches to stabilizing standard op amp circuits to drive capacitive loads. Here are a few:

Noise-gain manipulation: A powerful way to maintain stability in low-frequency applications—often overlooked by designers—involves increasing the circuit's closed-loop gain (a/k/a "noise gain") without changing signal gain, thus reducing the frequency at which the product of open-loop gain and feedback attenuation goes to unity. Some circuits to achieve this, by connecting R_D between the op amp inputs, are shown below. The "noise gain" of these circuits can be arrived at by the given equation.



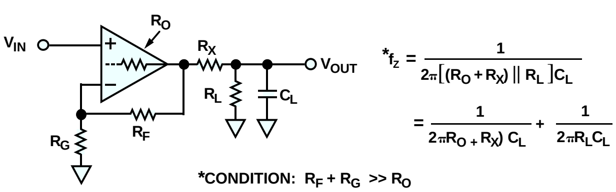
Since stability is governed by noise gain rather than by signal gain, the above circuits allow increased stability without affecting signal gain. Simply keep the "noise bandwidth" (GBP/A_{NOISE}) at least a decade below the load generated pole to guarantee stability.

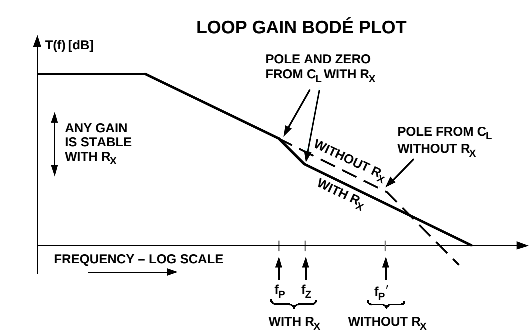


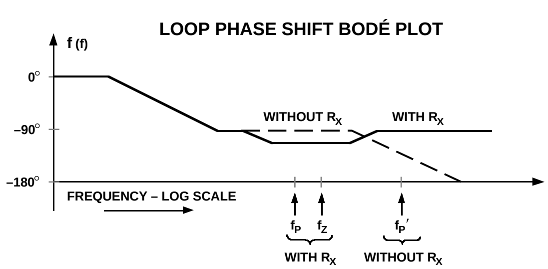
One disadvantage of this method of stabilization is the additional output noise and offset voltage caused by increased amplification of input-referred voltage noise and input offset voltage. The added dc offset can be eliminated by including C_D in series with R_D, but the added noise is inherent with this technique. The effective noise gain of these circuits with and without C_D are shown in the figure.

C_D, when used, should be as large as feasible; its minimum value should be 10 $A_{NOISE}/(2\pi R_D GBP)$ to keep the "noise pole" at least a decade below the "noise bandwidth".

Out-of-loop compensation: Another way to stabilize an op amp for capacitive load drive is by adding a resistor, R_X, between the op amp's output terminal and the load capacitance, as shown below. Though apparently outside the feedback loop, it acts with the load capacitor to introduce a zero into the transfer function of the feedback network, thereby reducing the loop phase shift at high frequencies.



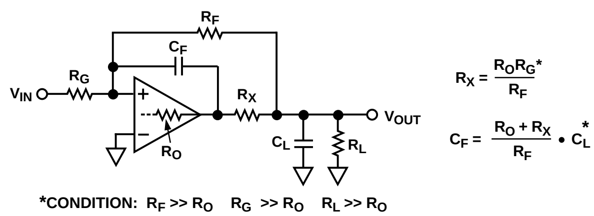




To ensure stability, the value of R_X should be such that the added zero (f_Z) is at least a decade below the closed loop bandwidth of the op amp circuit. With the addition of R_X, circuit performance will not suffer the increased output noise of the first method, but the output impedance as seen by the load will increase. This can decrease signal gain, due to the resistor divider formed by R_X and R_L. If R_L is known and reasonably constant, the results of gain loss can be offset by increasing the gain of the op amp circuit.

This method is very effective in driving transmission lines. The values of R_L and R_X must equal the characteristic impedance of the cable (often 50 Ω or 75 Ω) in order to avoid standing waves. So R_X is pre-determined, and all that remains is to double the gain of the amplifier in order to offset the signal loss from the resistor divider. Problem solved.

In-loop compensation: If R_L is either unknown or dynamic, the effective output resistance of the gain stage must be kept low. In this circumstance, it may be useful to connect R_X inside the overall feedback loop, as shown below. With this configuration, dc and low-frequency feedback comes from the load itself, allowing the signal gain from input to load to remain unaffected by the voltage divider, R_X and R_L.



The added capacitor, C_F, in this circuit allows cancellation of the pole and zero contributed by C_L. To put it simply, the zero from C_F is coincident with the pole from C_L, and the pole from C_F with the zero from C_L. Therefore, the overall transfer function and phase response are exactly as if there were no capacitance at all. In order to assure cancellation of both pole/zero combinations, the above equations must be solved accurately. Also note the conditions; they are easily met if the load resistance is relatively large.

Calculation is difficult when R_O is unknown. In this case, the design procedure turns into a guessing game—and a prototyping nightmare. A word of caution about SPICE: SPICE models of op amps don't accurately model open-loop output resistance (R_O); so they cannot fully replace empirical design of the compensation network.

It is also important to note that C_L must be of a known (and constant) value in order for this technique to be applicable. In many applications, the amplifier is driving a load "outside the box," and C_L can vary significantly from one load to the next. It is best to use the above circuit only when C_L is part of a closed system.

One such application involves the buffering or inverting of a reference voltage, driving a large decoupling capacitor. Here, C_L is a fixed value, allowing accurate cancellation of pole/zero combinations. The low dc output impedance and low noise of this method (compared to the previous two) can be very beneficial. Furthermore, the large amount of capacitance likely to decouple a reference voltage (often many microfarads) is impractical to compensate by any other method.

All three of the above compensation techniques have advantages and disadvantages. You should know enough by now to decide which is best for your application. All three are intended to be applied to "standard", unity gain stable, voltage feedback op amps. Read on to find out about some techniques using special purpose amplifiers.

Q. *My op amp has a "compensation" pin. Can I overcompensate the op amp so that it will remain stable when driving a capacitive load?*

A. Yes. This is the easiest way of all to compensate for load capacitance. Most op amps today are internally compensated for unity-gain stability and therefore do not offer the option to "overcompensate". But many devices still exist with inherent stability only at very high noise gains. These op amps have a pin to which an external capacitor can be connected in order to reduce the frequency of the dominant pole. To operate stably at lower gains, increased capacitance must be tied to this pin to reduce the gain-bandwidth product. When a capacitive load must be driven, a further increase (overcompensation) can increase stability—but at the expense of bandwidth.

Q. *So far you've only discussed voltage feedback op amps exclusively, right? Do current feedback (CF) op amps behave similarly with capacitive loading? Can I use any of the compensation techniques discussed here?*

A. Some characteristics of current feedback architectures require special attention when driving capacitive loads, but the overall effect on the circuit is the same. The added pole, in conjunction with op-amp output resistance, increases phase shift and reduces phase margin, potentially causing peaking, ringing, or even oscillation. However, since a CF op amp can't be said to have a "gain-bandwidth product" (bandwidth is much less dependent on gain), stability can't be substantially increased simply by increasing the noise gain. This makes the first method impractical. Also, a capacitor (C_F) should NEVER be put in the feedback loop of a CF op amp, nullifying the third method. The most direct way to compensate a current feedback op amp to drive a capacitive load is the addition of an "out of loop" series resistor at the amplifier output as in method 2.

Q. *This has been informative, but I'd rather not deal with any of these equations. Besides, my board is already laid out, and I don't want to scrap this production run. Are there any op amps that are inherently stable when driving capacitive loads?*

A. Yes. Analog Devices makes a handful of op amps that drive "unlimited" load capacitance while retaining excellent phase margin. They are listed in the table, along with some other op amps that can drive capacitive loads up to specified values. About the "unlimited" cap load drive devices: don't expect to get the same slew rate when driving 10 µF as you do when driving purely resistive loads. Read the data sheets for details.

Part Number	Ch	BW MHz	SR V/µs	v_n nV/√Hz	i_n fA/√Hz	V_{OS} mV	I_b nA	Supply Voltage Range [V]	I_Q mA	R_O Ω	Cap Load Drive [pF]	Notes
AD817	1	50	350	15	1500	0.5	3000	5-36	7	8	**unlim**	
AD826	2	50	350	15	1500	0.5	3000	5-36	6.8	8	**unlim**	
AD827	2	50	300	15	1500	0.5	3000	9-36	5.25	15	**unlim**	
AD847	1	50	300	15	1500	0.5	3000	9-36	4.8	15	**unlim**	
AD848	1	35	200	5	1500	0.5	3000	9-36	5.1	15	**unlim**	G_{MIN} = 5
AD849	1	29	200	3	1500	0.3	3000	9-36	5.1	15	**unlim**	G_{MIN} = 25
AD704	4	0.8	0.15	15	50	0.03	0.1	4-36	0.375		**10000**	
AD705	1	0.8	0.15	15	50	0.03	0.06	4-36	0.38		**10000**	
AD706	2	0.8	0.15	15	50	0.03	0.05	4-36	0.375		**10000**	
OP97	1	0.9	0.2	14	20	0.03	0.03	4-40	0.38		**10000**	
OP279	2	5	3	22	1000	4	300	4.5-12	2	22	**10000**	
OP400	4	0.5	0.15	11	600	0.08	0.75	6-40	0.6		**10000**	
AD549	1	1	3	35	0.22	0.5	0.00015	10-36	0.6		**4000**	
OP200	2	0.5	0.15	11	400	0.08	0.1	6-40	0.57		**2000**	
OP467	4	28	170	6	8000	0.2	150	9-36	2		**1600**	
AD744	1	13	75	16	10	0.3	0.03	9-36	3.5		**1000**	comp.term
AD8013	3	140	1000	3.5	12000	2	3000	4.5-13	3.4		**1000**	current fb
AD8532	2	3	5	30	50	25	0.005	3-6	1.4		**1000**	
AD8534	4	3	5	30	50	25	0.005	3-6	1.4		**1000**	
OP27	1	8	2.8	3.2	1700	0.03	15	8-44	6.7	70	**1000**	
OP37	1	12	17	3.2	1700	0.03	15	8-44	6.7	70	**1000**	G_{MIN} = 5
OP270	2	5	2.4	3.2	1100	0.05	15	9-36	2		**1000**	
OP470	4	6	2	3.2	1700	0.4	25	9-36	2.25		**1000**	
OP275	2	9	22	6	1500	1	100	9-44	2		**1000**	
OP184	1	4.25	4	3.9	400	0.18	80	4-36	2		**1000**	
OP284	2	4.25	4	3.9	400	0.18	80	4-36	2		**1000**	
OP484	4	4.25	4	3.9	400	0.25	80	4-36	2		**1000**	
OP193	1	0.04	15	65	50	0.15	20	3-36	0.03		**1000**	
OP293	2	0.04	15	65	50	0.25	20	3-36	0.03		**1000**	
OP493	4	0.04	15	65	50	0.28	20	3-36	0.03		**1000**	
OP297	2	0.5	0.15	17	20	0.08	0.05	4-40	0.525		**1000**	
OP497	4	0.5	0.15	25	20	0.08	0.06	4-40	0.525		**1000**	

REFERENCES

Practical Analog Design Techniques, Analog Devices 1995 seminar notes. Cap load drive information can be found in section 2, "High-speed op amps" (Walt Jung and Walt Kester). **Available on our Web site: www.analog.com or see the book purchase card**

Application Note AN-257: "Careful design tames high-speed op amps," by Joe Buxton, in ADI's *Applications Reference Manual* (1993). A detailed examination of the "in-loop compensation" method. Free.

"Current-feedback amplifiers," Part 1 and Part 2", by Erik Barnes, *Analog Dialogue* 30-3 and 30-4 (1996), now consolidated in *Ask The Applications Engineer* (1997). **Available on our Web site**. ▶