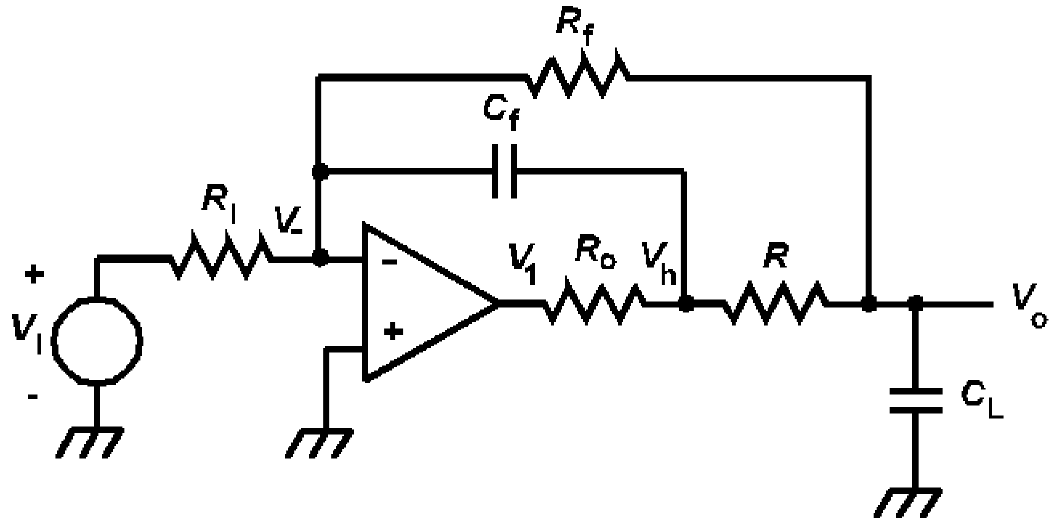
Why Circuits Oscillate Spuriously, Part 2: Amplifier Loading
by Dennis L Feucht

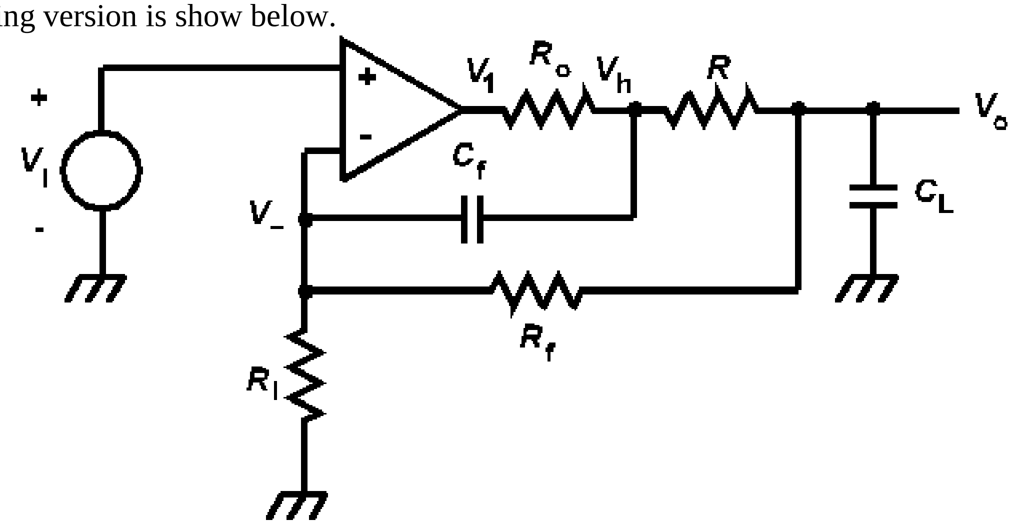
In this third, and final part, we continue this TechNote with a difficult aspect of amplifier design: instability due to reactive output loading of a feedback amplifier. In Part 2 amplifier hf-region oscillation due to reactive loading was considered. Reactive loading can also cause feedback-amplifier loop instability. The design equations needed to isolate the amplifier output from the load and achieve an acceptable dynamic response are developed and explained here.

Output Load Isolation

In some feedback amplifiers the load impedance is highly reactive and the amplifier has a significant output resistance R_o. This combination can add a load-dependent output pole to the loop. A method for isolating capacitive loads is shown below, where C_L is the load, and R_o is the amplifier open-loop output resistance.



The noninverting version is show below.



The compensation scheme has two feedback paths, an accurate low-frequency path and a load-isolated high-frequency path. The feedback compensation capacitor, C_f, is isolated from the load by output decoupling resistor R. The low-frequency feedback through R_f is taken at the output to eliminate dc error due to R_o and R.

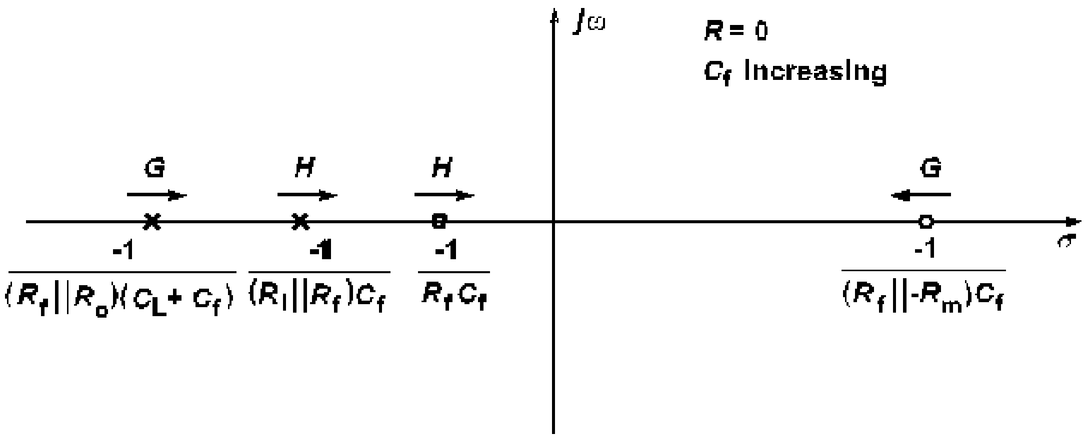
With no load isolation or compensation:

$$R = C_f = 0$$

The load introduces a pole in the loop at $-1/(R_f \| R_o)\cdot C_L$. If C_f is then added to compensate for this pole, the loop gain becomes:

$$GH = -\left(\frac{R_f \| R_o}{R_f \| (-R_m)}\right)\left(\frac{R_i}{R_f + R_i}\right)\frac{\{s[R_f \| (-R_m)]C_f + 1\}(sR_f C_f + 1)}{[s(R_f \| R_o)(C_f + C_L) + 1][s(R_f \| R_i)C_f + 1]}$$

where, $R_m = R_o/(-K)$. When $C_L = 0$ and $R_i >> R_o$, the poles are well separated. As C_L increases, pole separation decreases as the higher pole moves down in frequency, reducing stability. C_f introduces a feedback zero and pole as a phase-lead network. Pole movement is shown in the *s*-domain plot below.

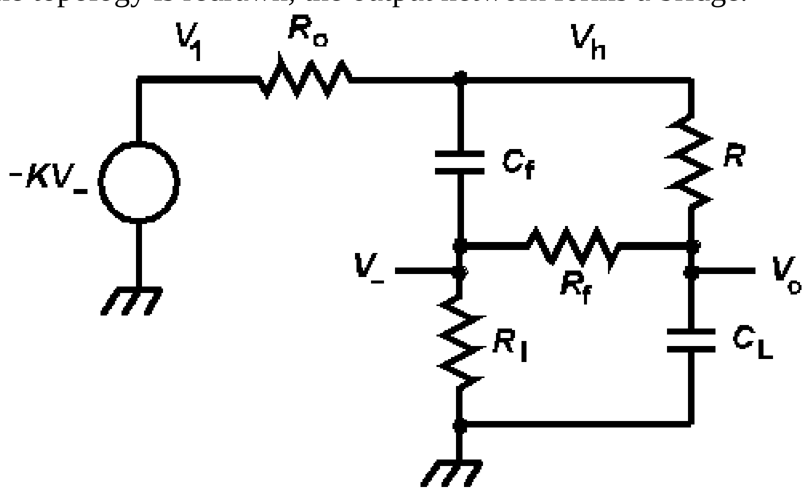


Its zero can be placed to cancel the amplifier output pole by setting:

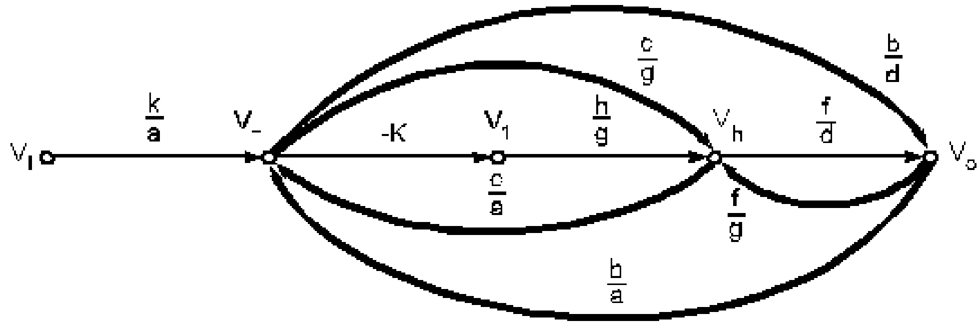
$$C_f = \frac{R_o}{R_f} C_L$$

From the parameter-variation plot above, as C_f increases, all poles and zeros shift toward the origin. For $C_L >> C_f$, the load pole is stationary, and the pole and zero in *H* move together and away from the load pole.

When *R* is added and the topology is redrawn, the output network forms a bridge.



The exact solution for this circuit, a nontrivial exercise, is found by applying KCL at the nodes of voltages: V_- , V_1, V_h, and V_o. This results in the flow graph for the inverting amplifier:



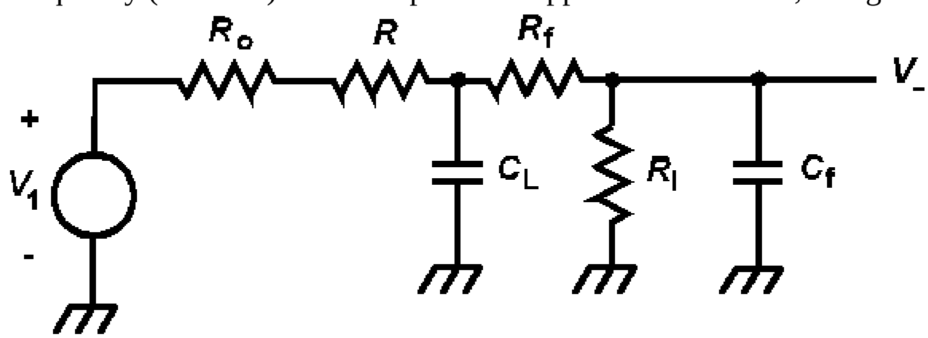
where,

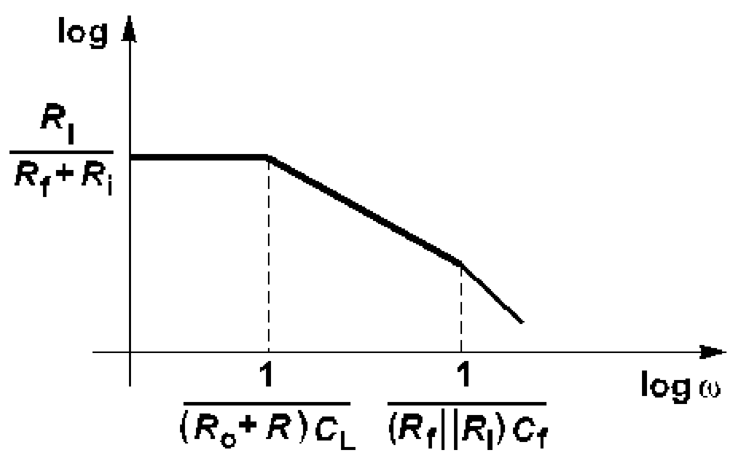
$$a = \frac{1}{(R_i \| R_f \| 1/sC_f)}, \qquad b = \frac{1}{R_f}, \qquad c = sC_f, \qquad d = \frac{1}{(Z_L \| R_f \| R)}$$

$$f = \frac{1}{R}, \qquad g = \frac{1}{(R_o \| 1/sC_f \| R)}, \qquad h = \frac{1}{R_o}, \qquad k = \frac{1}{R_i}$$

The amplifier gain is $-K$ and $V_1 = -KV_-$. Some simplifying assumptions can be made that reduce the complexity of the flow graph (such as removing b/d, c/g, and/or f/g) but the remaining circuit analysis is still unwieldy. We need a more functionally-oriented approach.

The low- and high-frequency (lf and hf) feedback paths are approximated below, along with their Bode plots.



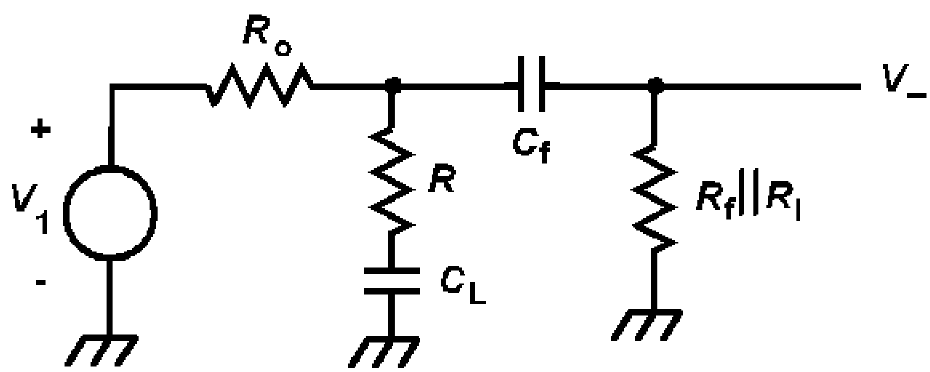


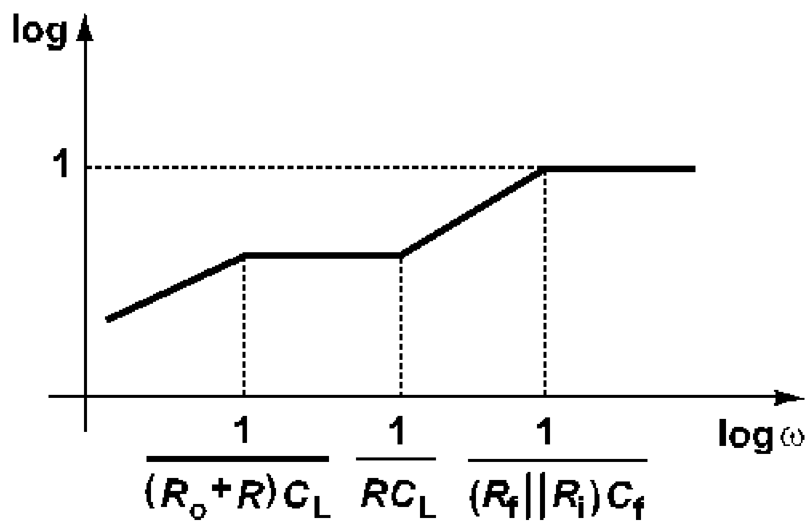
The lf path, shown above, has transmittance:

$$\left.\frac{V_-}{V_1}\right|_{lf} = \left(\frac{R_i}{R_f + R_i}\right)\left(\frac{1}{s(R_o + R)C_L + 1}\right)\left(\frac{1}{s(R_f \| R_i)C_f + 1}\right),$$

$$R_o << \frac{1}{sC_f}, \qquad R_o + R << R_f + R_i$$

where the simplifying assumptions are that C_f and $R_f + R_i$ do not load the smaller output resistances R_o and R.





The hf path, shown above, has a transmittance of:

$$\left.\frac{V_-}{V_1}\right|_{hf} = \left(\frac{sRC_L + 1}{s(R_o + R)C_L + 1}\right)\left(\frac{s(R_f \| R_i)C_f}{s(R_f \| R_i)C_f + 1}\right),$$

$$R_o, R << \frac{1}{sC_f}, \qquad \frac{1}{sC_L} << R_f$$

The hf-path approximations are similar to those of the lf path. At high frequencies this feedback transmittance approaches:

$$\frac{R}{R_o + R}$$

The composite feedback transmittance is the sum of the two paths, or:

$$\frac{V_-}{V_1} = \left(\frac{R_i}{R_f + R_i}\right)\frac{s^2 RC_L R_f C_f + sR_f C_f + 1}{[s(R_o + R)C_L + 1][s(R_f \| R_i)C_f + 1]}$$

Without R, we have one less LHP zero, as in GH. The feedback path is an all-pass network when the coefficients of the pole and zero terms are equated. This results in:

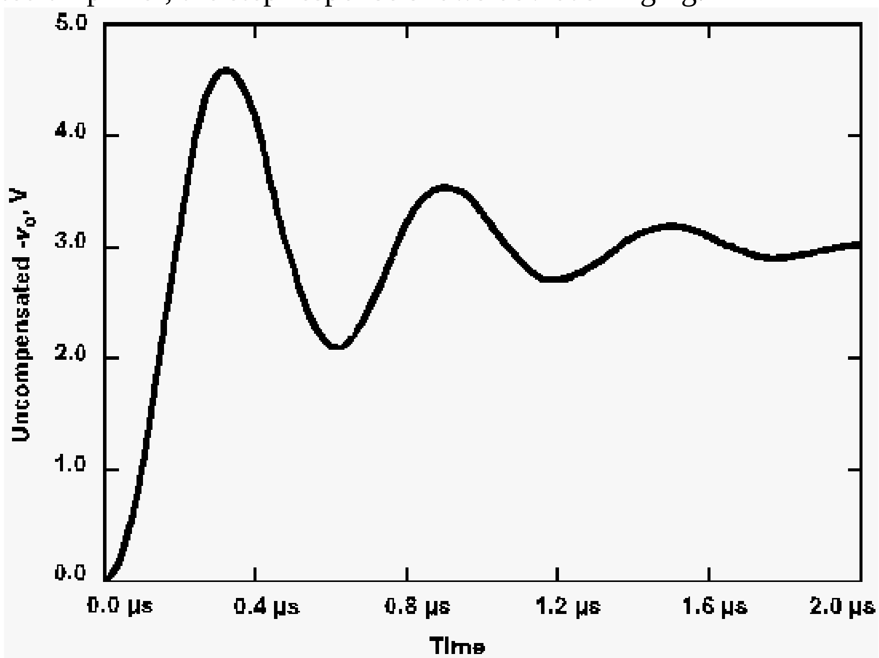
$$R = \left(\frac{R_i}{R_f}\right)R_o, \qquad C_f = \left(\frac{R_o + R}{R_f}\right)\left(\frac{R_f + R_i}{R_f}\right)C_L$$

and the load capacitance pole is removed from the loop gain. The closed-loop response, however, is still affected by C_L. The constraints of V_-/V_1 for lf and hf paths require that $1/R_oC_f$ be checked after applying these formulae for R and C_f, to make sure that it is well above f_T.

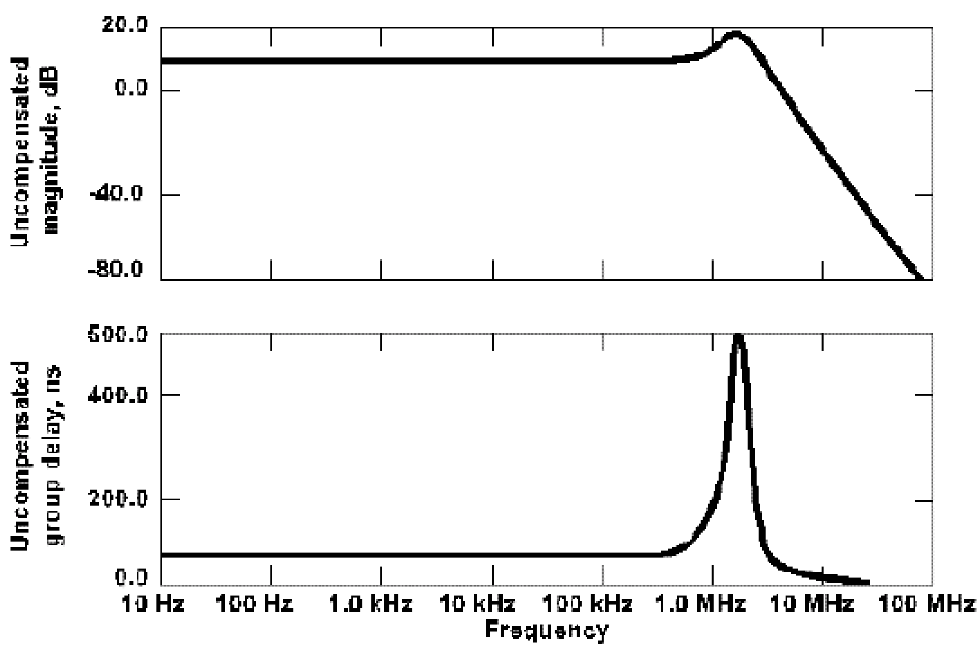
Example: Load Capacitance Compensation

A fast op-amp with $K = 10^5$ and poles at 100 Hz and 4 MHz is used in the inverting configuration to drive a 10 nF load with a voltage gain of –3. R_f = 30 kΩ and R_i = 10 kΩ. The open-loop output resistance is 10 Ω. The feedback capacitor C_f and decoupling resistor R are calculated as: R = *3.3 Ω and* C_f = *5.9 pF*

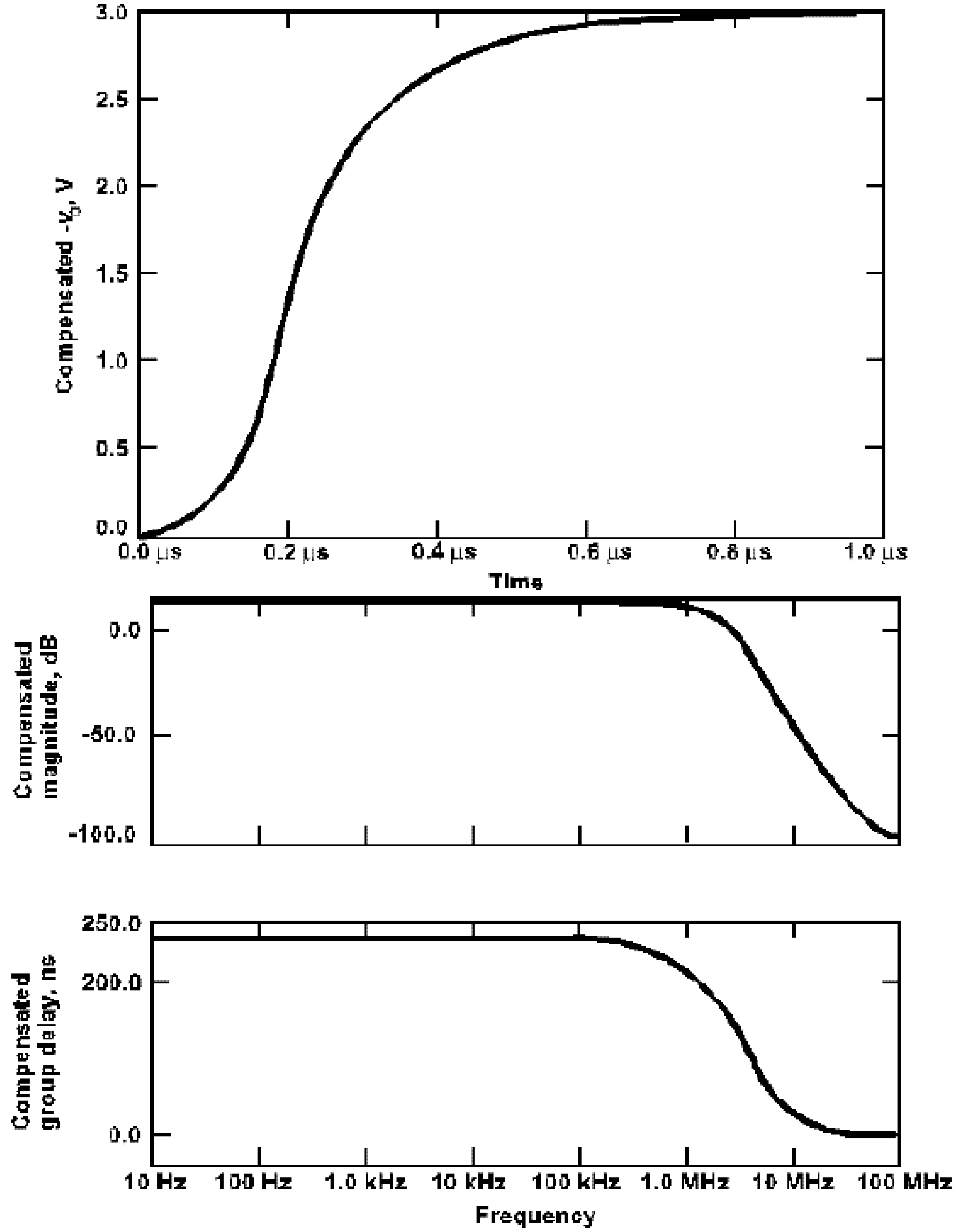
For the uncompensated amplifier, the step response shows obvious ringing:



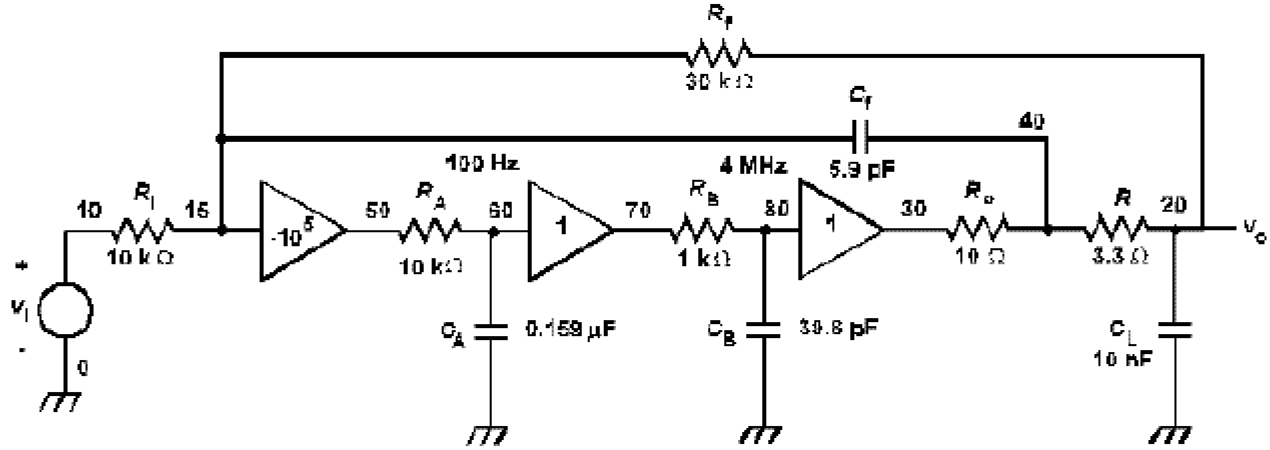
And peaking is evident in the frequency response and group delay plots:



Compensation is now applied, and the response improves. No ringing is evident in the step response, with no peaking in the group delay or frequency response (below).



The schematic diagram of the compensated amplifier shows how the op amp is modeled, using *RC* integrators and buffers to create the poles.



The SPICE program used for the simulation is listed below:

```
Load-compensated amplifier
.OPT NOMOD OPTS NOPAGE
.AC DEC 20 10 100MEG
.TRAN 20n 2u
VI 10 0 AC 1V PULSE (0 1V)
; amplifier with pole at 100Hz
EA 50 0 15 0 -1e5
RA 50 60 10k
CA 60 0 0.159uF
EB 70 0 60 0 1
RB 70 80 1k
CB 80 0 39.8pF
EC 30 0 80 0 1
RO 30 40 10
R 40 20 3.3
CL 20 0 10nF
CF 40 15 5.9pF
RF 10 20 10k
RO 20 15 30k
.PROBE
.END
```

Capacitive loads can also be isolated by placing a shunt *RL* in series with the amplifier output. At dc the transmittance to the load is one. At high frequencies, *L* appears open, leaving *R* as isolation. For excessive inductive loading, the load is often characterized by a series *RL*. If it is fixed, a series *RC* in parallel with it can form a constant-impedance network.

Closure

Various methods for preventing and eliminating spurious circuit oscillation have been presented. Each depends for its successful application on an understanding of the underlying circuit principles. Some of these principles are not very widely circulated among electronics engineers though they were discovered many years ago. They are developed in detail in *Analog Circuit Design* at http://www.innovatia.com This section on output load isolation was taken from it as were some of the contents of the previous Parts 1 and 2.

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