Get Fast Stable Response From Improved Unity-Gain Followers
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In many applications, a unity-gain follower (e.g. any operational amplifier with tight feedback to the inverting input) may oscillate or exhibit bad ringing when required to drive heavy load capacitance. For example, the LM110 follower will normally drive a 50 pF load capacitor, but will not drive 500 pF, because the open-loop output impedance is lagged by such a large capacitive load. The frequency at which this lag occurs is comparable to the gain-bandwidth product of the amplifier, and when the phase margin is decreased to zero, oscillation occurs.

While the solution to this problem is not widely known, an analysis of the general problem shown in Figure 2 can lead to a useful approach. It is generally known that increasing the noise gain of an op amp’s feedback network will improve tolerance of capacitive load. In Figure 2, adding a resistor $R_2 = R_F/10$ will do this. (A moderate capacitor $C_2$ is usually inserted in series with $R_2$, to prevent the DC noise gain from increasing also—to avoid degrading DC offset, drift and inaccuracy.) If the op amp has a 1 MHz gain bandwidth product, and $R_1 = R_F$, the closed-loop frequency response will be $1/2$ MHz. Adding $R_2 = R_F/10$ will drop the closed-loop frequency response to 90 kHz, where the amplifier can usually tolerate a much larger $C_L$.

A similar result will occur if you install $R_3$ and $C_3$, instead of $R_2$. Now the (AC) noise gain will be:

$$\text{Noise Gain} = \frac{R_F}{R_1} \left(1 + \frac{R_F}{R_2} + \frac{R_F}{R_3} \right)$$

As a simplification, if $R_1$ is an open circuit, the AC noise gain will be: $(R_4/R_3 + R_F/R_3 + 1)$. Now it can be seen that noise gain can be raised by having a low value of $R_3$ and a high value of $R_4$ or $R_F$ (or both).

In particular, where $R_F$ is required to be $0 \Omega$, as in a follower, the noise gain can be raised by adding a large $R_4$ and a
small R5, as shown in Figure 3. If Rs is low, the AC noise gain will be R4/R5 + 1. (If Rs is large and constant, R4 may be unnecessary, and the noise gain would then be Rs/R5 + 1.) For LM110/LM310’s R4 = 10 kΩ is recommended and when R5 = 3.3 kΩ, C5 = 200 pF, the LM110 will stably drive C_L up to 600 pF.

Another application of this technique is for making a fast follower with a high slew rate. An LF356 is specified as a follower, but an LF357 must be applied at an “Av = 5” minimum, because it has been “decompensated” with a smaller internal capacitor. Most people do not realize how easy it is to apply an LF357 as a follower. In Figure 4, an LF357 will have fast, stable response just like an LF356 does, when Rs is < 1 kΩ, but it will have a 50V/μs slew rate (typical) vs. 12V/μs for an LF356.

Similarly, an LM348 is a fast decompensated quad op amp. Its bipolar input stage has a finite bias current, 200 nA max. For best results, the resistance which makes up the noise gain should be put equally in the plus and minus input circuits, as shown in Figure 5. The LM349 can slew at 2V/μs typical, and is much faster for handling audio signals without distortion than the LM348 (which at 0.5V/μs is only as fast as an ordinary LM741). The same approach can be used for an LM101 with a 5 pF damping capacitor. While these circuits give faster slewing, the bandwidth may degrade if the source impedance Rs increases. Also, when the AC noise gain is raised, the AC noise will also be increased. While most modern op amps have low noise, a noise gain of 10 may make a significant increase in output noise, which the user should check to insure it is not objectionable.

If the series capacitor is much larger than necessary, noise will be increased more than necessary. In general, choose the C5 for Figure 3, (e.g.) per these guidelines: (where f_V = unity-gain bandwidth of op amp)

\[
C5 \text{ Min} = \frac{4 \cdot \left(1 + \frac{R4}{R5}\right)}{2\pi R5 \cdot f_V} = \frac{R4 + R5}{\pi \cdot f_V \cdot (R5)^2}
\]

For best results, choose the design center value of C5 to be 2 or 3 times C5 min.
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