Op-amp-gain error analysis

ONE OF MY PREVIOUS COLUMNS explains a method for calculating decreasing open-loop-gain-induced errors (Reference 1). Several readers requested a simpler error-function explanation, so this one uses op-amp equations to illustrate the effect of reduced gain on accuracy.

The gain of a typical voltage-feedback op amp starts falling off at very low frequencies. Op amps have an approximate open-loop gain of 100 dB at a frequency of 10 Hz, and the op-amp gain rolls off at a rate of −20 dB/decade. The closed-loop-gain equation for a noninverting op amp is:

\[ \frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{a}{1 + \frac{aR_G}{R_F + R_G}} \]

where \(a\) is the op-amp gain, \(R_f\) is the feedback resistor, and \(R_c\) is the gain-setting resistor (Reference 2).

Let the ideal closed-loop gain, \(V_{\text{OUT}}/V_{\text{IN}}=(1+R_F/R_g)=2\), so \(R_f=R_g\). Table 1 tabulates the actual gain for each decade increase in frequency. A 2% error exists at \(f=10\) kHz, and the circuit is usable in most applications. However, a higher bandwidth op amp reduces the error in applications with input frequencies greater than 10 kHz. The incoming signal is normally a complex waveform involving many frequencies, so it is apparent that this op amp degrades the high-frequency content of the input waveform. You don’t know whether the op amp is usable until you know what portion of the input signal is degraded. As Reference 1 suggests, prudent designers must carefully analyze the input signal to get the best bang for their buck; if 0.1% of the input signal is 10 kHz or higher, then 2% of the overall degradation shouldn’t hurt you at all.

The closed-loop gain for an inverting op amp is:

\[ \frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{-aR_F}{1 + \frac{aR_G}{R_F + R_G}} \]

The inverting-op-amp circuit complicates the situation because the \(R_f\) and \(R_c\) modify the op-amp gain in the numerator. Let the ideal closed-loop gain, \(V_{\text{OUT}}/V_{\text{IN}}=(−R_f/ R_g)=−2\), so \(R_f=2R_g\). Table 2 tabulates the actual gain for each decade increase in frequency.

Now for the surprise: The noninverting and inverting circuits with identical ideal closed-loop gains have different error functions. The inverting circuit error is higher for equivalent ideal closed-loop gains. This situation is always the case, but at higher ideal closed-loop gains, the errors begin to merge.

The differential amplifier uses both op-amp inputs. A voltage divider (\(R_f\) and \(R_c\)) and an inverting circuit precede the differential amplifier’s noninverting circuit. The amplifier’s gain equation is:

\[ V_{\text{OUT}} = \frac{V_{\text{IN}} \left( \frac{R_2}{R_1 + R_2} \right)}{1 + \frac{aR_F}{R_F + R_G}} \]

When \(R_f=2R_g\) and \(R_c=2R_g\), the inverting and noninverting errors are different, and that situation can lead to unexpected distortion because the error terms are different. But, when \(R_f=R_g\) and \(R_c=R_g\), the equation reduces to:

\[ V_{\text{OUT}} = (V_{\text{IN}} - V_{\text{IN}}) \left( \frac{aR_F}{R_F + R_G} \right) \]

and the error terms are identical.

Amplifier gain falls as frequency increases, and switching to a current-feedback amplifier can minimize this physical characteristic of voltage-feedback amplifiers. The switch is not always possible because current-feedback amplifiers have lower precision. The choice usually boils down to using a higher bandwidth voltage-feedback amplifier, accepting the error, or using frequency peaking to extend the bandwidth of the circuit. Frequency peaking is better left for a future column.

References

Ron Mancini is staff scientist at Texas Instruments. You can reach him at 1-352-568-1040, rmancini@ti.com.