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Op Amp Open-Loop Gain and Open-Loop Gain Nonlinearity

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IN THIS MINI TUTORIAL

This mini tutorial explores open-loop gain and open-loop gain nonlinearity when used for voltage feedback op amps, including methods for calculating and understanding these gain relationships.

INTRODUCTION

Open-Loop Gain

Open-loop voltage gain, usually referred to by the acronym, A_{VOL} (or simply A_V), for most voltage feedback (VFB) op amps is quite high. Common values are 100,000 to 1,000,000, and 10 or 100 times these figures for high precision devices. Some fast op amps have appreciably lower open-loop gain, but gains of less than a few thousand are unsatisfactory for high accuracy use. Note also that open-loop gain is not stable with temperature, and can vary quite widely from device to device of the same type, so it is important that it be reasonably high.

Because a voltage feedback op amp operates as voltage input/voltage output, its open-loop gain is a dimensionless ratio, so no unit is necessary. However, data sheets sometimes express gain in V/mV or V/μV instead of V/V, for the convenience of using smaller numbers. Voltage gain can also be expressed in dB terms, as gain in dB = 20 × logA_{VOL}. Thus, an open-loop gain of 1V/μV is equivalent to 120 dB.

Current feedback (CFB) op amps have a current input and a voltage output, so their open-loop transimpedance gain is expressed in volts per ampere or ohms (kΩ or MΩ). Values usually reside between hundreds of kΩ and tens of MΩ.

From basic feedback theory, it is understood that to maintain accuracy, the dc open-loop gain (A_{VOL}) of a precision amplifier should be high. This can be seen by examining the closed-loop gain equation, including errors due to finite gain. The expression for closed loop gain with a finite gain error is as follows:

$$G_{CL} = \frac{1}{\beta} \times \left(\frac{1}{1 + \frac{1}{A_{VOL}\beta}} \right) \quad (1)$$

where β is the feedback loop attenuation, or feedback factor (the voltage attenuation of the feedback network).

Because noise gain is equal to 1/β, there are alternate forms of this expression. Combining the two right side terms and using the noise gain (NG) expression, an alternate calculation is

$$G_{CL} = \frac{NG}{1 + \frac{NG}{A_{VOL}}} \quad (2)$$

Equation 1 and Equation 2 are equivalent, and either can be used. As previously noted, noise gain is simply the gain seen by a small voltage source in series with the op amp input; it is the ideal amplifier signal gain in the noninverting mode. If A_{VOL} in Equation 1 and Equation 2 is infinite, the closed-loop gain becomes exactly equal to the noise gain, 1/β.

However, for NG << A_{VOL} and finite A_{VOL}, there is a closed-loop gain error estimation of

$$\textit{Closed-Loop Error}\ (\%) \approx \frac{NG}{A_{VOL}} \times 100 \quad (3)$$

Notice from Equation 3 that the percent gain error is directly proportional to the noise gain; therefore, the effects of finite A_{VOL} are less for low gain. Some examples illustrate key points about these gain relationships.

Open-Loop Gain Uncertainty

Consider the following conditions for Example A and Example B:

- Ideal closed-loop gain = 1/β = NG
- Actual closed-loop gain = $\frac{1}{\beta} \times \left| \frac{1}{1 + \frac{1}{A_{VOL}\beta}} \right| = \frac{NG}{1 + \frac{NG}{A_{VOL}}}$
- Closed-loop gain error (%) $\approx \frac{NG}{A_{VOL}} \times 100$ (NG << A_{VOL})

For Example A, a noise gain of 1000 shows that for an open-loop gain of 2 million, the closed-loop gain error is about 0.05%. Note that, if the open-loop gain stays constant over temperature and for various output loads and voltages, the 0.05% gain error can be calibrated out of the measurement easily, leaving no overall system gain error. If, however, the open-loop gain changes, the resulting closed-loop gain also changes, thereby introducing gain uncertainty.

Thus, Example A assumes A_{VOL} = 2,000,000 and NG = 1000, thereby resulting in a gain error of ≈ 0.05%.

For Example B, assume A_{VOL} drops to 300,000; the resulting gain error becomes ≈ 0.33%. This situation introduces a gain uncertainty of 0.28% in the closed-loop gain, as follows:

$$\textit{Closed-Loop Gain Uncertainty} = 0.33\% - 0.05\% = 0.28\%$$

In most applications, when using a good amplifier, the gain resistors of the circuit are the largest source of absolute gain error. Furthermore, gain uncertainty cannot be removed by calibration.

Changes in the output voltage level and output loading are the most common causes of changes in the open-loop gain of op amps. A change in open-loop gain with signal level produces a nonlinearity in the closed-loop gain transfer function, which also cannot be removed during system calibration. Most op amps have fixed loads, so A_{VOL} changes with load are not generally important. However, the sensitivity of A_{VOL} to output signal levels may increase for higher load currents.

The severity of this nonlinearity varies widely from one device type to another, and generally is not specified on the data sheet. The minimum A_{VOL} is always specified, and choosing an op amp with a high A_{VOL} minimizes the probability of gain nonlinearity errors. Gain nonlinearity can come from many sources, depending on the design of the op amp. One common source is thermal feedback (for example, from a hot output stage back to the input stage). If temperature shift is the sole cause of the nonlinearity error, it can be assumed that minimizing the output loading is helpful. To verify this, the nonlinearity is measured with no load and then compared to the loaded condition.

MEASURING OPEN-LOOP GAIN NONLINEARITY

An oscilloscope X-Y display test circuit for measuring dc open-loop gain nonlinearity is shown in Figure 1. The precautions relating to the offset voltage test circuit discussed previously must be observed in this circuit also.

The amplifier is configured for a signal gain of −1. The open-loop gain is defined as the change in output voltage divided by the change in the input offset voltage. However, for large values of A_{VOL}, the actual offset may change only a few microvolts over the entire output voltage swing. Therefore, the divider consisting of the 10 Ω resistor and R_G (1 MΩ) forces the node voltage, V_Y, to be

$$V_Y = \left(1 + \frac{R_G}{10\ \Omega}\right) V_{OS} = 100{,}001 \times V_{OS} \quad (4)$$

The value of R_G is chosen to give measurable voltages at V_Y, depending on the expected values of V_{OS}.

The ±10 V ramp generator output is multiplied by the signal gain, −1, and forces the op amp output voltage V_X to swing from +10 V to −10 V. Because of the gain factor applied to the offset voltage, the offset adjust potentiometer is added to allow the initial output offset to be set to zero. The chosen resistor values null an input offset voltage of up to ±10 mV. Use stable 10 V voltage references, such as the AD688, at each end of the poten-tiometer to prevent output drift. Note that the ramp generator frequency must be quite low, probably no more than a fraction of 1 Hz because of the low corner frequency of the open-loop gain (0.1 Hz for the OP177, for example).

The plot on the right-hand side of Figure 1 shows V_Y plotted against V_X. If there is no gain nonlinearity, the graph has a constant slope, and A_{VOL} is calculated as follows:

$$A_{VOL} = \frac{\Delta V_X}{\Delta V_{OS}} = \left(1 + \frac{R_G}{10\Omega}\right)\left(\frac{\Delta V_X}{\Delta V_Y}\right) = 100{,}000 \times \left(\frac{\Delta V_X}{\Delta V_Y}\right) \quad (5)$$

If there is nonlinearity, A_{VOL} varies dynamically as the output signal changes.

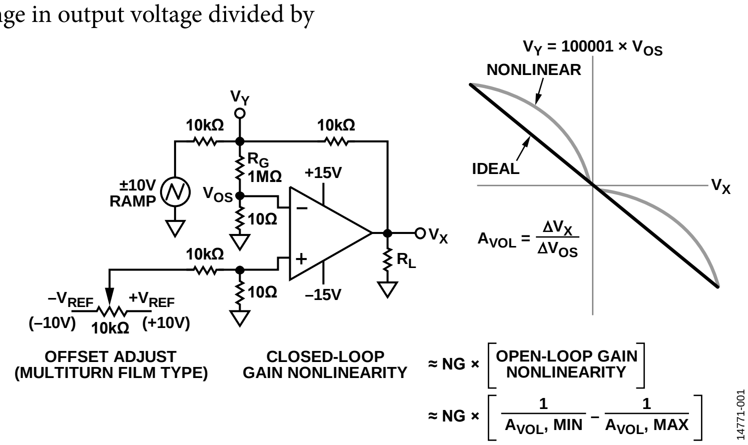

Figure 1. Circuit Measures Open-Loop Gain Nonlinearity

The approximate open-loop gain nonlinearity is calculated based on the maximum and minimum values of A_{VOL} over the output voltage range.

$$Open\text{-}Loop\ Gain\ Nonlinearity = \frac{1}{A_{VOL},\min} - \frac{1}{A_{VOL},\max} \quad (6)$$

The closed-loop gain nonlinearity is obtained by multiplying the open-loop gain nonlinearity by NG.

$$Closed\text{-}Loop\ Gain\ Nonlinearity \approx NG \times \frac{1}{A_{VOL},\min} - \frac{1}{A_{VOL},\max} \quad (7)$$

In an ideal case, the plot of V_{OS} vs. V_X has a constant slope, and the reciprocal of the slope is the open-loop gain, A_{VOL}. A horizontal line with zero slope indicates infinite open-loop gain. In an actual op amp, the slope may change across the output range because of nonlinearity, thermal feedback, and other factors. The slope can even change sign.

Figure 2 shows the V_Y (and V_{OS}) vs. V_X plot for an OP177 precision op amp. The plot is shown for two different loads, 2 kΩ and 10 kΩ. The reciprocal of the slope is calculated based on the endpoints, and the average A_{VOL} is about 8 million. The maximum and minimum values of A_{VOL} across the output voltage range are measured to be approximately 9.1 million, and 5.7 million, respectively. This corresponds to an open-loop gain nonlinearity of about 0.07 ppm. Thus, for a noise gain of 100, the corresponding closed-loop gain nonlinearity is about 7 ppm.

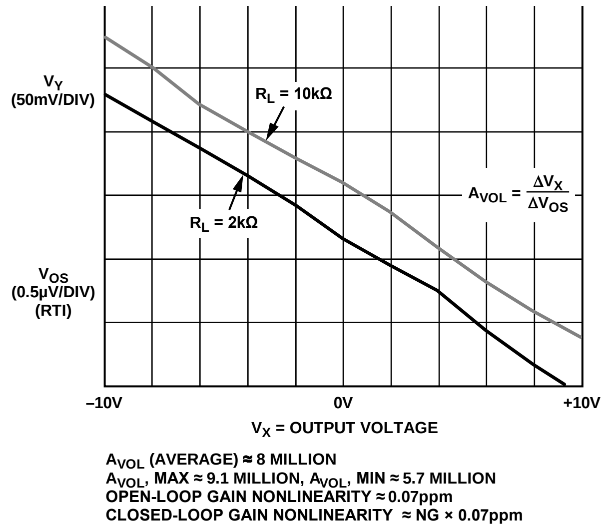

Figure 2. OP177 Gain Nonlinearity

These nonlinearity measurements are, of course, most applicable to high precision dc circuits. They are also applicable to wider bandwidth applications, such as audio. The X-Y display technique shown in Figure 1 easily shows crossover distortion as, for example, in a poorly designed op amp output stage.

REFERENCES AND RESOURCES

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