

## Op Amp Open Loop Gain and Open Loop Gain Nonlinearity

### OPEN LOOP GAIN

*Open-loop voltage gain*, usually called  $A_{VOL}$  (sometimes 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 parts. 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 isn't highly 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.

Since a voltage feedback op amp operates as voltage in/voltage out, its open-loop gain is a dimensionless ratio, so no unit is necessary. However, data sheets sometimes express gain in V/mV or V/ $\mu$ V instead of V/V, for the convenience of using smaller numbers. Or, voltage gain can also be expressed in dB terms, as gain in dB =  $20 \times \log A_{VOL}$ . Thus an open-loop gain of 1V/ $\mu$ V is equivalent to 120 dB, etc.

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 (or k $\Omega$  or M $\Omega$ ). Values usually lie between hundreds of k $\Omega$  and tens of M $\Omega$ .

From basic feedback theory, it is understood that in order to maintain accuracy, a precision amplifier's dc open-loop gain,  $A_{VOL}$ , 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:

$$G_{CL} = \frac{1}{\beta} \cdot \left[ \frac{1}{1 + \frac{1}{A_{VOL}\beta}} \right] \quad \text{Eq. 1}$$

where  $\beta$  is the *feedback loop attenuation*, or *feedback factor* (the voltage attenuation of the feedback network). Since noise gain is equal to  $1/\beta$ , there are alternate forms of this expression. Combining the two right side terms and using the NG expression, an alternate one is:

$$G_{CL} = \frac{NG}{1 + \frac{NG}{A_{VOL}}} \quad \text{Eq. 2}$$

Equations 1 and 2 are equivalent, and either can be used. As previously discussed, noise gain (NG) is simply the gain seen by a small voltage source in series with the op amp input, and is also the ideal amplifier signal gain in the non-inverting mode. If  $A_{VOL}$  in Equations 1 and 2 is infinite, the closed-loop gain becomes exactly equal to the noise gain,  $1/\beta$ .

However, for  $NG \ll A_{VOL}$  and finite  $A_{VOL}$ , there is a closed-loop gain error estimation:

$$\text{Closed loop error(\%)} \approx \frac{NG}{A_{VOL}} \cdot 100 \quad \text{Eq. 3}$$

Notice from Eq. 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

In Figure 1 below, the first example for a NG 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 easily be calibrated out of the measurement, and then there is then no overall system gain error. If, however, the open-loop gain *changes*, the resulting closed-loop gain will also change. This introduces a *gain uncertainty*. In the second example,  $A_{VOL}$  drops to 300,000, which produces a gain error of 0.33%. This situation introduces a *gain uncertainty* of 0.28% in the closed-loop gain. In most applications, when using a good amplifier, the gain resistors of the circuit will be the largest source of absolute gain error, but it should be noted that gain uncertainty cannot be removed by calibration.

- ◆ "IDEAL" CLOSED LOOP GAIN =  $1/\beta$  = NOISE GAIN (NG)
- ◆ ACTUAL CLOSED LOOP GAIN =  $\frac{1}{\beta} \cdot \frac{1}{1 + \frac{1}{A_{VOL}\beta}} = \frac{NG}{1 + \frac{NG}{A_{VOL}}}$
- ◆ CLOSED LOOP GAIN ERROR (%)  $\approx \frac{NG}{A_{VOL}} \times 100$  ( $NG \ll A_{VOL}$ )
  
- ◆ Ex. 1: Assume  $A_{VOL} = 2,000,000$ ,  $NG = 1,000$   
% GAIN ERROR  $\approx 0.05\%$
- ◆ Ex. 2: Assume  $A_{VOL}$  Drops to 300,000  
% GAIN ERROR  $\approx 0.33\%$
- ◆ CLOSED LOOP GAIN UNCERTAINTY  
=  $0.33\% - 0.05\% = 0.28\%$

**Figure 1: Changes in Open-Loop Gain Cause Closed-Loop Gain Uncertainty**

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 level may increase for higher load currents.

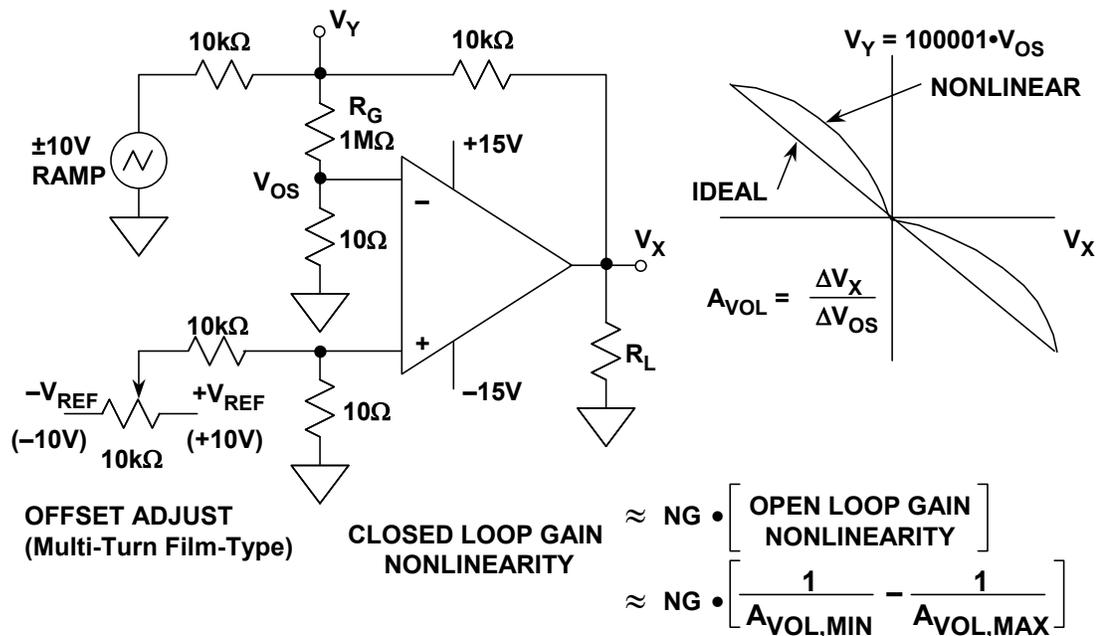
The severity of this non-linearity varies widely from one device type to another, and generally isn't specified on the data sheet. The minimum  $A_{VOL}$  is always specified, and choosing an op amp with a high  $A_{VOL}$  will minimize the probability of gain nonlinearity errors. Gain nonlinearity can 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 will help. 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 2 below. The same precautions previously discussed relating to the offset voltage test circuit must also be observed in this circuit. 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  $10\ \Omega$  resistor and  $R_G$  ( $1\ M\Omega$ ) forces the node voltage  $V_Y$  to be :

$$V_Y = \left[ 1 + \frac{R_G}{10\ \Omega} \right] V_{OS} = 100,001 \cdot V_{OS} . \tag{Eq. 4}$$

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



**Figure 2: Circuit Measures Open-Loop Gain Nonlinearity**

The  $\pm 10$  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 resistor values chosen will null an input offset voltage of up to  $\pm 10$  mV. Stable 10 V voltage references such as the [AD688](#) should be used at each end of the potentiometer to prevent output drift. *Also, note that the ramp generator frequency must be quite low, probably no more than a fraction of 1Hz because of the low corner frequency of the open-loop gain (0.1Hz for the [OP177](#), for example).*

The plot on the right-hand side of Fig. 2 shows  $V_Y$  plotted against  $V_X$ . If there is no gain nonlinearity the graph will have a constant slope, and  $A_{VOL}$  is calculated as follows:

$$A_{VOL} = \frac{\Delta V_X}{\Delta V_{OS}} = \left[ 1 + \frac{R_G}{10\Omega} \right] \left[ \frac{\Delta V_X}{\Delta V_Y} \right] = 100,001 \bullet \left[ \frac{\Delta V_X}{\Delta V_Y} \right]. \quad \text{Eq. 5}$$

If there is nonlinearity,  $A_{VOL}$  will vary dynamically as the output signal changes. The approximate open-loop gain nonlinearity is calculated based on the maximum and minimum values of  $A_{VOL}$  over the output voltage range:

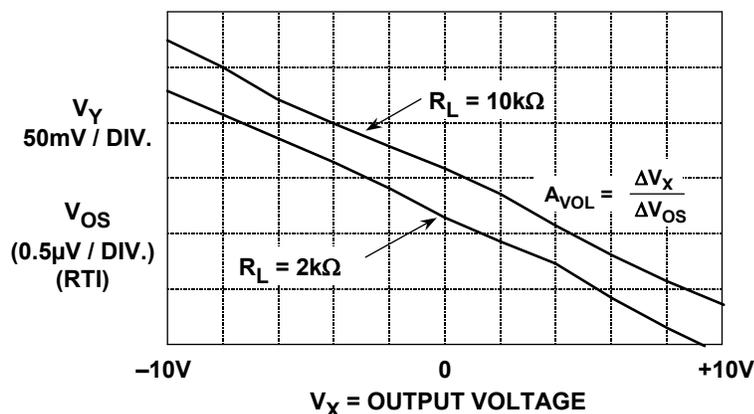
$$\text{Open Loop Gain Nonlinearity} = \frac{1}{A_{VOL,MIN}} - \frac{1}{A_{VOL,MAX}}. \quad \text{Eq. 6}$$

The closed-loop gain nonlinearity is obtained by multiplying the open-loop gain nonlinearity by the noise gain, NG:

$$\text{Closed Loop Gain Nonlinearity} \approx NG \bullet \left[ \frac{1}{A_{VOL,MIN}} - \frac{1}{A_{VOL,MAX}} \right]. \quad \text{Eq. 7}$$

In an ideal case, the plot of  $V_{OS}$  versus  $V_X$  would have a constant slope, and the reciprocal of the slope is the open-loop gain,  $A_{VOL}$ . A horizontal line with zero slope would indicate infinite open-loop gain. In an actual op amp, the slope may change across the output range because of nonlinearity, thermal feedback, etc. In fact, the slope can even change sign.

Figure 3 shows the  $V_Y$  (and  $V_{OS}$ ) versus  $V_X$  plot for an [OP177](#) precision op amp. The plot is shown for two different loads, 2 k $\Omega$  and 10 k $\Omega$ . The reciprocal of the slope is calculated based on the end points, 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.



$A_{VOL}$  (AVERAGE)  $\approx 8$  million

$A_{VOL,MAX} \approx 9.1$  million,  $A_{VOL,MIN} \approx 5.7$  million

OPEN LOOP GAIN NONLINEARITY  $\approx 0.07ppm$

CLOSED LOOP GAIN NONLINEARITY  $\approx NG \times 0.07ppm$

**Figure 3: [OP177](#) Gain Nonlinearity**

These nonlinearity measurements are, of course, most applicable to high precision dc circuits. But they are also applicable to wider bandwidth applications, such as audio. The X-Y display technique of Fig. 2 will easily show crossover distortion in a poorly designed op amp output stage, for example.

#### REFERENCES:

1. Hank Zumbahlen, *Basic Linear Design*, Analog Devices, 2006, ISBN: 0-915550-28-1. Also available as [Linear Circuit Design Handbook](#), Elsevier-Newnes, 2008, ISBN-10: 0750687037, ISBN-13: 978-0750687034. Chapter 1.
2. Walter G. Jung, *Op Amp Applications*, Analog Devices, 2002, ISBN 0-916550-26-5, Also available as [Op Amp Applications Handbook](#), Elsevier/Newnes, 2005, ISBN 0-7506-7844-5. Chapter 1.

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