AN-1671 Gain and Linearity Testing for Precision Operational Amplifiers

ABSTRACT

Many operational amplifiers are very linear — as a unity-gain inverter, they often have linearity in the range of 5 to 1 to 0.5 ppm. However, testing for gain linearity is not a standard or well-known test. Test procedures will be shown here, to permit any user to resolve the non-linearity errors.

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1   Introduction

It is possible to use op-amps for precision applications, even if they are not more linear than 5 ppm. Most people cannot hear an amplifier's distortion below 1 ppm, even if you cascade 10 of such stages. However, for precision instrumentation, or for high-fidelity audio, it is usually a good idea to select an op-amp with good linearity. Refer to AN-1485 which shows examples of good, moderate, and poor linearity. It shows Bipolar and also CMOS amplifiers. Contrary to many opinions, CMOS amplifiers with drain-loaded outputs do not necessarily have inferior linearity versus old bipolar-transistor amplifiers.

Linearity is often specified in dB below the signal level, (such as -110dB), or in percent (such as 0.0003%). However, most engineers are not familiar with nonlinearity below -120dB, so in this linear brief we will usually express the linearity in parts per million, (3 ppm or 0.3 ppm) compared to the output signal.

Linearity is often measured at low frequencies, because the testing is easier there. Linearity can be measured for an inverter or for a follower. In concept, one could subtract the input from the output, and these deviations could be plotted as a function of V_{OUT}. However, it is nearly impossible to do this with full resolution. So a real-time subtraction technique is employed. Test results can be seen in just a few seconds.

Conversely, a distortion analyzer such as an Audio Precision System Two Cascade SYS-2522, could be used to provide a direct reading of the distortion. However, even this procedure has limitations, when the distortion gets down below 3 ppm.

2   Test Fixturing and Test Procedure

The circuit of Figure 1 is a classic test fixture that has been used for over 40 years. Rin and Rf are used to force the input voltage (typically 20 volts p-p) to cause an output voltage of 20 volts p-p, as observed on an oscilloscope. The signal source should have an offset adjust control, which the user adjusts so the output is actually swinging ±10 volts with no offset. The Vos of the op-amp is thus effectively trimmed out. Meanwhile the R3 and R4 are used to magnify the error voltage (Vε) by a factor of ~1000, the ratio of R3 to R4. So if the amplifier's gain is 1 million, and its error voltage is 20µVp-p, the voltage at the oscilloscope's vertical input will be 20mVp-p. A good op-amp with a gain of 1 million can easily fulfill both gain requirements. This arrangement will avoid the need for a low-noise preamp, which is sure to add some extra noise. See Figure 1.
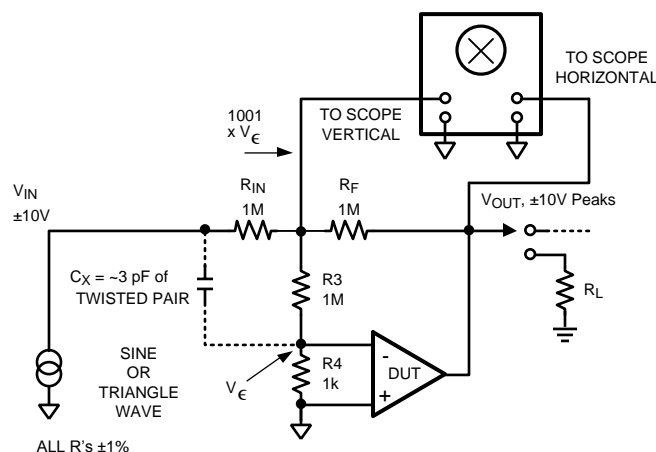

Figure 1. Gain Test
where $A_V = 1001$ ($V_{HORIZ. P-P}$ / $V_{VERT. P-P}$)

3   Crossplot Display

In concept you could look at the voltage "1000 Vε" with any kind of meter or scope. But to see the linear and non-linear components, it is best to use a scope in X-Y mode (Crossplot). Then any bumps or curves will correlate with the related level on the output swing. The slopes and bumps and curves can be resolved despite noise that is bigger than these signals! The eye can correlate out errors like noise, and offset, and linear errors, to let you see the non-linear errors.

It is also advantageous for many tests, to use a triangle wave input, rather than a sine wave. For a more complete discussion of why triangle waves are superior, see AN-1485. A frequency around 3 to 30Hz is usually suitable for a fast amplifier. See Figure 2.

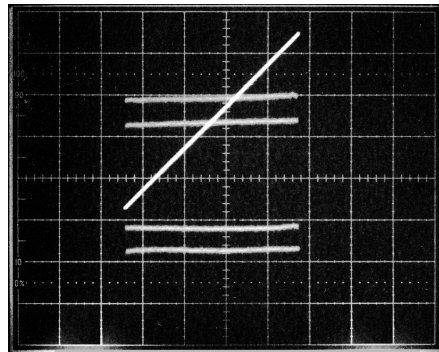**Figure 2. Test B10, LM4562 (also known as LME49720), F = 25Hz**
V_S = ±15V_{DC}; V_{OUT} = ±10 volts peak, I_{OUT} = ±10mA peak
Upper Trace: Gain Error, No Load, +1.5μV_{P-P} at 10μV/div
Lower Trace: Gain Error, Full Load, 1.5μV_{P-P} at 10μV/div

4   Audio Distortion

The LM4562 is a good fast 54MHz amplifier, (GBW Product). But at 1kHz with 20 volts p-p of output signal, the summing-point error (Vε) will be as big as ±118μV. The signal at the vertical scope input will be ±118mV peak, or 236mV p-p. When you turn down the scope's sensitivity to keep this signal on-scale, you cannot resolve 1μV any more - you can barely see 10μV. So how can we see 1μV of error at 1kHz?

The solution is to connect a small amount of twisted pair, to be used as an adjustable capacitor, Cx, as shown in Figure 1. Use Teflon-insulated wire. When you wind (or un-wind) the twisted pair -- to cancel out most of the dynamic errors of the op-amp -- the signal becomes just a few mVp-p, and you can resolve the equivalent 1 μV of nonlinearity, even in the presence of some noise. The amount of non-linearity on this amplifier seems to be down near 0.08 ppm, referred to input. That is about -159dB, referred to the 7-volt rms signal.

This circuit, using 1M,1M, 1k, 1M is a little noisy - which is not a surprise, as the noise of a 1k resistor is larger than the noise of the LM4562. To get a better resolution of the distortion, you can use new, lower R values in place of the 1M/1M resistors. I just went in and slapped in a 20k across the 1 meg's, and 20 ohms across the 1k. I chose this scale factor because it was easy for me to add a150pF variable air capacitor across the "3pF" capacitor. This worked very well. I could see some quadrature error, even with a triangle wave, and with a sine wave, I could see a small amount of distortion down below 0.08 ppm This seems to be second harmonic, at 2kHz, at about -159db down. However, we have not yet given up on the possibility of further improvements.

5   Distortion as a Non-Inverting Amplifier (Unity-Gain Follower)

Some of the early tests on the LM4562 showed it could get down to 0.3 ppm of nonlinearity. This was true, because at voltages larger than 3 volts (rms) of input swing, non-linearity started to be degraded, due to imperfect (nonlinear) CMRR. This was when applied as a unity gain follower as in Figure 3. If you are using an amplifier as a unity-gain follower, the LM4562 does have some nonlinearity, but this can be improved. Write to request advice. But the circuit of Figure 3 does provide so much gain (100) that you can see the signal, and the noise and the distortion. This gain is the ratio of (R5 + R6 + R7)/R6.

6 Analysis of Results

Figure 2 shows that the summing-point error has about 1/2 µVp-p of nonlinearity with a 1 Megohm load (upper trace.) With a 1k load (lower trace), it is closer to 1 µVp-p deviation from the best straight line. (1 mVp-p at the scope vertical input). The gain is therefore up near 10 million to 40 million, and the non-linearity is down near 1/20 part per million, also. This is one of the better amplifiers we can test, the LM4562. Other amplifiers with comparable non-linearity are the LME49710 and LME49740. If amplifier's linearity is any better than 1/20 ppm, the nonlinearity will be below the noise, and may require extreme techniques, such as adding a Spectrum Analyzer or Distortion Analyzer after the circuit of Figure 1.
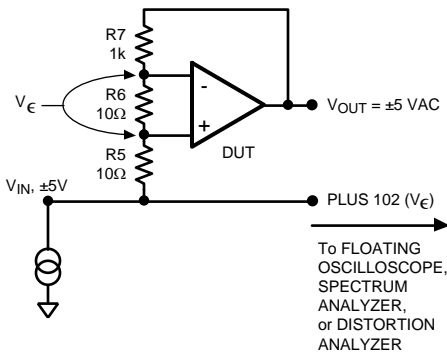
Figure 3. Test Circuit for Gain and Distortion of Amplifier at G = +1
(Including the nonlinearity of the CMRR)

7 Conclusion

The LM4562 is one of the best linear amplifiers in the world. It has some of the lowest distortion of any op-amp or any linear amplifier in the world, better than 0.2 PPM from 0.01 to 2kHz. This measurement technique is running out of capabilities to see much lower than 1/10 ppm. But it can be used with a Spectrum Analyzer to resolve a little lower. Unlike other amplifiers with good numbers and good plots, but which may not sound so great, the LM4562 also is said to "sound good", according to people who have good audio acuity (who have "good ears"). This is probably related to its good dynamic stability and clean slew rate. The electronic testing is consistent with these observations.

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