Precision Op Amps

PRECISION OP AMP CHARACTERISTICS

This tutorial examines in more detail some of the issues relating to amplifiers for use in precision signal conditioning applications. Although the OP177 op amp is used as the "gold standard" for precision bipolar amplifiers in these discussions, more recent product introductions such as the rail-to-rail output OP777, OP727, and OP747, along with the OP1177, OP2177, and OP4177 offer nearly as good performance in smaller packages.

Precision op amp open-loop gains greater than 1 million are available, along with common-mode and power supply rejection ratios of the same magnitude. Offset voltages of less than 25 µV and offset drift less than 0.1 µV/°C are available in dual supply op amps such as the OP177, however, the performance in single-supply precision bipolar op amps may sometimes fall short of this performance. This is the tradeoff that must sometimes be made in low power, low voltage applications. On the other hand, however, modern chopper stabilized (auto-zero) op amps provide offsets and offset voltage drifts which cannot be distinguished from noise, and these devices operate on single supplies and provide rail-to-rail inputs and outputs. They too come with their own set of problems that are discussed later within this section.

It is important to understand that dc open-loop gain, offset voltage, power supply rejection (PSR), and common-mode rejection (CMR) alone shouldn't be the only considerations in selecting precision amplifiers. The ac performance of the amplifier is also important, even at "low" frequencies. Open-loop gain, PSR, and CMR all have relatively low corner frequencies, and therefore what may be considered "low" frequency may actually fall above these corner frequencies, increasing errors above the value predicted solely by the dc parameters. For example, an amplifier having a dc open-loop gain of 10 million and a unity-gain crossover frequency of 1 MHz has a corresponding corner frequency of 0.1 Hz! One must therefore consider the open-loop gain at the actual *signal* frequency. The relationship between the single-pole unity-gain crossover frequency, f_u, the signal frequency, f_{sig}, and the open-loop gain $A_{VOL(fsig)}$ (measured at the signal frequency is given by:

$$A_{VOL(f_{sig})} = \frac{f_u}{f_{sig}}. \quad \text{Eq. 1}$$

It the example above, the open-loop gain is 10 at 100 kHz, and 100,000 at 10 Hz. Note that the constant gain-bandwidth product concept only holds true for VFB op amps. It doesn't apply to CFB op amps, but then they are rarely used in precision applications. Loss of open-loop gain at the frequency of interest can introduce distortion, especially at audio frequencies. Loss of CMR or PSR at the line frequency or harmonics thereof can also introduce errors.

The challenge of selecting the right amplifier for a particular signal conditioning application has been complicated by the sheer proliferation of various types of amplifiers in various processes (Bipolar, Complementary Bipolar, BiFET, CMOS, BiCMOS, etc.) and architectures (traditional op amps, instrumentation amplifiers, chopper amplifiers, isolation amplifiers, etc.)

In addition, a wide selection of precision amplifiers are now available which operate on single-supply voltages which complicates the design process even further because of the reduced signal swings and voltage input and output restrictions. Offset voltage and noise are now a more significant portion of the input signal. Some general attributes of precision op amps are summarized in Figure 1.

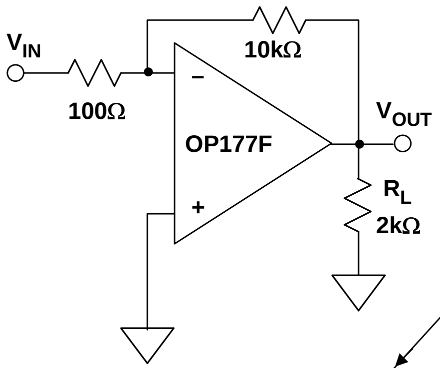
- **Input Offset Voltage** **<100μV**
- **Input Offset Voltage Drift** **<1μV/°C**
- **Input Bias Current** **<2nA**
- **Input Offset Current** **<2nA**
- **DC Open Loop Gain** **>1,000,000**
- **Unity Gain Bandwidth Product, f_u** **500kHz - 5MHz**
- **Always Check Open Loop Gain at Signal Frequency!**
- **1/f (0.1Hz to 10Hz) Noise** **<1μV p-p**
- **Wideband Noise** **<10nV/√Hz**
- **CMR, PSR** **>100dB**
- **Tradeoffs:**
  - **Single supply operation**
  - **Low supply currents**

Figure 1: Precision Op Amp Characteristics

PRECISION OP AMP AMPLIFIER DC ERROR BUDGET ANALYSIS

In order to develop a concept for the magnitudes of the various errors in a high precision op amp circuit, a simple room temperature analysis for the OP177F is shown in Figure 2. The amplifier is connected in the inverting mode with a signal gain of 100. The key data sheet specifications are also shown in the diagram. We assume an input signal of 100 mV fullscale which corresponds to an output signal of 10V. The various error sources are normalized to fullscale and expressed in parts per million (ppm). Note: parts per million (ppm) error = fractional error × 10^6 = % error × 10^4.

Note that the offset errors due to V_{OS} and I_{OS} and the gain error due to finite A_{VOL} can be removed with a system calibration. However, the error due to open-loop gain nonlinearity cannot be removed with calibration and produces a relative accuracy error, often called *resolution error*. A second contributor to resolution error is the 1/f noise. This noise is always present and adds to the uncertainty of the measurement. The overall relative accuracy of the circuit at room temperature is 9 ppm, equivalent to ~17 bits of resolution.



SPECS @ +25°C:
V_{OS} = 25µV max
I_{OS} = 1.5nA max
A_{VOL} = 5×10^6 min
A_{VOL} Nonlinearity = 0.07ppm
0.1Hz to 10Hz Noise = 200nV

MAXIMUM ERROR CONTRIBUTION, + 25°C
FULLSCALE: V_{IN}=100mV, V_{OUT} = 10V

V_{OS}	25µV ÷ 100mV	250ppm
I_{OS}	100Ω ×1.5nA ÷ 100mV	1.5ppm
A_{VOL}	$(100/ 5\times10^6) \times$ 100mV	20ppm
A_{VOL} Nonlinearity	100 × 0.07ppm	7ppm
0.1Hz to 10Hz 1/f Noise	200nV ÷ 100mV	2ppm
Total Unadjusted Error	≈ 12 Bits Accurate	280.5ppm
Resolution Error	≈ 17 Bits Accurate	9ppm

Figure 2: Precision Op Amp (OP177F) DC Error Budget Analysis

It is also useful to compare the performance of a number of single-supply op amps to that of the "gold standard" OP177, and this is done in Figure 3 below for some representative devices.

LISTED IN ORDER OF INCREASING SUPPLY CURRENT

PART NO.	V_{OS} max	V_{OS} TC	A_{VOL}min	NOISE (1kHz)	INPUT	OUTPUT	I_{SY}/AMP MAX
OP293	250µV	2µV/°C	200k	5nV/√Hz	0, 4V	5mV, 4V	20µA
OP196/296/496	300µV	2µV/°C	150k	26nV/√Hz	R/R	"R/R"	60µA
OP777	100µV	1.3µV/°C	300k	15nV√Hz	0, 4V	"R/R"	270µA
OP191/291/491	700µV	5µV/°C	25k	35nV/√Hz	R/R	"R/R"	350µA
*AD820/822/824	1000µV	20µV/°C	500k	16nV/√Hz	0, 4V	"R/R"	800µA
**AD8601/2/4	600µV	2µV/°C	20k	33nV/√Hz	R/R	"R/R"	1000µA
OP184/284/484	150µV	2µV/°C	50k	3.9nV/√Hz	R/R	"R/R"	1350µA
OP113/213/413	175µV	4µV/°C	2M	4.7nV/√Hz	0, 4V	5mV, 4V	3000µA
OP177F (±15V)	25µV	0.1µV/°C	5M	10nV/√Hz	N/A	N/A	2000µA

*JFET INPUT **CMOS

NOTE: Unless Otherwise Stated Specifications are Typical @ +25°C V_S = +5V

Figure 3: Precision Single-Supply Op Amp Performance Characteristics

Note that the Fig. 3 amplifier list does *not* include the category of chopper op amps, which excel in many of the categories. These are covered separately, in Tutorial MT-055.

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.

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