Chapter I

IN-AMP BASICS

INTRODUCTION

Instrumentation amplifiers (in-amps) are sometimes misunderstood. Not all amplifiers used in instrumentation applications are instrumentation amplifiers, and by no means are all in-amps used only in instrumentation applications. In-amps are used in many applications, from motor control to data acquisition to automotive. The intent of this guide is to explain the fundamentals of what an instrumentation amplifier is, how it operates, and how and where to use it. In addition, several different categories of instrumentation amplifiers are addressed in this guide.

IN-AMPS vs. OP AMPS: WHAT ARE THE DIFFERENCES?

An instrumentation amplifier is a closed-loop gain block that has a differential input and an output that is single-ended with respect to a reference terminal. Most commonly, the impedances of the two input terminals are balanced and have high values, typically $10^9 \ \Omega$, or greater. The input bias currents should also be low, typically 1 nA to 50 nA. As with op amps, output impedance is very low, nominally only a few milliohms, at low frequencies.

Unlike an op amp, for which closed-loop gain is determined by external resistors connected between its inverting input and its output, an in-amp employs an internal feedback resistor network that is isolated from its signal input terminals. With the input signal applied across the two differential inputs, gain is either preset internally or is user set (via pins) by an internal or external gain resistor, which is also isolated from the signal inputs.

Figure 1-1 shows a bridge preamp circuit, a typical in-amp application. When sensing a signal, the bridge resistor values change, unbalancing the bridge and causing a change in differential voltage across the bridge. The signal output of the bridge is this differential voltage, which connects directly to the in-amp's inputs. In addition, a constant dc voltage is also present on both lines. This dc voltage will normally be equal or *common mode* on both input lines. In its primary function, the in-amp will normally reject the common-mode dc voltage, or any other voltage common to both lines, while amplifying the *differential* signal voltage, the difference in voltage between the two lines.
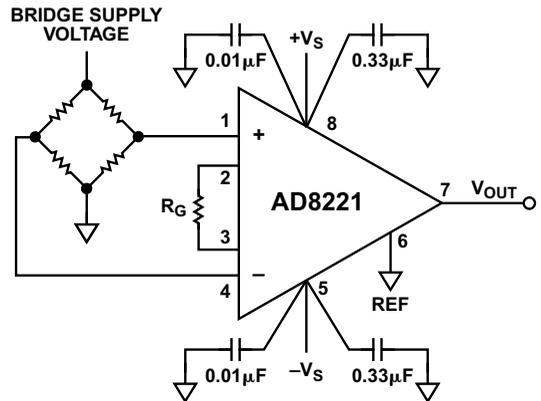

Figure 1-1. AD8221 bridge circuit.

In contrast, if a standard op amp amplifier circuit were used in this application, it would simply amplify *both* the signal voltage and any dc, noise, or other common-mode voltages. As a result, the signal would remain buried under the dc offset and noise. Because of this, even the best op amps are far less effective in extracting weak signals. Figure 1-2 contrasts the differences between op amp and in-amp input characteristics.

Signal Amplification and Common-Mode Rejection
An instrumentation amplifier is a device that amplifies the *difference* between two input signal voltages while rejecting any signals that are common to both inputs. The in-amp, therefore, provides the very important function of extracting small signals from transducers and other signal sources.

Common-mode rejection (CMR), the property of canceling out any signals that are common (the same potential on both inputs), while amplifying any signals that are differential (a potential difference between the inputs), is the most important function an instrumentation amplifier provides. Both dc and ac common-mode rejection are important in-amp specifications. Any errors due to dc common-mode voltage (i.e., dc voltage present at both inputs) will be reduced 80 dB to 120 dB by any modern in-amp of decent quality.

However, inadequate ac CMR causes a large, time-varying error that often changes greatly with frequency and, therefore, is difficult to remove at the IA's output. Fortunately, most modern monolithic IC in-amps provide excellent ac and dc common-mode rejection.

Common-mode gain (A_{CM}), the ratio of change in output voltage to change in common-mode input voltage, is related to common-mode rejection. It is the net gain (or attenuation) from input to output for voltages common to both inputs. For example, an in-amp with a common-mode gain of 1/1000 and a 10 V common-mode voltage at its inputs will exhibit a 10 mV output change. The differential or normal mode gain (A_D) is the gain between input and output for voltages applied differentially (or across) the two inputs. The common-mode rejection ratio (CMRR) is simply the ratio of the differential gain, A_D, to the common-mode gain. Note that in an ideal in-amp, CMRR will increase in proportion to gain.

Common-mode rejection is usually specified for full range common-mode voltage (CMV) change at a given frequency and a specified imbalance of source impedance (e.g., 1 kΩ source imbalance, at 60 Hz).

Mathematically, common-mode rejection can be represented as

$$CMRR = A_D\left(\frac{V_{CM}}{V_{OUT}}\right)$$

where:

A_D is the differential gain of the amplifier;

V_{CM} is the common-mode voltage present at the amplifier inputs;

V_{OUT} is the output voltage present when a common-mode input signal is applied to the amplifier.

The term CMR is a logarithmic expression of the common-mode rejection ratio (CMRR). That is, $CMR = 20 \log_{10} CMRR$.

To be effective, an in-amp needs to be able to amplify microvolt-level signals while rejecting common-mode voltage at its inputs. It is particularly important for the in-amp to be able to reject common-mode signals over the bandwidth of interest. This requires that instrumentation amplifiers have very high common-mode rejection over the main frequency of interest and its harmonics.

THE VERY HIGH VALUE, CLOSELY MATCHED INPUT RESISTANCES CHARACTERISTIC OF IN-AMPS MAKE THEM IDEAL FOR MEASURING LOW LEVEL VOLTAGES AND CURRENTS—WITHOUT LOADING DOWN THE SIGNAL SOURCE.
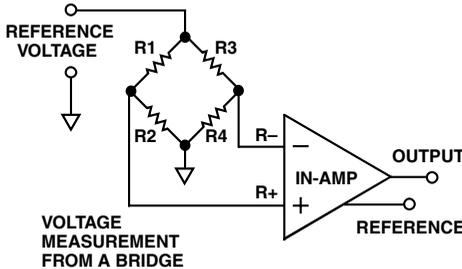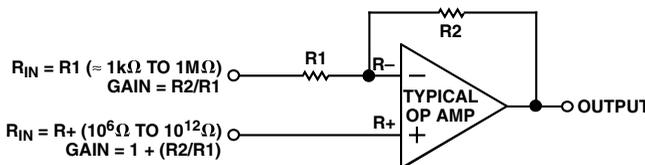
IN-LINE CURRENT MEASUREMENT
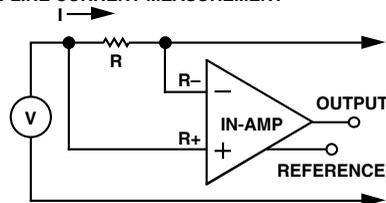
THE INPUT RESISTANCE OF A TYPICAL IN-AMP IS VERY HIGH AND IS EQUAL ON BOTH INPUTS. INPUT CURRENT IS LOW, SUCH THAT IB × R CREATES A NEGLIGIBLE ERROR VOLTAGE.

$R- = R+ = 10^9 \Omega$ TO $10^{12} \Omega$

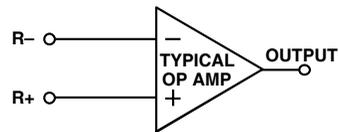**IN-AMP INPUT CHARACTERISTICS**

$R_{IN} = R1$ ($\approx$ 1kΩ TO 1MΩ)
GAIN = R2/R1

$R_{IN} = R+$ ($10^6 \Omega$ TO $10^{12}\Omega$)
GAIN = 1 + (R2/R1)

A MODEL SHOWING THE INPUT RESISTANCE OF A TYPICAL OP AMP OPERATING AS AN INVERTING AMPLIFIER—AS SEEN BY THE INPUT SOURCE

A MODEL SHOWING THE INPUT RESISTANCE OF A TYPICAL OP AMP IN THE OPEN-LOOP CONDITION

$(R-) = (R+) = 10^6 \Omega$ TO $10^{15}\Omega$

OP AMP INPUT CHARACTERISTICS

Figure 1-2. Op amp vs. in-amp input characteristics.

For techniques on reducing errors due to out-of-band signals that may appear as a dc output offset, please refer to the RFI section of this guide.

At unity gain, typical dc values of CMR are 70 dB to more than 100 dB, with CMR usually improving at higher gains. While it is true that operational amplifiers connected as subtractors also provide common-mode rejection, the user must provide closely matched external resistors (to provide adequate CMRR). On the other hand, monolithic in-amps, with their pretrimmed resistor networks, are far easier to apply.

Common-Mode Rejection: Op Amp vs. In-Amp
Op amps, in-amps, and difference amps all provide common-mode rejection. However, in-amps and diff amps are designed to reject common-mode signals so that they do not appear at the amplifier's output. In contrast, an op amp operated in the typical inverting or noninverting amplifier configuration will process common-mode signals, passing them through to the output, but will not normally reject them.

Figure 1-3a shows an op amp connected to an input source that is riding on a common-mode voltage. Because of feedback applied externally between the output and the summing junction, the voltage on the "–" input is forced to be the same as that on the "+" input voltage. Therefore, the op amp ideally will have zero volts *across* its input terminals. As a result, the voltage at the op amp output *must* equal V_{CM}, for zero volts differential input.

Even though the op amp has *common-mode rejection*, the common-mode voltage is transferred to the output along with the signal. In practice, the signal is amplified by the op amp's closed-loop gain, while the common-mode voltage receives only unity gain. This difference in gain does provide some reduction in common-mode voltage as a percentage of signal voltage. However, the common-mode voltage still appears at the output, and its presence reduces the amplifier's available output swing. For many reasons, any common-mode signal (dc or ac) appearing at the op amp's output is highly undesirable.

$$V_{OUT} = (V_{IN} \times GAIN) \pm V_{CM}$$
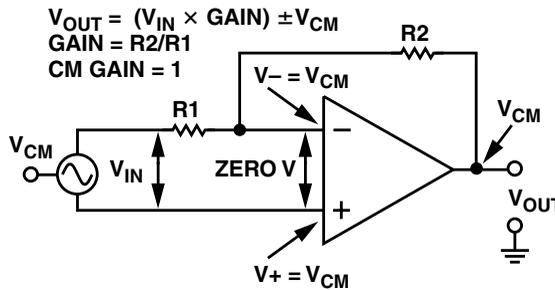$$GAIN = R2/R1$$
$$CM\ GAIN = 1$$

Figure 1-3a. In a typical inverting or noninverting amplifier circuit using an op amp, both the signal voltage and the common-mode voltage appear at the amplifier output.

Figure 1-3b shows a 3-op amp in-amp operating under the same conditions. Note that, just like the op amp circuit, the input buffer amplifiers of the in-amp pass the common-mode signal through at unity gain. In contrast, the signal is amplified by both buffers. The output signals from the two buffers connect to the subtractor section of the IA. Here the differential signal is amplified (typically at low gain or unity) while the common-mode voltage is attenuated (typically by 10,000:1 or more). Contrasting the two circuits, both provide signal amplification (and buffering), but because of its subtractor section, the in-amp rejects the common-mode voltage.

Figure 1-3c is an in-amp bridge circuit. The in-amp effectively rejects the dc common-mode voltage appearing at the two bridge outputs while amplifying the very weak bridge signal voltage. In addition, many modern in-amps provide a common-mode rejection approaching 80 dB, which allows powering of the bridge from an inexpensive, nonregulated dc power supply. In contrast, a self constructed in-amp, using op amps and 0.1% resistors, typically only achieves 48 dB CMR, thus requiring a regulated dc supply for bridge power.
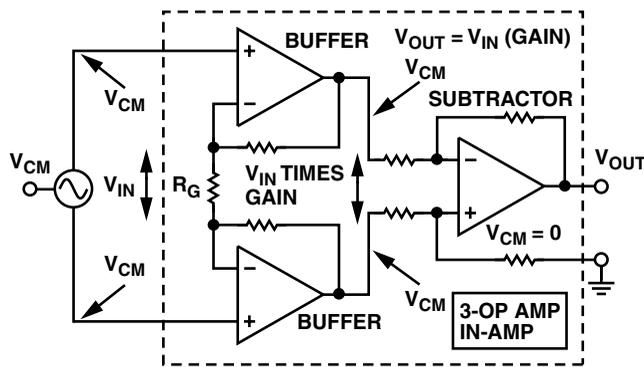

Figure 1-3b. As with the op amp circuit above, the input buffers of an in-amp circuit amplify the signal voltage while the common-mode voltage receives unity gain. However, the common-mode voltage is then rejected by the in-amp's subtractor section.
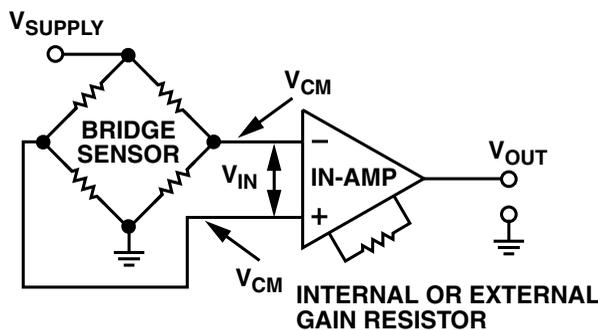

Figure 1-3c. An in-amp used in a bridge circuit. Here the dc common-mode voltage can easily be a large percentage of the supply voltage.

Figure 1-3d shows a difference (subtractor) amplifier being used to monitor the voltage of an individual cell that is part of a battery bank. Here the common-mode dc voltage can easily be much higher than the amplifier's supply voltage. Some monolithic difference amplifiers, such as the **AD629**, can operate with common-mode voltages as high as ±270 V.

DIFFERENCE AMPLIFIERS

Figure 1-4 is a block diagram of a difference amplifier. This type of IC is a special-purpose in-amp that normally consists of a subtractor amplifier followed by an output buffer, which may also be a gain stage. The four resistors used in the subtractor are normally internal to the IC, and, therefore, are closely matched for high CMR.

Many difference amplifiers are designed to be used in applications where the common-mode and signal voltages may easily exceed the supply voltage. These diff amps typically use very high value input resistors to attenuate both signal and common-mode input voltages.

WHERE ARE IN-AMPS AND DIFFERENCE AMPS USED?
Data Acquisition

In-amps find their primary use amplifying signals from low level output transducers in noisy environments. The amplification of pressure or temperature transducer signals is a common in-amp application. Common bridge applications include strain and weight measurement using load cells and temperature measurement using resistive temperature detectors, or RTDs.
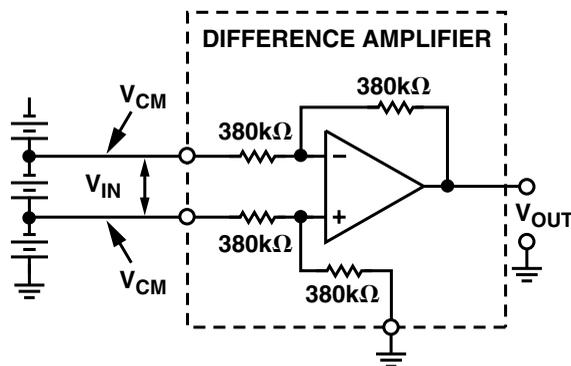

Figure 1-3d. A difference amp is especially useful in applications such as battery cell measurement, where the dc (or ac) common-mode voltage may be greater than the supply voltage.
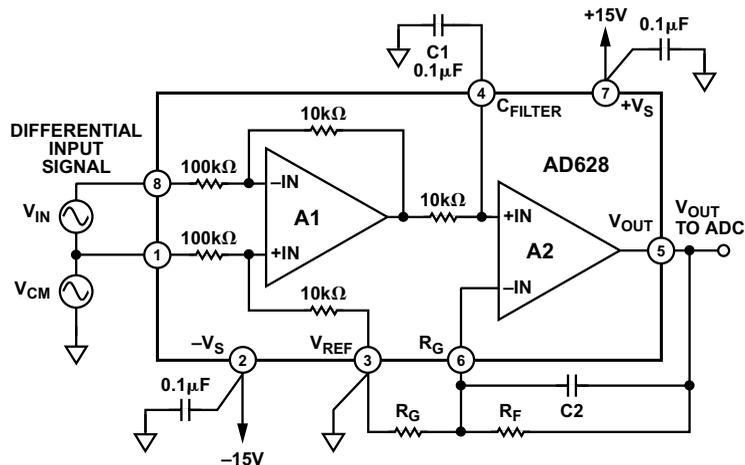

Figure 1-4. A difference amplifier IC.

Medical Instrumentation
In-amps are widely used in medical equipment such as EKG and EEG monitors, blood pressure monitors, and defibrillators.

Monitor and Control Electronics
Diff amps may be used to monitor voltage or current in a system and then trigger alarm systems when nominal operating levels are exceeded. Because of their ability to reject high common-mode voltages, diff amps are often used in these applications.

Software-Programmable Applications
An in-amp may be used with a software-programmable resistor chip to allow software control of hardware systems.

Audio Applications
Because of their high common-mode rejection, instrumentation amplifiers are sometimes used for audio applications (as microphone preamps, for example), to extract a weak signal from a noisy environment, and to minimize offsets and noise due to ground loops. Refer to Table 6-4 (page 6-26), Specialty Products Available from Analog Devices.

High Speed Signal Conditioning
Because the speed and accuracy of modern video data acquisition systems have improved, there is now a growing need for high bandwidth instrumentation amplifiers, particularly in the field of CCD imaging equipment where offset correction and input buffering are required. Double-correlated sampling techniques are often used in this area for offset correction of the CCD image. Two sample-and-hold amplifiers monitor the pixel and reference levels, and a dc-corrected output is provided by feeding their signals into an instrumentation amplifier.

Video Applications
High speed in-amps may be used in many video and cable RF systems to amplify or process high frequency signals.

Power Control Applications
In-amps can also be used for motor monitoring (to monitor and control motor speed, torque, etc.) by measuring the voltages, currents, and phase relationships of a 3-phase ac-phase motor. Diff amps are used in applications where the input signal exceeds the supply voltages.

IN-AMPS: AN EXTERNAL VIEW
Figure 1-5 provides a functional block diagram of an instrumentation amplifier.
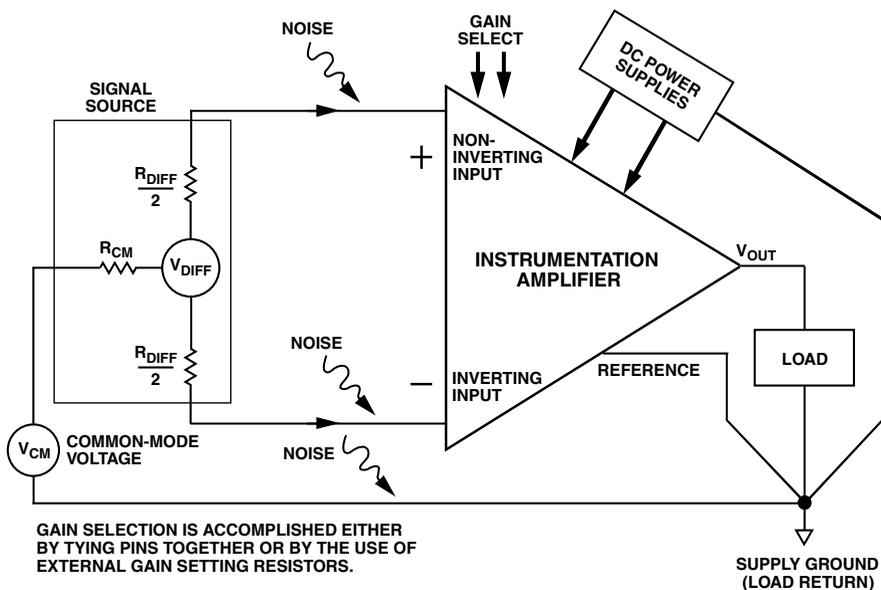

Figure 1-5. Differential vs. common-mode input signals.

Since an ideal instrumentation amplifier detects only the difference in voltage between its inputs, any common-mode signals (equal potentials for both inputs), such as noise or voltage drops in ground lines, are rejected at the input stage without being amplified.

Either internal or external resistors may be used to set the gain. Internal resistors are the most accurate and provide the lowest gain drift over temperature.

One common approach is to use a single external resistor, working with two internal resistors, to set the gain. The user can calculate the required value of resistance for a given gain, using the gain equation listed in the in-amp's spec sheet. This permits gain to be set anywhere within a very large range. However, the external resistor can seldom be exactly the correct value for the desired gain, and it will always be at a slightly different temperature than the IC's internal resistors. These practical limitations always contribute additional gain error and gain drift.

Sometimes two external resistors are employed. In general, a 2-resistor solution will have lower drift than a single resistor as the ratio of the two resistors sets the gain, and these resistors can be within a single IC array for close matching and very similar temperature coefficients (TC). Conversely, a single external resistor will always be a TC mismatch for an on-chip resistor.

The output of an instrumentation amplifier often has its own reference terminal, which, among other uses, allows the in-amp to drive a load that may be at a distant location.

Figure 1-5 shows the input and output commons being returned to the same potential, in this case to power supply ground. This star ground connection is a very effective means of minimizing ground loops in the circuit; however, some residual common-mode ground currents will still remain. These currents flowing through R_{CM} will develop a common-mode voltage error, V_{CM}. The in-amp, by virtue of its high common-mode rejection, will amplify the differential signal while rejecting V_{CM} and any common-mode noise.

Of course, power must be supplied to the in-amp. As with op amps, the power would normally be provided by a dual-supply voltage that operates the in-amp over a specified range. Alternatively, an in-amp specified for single-supply (rail-to-rail) operation may be used.

An instrumentation amplifier may be assembled using one or more operational amplifiers, or it may be of monolithic construction. Both technologies have their advantages and limitations.

In general, discrete (op amp) in-amps offer design flexibility at low cost and can sometimes provide performance unattainable with monolithic designs, such as very high bandwidth. In contrast, monolithic designs provide complete in-amp functionality and are fully specified and usually factory trimmed, often to higher dc precision than discrete designs. Monolithic in-amps are also much smaller, lower in cost, and easier to apply.

WHAT OTHER PROPERTIES DEFINE A HIGH QUALITY IN-AMP?

Possessing a high common-mode rejection ratio, an instrumentation amplifier requires the properties described below.

High AC (and DC) Common-Mode Rejection

At a minimum, an in-amp's CMR should be high over the range of input frequencies that need to be rejected. This includes high CMR at power line frequencies and at the second harmonic of the power line frequency.

Low Offset Voltage and Offset Voltage Drift

As with an operational amplifier, an in-amp must have low offset voltage. Since an instrumentation amplifier consists of two independent sections, an input stage and an output amplifier, total output offset will equal the sum of the gain times the input offset plus the offset of the output amplifier (within the in-amp). Typical values for input and output offset drift are 1 µV/°C and 10 µV/°C, respectively. Although the initial offset voltage may be nulled with external trimming, offset voltage drift cannot be adjusted out. As with initial offset, offset drift has two components, with the input and output section of the in-amp each contributing its portion of error to the total. As gain is increased, the offset drift of the input stage becomes the dominant source of offset error.

A Matched, High Input Impedance

The impedances of the inverting and noninverting input terminals of an in-amp must be high and closely matched to one another. High input impedance is necessary to avoid loading down the input signal source, which could also lower the input signal voltage.

Values of input impedance from 10^9 Ω to 10^{12} Ω are typical. Difference amplifiers, such as the AD629, have lower input impedances, but can be very effective in high common-mode voltage applications.

Low Input Bias and Offset Current Errors

Again, as with an op amp, an instrumentation amplifier has bias currents that flow into, or out of, its input terminals; bipolar in-amps have base currents and FET amplifiers have gate leakage currents. This bias current flowing through an imbalance in the signal source resistance will create an offset error. Note that if the input source resistance becomes infinite, as with ac (capacitive) input coupling, without a resistive return to power supply ground, the input common-mode voltage will climb until the amplifier saturates. A high value resistor connected between each input and ground is normally used to prevent this problem. Typically, the input bias current multiplied by the resistor's value in ohms should be less than 10 mV (see Chapter V). Input offset current errors are defined as the mismatch between the bias currents flowing into the two inputs. Typical values of input bias current for a bipolar in-amp range from 1 nA to 50 nA; for a FET input device, values of 1 pA to 50 pA are typical at room temperature.

Low Noise

Because it must be able to handle very low level input voltages, an in-amp must not add its own noise to that of the signal. A minimum input noise level of 10 nV/$\sqrt{\text{Hz}}$ @ 1 kHz (gain > 100) referred to input (RTI) is desirable. Micropower in-amps are optimized for the lowest possible input stage current and, therefore, typically have higher noise levels than their higher current cousins.

Low Nonlinearity

Input offset and scale factor errors can be corrected by external trimming, but nonlinearity is an inherent performance limitation of the device and cannot be removed by external adjustment. Low nonlinearity must be designed in by the manufacturer. Nonlinearity is normally specified as a percentage of full scale, whereas the manufacturer measures the in-amp's error at the plus and minus full-scale voltage and at zero. A nonlinearity error of 0.01% is typical for a high quality in-amp; some devices have levels as low as 0.0001%.

Simple Gain Selection

Gain selection should be easy. The use of a single external gain resistor is common, but an external resistor will affect the circuit's accuracy and gain drift with temperature. In-amps, such as the **AD621**, provide a choice of internally preset gains that are pin-selectable, with very low gain TC.

Adequate Bandwidth

An instrumentation amplifier must provide bandwidth sufficient for the particular application. Since typical unity-gain, small-signal bandwidths fall between 500 kHz and 4 MHz, performance at low gains is easily achieved, but at higher gains bandwidth becomes much more of an issue. Micropower in-amps typically have lower bandwidth than comparable standard in-amps, as micropower input stages are operated at much lower current levels.

Differential to Single-Ended Conversion

Differential to single-ended conversion is, of course, an integral part of an in-amp's function: A differential input voltage is amplified and a buffered, single-ended output voltage is provided. There are many in-amp applications that require amplifying a differential voltage that is *riding* on top of a much larger common-mode voltage. This common-mode voltage may be noise, or ADC offset, or both. The use of an op amp rather than an in-amp would simply amplify *both* the common mode and the signal by equal amounts. The great benefit provided by an in-amp is that it selectively amplifies the (differential) signal while rejecting the common-mode signal.

Rail-to-Rail Input and Output Swing

Modern in-amps often need to operate on single-supply voltages of 5 V or less. In many of these applications, a rail-to-rail input ADC is often used. So-called rail-to-rail operation means that an amplifier's maximum input or output swing is essentially equal to the power supply voltage. In fact, the input swing can sometimes exceed the supply voltage slightly, while the output swing is often within 100 mV of the supply voltage or ground. Careful attention to the data sheet specifications is advised.

Power vs. Bandwidth, Slew Rate, and Noise

As a general rule, the higher the operating current of the in-amp's input section, the greater the bandwidth and slew rate and the lower the noise. But higher operating current means higher power dissipation and heat. Battery-operated equipment needs to use low power devices, and densely packed printed circuit boards must be able to dissipate the collective heat of all their active components. Device heating also increases offset drift and other temperature-related errors. IC designers often must trade off some specifications to keep power dissipation and drift to acceptable levels.