III Instrumentation Amplifiers

Chapter 2

As we have noted in the chapter on Data Acquisition, and elsewhere, it is often necessary to retrieve millivolts of analog data from volts of common-mode interference. In some cases, it is also necessary to galvanically isolate the amplifier's input from its output and the power source, either to protect the amplifier from high voltage, to protect the device being measured (viz., a hospital patient) from stray leakage current, or simply to obtain better common-mode rejection.

The instrumentalities for achieving these objectives are called *instrumentation amplifiers,* and they include a special subclass of *isolation amplifiers.* Although amplifiers of this class often contain operational amplifiers, they are distinguished from op amps in being *committed* devices with a definite (set of) output-input relationship(s) and an essentially fixed configuration. They are designed to meet the specific objectives of high CMRR, low noise and drift, moderate bandwidth, and a limited range of gains (usually 1 to 1000, programmable by a single resistor).

Although there are a wide variety of frills and added-cost "extras" in the $250+ range on the market, ranging from digitally-programmed gain to autoranging (primarily for use in low-level-multiplexed systems), simple instrumentation amplifiers are becoming available at such low cost* that they seem destined to encourage the growth of per-channel amplification in instrument applications. For example, as this is written, the AD520 Monolithic

*both from manufacturers, such as Analog Devices, and built in-house using low-cost IC op amps

Instrumentation Amplifier has just been introduced (Spring, 1972) at an initial price of $12 in 100's.†

Accordingly, this chapter will focus on the properties, specification, and application of simple instrumentation and isolation amplifiers, while recognizing that more-complex devices exist and do have a role (albeit somewhat limited) in A/D conversion systems.

INSTRUMENTATION AMPLIFIERS

The instrumentation amplifier is a committed-gain amplifier with internal high-precision feedback networks. Its excellent drift, linearity, and noise-rejection capability make it a natural choice for extracting and amplifying low-level signals in the presence of high common-mode-noise voltages.

These devices are commonly used as transducer amplifiers for thermocouples, strain-gage bridges, current shunts, and biological probes. As preamplifiers, they are capable of extracting small differential signals superimposed on large common-mode voltages. Wideband designs are also available for data-acquisition systems.

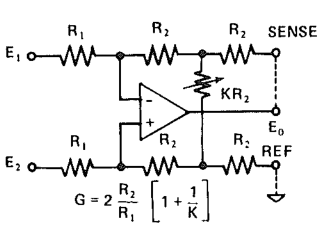
Design

Figure 1 shows a number of commonly-used circuit-design approaches. All require that only one resistor be adjusted to control the gain. Most commercially-available types have feedback *sense* and *reference* terminals for lead compensation, current-output sensing, and adjustable offset reference voltage. A few uses of these terminals are discussed under Applications.

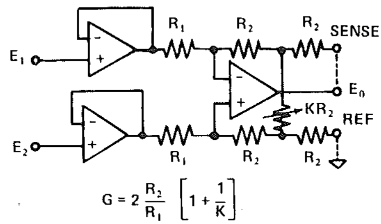
The simple subtractor (1a), uses only one operational amplifier. It has the disadvantage of poor source unbalance characteristics, because of its low input impedance, for normal values of R_1 (CMR

†The AD520J, in a 14-pin hermetically-sealed DIL package (small size, environmentally protected), is *not* an op amp but a true-differential instrumentation amplifier, with $2 \times 10^9\,\Omega$ Z_{in}, 90dB minimum CMRR at gain of 100 (0-100Hz, 1kΩ source unbalance), 50kHz full-power bandwidth, single-resistor gain adjustment.

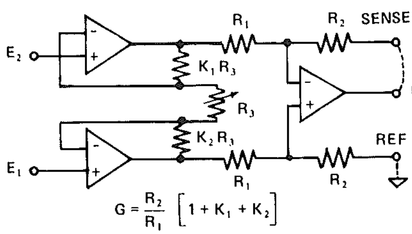
depends critically on resistance matching). If a FET-input amplifier is used with very large values of resistance, noise and bandwidth characteristics will suffer.



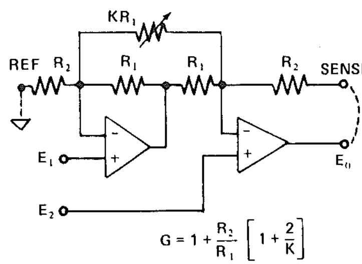
a. Simple Subtractor



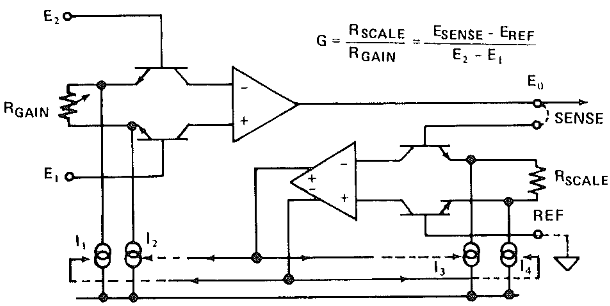
b. Buffered Subtractor



c. Buffered Subtractor With Gain



d. High-Input-Impedance Image of Subtractor



e. Current-Feedback Type (AD520)

Figure 1. Instrumentation-Amplifier Designs

The buffered subtractor (1b) gets around the problem, at the cost of two additional op amps. Bipolar types are ordinarily adequate, but FET-input types would be used with signal inputs having high source impedance. Matched input-followers will provide low drift and keep high CMRR, if the main amplifier's drift is low and the resistances are well-matched.

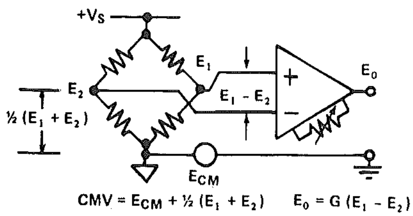
Reliance on resistance match for CMR is reduced, and bandwidth is improved in high-gain applications by using the buffered subtractor-with-gain (1c). The first stage has unity gain for the common-mode signal, thus increasing overall CMR by the differential gain of the first stage. (Separate followers-with-gain would not be capable of this improvement, because they would amplify differential and common-mode signals equally.) Matched amplifiers will help CMR and drift-stability.

The two-amplifier circuit (1d) has high input impedance, saves the cost of an amplifier, but it also increases dependence on resistance match for high CMR.

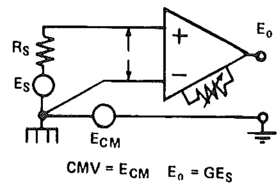
Unlike all of the other schemes, the differential current-feedback circuit (1e) has high-impedance *sense* and *reference* input terminals, allowing them to play a more important part in a wider range of applications. (It will be noted, in all of the other circuits, that resistance in series with either of those terminals, unless matched at the other, will cause common-mode errors.) The scheme also has a simple relationship between the gain and the resistance used to adjust it. The ability to match transistors and current-sources, and the close spacing on the monolithic chip, tend to make this approach feasible at low cost.

Applications

In data systems, instrumentation amplifiers are used primarily for pre-amplification and for adapting the input signal range to the usually-fixed range of the A/D converter. Because they ideally respond only to the difference between two voltages, they can be used in both balanced and unbalanced systems. *Balanced* implies that the output of the signal source appears on two lines, both having essentially equal source resistances and output voltages in relation to either ground or the local common-mode level, e.g., bridge outputs (Figure 2a); *unbalanced* means that inherent symmetry is not a property of the configuration – in fact, a major application of instrumentation amplifiers is in eliminating the effects of ground-potential differences in non-ideal single-ended systems (Figure 2b).



a. Balanced Input



b. Unbalanced Input

Figure 2. Balanced and Unbalanced Inputs

Because instrumentation amplifiers can measure voltage differences at any level within their specified range, they are useful in current measurement. Typically, they will measure and amplify the voltage appearing across a low-resistance shunt, often in the "high" line (Figure 3).

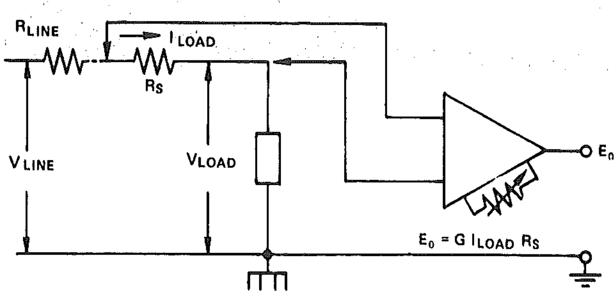


Figure 3. Current Measurement

If the *reference* terminal is available, it may be used for biasing the location of the pen in chart-recorder applications; it may be used to bias out dc normal-mode voltages, e.g., contact potentials; or it may be used to bias relay or comparator trip points. The reference terminal may be driven by the output of an operational amplifier with either constant or variable voltage; in addition, if the amplifier has high input impedance at the reference terminal, it may be driven passively by a voltage divider or a potentiometer.

In normal applications, the *sense* and *reference* terminals are connected to the specific points at which the output is to be accurately maintained; the circuit will then ignore voltage drops in the output signal or ground lines.

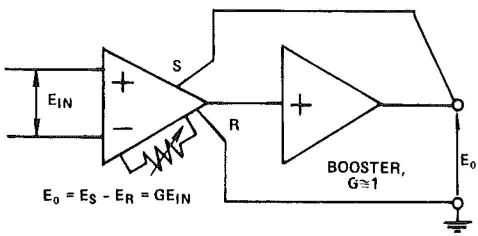


Figure 4. Maintaining Accuracy With an External Current Booster

The *sense* terminal is especially useful in circuits employing current-booster followers, since the booster may then be included within the feedback loop, and its offsets, drifts, and gain errors nullified (Figure 4). The sense and reference terminals, if high enough in impedance to avoid significant loading, are also useful for driving current to either floating or grounded loads. (In the circuit of Figure 5, for floating load, the reference is grounded, for grounded load, the sense terminal is connected to the output.)

For circuits employing the sense and reference terminals in other than "straight" differential amplification, it is essential to consider the possibility of and, if necessary, to take proper precautions to avoid dynamic instabilities: overshoots, ringing, or oscillation.

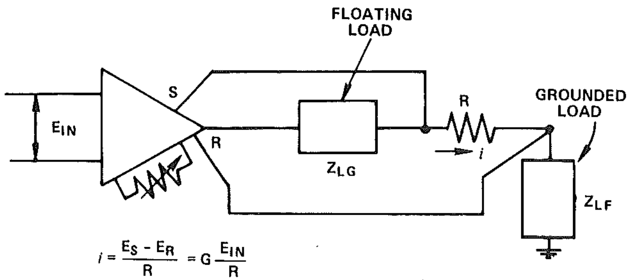


Figure 5. Current Drive to Floating or Grounded Load

Specifications

The table on the following page indicates specifications for typical instrumentation amplifiers. In many respects they appear similar to those for operational amplifiers. Differences include:

Gain An open-loop gain specification is unnecessary; However, gain nonlinearity and instability are specified.

Offset Offset drift specifications are given, referred to the *input,* at the two extremes, 1 and 1000. To determine the corresponding specification at any arbitrary value of gain, referred to the *output,* the following formula is used, to an excellent approximation:

$$\text{Drift}|_G \cong \frac{1000 \cdot \text{Drift(rti)}|_{1000} - \text{Drift}|_1}{1000} \cdot G + \text{Drift}|_1$$

Other specifications are listed at specific values of gain. Intermediate values may usually be interpolated. Unless noted otherwise, specifications not associated with a gain value are essentially independent of gain.

An Example

Since errors from all sources, though not individually significant, can add up to a substantial amount, it is important to perform an

Table 1. *Capsule Specifications - Instrumentation Amplifiers*

	High CMR, Low Drift 0.005% Linearity 605			Wideband, Low Drift 25µs Settling to 0.01% 604			Economy Monolithic AD520
Model	J	K	L	J	K	L	J
Gain							
Range		1 to 1000			1 to 1000		1 to 1000
Formula		G = 1 + (200k/Rg)			G = (3 x 10^5)/Rg		G = 10^5/Rg
Deviation From Formula, max		±0.1%			±0.1%		±0.05%
vs. Temp, max		±15ppm/°C			±15ppm/°C(±5ppm/°C typ)		—
vs. Time		±0.0003%/mo.			±0.0003%/mo.		—
Nonlinearity, max		±0.005%			±0.01% (0.005% typ)		±0.02% typ
Rated Output, min		±10V@5mA			±10V@10mA		±10V@5mA
Frequency Response							
Unity Gain, Small Signal, (-3dB)							
G = 1		300kHz			50kHz		300kHz
G = 1000		300Hz			50kHz		35kHz
Full Power Response, min		1.5kHz typ			50kHz[1] typ		60kHz typ
Slew Rate		0.1V/µs			3V/µs[2]		3.5V/µs typ
Unity Gain Settling Time to 0.1%		130µs(0.01%, G = 1)			25µs (to 0.01%)[1]		—
Offsets Referred to Input							
Initial Offset Voltage		Adjust to 0			Adjust to 0		Adjust to 0
vs. Temp, max G = 1		±150µV/°C		±3	±1	±0.5mV/°C	±1.0mV/°C typ
G = 1000	±3	±1.0	±0.5µV/°C	±3	±1	±0.5µV/°C	±5.0µV/°C typ
vs. Supply G = 1		±0.2mV/%			±2mV/% max		—
G = 1000		±4µV/%			±0.2 µV/% max		±300µV/% typ
Input Bias Current							
Initial, 25°C		0, +100nA			0, +100nA		±100nA
vs. Temp		-1nA/°C max			0, -1.0nA/°C max		±1nA/°C
Input Difference Current							
Initial, 25°C		±100nA max			±10nA max		±25nA
vs. Temp.		±1nA/°C max			±100pA/°C max		0.25nA/°C
Input Impedance							
Differential		10^9 Ω			(10^{11} Ω/G)//10pF		2 x 10^9 Ω
Common Mode		10^9 Ω			10^{11} Ω//10pF		—
Noise Referred to Input							
Voltage Noise, 0.01 to 1Hz, p-p							
G = 1		15µV(0.1 to 10Hz)			100µV (0.1 to 10Hz)		1.0mV (0.1 to 10Hz)
G = 1000		1.5µV(0.1 to 10Hz)			1µV (0.1 to 10Hz)		
Voltage Noise, 10Hz to 10kHz, rms							
G = 1		5.0µV			100µV (1.5µV, G = 1000)		—
Input Voltage Range							
Linear Differential Input		±10V			±10V		±12V
Max Differential Input		±20V			±20V		—
Max Common Mode		±V_S			±10V		±10V
CMR @ ±10V, DC to 60Hz							
(1kΩImbalance) G = 1		70dB[3]			60dB[3]		70dB
G = 1000		94dB(120dB typ)DC to 5Hz[3]			120dB DC to 5Hz[3]		106dB
Reference Terminal							
R_{in}		10^4 Ω			5 x 10^9 Ω		10^7 Ω
Output Offset Range		±10V			±10V		±10V
Gain Offset Range		+1.00			+1.000		1.000
Bias Current		200nA			200nA		4µA
Power Supply Range, ±V_S(VDC)		±(12 to 18)V			±(12 to 18)V		±(12 to 18)V
Operating, Rated Specifications (VDC)		±15V@7mA			±15V@7mA		±15V@4mA
Temperature Range							
Operating, Rated Specifications		0 to +70°C			0 to +50°C		0 to +70°C
Package Outline		FA–5			C–15		TO–116
Case Dimensions		1.5" x 1.5" x 0.4"			2" x 3" x 0.4"		—

(Specifications typical @ +25°C and ±15VDC power supply unless otherwise noted.)

(1)±0.1% amplitude accuracy to 1kHz min.
(2)Constant with gains from 3V/V to 1000V/V.
(3)Minimum CMR with 1kΩ imbalance.

error-budget analysis to find (and if possible reduce) the most significant terms. An example of a circuit application is given in Figure 6.

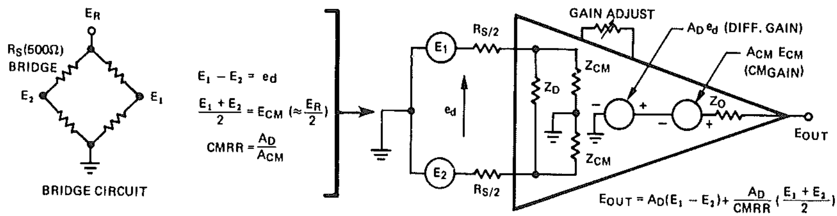


Figure 6. Instrumentation Amplifier-Equivalent Model When Used as a Bridge Amplifier

These are the given operating conditions and hypothetical amplifier specifications to be used in the example:

Operating Conditions		*Amplifier Specifications*
e_{IN}	$= \pm 5mV$	e_{OS} Drift 11mV/°C (G = 1000) at output
e_{OUT}	$= \pm 5V$	Gain Drift = ±0.01% (G = 1000)
E_{CM}	$= +5V$	I_B = 20nA
ΔT	$= \pm 20°C$	Z_d = 300MΩ
T_A	= +25°C(ambient)	Z_{CM} = 1000MΩ
R_L	= 10kΩ	CMRR (A_D/A_{CM}) = 10^5 (100dB CMR)
R_{BRIDGE}	= 500Ω	Gain = 1000
		Nonlinearity = ±0.01%
		R_o = 10Ω

The error budget is computed as follows:

Error Source	*Calculation*	*Value*	*%F.S.(5V)*
Gain Drift (+5° to 45°C)	0.01%/°C × ΔT × E_{OUT}	± 10mV	0.2%
Offset Drift (+5° to 45°C)	11mV/°C × ΔT	±220mV	4.4%
Total Drift Error		230mV	4.6%
Linearity Error	0.01% @ 10V (independent of output)	± 10mV	0.2%
Common-Mode Error	E_{CM} × A_D/CMRR	± 50mV	1.0%
Offset Error	(adjust to zero)	negligible	
Input Loading Error	R_{BRIDGE}/R_D	negligible	
Output Loading Error	(R_o/R_L) × e_{OUT}	5mV	0.1%
Total Error at 25°C		± 65mV	1.3%
Total Error (+5°C to +45°C)		±295mV	5.9%

For the given example, the error is 5.9%. Its largest components are offset drift (4.4%) and CME (1%).

If an amplifier having output drift of 2mV/°C at G = 1000 were used, the offset drift error would be reduced to ±40mV (0.8%). If the common-mode voltage is relatively constant (this is the case for a bridge circuit), then a simple offset adjustment can reduce the common-mode error virtually to zero, a 50mV, or 1% improvement. The total error will then be approximately ±55mV (1.1%).

This error-budget analysis demonstrates the importance of analyzing the problem and applying major error-reduction effort to the most-important sources of error.

ISOLATION AMPLIFIERS

There are certain classes of application conditions that require actual galvanic isolation of the amplifier's input circuit from its output and the power supply.

1. Very-high common-mode voltage, well beyond 500V, between input and output.
2. Safety requirements for medical-electronics equipment
3. Two-wire input, with no ground return for bias current
4. High CMRR required, with appreciable source unbalance

The two most promising approaches to obtaining isolation at the present time appear to be transformer and optical coupling. While optical coupling appears to be quite effective at isolation, since it uses a portion of the electromagnetic spectrum that completely abandons voltage, current, charge, and magnetic flux for energy transmission, the components and techniques applicable to low-cost high-performance linear circuits are still relatively primitive (but developing rapidly).

Recognizing these realities, as well as the present urgent needs, Analog Devices has developed, for sale at low cost, a series of isolation amplifiers, employing transformer coupling, that offers total galvanic isolation, low capacitance (< 10pF between input and output ground circuits), high CMR (115dB at 60Hz), and high common-mode voltage ratings (to 5kV). Capable of transmitting millivolt signals in the presence of up to 1000 volts common-mode, with unity gain, or with adjustable gain, these devices (the

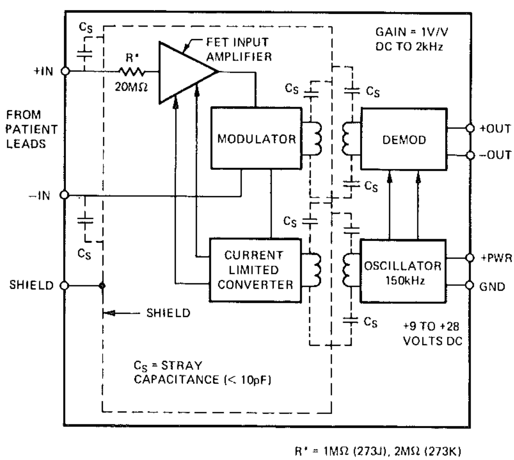


Figure 7. Block Diagram of Unity Gain Isolation Amplifiers

272, 273, 274 class) are ideal for medical applications (where an ECG waveform is the input signal to the data system), where it is mandatory to isolate hospital patients from potentially-lethal ground-fault currents, and for industrial applications, to interrupt ground loops between transducers and output-conditioning circuits.

Like instrumentation amplifiers, amplifiers of this type have committed gain circuits with internal feedback networks. All models operate from dc to 2kHz. They are designed in two parts: an isolated front-end amplifier section, and a grounded output section (Figure 7). The front end includes the fixed-gain op amp, a modulator, and a dc regulator circuit, all enclosed in a floating guard-shield. The output section contains a demodulator, filter, and power-supply oscillator circuit, operating from a single

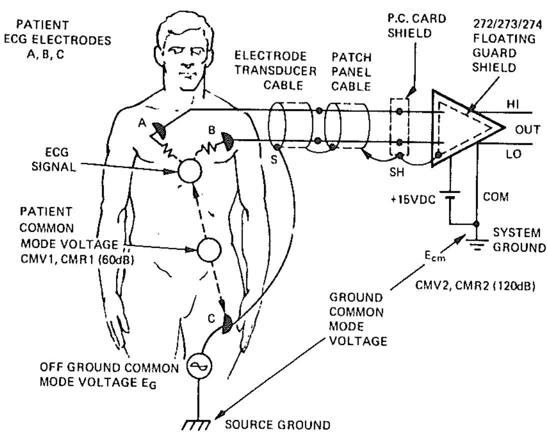


Figure 8. Patient-Amplifier Interconnection Diagram

+15Vdc supply. Operating power is transformer-coupled into the shielded input circuits and capacitively or magnetically coupled to the output demodulator circuit.

A typical connection in a medical-electronics data-acquisition system front end is shown in Figure 8.