Amplifiers and Signal Translation

Chapter 4

Transducers usually require amplifiers or related devices for buffering, isolation, gain, level translation, and current-to-voltage or voltage-to-current conversion. Most of these functions can be (and are) performed by operational amplifiers. However, the level and character of the circuit techniques required for best design and implementation may well cause the prudent system designer to seek packaged "system solutions."

In this chapter, we will briefly discuss the basics of op-amp circuits and device selection.* Instrumentation and isolation amplifiers, which were mentioned briefly in Chapter 2, will be discussed further here, and there will be a brief treatment of signal conditioners, level translators, and other subsystems. Practical aspects of these devices are generally discussed in relation to actual applications in the Applications section.

OPERATIONAL AMPLIFIERS

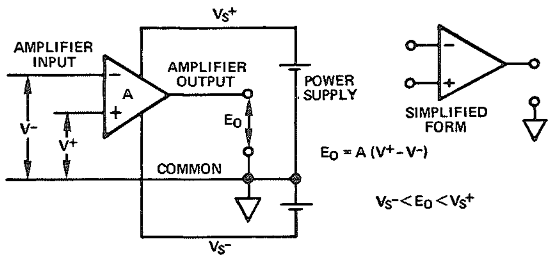
The operational amplifier (op amp†) is a high-gain amplifier designed for use in feedback circuits to perform stable predictable *operations*, which are inherently determined by the external components and configuration rather than by the amplifier's open-loop gain magnitude.

Figure 4-1 shows the symbol of a *differential operational amplifier* and its basic open-loop response. Since the gain, A, is ideally infinite

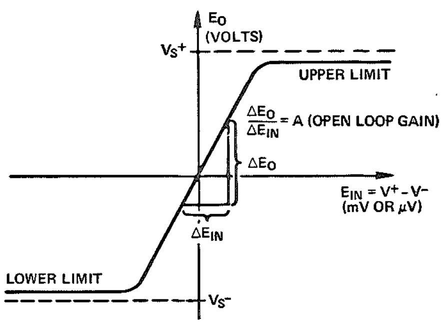
*There are many good sources of information on the theory and application of op amps. Several that we have found valuable are listed in the Bibliography.

†An *operational amplifier* is any circuit configuration, wherever found, that behaves in the manner described here. The term *op amp* is an abbreviation for a *device* manufactured for use in operational-amplifier applications.

and usually quite high (10^5 to 10^6 at low frequencies), the differential input signal must be nearly zero for the output to be within the limits.* If an operational amplifier is *ideal* (infinite gain, bandwidth, and input impedance, zero input offset voltage and bias current, zero output impedance), a number of useful consequences may be inferred. Usually, a real amplifier can be found with sufficiently ideal parameters for use in a given application based on postulating an ideal amplifier.



a. Differential operational amplifier circuit, open-loop



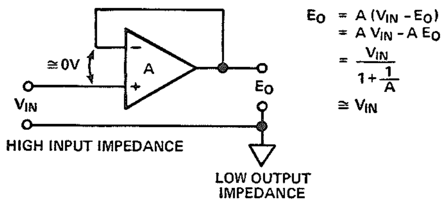
b. Plot of output vs. input for circuit in (a). Note that input scale is millivolts or microvolts.

Figure 4-1. Op amp basic circuit and response

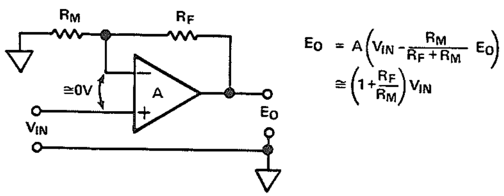
Since the output must be whatever is necessary to make the input voltages, V^+ and V^-, nearly equal via feedback, the op amp is an excellent unity-gain *follower* (Figure 4-2a). If the feedback is attenuated, we have a *follower with gain* (b), where the gain is

*Most op amps may also be used as *comparators,* where the output is always at one limit or the other, depending on the polarity of the input signal (beyond the threshold of linear operation).

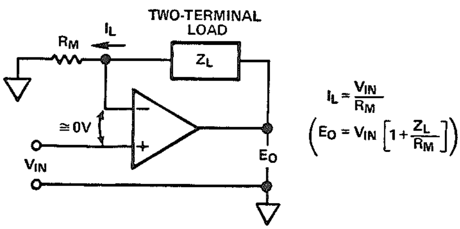
accurately set by a resistance ratio. If a metering resistor, R_M, is connected from the negative input to common, then the output must provide a current through the non-grounded load element, Z_L, precisely equal to V_{IN}/R_M (and independent of the nature of Z_L), in order to maintain the inputs at equality (c).



a. Unity-gain follower



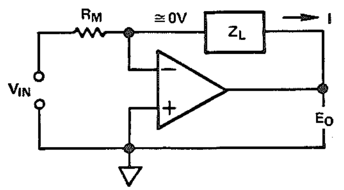
b. Follower with gain has high input impedance, low output impedance, gain depends only on R_F/R_M



c. Current generator—I_L depends only on V_{IN} and R_M; it is independent of Z_L and E_O

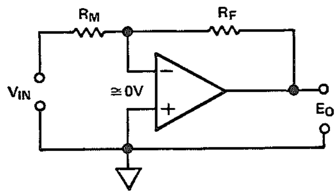
Figure 4-2. The op amp as a follower

If the plus input is connected to common, the output voltage must be whatever is required to hold the negative input at zero (*virtual ground*). Connecting a resistance in series with an input voltage will cause a current to flow (through the non-grounded element Z_L) equal to V_{IN}/R_M (Figure 4-3a). If Z_L is a resistance, R_F, the output voltage, E_O, must be $-(R_F/R_M)\ V_{IN}$, a polarity-inverted voltage that may be greater than, less than, or equal to V_{IN} in magnitude, depending only on the resistance ratio (b). If a second voltage, V_S, is applied to the negative input via a re-



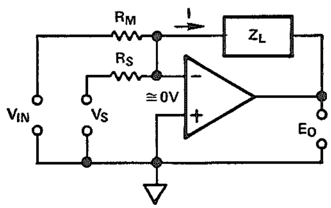
$$I = \frac{V_{IN}}{R_M}$$
$$\left(E_O = -V_{IN}\,\frac{Z_L}{R_M}\right)$$

a. Current source with input at virtual ground. Current depends only on V_{IN} and R_M, is independent of Z_L or E_O



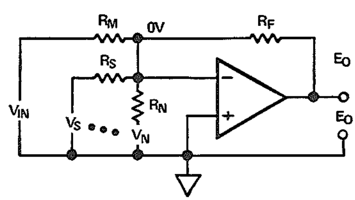
$$E_O = -\frac{R_F}{R_M}\,V_{IN}$$

b. Op amp as inverting amplifier. Gain depends only on R_F/R_M and may be greater than, less than, or equal to unity



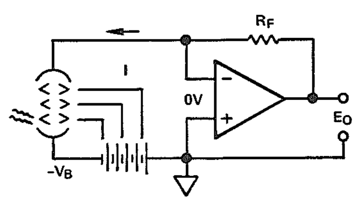
$$I = \frac{V_{IN}}{R_M} + \frac{V_S}{R_S}$$

c. Op amp as summing current source. Currents are independent of one another and of E_O or Z_L



$$E_O = -\left(\frac{R_F}{R_M}V_{IN} + \frac{R_F}{R_S}V_S + \ldots \frac{R_F}{R_N}V_N\right)$$

d. Op amp as summing amplifier. Resistance ratios determine individual gains or attenuations independently

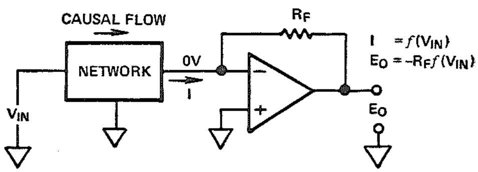


$$E_O = I\,R_F$$

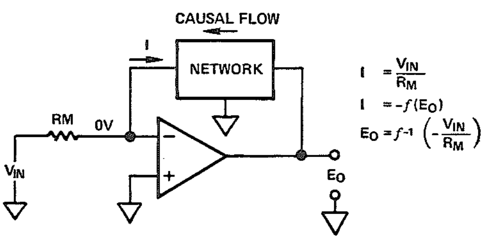
e. Op amp as current-to-voltage converter. Photomultiplier tube sees zero impedance—an ideal load. Output voltage is scaled by R_F.

Figure 4-3. Inverting applications of an op amp sistor, R_S, the current through Z_L will depend on the sum of the two independent input currents, V_{IN}/R_M and V_S/R_S; the currents are independent because the input resistors appear to the input voltages to be grounded (c). Since the currents are summed in R_F, the output voltage depends on the independently weighted sum, $V_{IN}(R_F/R_M) + V_S(R_F/R_S + \ldots V_N(R_F/R_N)$ (d). An input current source (such as a photomultiplier tube) can be connected directly to the negative input (an ideal zero-impedance load); its current is summed and transconducted to a voltage (e).

Since the current through R_M depends only on V_{IN} and the nature of R_M, R_M could be replaced by a capacitor (to form a differentiator, $I = CdV/dt$), by an element having a nonlinear voltage-current relationship (e.g., a diode in series with a resistor), or by an n-terminal network of linear and nonlinear impedances, with a number of inputs (Figure 4-4a); the resulting current through R_M would depend only on the short-circuit property of the input circuit. That current could be measured by a voltage via R_F and the amplifier output, without disturbing the value of the current. Similarly, the feedback network could be dynamic, nonlinear, and/or an n-terminal network; for an input current deter-



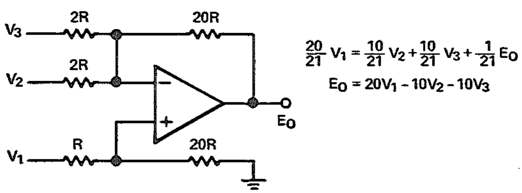
a. Output voltage is an arbitrary function of V_{IN}, determined by the nature of the input network, whether purely resistive, fixed or dynamic, linear or nonlinear, constant or time-varying



b. The output voltage is an inverse function of V_{IN}. The amplifier causes the output current of the network to be equal to $-V_{IN}/R_M$ by the manipulation of E_O

Figure 4-4. Direct and inverse functions using an op amp mined by V_{IN} and R_M, the output would have to be whatever voltage is necessary to maintain that current (b). For example, if R_F were replaced by a capacitor, the circuit would be an integrator; if R_F were shunted by a capacitor, the circuit would have a unit-lag response: if the forward drop of a diode were being tested, the diode could be the feedback element—the output voltage would be equal to the diode drop at a given current determined by V_{IN}/R_M.

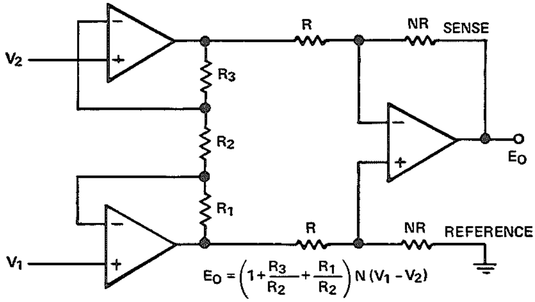
In the differential mode, an op amp will function as an analog adder, subtractor, and multi-input adder-subtractor (Figure 4-5a). A subtractor with gain can be used as an instrumentation amplifier, if care is taken to null out common-mode errors due to the amplifier, resistive elements, and input loading. The subtractor-with-gain can be combined with two cross-coupled followers-with-gain to form the circuit used in many conventional instrumentation amplifiers (b). The common-mode rejection of the subtractor is increased by the gain of the input followers, and the signal source is unloaded by the high input impedance of the followers.



$$\frac{20}{21}V_1 = \frac{10}{21}V_2 + \frac{10}{21}V_3 + \frac{1}{21}E_O$$

$$E_O = 20V_1 - 10V_2 - 10V_3$$

a. Adder-subtractor circuit. Simple rules for computing resistor ratios for any number of positive and negative inputs and any combination of gains or attenuations can be found in Analog Dialogue 10-1 (1976), page 14



b. Classical 3 op-amp instrumentation amplifier configuration

Figure 4-5. Differential op-amp configurations

There are many useful applications of op amps, both singly and in groups; indeed, the op amp has become the most versatile of elements in the circuit-designer's kit. This brief review has sought to establish the basic elements that constitute this versatility (and if pondered can suggest a great many more applications):

High gain and low input excursion

Negative input terminal must follow positive input terminal

Output voltage must be whatever value (within limits) is necessary to achieve this.

Op amp can generate inverse functions (e.g., gain is equal to inverse of attenuation of feedback circuit).

Op amp can convert current to voltage, voltage to current.

Op amp can establish virtual ground: voltage null and current balance.

Op amp can sum inputs independently.

Op amp can function as sign inverter.

Op amp activates passive circuitry, linear or nonlinear, static or dynamic, single-element or network.

Differential signal handling

Differences between op amps

Although the "ideal op amp" doesn't exist, op amps have been designed to optimize one or another set of parameters that are crucial in a given family of applications. The titles of selection charts in an op-amp catalog listing[2] provide some indication of the groupings of parameters that are commonly required:

1. General purpose (lowest cost)
2. FET-input, low bias current
3. Electrometers (lowest bias current)
4. High accuracy, low-drift differential
5. Chopper amplifiers (lowest drift)
6. Fast wideband
7. High output
8. Isolated op amps

For transducer interfacing: categories 1, 2, and 4 are the most relevant; 3 & 5 are required frequently; 8 is needed often (and will be discussed in the Isolator section); 6 is not commonly re-

[2] *Data-Acquisition Products Catalog*, Analog Devices, Inc.

quired; and 7 includes a potpourri of special requirements, often arrived at most economically by a proprietary design or an external device. The key specifications are *input offset*, *offset drift* with time, temperature, and power-supply voltage, *input bias current* and its drift, and *common-mode rejection*. Open-loop gain, bandwidth, noise, rated output voltage and current, stability with feedback and capacitive loading, etc., are all relevant (often critical) considerations, but the key specifications are usually the starting point in narrowing the universe in which the search for the "best choice" is conducted.

Offset is a small voltage, from tens of microvolts to millivolts, that appears—in effect—in series with the inputs of an operational amplifier (Figure 4-6); it acts just like a small voltage applied to the + input and is amplified in the same way. The principal cause of offset is mismatches in the input differential gain stage. A set of terminals is usually provided for connecting a potentiometer for adjusting the offset to zero, in an analogy to the zero-adjustment of a mechanical scale. If the amplifier's offset is substantial compared to the voltage representing the phenomenon being measured, these terminals should be used for nulling the offset. What is "substantial" depends on the application. Sometimes, a 5% error can be tolerated; in other cases, 0.01% is excessive. The amplifier's offset-adjustment terminals should be used *only* for adjusting the amplifier's voltage offset to zero. They should not be used to compensate for other errors in the amplifier or for offsetting the input signal itself; adjustment of offset will unbalance the amplifier, usually causing increased temperature sensitivity; if additional adjustments are made to correct other errors, the errors with temperature may become intolerable.

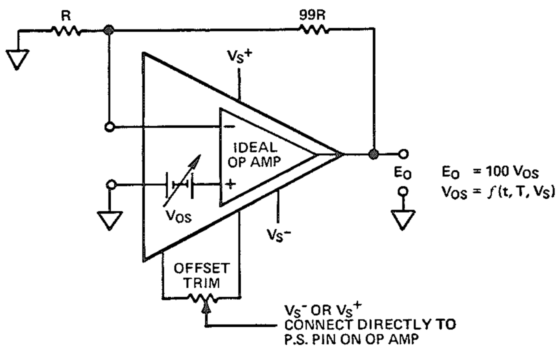


Figure 4-6. Offset voltage of an operational amplifier, and circuit for measuring it directly

The offset voltage is not absolutely stable. It drifts with time, temperature, and power-supply variations. This last is not usually a source of concern, since well-regulated power supplies are easy to buy. Drift with temperature (*tempco – temperature coefficient*) ranges from *tenths* of microvolts per °C to *tens* of microvolts per °C.

The drift error is specified as an average over a range (or ranges) of amplifier operating temperatures. Drift is usually nonlinear with temperature, and the worst drifts are generally at the extremes. For this reason, somewhat better drift performance may occur at mild temperatures ("room temperature"), but it is risky practice to place absolute reliance on this effect to save small amounts of money.

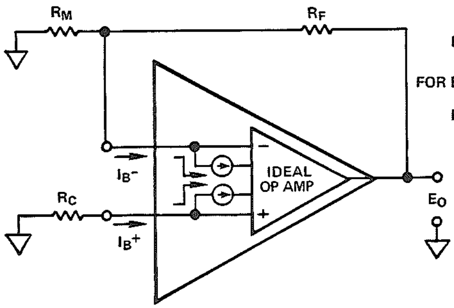
Amplifiers at constant temperature tend to drift with time in random-walk fashion. The drift *is* random and rarely–if ever–accumulates (at least, for a well-constructed device). The magnitude of drift expected over a year is $\sqrt{12}$ times the drift per month.

For the greatest stability with time and temperature, *choppers* are used. A chopper is simply a switch, exercised at a rapid rate, that compares the amplifier input with the desired null. Any offset produces a square wave, which may be ac-coupled without drift, amplified, then demodulated synchronously to form a low-frequency (dc) voltage, which is an amplified version of the offset. This dc is then fed back to provide an offset reduction proportional to the net gain. Chopper amplifiers have narrow bandwidth and tend to be single-ended; they are used in two ways, either as an adjunct to an inverting op amp for obtaining reduced drift, while maintaining the full bandwidth of the main amplifier (*chopper-stabilized op amp*), or as a narrow-band non-inverting high-input-impedance amplifier (*chopper op amp*).*

Bias current is the dc current that must flow at the input terminals of an op amp; in some cases it is a leakage current, in other cases it is the actual base current required by bipolar transistors for transistor bias. It flows through the external circuitry of the op amp and develops voltage across resistors or rates-of-change of voltage in capacitors ("open circuits"). For example, a bias current of 10nA (10^{-8}A) flowing from the negative input terminal of an op amp through a 1MΩ feedback resistor produces a 10mV output

*Analog Devices Models 235 and 261 are respective examples of the two categories.

offset. If the amplifier is a unity-gain inverter, this offset is equivalent to a 5mV voltage offset. In many types of differential-input op amps (*but not all*), the bias currents at the + and – inputs tend to be equal and to track one another; this permits first-order error reduction if the effective resistances at the two inputs are made equal, usually by insertion of a resistor of appropriate value in series with a low-impedance input (Figure 4-7).



$$E_O = I_B^- R_F - I_B^+ R_C \left(1 + \frac{R_F}{R_M}\right)$$

FOR $E_O = 0$,

$$R_C = \frac{I_B^-}{I_B^+} \frac{R_F R_M}{R_F + R_M}$$

Figure 4-7. Bias-current contributions to amplifier output offset (V_{OS} nulled). If currents are matched and tracking, voltage can be nulled if effective parallel resistances at the two inputs are equal

For low bias current, field-effect transistors (FET's) are used at the amplifier inputs; bias current for FET-input op amps ranges from 75fA (75×10^{-15}A) max for the AD515L to 50pA max for the AD542J, while for bipolar op amps it ranges from 1nA max (AD517L) to 500nA max (AD741).The lowest bias currents are found in parametric op amps (using varactor choppers*), 10fA max in Models 310/11†. Bias current changes by about 1%/°C (decreasing with increasing temperature) in bipolar op amps, doubles every +10°C in FET's and doubles every +7°C in parametrics.

Common-mode rejection affects an op amp's ability to deal with common-mode signals, when the positive input is active. Examples are found in follower circuits (measuring potentiometer outputs) and differential-amplifier circuits, (measuring bridges). An ideal operational amplifier responds only to the *difference* voltage between the inputs (normally very small, as noted in Figure 4-1), independently of whether the inputs are at +10V, –10V, or zero

*See *Analog Dialogue*, Volume 1, No. 3 for an explanation of how amplifiers can achieve low bias current using the parametric approach.

†Modules–they should not be confused with quite different IC's having nearly the same designations, but with the prefix, "AD": viz., AD310 and AD311.

(with respect to the power-supply common). However, due to slightly different sensitivities of the + and – inputs, or variations in offset voltage as a function of common-mode level, some common-mode voltage may appear at the output. If the output error voltage, due to a known magnitude of common-mode voltage (CMV), is referred to the input (dividing by the gain-for-a-voltage-at-the + input, or *closed-loop gain*), it reflects the equivalent *common-mode error* (CME) voltage effectively in series with the inputs.

Common-mode rejection ratio (CMRR) is defined as the ratio of common-mode voltage to the resulting common-mode error voltage (referred to the input). Common-mode rejection (CMR) is often expressed logarithmically:

$$\text{CMR (in decibels)} = 20 \log_{10} \text{CMRR}$$

For CMRR = 20,000, CMR = 86dB.

The precise specification of CMR is complicated by the fact that the common-mode voltage error can be a nonlinear function of common-mode voltage (and also varies with temperature). As a consequence, CMR data published by Analog Devices are average figures, assuming an end-point measurement over the common-mode range specified. The incremental CMR about small values of CMV may be greater than the average CMR specified (and smaller in the neighborhood of a large CMV). Published CMR specifications for op amps pertain to very low-frequency voltages, unless specified otherwise; CMR decreases with increasing frequency (often characterized graphically on op-amp data sheets).

When op amps are used singly or in groups to form instrumentation amplifiers to measure input difference voltage at arbitrary common-mode levels, the amplifier's common-mode error is only one source of CME; in addition, one must consider the effects of impedance-ratio mismatches in the feedback circuit and loading of the source by the amplifier's input circuit. For such applications, it is a good idea to consider using a committed *gain block*, which incorporates all required circuit elements (except perhaps for the gain-determining element, which must be at the user's option and may be fixed, variable, or programmable). Such gain blocks, available in IC and modular form, and also as input elements of data-acquisition systems, are known as *instrumentation amplifiers*. When an instrumentation amplifier's gain is programmed by digital logic, it is known as a *Programmable-Gain-Amplifier,* (PGA).

INSTRUMENTATION AMPLIFIERS

An instrumentation amplifier is a committed "gain block" that measures the difference between the voltages existing at its two input terminals, amplifies it by a precisely set gain—usually from 1V/V to 1000V/V or more—and causes the result to appear between a pair of terminals in the output circuit. Referring to Figure 4-8,

$$V_S - V_R = G\,(V^+ - V^-)$$

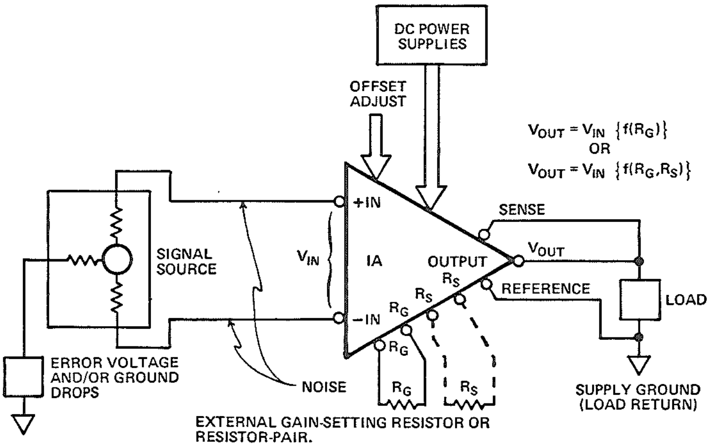


Figure 4-8. Basic instrumentation amplifier functional diagram

An ideal instrumentation amplifier responds only to the *difference* between the input voltages. If the input voltages are equal ($V^+ = V^- = V_{CM}$, the *common-mode voltage*), the output of the ideal instrumentation amplifier will be zero. The gain, G, is described by an equation that is specfic to each Model.

An amplifier circuit which is optimized for performance as an instrumentation-amplifier gain block has high input impedance, low offset and drift, low nonlinearity, stable gain, and low effective output impedance. Example of applications which capitalize on these advantages include the interfacing of thermocouples, strain gage bridges, current shunts, and biological probes; preamplification of small differential signals superimposed on large common-mode voltages; signal-conditioning and (moderate) isolation for data acquisition; and signal translation for differential and single-ended signals wherever the common "ground" is noisy or of questionable integrity.

Instrumentation-amplifier modules, IC's, and front-ends are usually used in preference to user-assembled op-amp circuitry because they offer optimized, specified performance in low-cost, easy-to-use compact packages. For applications that call for very high common-mode voltages or isolation impedances, with galvanic isolation, the designer will choose Isolators (to be discussed).

As Figure 4-8 shows, instrumentation amplifiers have two high-impedance input terminals, a set of terminals for gain-setting resistance(s)—except for those units that have digitally programmable gain—and a pair of feedback terminals, labeled "sense" and "reference", as well as a set of power-supply and offset-trim terminals.* When the *sense* (V_S) feedback terminal is connected to the output terminal and the *reference* terminal (V_R) is connected to power common, the output voltage appears between the output terminal and power common.

The V_S and V_R terminals may be used for remote sensing—to establish precise outputs in the presence of line drops; they may be used with an inside-the-loop booster follower to obtain power amplification without loss of accuracy; and they may be used to establish an output current that is precisely proportional to the input difference signal. A voltage applied to the V_R terminal will bias the output by a predetermined amount. It is important always to maintain very low impedance (in relation to the specified V_S and V_R terminal input impedances), when driving the V_S and V_R inputs, in order not to introduce common-mode, gain, and/or offset errors. In some devices, the V_R terminal is used for fine adjustments to common-mode rejection and/or offset.

Specifications

Although all specifications are relevant and none should be neglected, the most-important specs in transducer interfacing are those relating to *gain* (range, equation, linearity), *offset, bias current*, and *common-mode rejection*.

Gain range is the range of gains for which performance is specified. Although specified at 1 to 1000, for example, a device may work at higher (and, in the case of the AD521, *lower*) gain, but performance is not specified outside that range. In practice, noise and drift may make higher gains impractical for a given device.

*Some units include a *guard* terminal, which follows the common-mode voltage. It may be used to drive a guard conductor to reduce unbalanced noise, leakage, and capacitance (see *guarding*, Chapter 3).

Gain equation error or "gain accuracy" specifications describe the deviation from the gain equation when R_G is at its nominal value. The user can trim the gain or compensate for gain error elsewhere in the overall system. Systems using digital processing can be made self-calibrating, to take into account the lumped gain errors of *all* the stages in the analog portion of the system, from the transducer to the a/d converter. *Gain vs. temperature* specifications give the deviations from the gain equation as a function of temperature.

Nonlinearity is defined as the deviation from a straight line on the plot of output vs. input. The magnitude of linearity error is the maximum deviation from a "best straight line", with the output swinging through its full-scale range, expressed as a percentage of full-scale output range.

While initial *voltage offset* can be adjusted to zero, shifts in offset voltage with time and temperature introduce errors. Systems that involve "intelligent" processors can correct for offset errors in the whole measurement chain, but such applications are still relatively infrequent; in most applications, the instrumentation amplifier's contribution to system offset error must be considered.

Voltage offset and *drift* are functions of gain. The offset, measured at the output, is equal to a constant plus a term proportional to gain. For amplifier with specified performance over the gain range from 1 to 1000, the constant offset is essentially the offset at unity gain, and the proportionality term (or slope) is equal to the change in output offset between G = 1 and G = 1000, divided by 999. To refer offset to the input, divide the total output offset by the gain. Since offset at a gain of 1000 is dominated by the proportional term, the slope is often called the "RTI offset, G = 1000". At any value of gain, the offset is equal to the unity-gain offset plus the product of the gain and the "RTI offset, G = 1000".

The same considerations apply to offset drift. For example, if the maximum RTI drift is specified at $25\mu V/^\circ C$ at G = 1, $2\mu V/^\circ C$ at G = 1000, it will be $(23/G + 2)\mu V/^\circ C$ at any arbitrary gain in the range. At the output, the corresponding drift will be $(23 + 2G)$ $\mu V/^\circ C$. Voltage offset as a function of power-supply voltage is also specified RTI at one or more values of gain.

Input bias currents have the same causes as in op amps. They can be considered as sources of voltage offset (when multiplied by the source resistance). For balanced sources, the *offset current*, or difference between the bias currents, determines the bias-current contribution to error. Differences between the bias currents with temperature, common-mode level, and power supply voltage can lead to voltage offset or common-mode error.

Although instrumentation amplifiers have differential inputs, there must be a return path for the bias currents, however small. If the path is not provided, those currents will charge stray capacitances, causing the output to drift uncontrollably or to saturate. Therefore, when amplifying the outputs of "floating" sources, such as transformers and thermocouples, as well as ac-coupled sources, there must be a dc "leak" from both inputs to common*. If a dc return path is impracticable, an *isolator* must be used.

Common-mode rejection, in instrumentation amplifiers, is a measure of the change in output when both inputs are changed by equal amounts. CMR is usually specified for a full-range common-mode voltage change, at a given frequency, and a specified imbalance of source impedance (e.g., 1kΩ source unbalance, at 60Hz). The common-mode rejection ratio (CMRR) in instrumentation amplifiers is defined as the ratio of the signal gain, G, to the ratio of common-mode signal appearing at the output to the input CMV. In logarithmic form, CMR (in dB) = 20 $\log_{10}$ (CMRR). Typical values of CMR in instrumentation amplifiers range from 70dB to 110dB. In the high-gain bridge amplifiers found in modular signal-conditioners†, the minimum line-frequency common-mode rejection is of the order of 140dB.

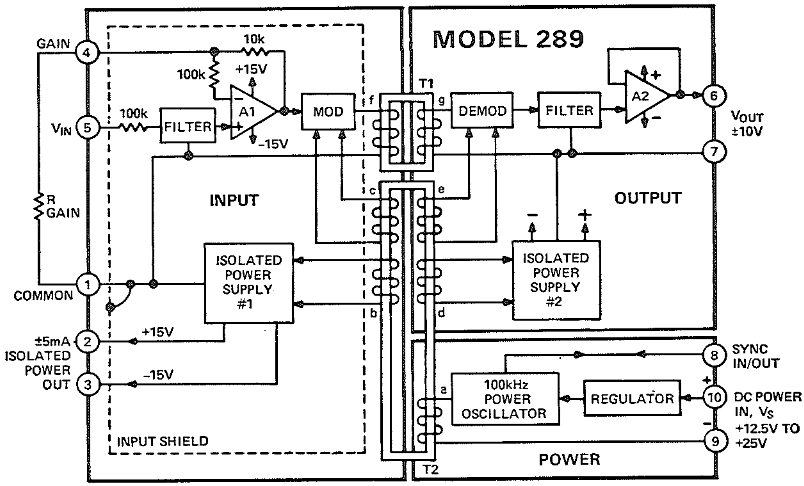
ISOLATION AMPLIFIERS

The isolation amplifier, or *isolator*, has an input circuit that is galvanically isolated from the power supply and the output circuit. Isolators are intended for: applications requiring safe, accurate measurement of dc and low-frequency voltage or current in the presence of high common-mode voltage (to thousands of volts) with high common-mode rejection; line-receiving of signals transmitted at high impedance in noisy environments; and for safety in general-purpose measurements where dc and line-frequency leakage must be maintained at levels well below certain mandated

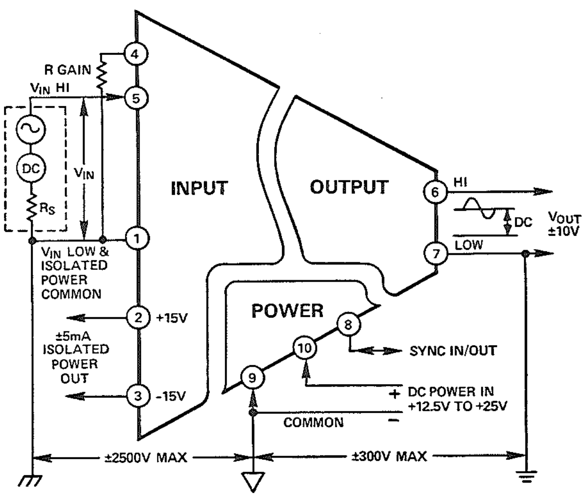
*This consideration, often neglected, is perhaps the most frequent cause of phone calls for help from our application engineers.
†Analog Devices 2B30 and 2B31

minima.* Principal applications are in electrical environments of the kind associated with medical equipment, conventional and nuclear power plants, automatic test equipment, industrial process-control systems, and field-portable instrumentation.

While, in concept, any non-conducting medium may be used for



a. Block diagram



b. Simplified functional diagram

Figure 4-9. Typical isolation-amplifier configuration

*Examples of such requirements may be found in UL STD 544 and SWC (Surge Withstand Capability) in IEEE Standard for Transient Voltage Protection 472–1974.

isolation, including light, ultrasonics and radio waves, the medium that is currently in widest use, because of its low cost and (relatively) easy implementation, is transformer-coupling of a high-frequency carrier for communicating power to and signals from the input circuit. Figure 4-9 is a diagram of a *3-port isolator*, one in which the power source, the front end, and the output circuit are all isolated from one another.

The two-wire primary dc power source provides excitation for a high-frequency oscillator. The oscillator output is coupled across the isolation barrier to the input section, providing power for the front end and for external isolated accessories (such as preamplifier circuitry). The input signal is amplified and modulates the carrier; the modulated waveform is coupled across the isolation barrier to the output section, where it is demodulated by a phase-sensitive demodulator (using the oscillator as a reference), and filtered.

The amplifier in this example is a resistor-protected op amp (actually, the protection works both ways–it protects the amplifier against differential overloads and it protects sensitive input sources from supply voltage if the amplifier malfunctions), connected for a programmable gain from 1 to 100 volts/volt, as determined by a single external resistor.

Since both input terminals are floating, the amplifier functions effectively as an instrumentation amplifier. Because of the transformer coupling, the output of these devices is isolated from the input stage.

The isolated power-supply output terminals can be used to provide floating power to transducers, preamplifiers, and other circuitry within the current limitations of the supply. Examples of the various ways of using isolation amplifiers in transducer interfacing will be found in the Applications section.*

The device pictured in Figure 4-9, typical of Model 289 and similar types, is a completely self-contained device. However, isolators are also available in several other useful forms. For example, if there are many input channels to be isolated, economies can be realized by the use of a common oscillator, which has the additional benefit of making it possible to avoid the possibility of

*Additional information on isolation and instrumentation amplifiers is to be found in the *Isolation and Instrumentation Amplifier Designers' Guide*, available from Analog Devices, Inc., at no charge.

small errors due to beat frequencies developed by small amounts of crosstalk. In any event, isolators intended for use in multichannel systems should be *synchronizable.*

Another type of isolated amplifier, of interest for many applications, is the *isolated operational amplifier**. This device has an operational-amplifier front end, which may be used to perform the many operations of which op amps are capable (including integration, differentiation, summing, etc.) and provide an output that is isolated from the input.

Specifications of Isolation Amplifiers

The key specifications of isolation amplifiers are of two kinds: performance specifications and isolation specs. The key performance specifications are similar to those for instrumentation and operational amplifiers, with a few additions: Nonlinearity, CMR – inputs to outputs, CMR – input to guard, offset voltage referred to input, input noise. Key isolation (and protection) specs include: maximum safe differential input, CMV – inputs to outputs, leakage current, overload resistance.

CMR – inputs to outputs indicates ability to reject common-mode voltages between the input and output terminals. It is important when processing small signals riding on high common-mode voltages.

CMR – input to guard indicates the ability to reject differential voltage between the low side of the signal and the guard. It should be considered in applications where the guard cannot be directly connected to the signal low.

Maximum safe differential input is the maximum voltage that can be safely applied across the input terminals. It is important to consider it for fail-safe designs in the presence of high fault voitages.

CMV – inputs to outputs is the voltage that may be safely applied to both inputs with respect to the outputs or power common. It is a necessary consideration in applications with high CMV input or when high-voltage transients may occur at the input.

Leakage current is the maximum input leakage current when power-line voltage is impressed on the inputs. It is a vital consideration for patient safety in medical applications.

Overload resistance is the apparent input impedance under con-

*Model 277 is an example of this type.

ditions of amplifier saturation. It limits differential fault currents.

The family of isolated devices is a growing one. Besides today's isolation amplifiers, isolated op amps, and isolated power supplies (dc-to-dc converters), there are isolated *voltage-to-current converters**, *thermocouple signal-conditioners*†, *high- and low-level multiplexers*§, and *d/a converters*‡, with yet more to come.

SYSTEM SOLUTIONS

Beyond the basic elements, such an op amps, instrumentation amplifiers, and isolators there are families of increasingly committed devices, which take more and more of the interfacing burden from the shoulders of the system designer. Since this volume is concerned with making the burden lighter for those who desire to bear it, we will mention system solutions only briefly, with the suggestion that complete information on the topics covered can be had merely by inquiring in the appropriate quarters.

Complete signal conditioners have already been mentioned. Several applications of these devices, which incorporate excitation, bridge amplification, and filtering, will be found in the Applications section.

Microcomputer interface cards|| are available in great number to interface with the most-popular microcomputers. *Input* cards respond to current inputs, and single-ended or differential high-level voltage sources, providing multiplexing, programmable-gain amplification, sample-hold, conversion, and enough memory-mapped software compatibility to make programming easy. *Output* cards provide the choice of voltage output or 4-20mA current output, for a number of channels (typically four). Compact *combined I/O* cards provide much of the capability of both types. Although low-level signal-handling and transducer interfacing must be dealt with off-board, these devices solve the problem of interfacing the medium-to-high-level analog signal to a microcomputer without tears.

*For example, Model 2B22 0 to +10V to 4-to-20mA V/I converter, 1500V dc continuous isolation

†For example, Model 2B50 isolated (±1500V), cold-junction-compensated, 12 bit-accurate, direct-connected (screw terminal) thermocouple signal conditioners

§For example, Models 2B54 and 2B55 Low-level (with gain) and high-level isolated 4-channel multiplexers (±1000V dc CMV, 12-bit accuracy, 400 channel/s scan speed), companion cold-junction compensator: 2B56

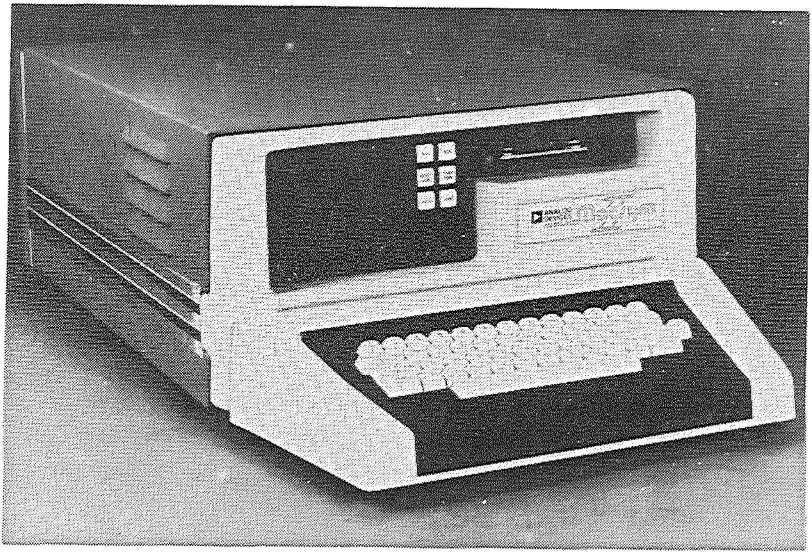
‡For example, DAC1423 10-bit isolated DAC with 4-20mA output: bus compatible, bumpless transfer, total power from loop supply, manual control backup, 1500V isolation

||The RTI-1200 real-time-interface family

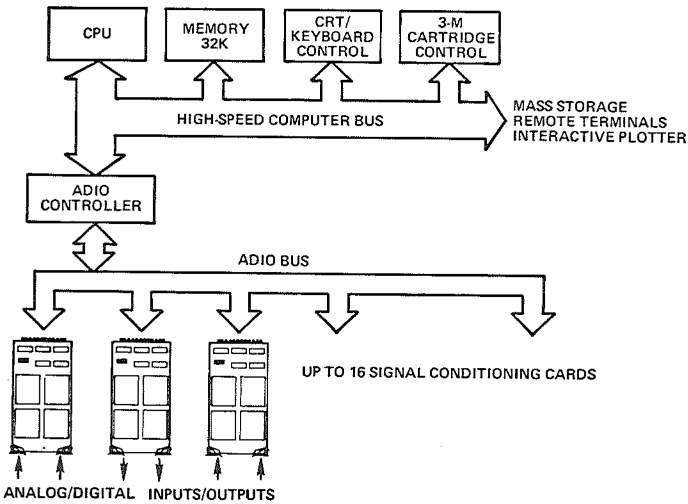
MACSYM 2 Measurement And Control SYsteM is designed to bring the entire job of interfacing under the control of the system user. Its function cards (in wide variety) permit direct wiring of signals to and from the transducers. From that point on, the amplification, signal conditioning, data acquisition, display, control, and programming are unified in an easy-to-understand-and-use subsystem, with its own keyboard, fast, flexible multitasking MACBASIC programming language, and interactive display. A block diagram and photograph of the system can be seen in Figure 4-10.*

A compatible system, MACSYM 20, has the same transducer interfacing capability as MACSYM 2, with somewhat less intelligence, at less than half the cost of MACSYM 2.

*MACSYM 2 is described in a comprehensive overview in *Analog Dialogue* 13-1. A description of MACSYM 20 can be found in *Analog Dialogue* 14-1.



a. Front view of MACSYM 2, showing keyboard and display



b. Block diagram of MACSYM 2

Figure 4-10. MACSYM 2 measurement and control system