Fundamental Signal Conditioning

AMPLIFICATION

Data Acquisition Front Ends

Data acquisition systems differ from single or dual-channel instruments in several ways. They can measure and store data collected from hundreds of channels simultaneously. However, the majority of systems contain from eight to 32 channels, typically in multiples of eight. By comparison, a simple voltmeter that can select a measurement among several different ranges can be considered a data acquisition system, but the need to manually change voltage ranges and a lack of data storage hobbles its usefulness.

Figure 5.01 illustrates a simple data acquisition system consisting of a switching network (multiplexer) and an analog-to-digital converter (ADC). The main subject of this chapter, the instrumentation amplifier (IA), is placed between the multiplexer and ADC. The individual circuit blocks each have unique capabilities and limitations, which together define the system performance.

The ADC is the last in a series of stages between the analog domain and the digitized signal path. In any sampled-data system, such as a multiplexed data acquisition system, a sample-and-hold stage preceding the ADC is necessary. The ADC cannot digitize a time-varying voltage to the full resolution of the ADC unless the voltage changes relatively slowly with respect to sample rate. Some ADCs have internal sample-and-hold circuits or use architectures that emulate the function of the sample-and-hold stage. The discussion that follows assumes that the ADC block includes a suitable sample-and-hold circuit (either internal or external to the chip) to stabilize the input signal during the conversion period.

The primary parameters concerning ADCs in data acquisition systems are resolution and speed. Data acquisition ADCs typically run from 20 kHz to 1 MHz with resolutions of 16 to 24 bits, and have one of two types of inputs, unipolar or bipolar. The unipolar-type typically ranges from 0V to a positive or negative voltage such as 5V. The bipolar-type typically ranges from a negative voltage to a positive voltage of the same magnitude. Many data acquisition systems can read bipolar or unipolar voltages to the full resolution of the ADC, which requires a level-shifting stage to let bipolar
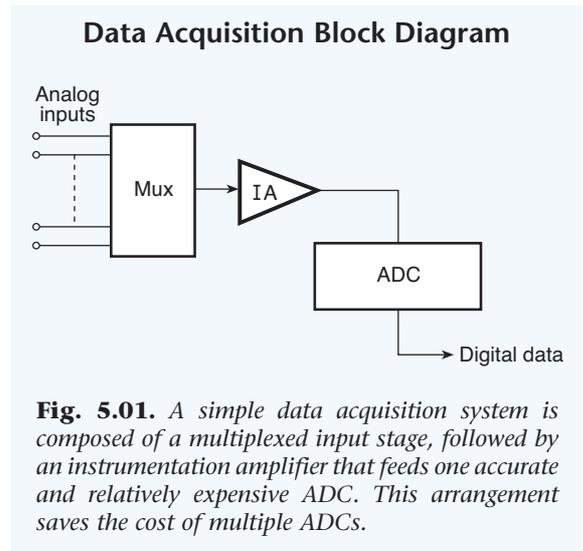
Data Acquisition Block Diagram

Fig. 5.01. *A simple data acquisition system is composed of a multiplexed input stage, followed by an instrumentation amplifier that feeds one accurate and relatively expensive ADC. This arrangement saves the cost of multiple ADCs.*
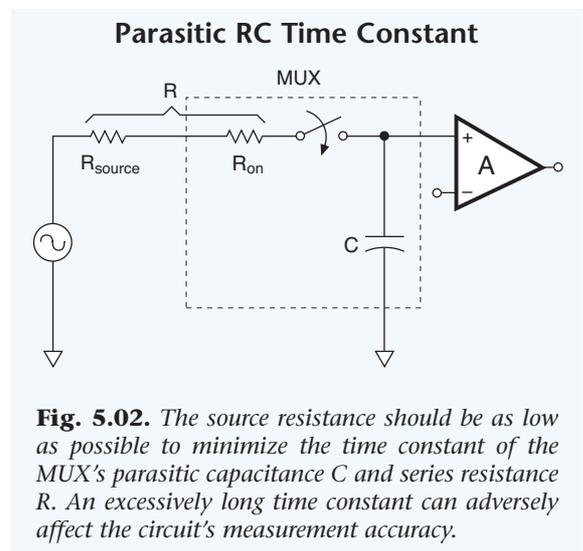
Parasitic RC Time Constant

Fig. 5.02. *The source resistance should be as low as possible to minimize the time constant of the MUX's parasitic capacitance C and series resistance R. An excessively long time constant can adversely affect the circuit's measurement accuracy.*

signals use unipolar ADC inputs and vice versa. For example, a typical 16-bit, 100 kHz ADC has an input range of -5V to +5V and a full-scale count of 65,536. Zero volts corresponds to a nominal 32,768 count. If the number 65,536 divides the 10V range, the quotient is an LSB (least significant bit) magnitude of 153 µv.
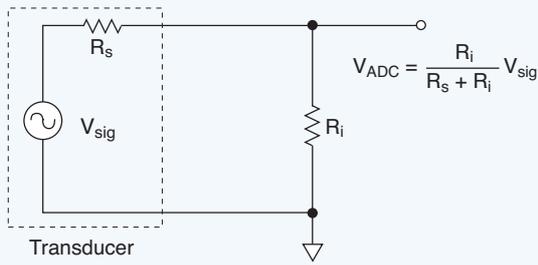
1

Input and Source Impedance

$$V_{ADC} = \frac{R_i}{R_s + R_i} V_{sig}$$

Fig. 5.03A. *The sensor's source impedance R_S should be relatively small to increase the voltage divider drop across R_i, the amplifier's input. This can substantially improve the signal-to-noise ratio for mV range sensor signals.*

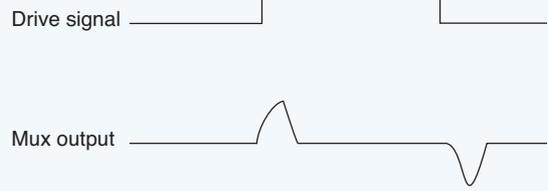## MUX Charge Injection Effects

Fig. 5.03B. *Analog-switching devices can produce spikes in the MUX output during level transitions in the drive signal. This is called charge-injection effect and can be minimized with low source impedance.*

Multiplexing through high source impedances does not work well. The reason that low source impedance is necessary in a multiplexed system is easily explained with a simple RC circuit shown in Figure 5.02. Multiplexers have a small parasitic capacitance from all signal inputs and outputs to analog common. These small capacitance values affect measurement accuracy when combined with source resistance and fast sampling rates. A simple RC equivalent circuit consists of a DC voltage source with a series resistance, a switch, and a capacitor. When the switch closes at T = 0, the voltage source charges the capacitor through the resistance. When charging 100 pF through 10 kΩ, the RC time constant is 1 μs. In a 10-μs-time interval (of which 2 μs is available for settling time), the capacitor only charges to 86% of the value of the signal, which introduces a major error. But a 1 kΩ resistor lets the capacitor easily charge to an accurate value in 20 time constants.

Figure 5.03A shows how system input impedance and the transducer's source impedance combine to form a voltage divider, which reduces the voltage read by the ADC. The input impedance of most input channels is 1 MΩ or more, so it's usually not a problem when the source impedance is low. However,

some transducers (piezoelectric, for example) have high source impedance and should be used with a special charge amplifier. In addition, multiplexing can greatly reduce a data acquisition system's effective input impedance. The charge injection effects are shown in Figure 5.03B.

Operational Amplifiers

Many sensors develop extremely low-level output signals. The signals are usually too small for applying directly to low-gain, multiplexed data acquisition system inputs, so some amplification is necessary. Two common examples of low-level sensors are thermocouples and strain-gage bridges that typically deliver full-scale outputs of less than 50 mV.

Most data acquisition systems use a number of different types of circuits to amplify the signal before processing. Modern analog circuits intended for these data acquisition systems comprise basic integrated operational amplifiers, which are configured easily to amplify or buffer signals. Integrated operational amplifiers contain many circuit components, but are typically portrayed on schematic diagrams as a simple logical functional block. A few

Operational Amplifiers

$$\text{Gain} = -\frac{R_f}{R_i}$$

Inverting

$$\text{Gain} = \frac{R_f}{R_i} + 1$$
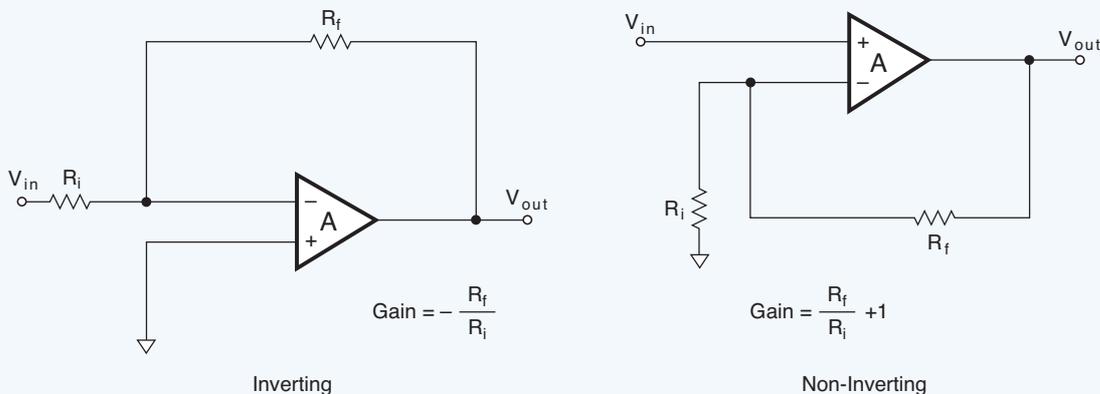
Non-Inverting

Fig. 5.04. *The two basic types of operational amplifiers are called inverting and non-inverting. The stage gain equals the ratio between the feedback and input resistor values.*
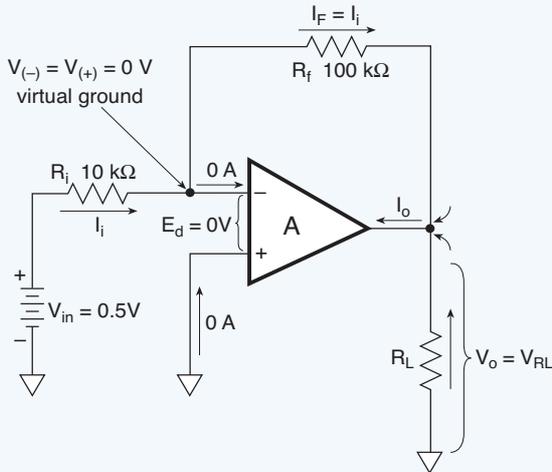
Inverting Amplifier Stage

Fig. 5.05. *The output polarity of the inverting amplifier is opposite to that of the input voltage. The closed-loop amplification or gain of this stage is $A_{cl} = 10$, which is the ratio of R_f/R_i or 100 kΩ/10 kΩ.*

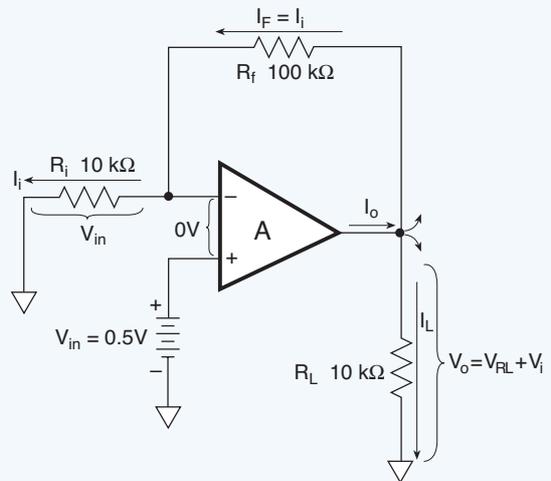## Non-Inverting Amplifier Stage

Fig. 5.06. *The input and output polarities of the non-inverting amplifier are the same. The gain of the stage is $A_{cl} = 11$ or $(R_f + R_i)/R_i$.*

external resistors and capacitors determine how they function in the system. Their extreme versatility makes them the universal analog building block for signal conditioning.

Most operational amplifier stages are called inverting or non-inverting. (See Figure 5.04.) A simple equation relating to each configuration provides the idealized circuit gains as a function of the input and feedback resistors and capacitors. Also, special cases of each configuration make up the rest of the fundamental building blocks, namely the unity-gain follower and the difference amplifier.

Inverting Amplifier Stages

The inverter stage is the most basic operational amplifier configuration. It simply accepts an input signal referenced to common, amplifies it, and inverts the polarity at the output terminals. The open-loop gain of a typical operational amplifier is in the hundreds of thousands. But the idealized amplifier used to derive the transfer function assumes a gain of infinity to simplify its derivation without introducing significant errors in calculating the stage gain. With such a high stage gain, the input voltage sees only the voltage divider composed of R_f and R_i. The negative sign in the transfer function indicates that the output signal is the inverse polarity of the input. Without deriving the transfer function, the output is calculated from:

EQN 5.01. Inverting Amplifier

$V_o = -V_{in}(R_f/R_i)$
Where:
V_o = output signal, V
V_{in} = input signal, V
R_f = feedback resistor, Ω
R_i = input resistor, Ω

For example, for a 500 mV input signal and a desired output of -5V:

$V_o = V_{in}(R_f/R_i)$
$V_o/V_{in} = R_f/R_i$
$5/0.50 = R_f/R_i = 10$

Therefore, the ratio between input and feedback resistors should be 10, so R_f must be 100 kΩ when selecting a 10 kΩ resistor for R_i. (See Figure 5.05.)

The maximum input signal that the amplifier can handle without damage is usually about 2V less than the supply voltage. For example, when the supply is ±15 VDC, the input signal should not exceed ±13 VDC. This is the single most critical characteristic of the operational amplifier that limits its voltage handling ability.

Non-Inverting Amplifier Stages

The non-inverting amplifier is similar to the previous circuit but the phase of the output signal matches the input. Also, the gain equation simply depends on the voltage divider composed of R_f and R_i. (See Figure 5.06.)

The simplified transfer function is:

EQN 5.02. Non-Inverting Amplifier

$V_o = V_{in}(R_f + R_i)/R_i$

For the same 500 mV input signal,
R_f = 100 kΩ, and R_i = 10 kΩ:

$V_o/V_{in} = (R_f + R_i)/R_i,$
$V_o = V_i(R_f + R_i)/R_i$
$V_o = 0.50(100k + 10 k)/10k$
$V_o = 0.50(110k/10k) = 0.50(11)$
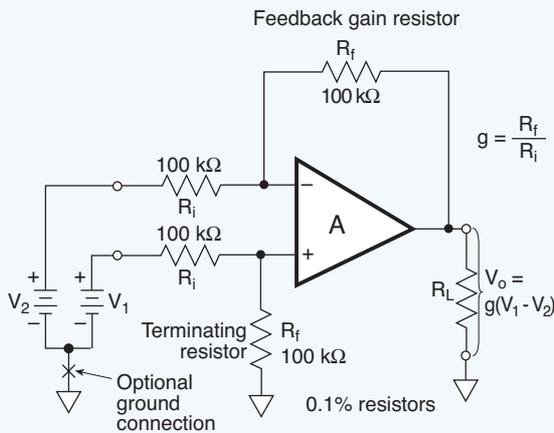$V_o = 5.5V$

3

Differential Amplifier

Fig. 5.07. *The output voltage of the basic differential amplifier is the difference between the two inputs, or $A_{cl} = g(V_1 \text{-} V_2)$, where g is the gain factor. Because all resistors in this example are of equal value, the gain is unity. However, a gain of 10 may be obtained by making the feedback resistor 10 times larger than the input resistors, under the conditions that both feedback resistors are equal and the input resistors are equal.*

The input voltage limitations discussed for inverting amplifiers applies equally well to the non-inverting amplifier configuration.

Differential Amplifiers

Differential-input amplifiers offer some advantages over inverting and non-inverting amplifiers. It appears as a combination of the inverting and non-inverting amplifiers as shown in Figure 5.07. The input signal is impressed between the operational amplifier's positive and negative input terminals and can be isolated from common or a ground pin. The optional ground pin is the key to the amplifier's flexibility. The output signal of the differential input amplifier responds only to the differential voltage that exists between the two input terminals. The transfer function for this amplifier is:

EQN 5.03. Differential Amplifier

$$V_O = (R_f/R_i)(V_1 - V_2)$$

For an input signal of 50 mV, Where:

$V_1 = 1.050V$ and $V_2 = 1.000V$
$V_O = (R_f/R_i)(V_1 - V_2)$
$V_O = (100k/100k)(0.05V)$
$V_O = 0.05V$

For a gain of 10 where $R_f = 100k$ and $R_i = 10k$:

$V_O = (R_f/R_i)(V_1 - V_2)$
$V_O = (100k/10k)(0.05V)$
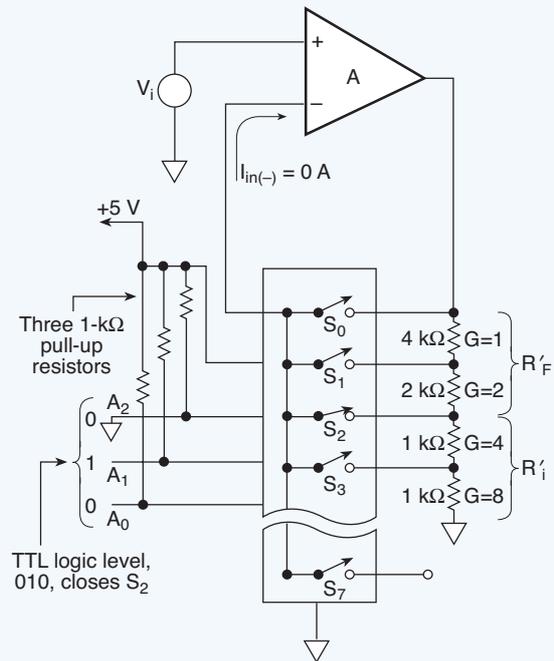$V_O = 0.50V$

Programmable-Gain Amplifier

Fig. 5.08. *The non-inverting amplifier is configured for programmable gain and controlled by the binary input signals from a computer to the addressable inputs of the analog switch.*

The major benefit of the differential amplifier is its ability to reject any voltages that are common to both inputs while amplifying the difference voltage. The voltages that are common to both inputs are appropriately called common mode voltages (V_{cm} or CMV). The common-mode voltage rejection quality can be demonstrated by connecting the two inputs together and to a voltage source referenced to ground. Although a voltage is present at both inputs, the differential amplifier responds only to the difference, which in this case is zero. The ideal operational amplifier, then, yields zero output volts under this arrangement. (See the following section on Instrumentation Amplifiers, High-Common-Mode Amplifiers.)

Programmable-Gain Amplifiers

Programmable gain amplifiers are typically non-inverting operational amplifiers with a digitally controlled analog switch connected to several resistors in its feedback loop. An external computer or another logic or binary signal controls the addressable inputs of the analog switch so it selects a certain resistor for particular gain. (See Figure 5.08.) The data acquisition system's signal conditioners sense the input signal amplitude and automatically send the proper binary code to the programmable gain amplifier (PGA) to increase the gain for a low signal, or decrease the gain for a large signal. The input signal then can be measured and displayed without distortion.
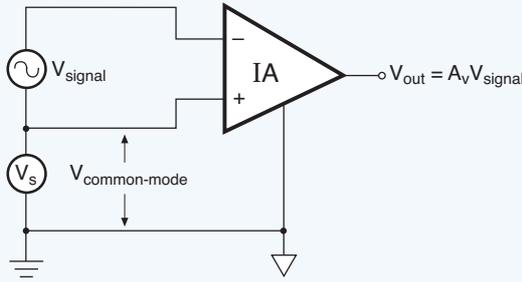
4

Instrument Amplifier

Fig. 5.09. *An instrumentation amplifier is typically a differential input operational amplifier with a high common-mode rejection ratio.*

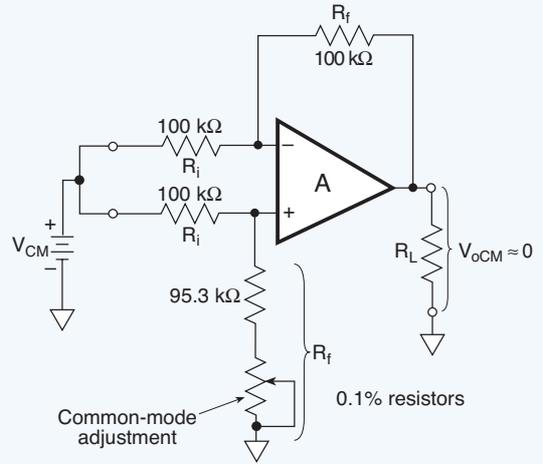## High Common-Mode Amplifiers

Fig. 5.10. *The common mode voltage rejection is measured with the two inputs shorted together and a voltage applied to the node. The potentiometer is then adjusted for minimum (V_{oCM}) output from the amplifier, signifying that the best balance was reached between the two inputs.*

INSTRUMENTATION AMPLIFIERS

A Fundamental Problem

Because signal levels from some transducers may be just a few microvolts, special problems concerning ground loops and spurious interference frequently arise when amplifying them. Other transducers provide output signals from differential signal sources to minimize grounding problems and reduce the effect of common-mode interfering signals. Amplifiers used in these applications must have extremely low input current, drift, and offset voltage; stable and accurate voltage gain; and high input impedance and common-mode rejection.

Although common integrated operational amplifiers with several stages and extremely tight resistor ratios are often used, specially designed instrumentation amplifiers are preferred for these applications. The high-performance operational amplifiers still use basic circuits but ensure that they provide extremely high common-mode rejection and don't need high precision matched resistors to set the gain. Many instrumentation amplifiers are designed for special applications and provide unique features to increase their accuracy and stability for those applications.

For example, the functional block following the switching network in a data acquisition system, Figure 5.09, is an instrumentation amplifier with several critical functions. It rejects common-mode voltages, amplifies signal voltages, minimizes the effect of the multiplexer on resistance, and drives the ADC input.

High Common-Mode Amplifiers

The common mode voltage is defined as the voltage applied from analog common to both inputs when the inputs are identical. (See Figure 5.10.) However, when the two input voltages are different, 4.10 and 4.20V for example, the common mode voltage, V_{cm}, is 4.10V and the differential voltage between the two is 0.10V. Ideally, the instrumentation amplifier ignores the common mode voltage and amplifies only the difference between the two inputs. The degree to which the amplifier rejects common mode voltages is given by a parameter called common mode rejection ratio CMRR. The ability of an instrumentation amplifier (IA) to reject high common mode voltages is sometimes confused with its ability to reject high voltages.

The signal voltages measured are frequently much smaller than the maximum allowed input of the system's ADC. For example, a 0 to 100 mV signal is much smaller than the 0 to 5V range of a typical ADC. A gain of 50 is needed to obtain the maximum practical resolution for this measurement. Instrumentation amplifiers are capable of gains from 1 to more than 10,000, but in multiplexed systems, the gains are usually restricted to a range of 1 to 1,000.

Measurement errors come from the non-ideal ON resistance of analog switches added to the impedance of any signal source. But the extremely high input impedance of the IA minimizes this effect. The input stage of an IA consists of two voltage followers, which have the highest input impedance of any common amplifier configuration. The high impedance and extremely low bias current drawn from the input signal generate a minimal voltage drop across the analog switch sections and produce a more accurate signal for the IA input.

The instrumentation amplifier has low output impedance, which is ideal for driving the ADC input. The typical ADC does not have high or constant input impedance, so the preceding stage must provide a signal with the lowest impedance practical.

Some instrumentation amplifiers have limitations concerning offset voltage, gain error, limited bandwidth, and settling time. The offset voltage and gain error can be calibrated out as part of the measurement, but the bandwidth and settling time are parameters that limit the frequencies of amplified signals and the frequency at which the input switching system can switch channels between signals. A series of steady DC voltages applied to an instrumentation amplifier in rapid succession generates a difficult composite signal to amplify. The settling time of the amplifier is the time necessary for the output to reach final amplitude to within some small error (often 0.01%) after the signal is applied to the input. In a system that scans inputs at 100 kHz,
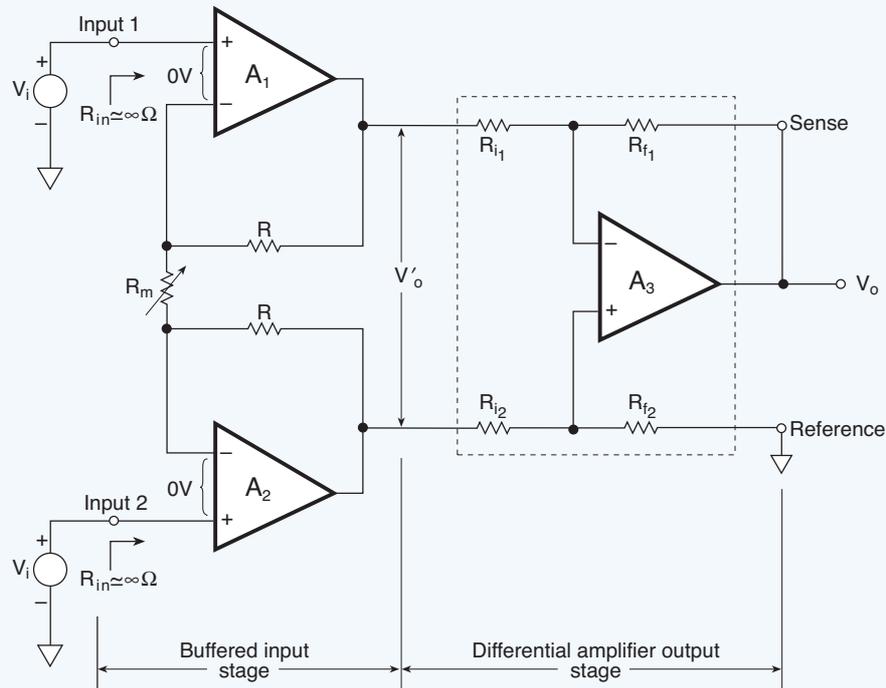
Integrated Instrumentation Amplifiers

Fig. 5.11. *The instrumentation amplifier exhibits extremely high impedance to the inputs V_1 and V_2. Resistor R_m adjusts the gain, and the single-ended output is a function of the difference between V_1 and V_2.*

the total time spent reading each channel is 10 μs. If analog-to-digital conversion requires 8 μs, settling time of the input signal to the required accuracy must be less than 2 μs.

Although calibrating a system can minimize offset voltage and gain error, it is not always necessary to do so. For example, an amplifier with an offset voltage of 0.5 mV and a gain of 2 measuring a 2V signal develops an error of only 1 mV in 4V on the output, or 0.025%. By comparison, an offset of 0.5 mV and a gain of 50 measuring a 100 mV signal develop an error of 25 mV in 5V or 0.5%. Gain error is similar. A stage gain error of 0.25% has a greater overall effect as gain increases producing larger errors at higher gains and minimal errors at unity gain. System software can generally handle known calibration constants with mx+b routines, but some measurements are not critical enough to justify the effort.

Integrated Instrumentation Amplifiers
Integrated instrumentation amplifiers are high-quality op amps that contain internal precision feedback networks. They are ideal for measuring low-level signals in noisy environments without error, and amplifying small signals in the midst of high common-mode voltages. Integrated instrumentation amplifiers are well suited for direct connection to a wide variety of sensors such as strain gages, thermocouples, RTDs, current shunts, and load cells. They are commonly configured with three op amps – two differential inputs and one differential output amplifier. (See Figure 5.11.) Some have built-in gain settings of 1 to 100 and others are programmable.

Programmable-Gain Instrumentation Amplifiers
A special class of instrumentation amplifiers, called programmable-gain instrumentation amplifiers (PGIA), switch between fixed gain levels at high speeds for different input signals delivered by the input switching system. The same digital control circuitry that selects the input channel also can select a gain range. The principle of operation is the same as that described above for Programmable Gain Amplifiers.

FILTERING
The three most common types of filters are called Butterworth, Chebyshev, and Bessel. (See Figures 5.12A, B, and C.) Each type has unique characteristics that make it more suitable for one application than another. All may be used for high-pass, low-pass, band-pass, and band-reject applications, but they have different response profiles. They may be used in passive or active filter networks.

The Butterworth filter has a fairly flat response in the pass-band for which it is intended and a steep attenuation rate. It works quite well for a step function, but shows a non-linear phase response. Chebyshev filters have a steeper attenuation than Butterworth, but develop some ripple in the pass band and ring with a step response. The phase response is much more non-linear than the Butterworth. Finally, Bessel filters have the best step response and phase linearity. But to be most useful, Bessel filters need to have a high order (number of sections) to compensate for their slower rate of attenuation beyond the cut-off frequency.
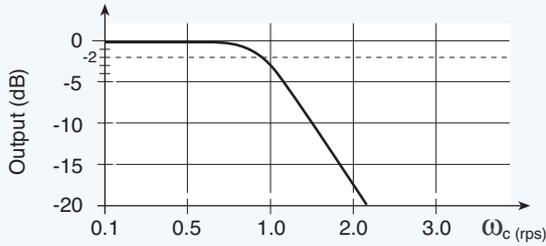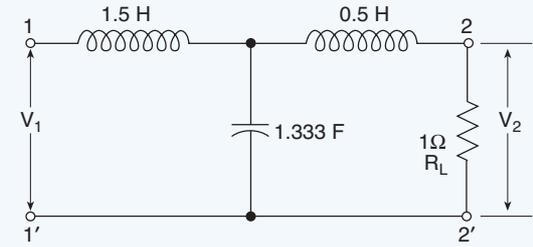
6

Butterworth Filter

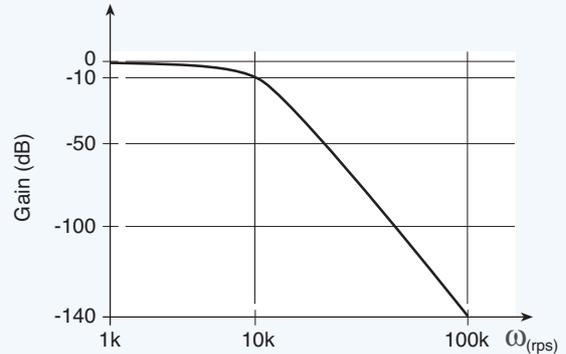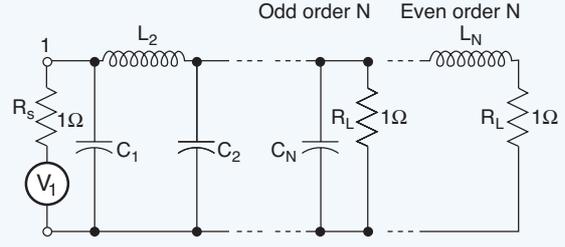**Fig. 5.12A.** *Butterworth filter and response characteristics*

Chebyshev Filter
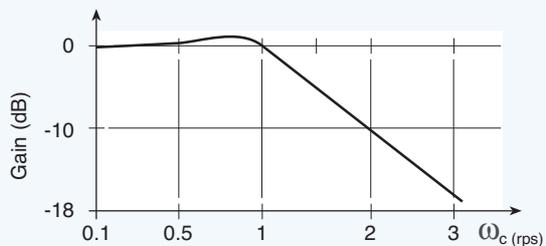
Fig. 5.12B. *Chebyshev filter and response characteristics*

Bessel Filter

Fig. 5.12C. *Bessel filter and response characteristics*

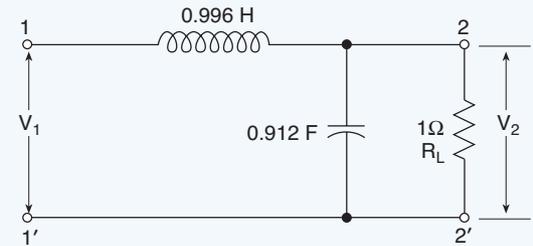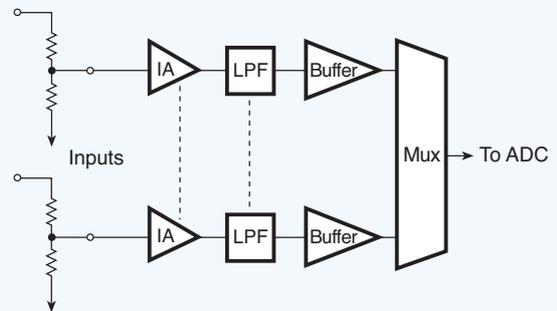## Filtered/Buffered Data Acquisition System

Fig.5.13A. *An instrumentation amplifier, a low-pass filter, and a unity gain buffer amplifier placed between the sensor output and MUX input transforms the sensor's high output impedance to a low impedance. This is required by the MUX to maintain accuracy.*

Low-Pass Filters

Low pass filters attenuate higher frequencies in varying degrees depending on the number of stages and the magnitude of the high frequency relative to the corner frequency. An amplifier stage doesn't need high bandwidth when the measured signal is at a much lower frequency. In fact, the design is intended to eliminate excessive bandwidth in all circuits, which reduces noise. One major benefit of individual signal conditioning stages for low-level sensors (as opposed to multiplexed stages) is to include low-pass filtering on a per-channel basis in the signal path. In a multiplexed circuit (an amplifier which is being shared by multiple low-level DC signals), the main signal path generally cannot operate as a low-pass filter due to the fast settling time necessary in multiplexed systems. (See Figure 5.13A.)

The best place for low-pass filters is in the individual signal path before buffering and multiplexing. (See Figure 5.13B.) For small signals, amplifying with an instrumentation amplifier prior to filtering lets an active low-pass filter operate at optimum signal-to-noise ratios. Figure 5.13C illustrates a typical amplifier-filter-multiplexer configuration.
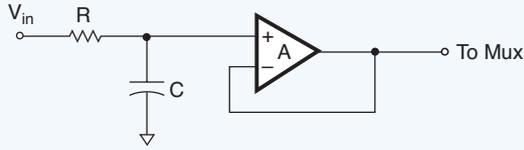
Simple RC Filter

Fig.5.13B. *Low-pass filters inserted in each channel as needed simultaneously reduce the bandwidth and noise while passing the targeted, lower frequency signals.*

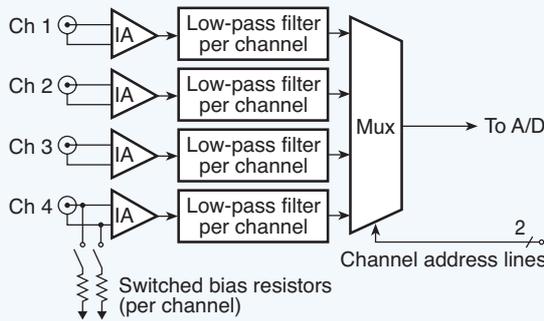## Amplifier/Filter/MUX Combination

Fig. 5.13C. *A typical production type data acquisition system contains an instrumentation amplifier and a low-pass filter in each channel preceding the MUX. The amplifier boosts low-level signals sufficiently well to let the active filter work at an optimum signal-to-noise ratio.*
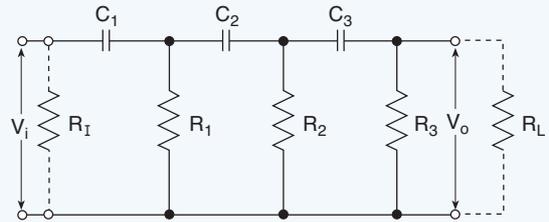
High-Pass Filter

Fig. 5.14. *The high-pass filter is designed to have a lower corner frequency near zero and the cutoff frequency at some higher value. The number of capacitor/resistor pairs determines the number of poles and the degree of cutoff sharpness.*

High-Pass Filters

High-pass filters operate in reverse to low-pass filters. They attenuate the lower frequencies and are needed when low-frequency interference can mask high-frequency signals carrying the desired information or data. Low frequency electrical interference sometimes couples into the system from 50 or 60 Hz power lines. Similarly, when analyzing a machine for vibration, the desired signals can be corrupted by low frequency mechanical interference from the vibrating laminations of a power transformer mounted to its frame. Moreover, a combination of high-pass and low-pass filters may be used to create a notch filter to attenuate a narrow band of frequencies, such as 50 to 60 Hz and their first harmonic. A 3-pole high-pass filter is shown in Figure 5.14.

Passive vs. Active Filters

Passive filters comprise discrete capacitors, inductors, and resistors. As the frequencies propagate through these networks, two problems arise: the desired signal is attenuated by a relatively small amount, and when connected to a load, the original filtering characteristics change. However, active filters circumvent these problems. (See Figure 5.15.) They comprise operational amplifiers built with both discrete and integrated resistors, capacitors, and inductors. They can provide the proper pass-band (or stop-band) capability without loading the circuit, attenuating the desired signals, or changing the original filtering

characteristics. The advantages of such a filter is; it is easier to design, and it has finer tuning, fewer parts count, and improved filter characteristics.

Switched-Capacitance Filters

Although active filters built around operational amplifiers are superior to passive filters, they still contain both integrated and discrete resistors. Integrated-circuit resistors occupy a large space on the substrate and their values can't be made easily to high tolerances, either in relative or absolute values. But capacitors with virtually identical values can be formed on integrated circuits more easily, and when used in a switching mode, they can replace the resistors in filters.

The switched-capacitor filter is a relatively recent improvement over the traditional active filter. James Clerk Maxwell compared a switched capacitor to a resistor in a treatise in 1892, but only recently has the idea taken hold in a zero-offset electronic switch and a high input impedance amplifier. The switched-capacitor concept is now used in extremely complex and accurate analog filter circuits.

The theory of operation is depicted in Figure 5.16. It shows that with S_2 closed and S_1 open, a charge from V_2 accumulates on C. Then, when S_2 opens, S_1 closes, and the capacitor transfers the charge to V_1. This process repeats at a particular frequency, and the charge becomes a current by definition, that is, current equals the transfer of charge per unit time.

The derivation of the equation is beyond the scope of this handbook, but it can be shown that the equivalent resistor may be determined by:

EQN 5.04 Switched-Capacitance Filters

$(V_2 - V_1)/i = 1/(fC) = R$
Where:
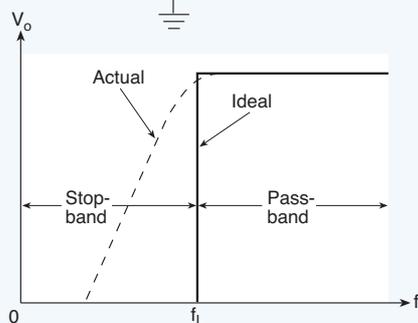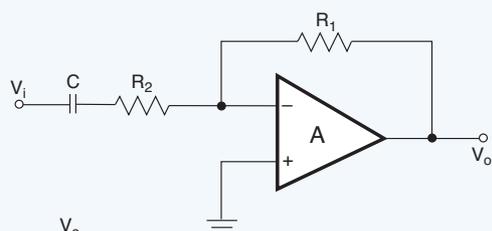V_2 = voltage source 2, V
V_1 = voltage source 1, V
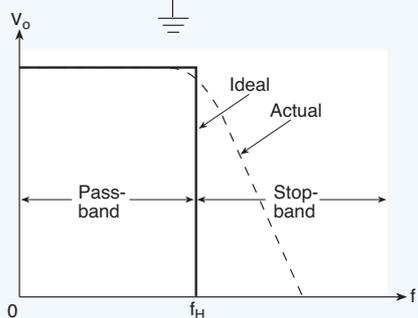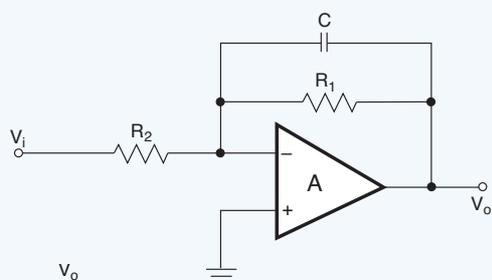i = equivalent current, A
f = clock frequency, Hz
C = capacitor, F
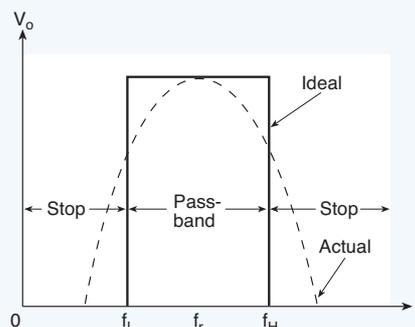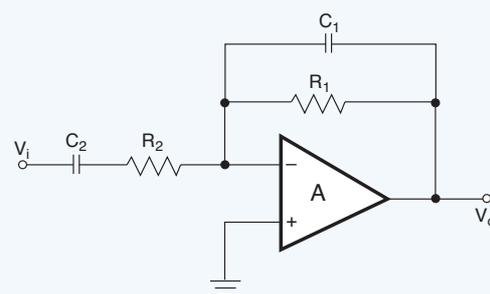R = equivalent resistor, Ω

Active Filters

High-Pass Filter

Low-Pass Filter

Band-Pass Filter

Fig. 5.15. *Passive filters tend to change in frequency-cutoff characteristics with a change in load. To prevent this, an active device such as a transistor or op amp isolates the last pole from the load to maintain stable filter characteristics.*

The above equation states that the switched capacitor is identical to a resistor within the constraints of the clock frequency and fixed capacitors. Moreover, the equivalent resistor's effective value is inversely proportional to the frequency or the size of the capacitor.

ATTENUATION
Voltage Dividers
Most data acquisition system inputs can measure voltages only within a range of 5 to 10V. Voltages higher than this must be attenuated. Straightforward resistive dividers can easily attenuate any range of voltages (see Figure 5.17), but two drawbacks complicate this simple solution. First, voltage dividers present substantially lower impedances to the source than direct analog inputs. Second, their output impedance is much too high for multiplexer inputs. For example, consider a 10:1 divider

reading 50V. If a 900 kΩ and a 100 kΩ resistor are chosen to provide a 1 MΩ load to the source, the impedance seen by the analog multiplexer input is about 90 kΩ, still too high for the multiplexed reading to be accurate. When the values are both downsized by a factor of 100 so the output impedance is less than 1 kΩ, the input impedance seen by the measured source is 10 kΩ, or 2 kΩ/V, which most instruments cannot tolerate in a voltage measurement. Hence, simple attenuation is not practical with multiplexed inputs.

Buffered Voltage Dividers
The low impedance loading effect of simple voltage dividers can be overcome using unity-gain buffer amplifiers on divider outputs. A dedicated unity-gain buffer has high-input impedance in the MΩ range and does not load down the source, as does the network in the previous example. Moreover, the buffers' output impedance is extremely low, which is necessary for the multiplexed analog input. (See Figure 5.18.)

Balanced Differential Dividers
Not all voltage divider networks connect to a ground or a common reference point at one end. Sometimes, a balanced differential divider is a better solution for driving the data acquisition system's input terminals. (See Figure 5.19.) In this case, the CMRR of the differential amplifier effectively reduces the common-mode noise that can develop between different grounds in the system.
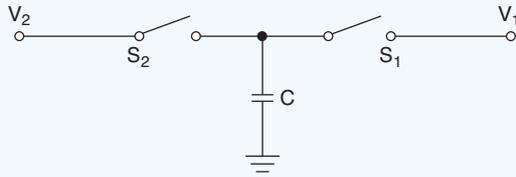
9

Switched-Capacitor Filters

Fig. 5.16. *Because resistors have wider tolerances and require more substrate area than capacitors, a technique that uses multiple precision capacitors to replace resistors in filters is called a switched capacitor circuit.*
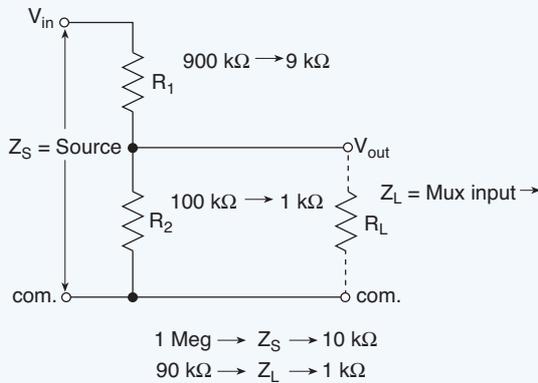
Attenuator/Buffer

$$900 \text{ k}\Omega \rightarrow 9 \text{ k}\Omega$$

$Z_S = \text{Source}$

$$100 \text{ k}\Omega \rightarrow 1 \text{ k}\Omega$$

$Z_L = \text{Mux input} \rightarrow$

$$1 \text{ Meg} \rightarrow Z_S \rightarrow 10 \text{ k}\Omega$$
$$90 \text{ k}\Omega \rightarrow Z_L \rightarrow 1 \text{ k}\Omega$$

Fig. 5.17. *When the input signal exceeds about 10V, the divider drops the excess voltage to prevent input amplifier damage or saturation.*

Buffered Voltage Dividers

$$V_{out} = \frac{R_B}{R_A + R_B} V_{in}$$

Fig. 5.18. *An op amp or a transistor serves as an impedance matching buffer to prevent the load from affecting the divider's output voltage.*
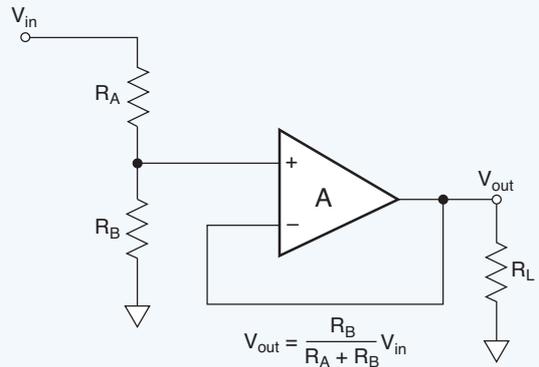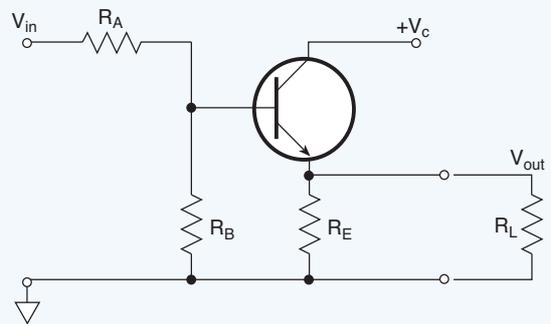
High-Voltage Dividers

Some data acquisition systems employ special input modules containing high-voltage dividers that can easily measure up to 1,200V. They are properly insulated to handle the high voltage and have resistor networks to select a number of different divider ratios. They also contain internal trim potentiometers to calibrate the setup to extremely close tolerances.

Compensated Voltage Dividers and Probes

Voltage divider ratios applied to DC voltages are consistently accurate over relatively long distances between the divider network and data acquisition system input when the measurement technique eliminates the DC resistance of the wiring and cables. These techniques include a second set of input measuring leads separate from those that apply power to the divider.

Voltage dividers used on AC voltages, however, must always compensate for the effective capacitance between the conductors and ground or common, even when the frequency is as low as 60 Hz. It's not uncommon to find that when the AC voltages are calibrated to within 0.01% at the divider network, the voltages reaching the data acquisition system input terminals may be out of tolerance by as much as 5%. This is because the lead capacitance enters into the divider equation. One way around the problem is to shunt the data acquisition input terminals (or the divider network) with a compensating capacitor. For example, oscilloscope probes contain a variable capacitor precisely for this purpose. The probe capacitor is adjusted to match the oscilloscope's input impedance and as a result, it faithfully passes the leading edge of the oscilloscope's built-in 1,000 Hz square-wave generator without undershoot or overshoot.

ISOLATION

When Isolation Is Required

Frequently, data acquisition system inputs must measure low-level signals where relatively high voltages are common, such as in motor controllers, transformers, and motor windings. In these cases, isolation amplifiers can measure low-level signals among high common-mode voltages, break ground loops, and eliminate source ground connections without subjecting operators and equipment to the high voltage. They also provide a safe interface in a hospital between a patient and a monitor or between the source and other electronic instruments and equipment. Yet other applications include precision bridge isolation amplifiers, photodiode amplifiers, multiple-port thermocouple and summing amplifiers, and isolated 4 to 20 mA current-control loops.
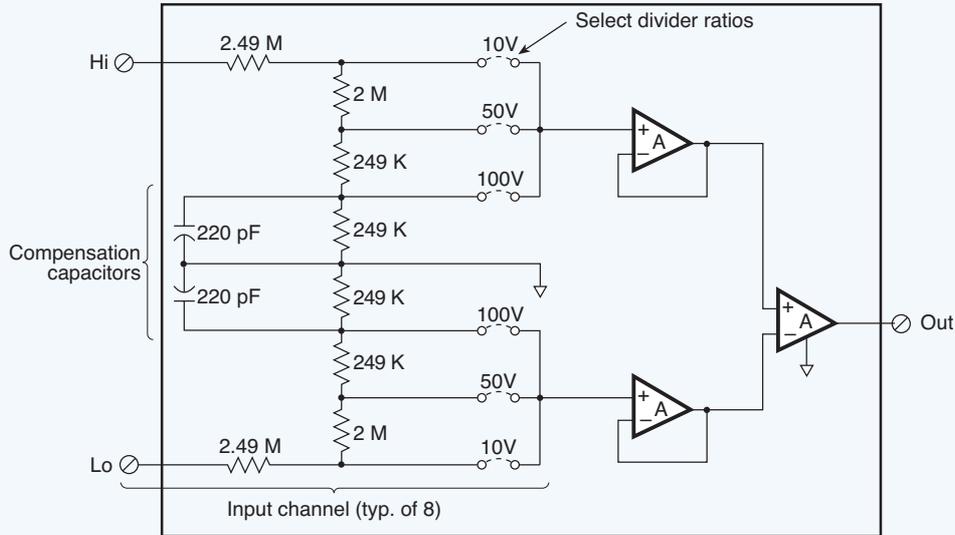
Compensated High-Voltage Dividers

Fig. 5.19. *A typical high-voltage input card for a data acquisition system contains a balanced differential input and jumpers for selecting an input voltage range of 10 V, 50 V, or 100 V. The input circuit also compensates for long lead wire capacitance that tends to form an AC voltage divider, which would reduce accuracy.*

Isolation Amplifiers

Isolation amplifiers are divided into input and output sections, galvanically isolated from each other. Several techniques provide the isolation; the most widely used include capacitive, inductive, and optical means. The isolation voltage rating is usually 1,200 to 1,500 VAC, at 60 Hz with a typical input signal range of ±10V. They normally have a high isolation mode rejection (IMR) ratio of around 140 dB. Because the primary job of relatively low-cost amplifiers is to provide isolation, many come with unity gain. But more expensive units are available with adjustable or programmable gains. (See Figure 5.20.)

One benefit of an isolation amplifier is that it eliminates ground loops. The input section's signal-return, or common connection is isolated from the output signal ground connection. Also, two
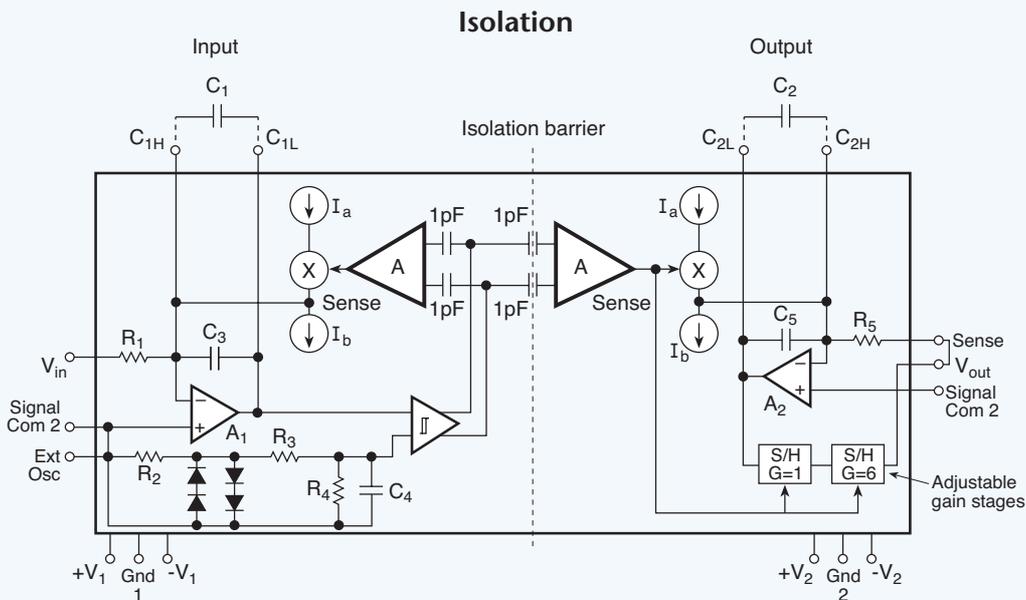

Fig. 5.20. *A differential isolation amplifier's front end can float as high as the value of the common mode voltage (CMV) rating without damage or diminished accuracy. The isolation barrier in some signal conditioners can withstand from 1,500 to 2,200 VDC.*
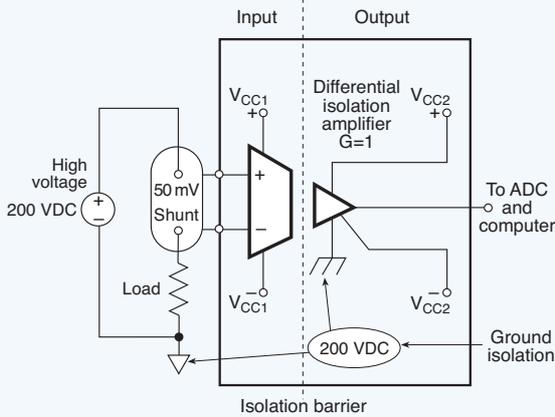
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Galvanic Isolation Amplifier

Fig. 5.21. *Galvanic isolation can use any one of several techniques to isolate the input from the output circuitry. The goal is to allow the device to withstand a large common mode voltage (CMV) between the input and output signal and power grounds.*
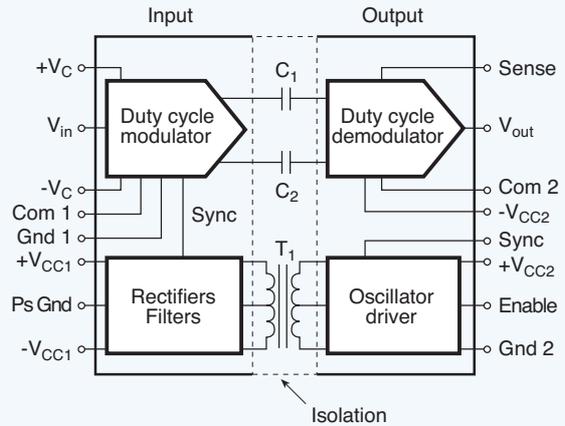
Capacitive Isolation Amplifier

Fig. 5.22. *The isolation barrier in this amplifier protects both the signal path and the power supply from CMV breakdown. The signal couples through a capacitor and the power through an isolation transformer.*

different power supplies are used, V_{CC1} and V_{CC2}, one for each section, which further helps isolate the amplifiers. (See Figure 5.21.)

Analog Isolation Modules
Analog isolation amplifiers use all three types of isolation between input and output sections: capacitive, optical, and magnetic. One type of capacitively coupled amplifier modulates the input signal and couples it across a capacitive barrier with a value determined by the duty cycle. (See Figure 5.22.) The output section demodulates the signal, restores it to the original analog input equivalent, and filters the ripple component, which resulted from the demodulation process. After the input and output sections of the integrated circuit

are fabricated, a laser trims both stages to precisely match their performance characteristics. Then they are mounted on either end of the package separated by the isolation capacitors. Although the schematic diagram of the isolation amplifier looks quite simple, it can contain up to 250 or more integrated transistors.

Another isolation amplifier optically couples the input section to the output section through an LED transmitter and receiver pair as shown in Figure 5.23. An ADC converts the input signal to a time-averaged bit stream and transmits it to the output section via the LED. The output section converts the digital signal back to an analog voltage and filters it to remove the ripple voltage.
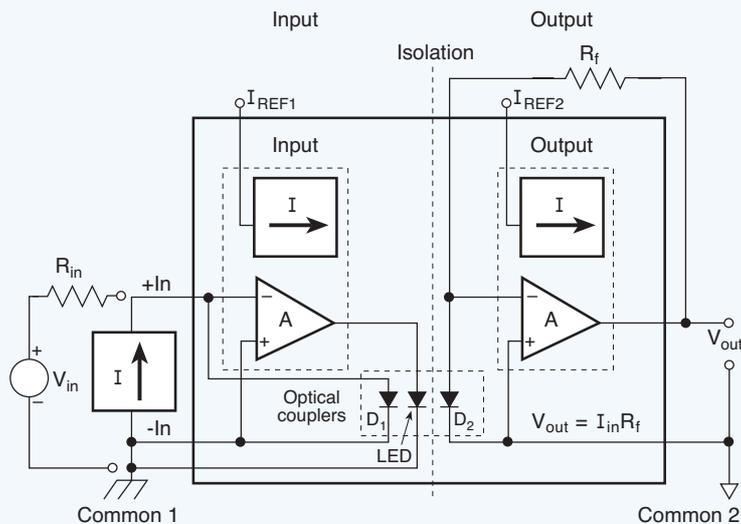
Optical Isolation Amplifier

Fig. 5.23. *This is a simplified diagram of a unity gain current amplifier using optical couplers between input and output stages to achieve isolation. The output current passing through the feedback resistor (R_f) generates the output voltage.*
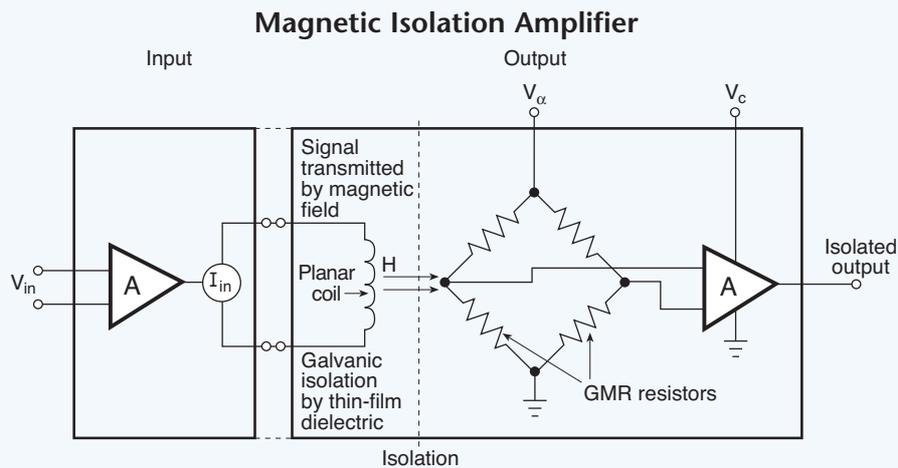
Magnetic Isolation Amplifier

Fig. 5.24A. *Magnetic couplers transfer signals through a magnetic field across a thin film dielectric. In this case, a magneto-resistance bridge circuit sensitive to the field exhibits a large change in resistance when exposed to the magnetic field from a small coil sitting above it.*

Magnetically coupled isolation amplifiers come in two types. One contains hybrid toroid transformers in both the signal and power paths, and the other contains one coil that transmits the signal across a barrier to a giant magnetoresistor (GMR) bridge circuit. (See Figure 5.24A.) In the transformer type, Figure 5.24B, the rectified output of a pulse generator (T1) supplies power to the input and output stages (T3). Another winding of the transformer (T2) operates a modulator and demodulator that carry the signal across the barrier. It provides from 1,000 to 3,500 VDC isolation among the amplifier's three grounds, as well as an isolated out-put signal equal to the input signal with total galvanic isolation between input and output terminals.

The second type, the giant magnetoresistor amplifier uses the same basic technology as does high-speed hard disc drives. The coil generates a magnetic field with strength proportional to its input drive current signal, and the dielectric GMR amplifies and conditions it. Ground potential variations at the input do not generate current so they are not detected by the magnetoresistor structure. As a result, the output signal equals the input signal with complete galvanic isolation. These units are relatively inexpensive, and can withstand from 1,000 to 3,500 VDC. Full-power signal frequency response is less than 2 kHz, but small signal response is as much as 30 kHz.

Digital Method of Isolation

Digital isolation packages are similar in many respects to analog amplifiers. They transmit digital data across the isolation barrier at rates up to 80 Mbaud, and some can be programmed to transmit
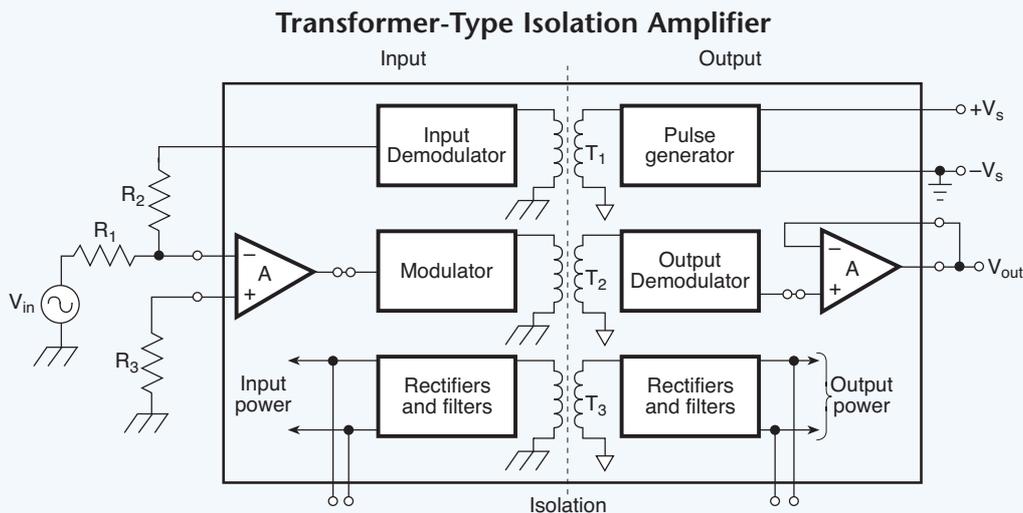
Fig. 5.24B. *The transformer-coupled isolation amplifier uses separate power supplies for the input and output stages, which are iso-lated by virtue of the individual transformer windings. This provides the input and output stages with decoupled ground or common returns. In addition, the modulator/demodulator transfers the measured signal across the barrier via other transformer windings for complete galvanic isolation between input and output.*
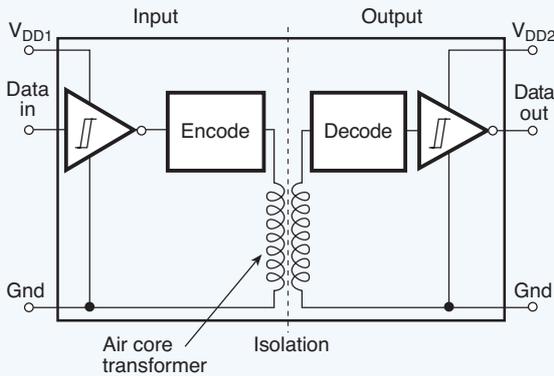
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Digital Method of Isolation

Fig. 5.25. *Yet another isolation method specifically intended for digital circuits employs a high-speed CMOS encoder and decoder at the input and output, coupled with a monolithic air-core transformer.*

Isolated Sensors – Hall Effect

Conditioned Output

Fig. 5.26A. *This Hall-Effect sensor is switched with a series of alternating magnets in a target wheel. Each pass between N and S magnets changes the sensor's state.*
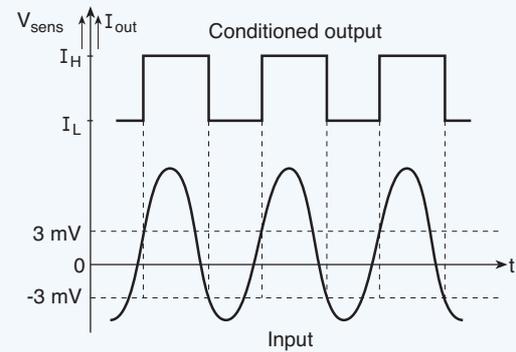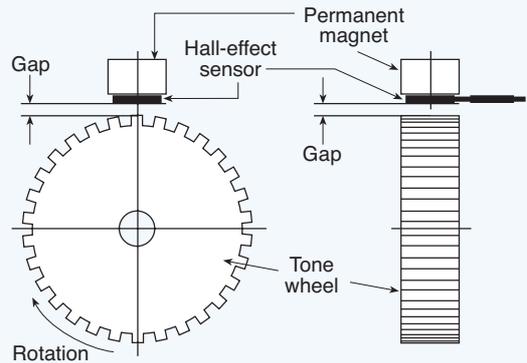
Isolated Sensors – Hall Effect

Fig. 5.26B. *This Hall-Effect sensor configuration uses a bias magnet and a tone wheel that modulates the magnetic field intensity to produce an output signal.*

data in either direction, that is, through input to output or output to input terminals. Data, in the form of complementary pulses, couple across the barrier through high-voltage capacitors or air-core inductors. Faraday shields usually surround the inductors or capacitors to prevent false triggering from external fields. The receiver restores the pulses to the original standard logic levels. As with analog amplifiers, the power supplies for each section are also galvanically isolated. (See Figure 5.25.)

Inherently Isolated Sensors

In addition to directly measuring voltage, current, and resistance, which require some degree of isolation, certain sensors that measure other quantities are inherently isolated by virtue of their construction or principle of operation. The most widely used sensors measure position, velocity, pressure, temperature, acceleration, and proximity. They also use a number of different devices to measure these quantities, including potentiometers, LVDTs (linear variable differential transformers), optical devices, Hall-effect devices, magnetic devices, and semiconductors.

Hall-effect devices, for example, measure magnetic fields, and are electrically insulated from the magnetic source that they are designed to measure. The insulation may be air or another material such as plastic or ceramic, and the arrangement essentially isolates them from ground loops and high voltages. Figures 5.26A and B illustrate two applications where Hall-effect devices measure speed. The first senses the alternating magnetic field directly from the

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Isolated Sensor – Current Transformer

To data acquisition system

R_s

Ammeter

AC

To ammeter or shunt resistor, R_s

Donut-shaped current transformer

220 VAC power input

50 to 100A load

1 turn

I

I

Common or return

Ratio 1:1

2 turns

I

I

Common or return

Ratio 2:1

4 turns

I

I

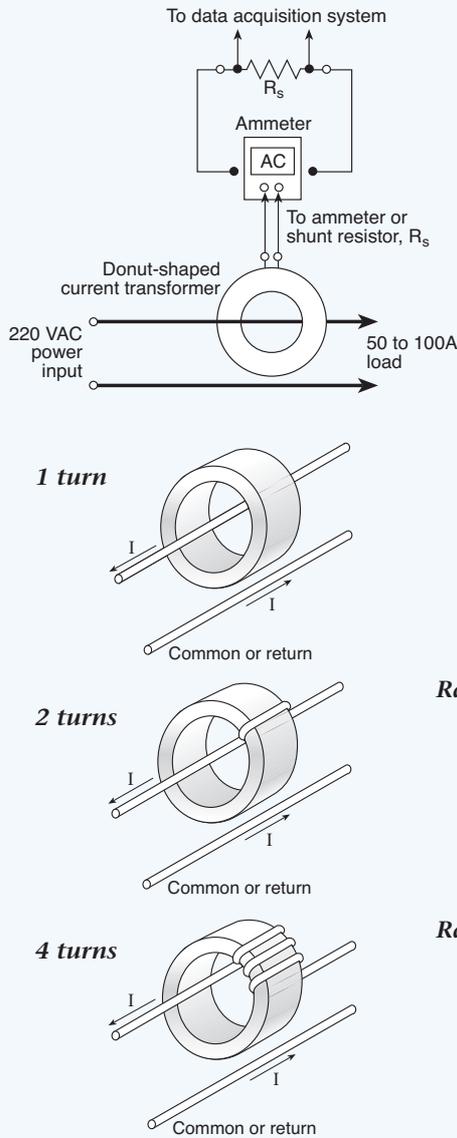Common or return

Ratio 4:1

Fig. 5.27. *Because it does not need a ground connection, a current transformer is isolated from both the input and output of the signal conditioner.*

Isolated Sensor – Variable Reluctance/Magnetic

Antilock brake controller

AC input from sensor

DC reference

AC input from sensor

Variable reluctance wheel speed sensor

Gear wheel

1.70V

1.0V

15 mA

5 mA

Digital output signal

Target

Wire coil

Magnet

Analog in

Signal processing

Digital output

VR transducer
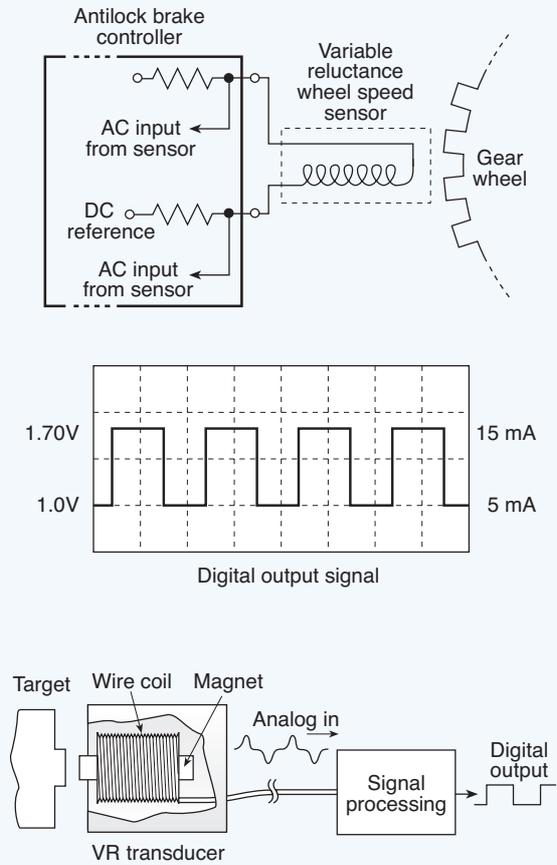
Fig. 5.28. *Variable reluctance sensors comprise a coil of wire wound around a magnetic core. As a ferrous metal passes near one pole it disturbs the magnetic field and induces a small voltage in the coil. In this example, the voltage is amplified, shaped, and converted to a digital signal for indicating vehicle wheel speed.*

revolving wheel. In the second application, a permanent magnet sitting behind the Hall effect device supplies the magnetic field. The gear teeth passing by the unit disturb the field, and the Hall device senses the resulting fluctuations. In addition, see Figure 4.08. It shows a third example, where the Hall-effect device is used in a wattmeter circuit.

Current transformers and potential transformers for measuring AC voltage and current are also inherently isolated between primary and secondary windings. (See Figure 5.27.) Transformer insulation between primary and secondary can be made to withstand thousands of volts and have extremely low leakage values. The turns ratio also is easy to select for stepping down a high voltage to a lower standard voltage of 5 to 10 VAC.

Other sensors include magnetic pickups composed of wire coils wound around a permanent magnetic core. A ferrous metal passing over one end of the coil disturbs the magnetic flux and generates a voltage at the coil terminals. The sensor does not require a separate power supply, and the output voltage is typically small enough to require only ordinary signal conditioners. (See Figure 5.28.)

Piezoelectric materials and strain gages are typically used for measuring acceleration, and are inherently isolated from the objects on which they are mounted by virtue of their protective housings. High-voltage insulation and magnetic shielding may be added to the mounting base if needed in some rare applications.

Thermocouple Output Voltage
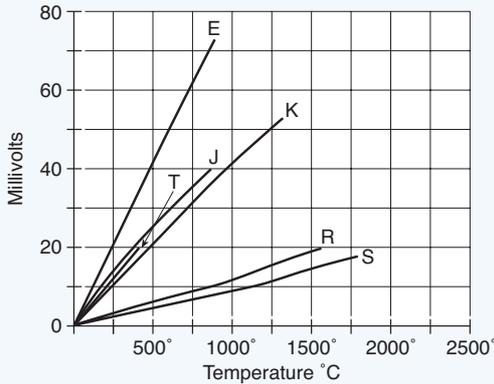
TYPE	METALS		
	+		**−**
E	Chromel	vs.	Constantan
J	Iron	vs.	Constantan
K	Chromel	vs.	Alumel
R	Platinum	vs.	Platinum
			13% Rhodium
S	Platinum	vs.	Platinum
			10% Rhodium
T	Copper	vs.	Constantan

Fig. 5.29. *Although some thermocouples must be both thermally and electrically connected to the specimen under test, many may be purchased with insulated junctions, which isolates them from making high-voltage and ground-loop connections to the signal conditioner.*

LVDTs contain a modulator and demodulator, either internally or externally, require some small DC power, and provide a small AC or DC signal to the data acquisition system. Often they are scaled to output 0 to 5V. LVDTs can measure both position and acceleration.

Optical devices such as encoders are widely used in linear and rotary position sensors. The possible configurations are many, but basically, their principle of operation is based on the interruption
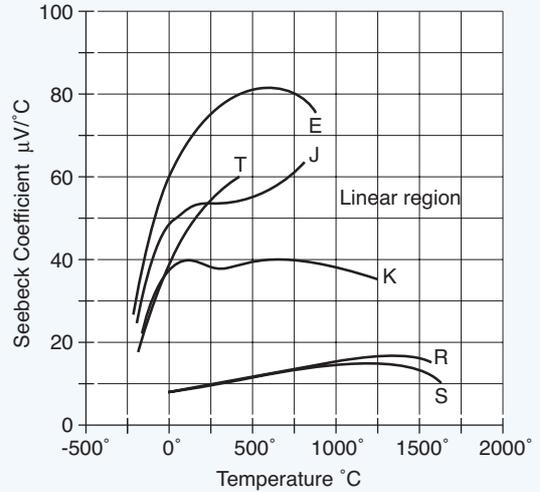
Seebeck Coefficient Plot

Fig. 5.30. *The slope of the Seebeck coefficient plotted against temperature clearly illustrates that the thermocouple is a non-linear device.*

of a light beam between an optical transmitter and receiver. A revolving opaque disc with multiple apertures placed between the transmitter and receiver alternately lets light through to generate pulses. Usually, LEDs generate the light and a photo diode on the opposite side detects the resulting pulses, which are then counted. The pulses can indicate position or velocity.

LINEARIZATION

Why Linearization Is Needed
The transfer function for many electronic devices, which relates the input to output, contains a nonlinear factor. In most cases this factor is small enough to be ignored. However, in some applications it must be compensated either in hardware or software.

mV	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	.10	mV
0.00	0.00	0.17	0.34	0.51	0.68	0.85	1.02	1.19	1.36	1.53	1.70	0.00
0.10	1.70	1.87	2.04	2.21	2.38	2.55	2.72	2.89	3.06	3.23	3.40	0.10
0.20	3.40	3.57	3.74	3.91	4.08	4.25	4.42	4.58	4.75	4.92	5.09	0.20
0.30	5.09	5.26	5.43	5.60	5.77	5.94	6.11	6.27	6.44	6.61	6.78	0.30
0.40	6.78	6.95	7.12	7.29	7.46	7.62	7.79	7.96	8.13	8.30	8.47	0.40
0.50	8.47	8.63	8.80	8.97	9.14	9.31	9.47	9.64	9.81	9.98	10.15	0.50
0.60	10.15	10.31	10.48	10.65	10.82	10.98	11.15	11.32	11.49	11.65	11.82	0.60
0.70	11.82	11.99	12.16	12.32	12.49	12.66	12.83	12.99	13.16	13.33	13.49	0.70
0.80	13.49	13.66	13.83	13.99	14.16	14.33	14.49	14.66	14.83	14.99	15.16	0.80
0.90	15.16	15.33	15.49	15.66	15.83	15.99	16.16	16.33	16.49	16.66	16.83	0.90
1.00	16.83	16.99	17.16	17.32	17.49	17.66	17.82	17.99	18.15	18.32	18.48	1.00
1.10	18.48	18.65	18.82	18.98	19.15	19.31	19.48	19.64	19.81	19.97	20.14	1.10
1.20	20.14	20.13	20.47	20.64	20.80	20.97	21.13	21.30	21.46	21.63	21.79	1.20
1.30	21.79	21.96	22.12	22.29	22.45	22.62	22.78	22.94	23.11	23.27	23.44	1.30
1.40	23.44	23.60	23.77	23.93	24.10	24.26	24.42	24.59	24.75	24.92	25.08	1.40

Temperature Conversion Table in °C (IPTS 1968)

Fig. 5.31. *Because thermocouple outputs are non-linear, a table is an accurate method for converting a voltage reading to temperature for a specific type of thermocouple.*

NIST Polynomial Coefficients					
TYPE E	TYPE J	TYPE K	TYPE R	TYPE S	TYPE T
Nickel-10% Chromium(+) Versus Constantan (–)	Iron (+) Versus Constantan (–)	Nickel-10% Chromium (+) Versus Nickel-5% (–) (Aluminum Silicon)	Platinum-13% Rhodium (+) Versus Platinum (–)	Platinum-10% Rhodium Versus Platinum (–)	Copper (+) Versus Constantan (–)
-100˚C to 1000˚C ±0.5˚C 9th order	0˚C to 760˚C ±0.1˚C 5th order	0˚C to 1370˚C ±0.7˚C 8th order	0˚C to 1000˚C ±0.5˚C 8th order	0˚C to 1750˚C ±1˚C 9th order	-160˚C to 400˚C ±0.5˚C 7th order
a_0 0.104967248	-0.048868252	0.226584602	0.263632917	0.927763167	0.100860910
a_1 17189.45282	19873.14503	24152.10900	179075.491	169526.5150	25727.94369
a_2 -282639.0850	-218614.5353	67233.4248	-48840341.37	-31568363.94	-767345.8295
a_3 12695339.5	11569199.78	2210340.682	1.90002E + 10	8990730663	78025595.81
a_4 -448703084.6	-264917531.4	-860963914.9	-4.82704E + 12	-1.63565E + 12	-9247486589
a_5 1.10866E + 10	2018441314	4.83506E + 10	7.62091E + 14	1.88027E + 14	6.97688E + 11
a_6 -1.76807E + 11		-1.18452E + 12	-7.20026E + 16	-1.37241E + 16	-2.66192E + 13
a_7 1.71842E + 12		1.38690E + 13	3.71496E + 18	6.17501E + 17	3.94078E + 14
a_8 -9.19278E +12		-6.33708E + 13	-8.03104E + 19	-1.56105E + 19	
a_9 2.06132E + 13				1.69535E + 20	

Temperature Conversion Equation: $T = a_0 + a_1x + a_2x^2 + ... + a_nx^n$

Nested Polynomial Form: $T = a_0 + x(a_1 + x(a_2 + x(a_3 + x(a_4 + a_5x))))$ (5th order)

Fig. 5.32. *The NIST polynomial table is a more accurate means of calculating a linearizing function for a particular thermocouple than a single coefficient, even though it uses a polynomial equation.*
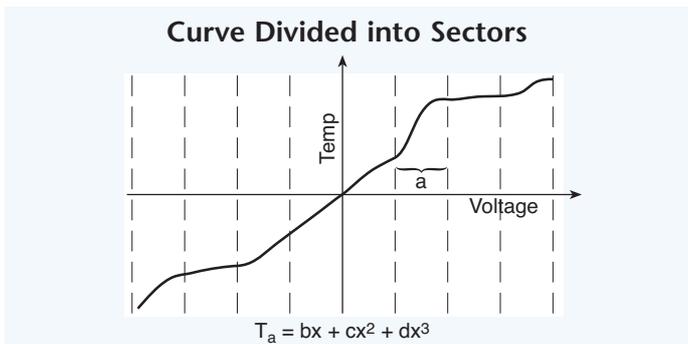
Curve Divided into Sectors

$T_a = bx + cx^2 + dx^3$

Fig. 5.33. *Although a computer usually finds the solution to the NIST polynomial, breaking the curve into sections representing lower order polynomials can accelerate the process.*

Thermocouples, for example, have a nonlinear relationship from input temperature to output voltage, severe enough to require compensation. Figure 5.29 shows the output voltage for several types of thermocouples plotted against temperature. Thermocouple output voltages are based on the Seebeck effect. When the slope of the Seebeck coefficient is plotted vs. temperature, the output response is clearly nonlinear as shown in Figure 5.30. A linear device, by comparison, would plot a straight horizontal line. Only the K type thermocouple most readily approaches a straight line in the range from about 0 to 1,000˚C.

The curve shows that one constant scale factor is not sufficient over the entire temperature range for a particular thermocouple type to maintain adequate accuracy. Higher accuracy comes from reading the thermocouple voltage with a voltmeter and applying it to the thermocouple table from the National Institute of Standards and Technology as shown in Figure 5.31. A computer-based data acquisition system, in contrast, automates the temperature conversion process using the thermocouple voltage reading and an algorithm to solve a polynomial equation. The equation describing this relationship is:

EQN 5.05. Temperature Polynomial

$T = a_0 + a_1x + a_2x^2 + a_3x^3 + ...a_nx^n$

Where:

T = temperature, ˚C

x = thermocouple voltage, V

a = polynomial coefficients unique to each type of thermocouple

n = maximum order of the polynomial

The accuracy increases proportionally to the order of n. For example, when n = 9, a ±1˚C accuracy may be realized. But because high order polynomials take time to process, lower orders may be used over limited temperature ranges to increase the processing speed.

Software Linearization

The polynomials are put to work in the data acquisition system's computer to calculate the real temperature for the thermocouple voltage. Typically, the computer program handles a nested polynomial to speed the process rather than compute the exponents directly. Nested polynomials are the only practical way of dealing with complicated equations. Without such techniques it is difficult to handle large state tables that have more than a few hundred entries. (See Figure 5.32.) Also, high order polynomials can be computed faster when the thermocouple characteristic curve can be divided into several sectors and each sector approximated by a third order polynomial as shown in Figure 5.33.

Hardware Linearization

Hardware also may be designed to accommodate the nonlinearity of a thermocouple, but the circuitry becomes complex and expensive in order to reduce its susceptibility to errors from outside influences such as electrical noise and temperature variations within the circuits. The compensating circuitry is nonlinear,
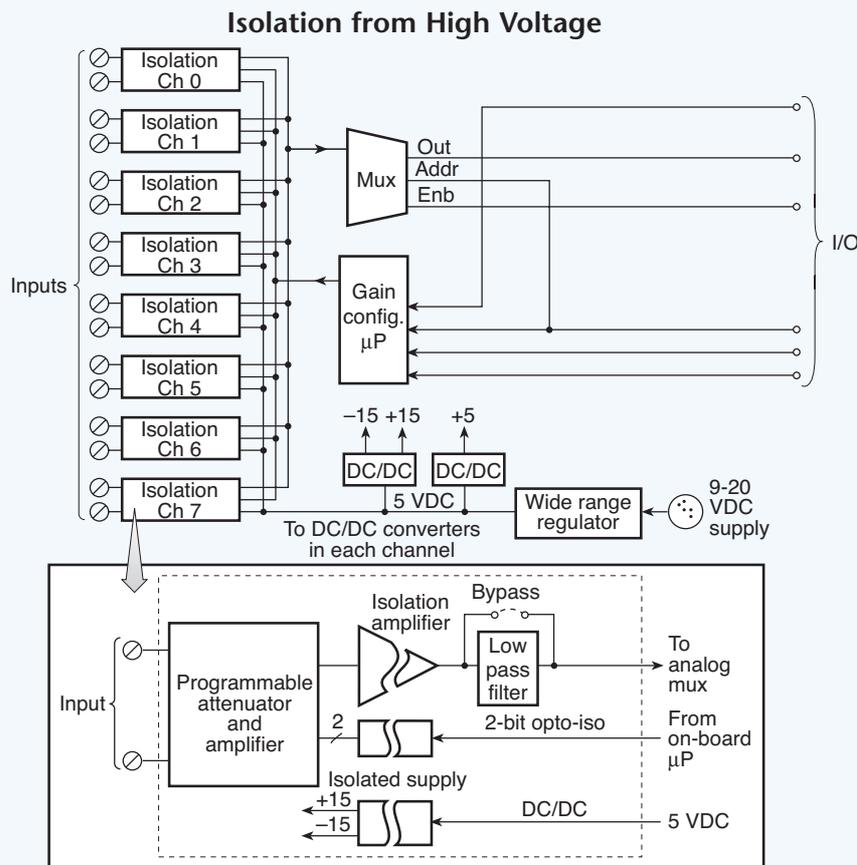
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Fig. 5.34. *The isolated voltage-input modules let data acquisition systems isolate several channels of analog input, up to 500V channel-to-channel and channel-to-system.*

and contains breakpoints programmed with diodes, resistors, and reference voltages, all subject to errors that are avoided in software compensation methods. However, several modules are commercially available with excellent, stable, built-in linearizing circuits. The thermocouple voltage is extremely small and most signal conditioners concentrate less on compensation and more on amplifying the signal while rejecting common-mode noise. Alternative digital hardware methods use a look-up table to convert the thermocouple voltage to a corresponding temperature.

CIRCUIT PROTECTION

Hazards to Instrumentation Circuits
Many data acquisition systems contain solid-state multiplexing circuits to rapidly scan multiple input channels. Their inputs are typically limited to less than 30V and may be damaged when exposed to higher voltages. Other solid-state devices in a measurement system including input amplifiers and bias sources also are limited to low voltages. However, these inputs can be protected with a programmable attenuator and isolation amplifiers that isolate the high voltage input stage from the solid-state circuitry. (See Figure 5.34.)

Another consideration often overlooked is connecting active inputs to an unpowered data acquisition system. Common safety practice calls for all signals connected to the input of the unpowered data acquisition system to be disconnected or their power removed. Frequently, de-energized data acquisition system signal conditioners have substantially lower input impedances than when energized, and even low voltage input signals higher than 0.5 VDC can damage the signal conditioners' input circuits.

Overload Protection
Several methods are used to protect signal conditioner inputs from damage when exposed to transients of 10 to 100V. Often, a 1,000 Ω, current-limiting resistor is in series with the input when no voltage is applied to the instrument amplifiers' input. For transient input voltages to 3,000V and above, a series resistor and a transient voltage suppressor are installed across the input terminals. (See Figure 5.35.)

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Overload Protection
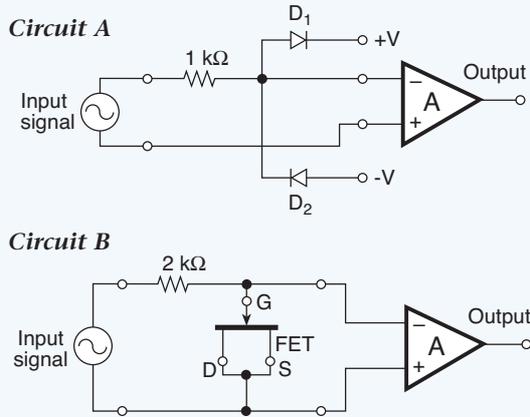
Circuit A

Circuit B

Fig. 5.35. *Certain CMOS multiplexers may be protected against overvoltage destruction with diode and resistor networks that shut down any parasitic transistors in the device, limit the current input to a safe level, and shunt input signals to ground when the power supplies are turned off (Circuit A). JFET transistors also protect multiplexer inputs when they are connected as diodes. The JFET clamps at about 0.6V, protecting the sensitive op amp input from destruction (Circuit B).*

ESD Protection

Electrostatic discharge damage is a special problem that can be avoided by handling individual circuit boards carefully and providing proper shielding. ESD comes from the static charge accumulated on many different kinds of materials, which finds a return to ground or a mass that attracts the excess electrons. The charge can create potential differences that can eventually arc over large distances. An arc containing only several micro-joules of energy can destroy or damage a semiconductor device. Grounding alone is not sufficient to control ESD build up, it only ensures all conductors are at the same potential. Control-ling humidity to about 40% and slightly ionizing the air are the most effective methods of controlling static charge.

A discharge can travel one foot in one nanosecond and could rise to 5 A. A number of devices simulate conditions for static discharge protection, including a gun that generates pulses at a fixed voltage and rate. Component testing usually begins with relatively low voltages and gradually progresses to higher values.

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