CHAPTER III

SENSOR TECHNOLOGY

3.1 Basic Sensor Technology

A ***sensor*** is a device that converts a physical phenomenon into an electrical signal. As such, sensors represent part of the interface between the physical world and the world of electrical devices, such as computers. The other part of this interface is represented by ***actuators***, which convert electrical signals into physical phenomena.

A sensor differs from a transducer in that a sensor converts the received signal into electrical form only. A sensor collects information from the real world. A transducer only converts energy from one form to another.

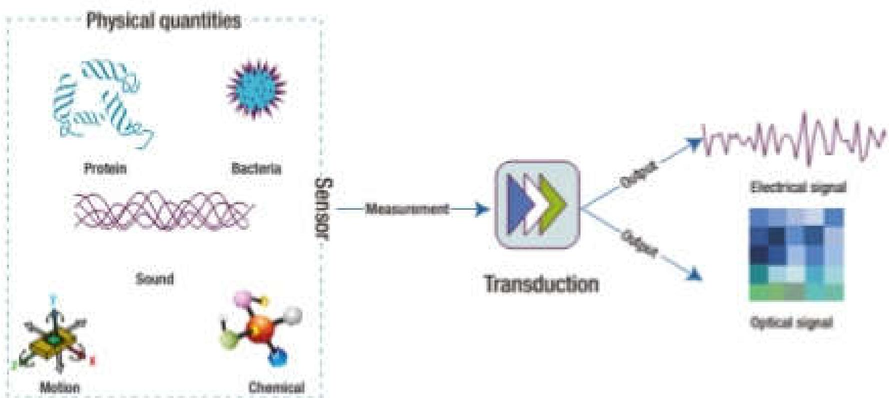


Figure 3.1: the sensing process

Sensor Data Sheets

It is important to understand the function of the data sheet in order to deal with this variability. ***The data sheet*** is primarily a marketing document. It is typically designed to highlight the positive attributes of a particular sensor and emphasize some of the potential uses of the sensor, and might neglect to comment on some of the negative characteristics of the sensor.

Sensor Performance Characteristics Definitions

The following are some of the more important sensor characteristics:

1. Transfer Function: shows the functional relationship between physical input signal and electrical output signal. Usually, this relationship is represented as a graph showing the relationship between the input and output signal, and the details of this relationship may constitute a complete description of the sensor characteristics.

2. Sensitivity: is defined in terms of the relationship between input physical signal and output electrical signal. It is generally the ratio between a small change in electrical signal to a small change in physical signal. As such, it may be expressed as the derivative of the transfer function with respect to physical signal. Typical units are volts/kelvin, millivolts/kilopascal, etc... A thermometer would have "high sensitivity" if a small temperature change resulted in a large voltage change.

3. Span or Dynamic Range: The range of input physical signals that may be converted to electrical signals by the sensor is the dynamic range (span). Signals outside of this range are expected to cause unacceptably large inaccuracy. This span or dynamic range is usually specified by the sensor supplier as the range over which other performance characteristics described in the data sheets are expected to apply. Typical units are kelvin, Pascal, newton…

4. Accuracy or Uncertainty: Uncertainty is generally defined as the largest expected error between actual and ideal output signals. Typical units are kelvin. Sometimes this is quoted as a fraction of the full-scale output or a fraction of the reading. For example, a thermometer might be guaranteed accurate to within 5% of FSO (Full Scale Output).

"Accuracy" is generally considered by metrologists to be a qualitative term, while "uncertainty" is quantitative. For example one sensor might have better accuracy than another if its uncertainty is 1% compared to the other with an uncertainty of 3%.

5. Hysteresis: Some sensors do not return to the same output value when the input stimulus is cycled up or down. The width of the expected error in terms of the measured quantity is defined as the hysteresis. Typical units are kelvin or percent of FSO.

6. Nonlinearity (often called Linearity): The maximum deviation from a linear transfer function over the specified dynamic range. There are several measures of this error. The most common compares the actual transfer function with the "best straight line," which lies midway between the two parallel lines that encompass the entire transfer function over the specified dynamic range of the device. This choice of comparison method is popular because it makes most sensors look the best. Other reference lines may be used, so the user should be careful to compare using the same reference.

7. Noise: All sensors produce some output noise in addition to the output signal. In some cases, the noise of the sensor is less than the noise of the next element in the electronics, or less than the fluctuations in the physical signal, in which case it is not important. Many other cases exist in which the noise of the sensor limits the performance of the system based on the sensor. Noise is generally distributed across the frequency spectrum.

Many common noise sources produce a ***white noise distribution***, which is to say that the spectral noise density is the same at all frequencies. ***Johnson noise*** in a resistor is a good example of such a noise distribution. For white noise, the spectral noise density is characterized in units of volts/Root (Hz). A distribution of this nature adds noise to a measurement with amplitude proportional to the square root of the measurement bandwidth. Since there is an inverse relationship between the bandwidth and measurement time, it can be said that the noise decreases with the square root of the measurement time.

8. Resolution: The resolution of a sensor is defined as the minimum detectable signal fluctuation. Since fluctuations are temporal phenomena, there is some relationship between the timescale for the fluctuation and the minimum detectable amplitude. Therefore, the definition of resolution must include some information about the nature of the measurement being carried out.

9. Bandwidth: All sensors have finite response times to an instantaneous change in physical signal. In addition, many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. The reciprocal of these times correspond to the upper and lower cutoff frequencies, respectively. The ***bandwidth of a sensor*** is the frequency range between these two frequencies. The bandwidth of this sensor depends on choices of external capacitors and resistors.

3.2 Sensor Systems

Strictly speaking, a ***sensor*** is a device that receives a signal or stimulus and responds with an electrical signal, while a ***transducer*** is a converter of one type of energy into another. In practice, however, the terms are often used interchangeably. Sensors and their associated circuits are used to measure various physical properties such as *temperature, force, pressure, flow, position, light intensity,* etc. These properties act as the stimulus to the sensor, and the sensor output is conditioned and processed to provide the corresponding measurement of the physical property.

Sensors do not operate by themselves. They are generally part of a larger system consisting of signal conditioners and various analog or digital signal processing circuits.

The ***system*** could be a measurement system, data acquisition system, or process control system, for example Sensors may be classified in a number of ways. From a signal conditioning viewpoint it is useful to classify sensors as either *active* or *passive*.

An ***active sensor*** requires an external source of excitation. Resistor-based sensors such as ***thermistors, RTDs (Resistance Temperature Detectors), and strain gages*** are examples of active sensors, because a current must be passed through them and the corresponding voltage measured in order to determine the resistance value. An alternative would be to place the devices in a bridge circuit; however, in either case, an external current or voltage is required.

Passive (or self-generating) sensors generate their own electrical output signal without requiring external voltages or currents. Examples of passive sensors are ***thermocouples and photodiodes*** which generate thermo-electric voltages and photo-currents, respectively, which are independent of external circuits.

Table 3.1: Typical sensors and their outputs

PROPERTY	***SENSOR***	***ACTIVE/PASSIVE***	***OUTPUT***
Temperature	Thermocouple	Passive	Voltage
	Silicon	Active	Voltage/Current
	RTD	Active	Resistance
	Thermistor	Active	Resistance
Force/Pressure	Strain Gage	Active	Resistance
	Piezoelectric	Passive	Voltage
Acceleration	Accelerometer	Active	Capacitance
Position	LVDT	Active	AC Voltage
Light Intensity	Photodiode	Passive	Current

The full-scale outputs of most sensors (passive or active) are relatively *small voltages, currents, or resistance changes*, and therefore their outputs must be properly conditioned before further analog or digital processing can occur. Because of this, an entire class of circuits have evolved, generally referred to as *signal conditioning* circuits. ***Amplification, level translation, galvanic isolation, impedance transformation, linearization, and filtering*** are fundamental signal conditioning functions that may be required. Whatever form the conditioning takes, however, the circuitry and performance will be governed by the electrical character of the sensor and its output. Accurate characterization of the sensor in terms of parameters appropriate to the application, e.g., ***sensitivity, voltage and current levels, linearity, impedances, gain, offset, drift, time constants, maximum electrical***

ratings*, *and stray impedances and other important considerations can spell the difference between sub-standard and successful application of the device, especially in cases where high resolution and precision, or low-level measurements are involved.

Higher levels of integration now allow ICs to play a significant role in both analog and digital signal conditioning. ADCs (analog-to-digital converters) specifically designed for measurement applications often contain on-chip programmable-gain amplifiers (PGAs) and other useful circuits, such as current sources for driving RTDs, thereby minimizing the external conditioning circuit requirements.

Most sensor outputs are nonlinear with respect to the stimulus, and their outputs must be linearized in order to yield correct measurements. Analog techniques may be used to perform this function. However, the recent introduction of high performance ADCs now allows linearization to be done much more efficiently and accurately in software and eliminates the need for tedious manual calibration using multiple and sometimes interactive trim pots.

3.3 Applications Considerations

The highest quality, most up-to-date, most accurately calibrated and most carefully selected sensor can still give totally erroneous data if it is not correctly applied. This section will address some of the issues that need to be considered to assure correct application of any sensor.

3.3.1 Sensor Characteristics

The prospective user is generally forced to make a selection based on the characteristics available on the product data sheet. Many performance characteristics are shown on a typical data sheet. Many manufacturers feel that the data sheet should provide as much information as possible. Unfortunately, this abundance of data may create some confusion for a potential user, particularly the new user. Therefore the instrumentation engineer must be sure he or she understands the pertinent characteristics and how they will affect the measurement. If there is any doubt, the manufacturer should be contacted for clarification.

3.3.2 System Characteristics

The sensor and signal conditioners must be selected to work together as a system. Moreover, the system must be selected to perform well in the intended applications. Overall system accuracy is usually affected most by sensor characteristics such as environmental effects and dynamic characteristics. Amplifier characteristics such as nonlinearity, harmonic distortion and flatness of the frequency response curve are usually negligible when compared to sensor errors.

3.3.3 Instrument Selection

Selecting a sensor/signal conditioner system for highly accurate measurements requires very skillful and careful measurement engineering. All environmental, mechanical, and measurement conditions must be considered. Installation must be carefully planned and carried out. The following guidelines are offered as an aid to selecting and installing measurement systems for the best possible accuracy.

Sensor

The most important element in a measurement system is the sensor. If the data is distorted or corrupted by the sensor, there is often little that can be done to correct it.

Will the sensor operate satisfactorily in the measurement environment? Check:

- ✓ Temperature Range
- ✓ Maximum Shock and Vibration
- ✓ Humidity
- ✓ Pressure
- ✓ Acoustic Level
- ✓ Corrosive Gases
- ✓ Magnetic and RF Fields
- ✓ Nuclear Radiation
- ✓ Salt Spray
- ✓ Transient Temperatures
- ✓ Strain in the Mounting Surface

Will the sensor characteristics provide the desired data accuracy? Check:

- ✓ Sensitivity
    - o Frequency Response
        - ▪ Resonance Frequency
- ✓ Minor Resonances
- ✓ Internal Capacitance
- ✓ Transverse Sensitivity
- ✓ Amplitude Linearity and Hysteresis
- ✓ Temperature Deviation
- ✓ Weight and size
- ✓ Internal Resistance at Maximum Temperature
- ✓ Calibration Accuracy
- ✓ Strain Sensitivity

- ✓ Damping at Temperature Extremes
- ✓ Zero Measurand Output
- ✓ Thermal Zero Shift
- ✓ Thermal Transient Response

Is the proper mounting being used for this application? Check:

- ✓ Is Insulating Stud Required?
  - Ground Loops
  - Calibration Simulation
  - Is Adhesive (strictly) mounting required?
  - Thread Size, Depth and Class

Cable

Cables and connectors are usually the weakest link in the measurement system chain. Will the cable operate satisfactorily in the measurement environment? Check:

- ✓ Temperature Range
- ✓ Humidity Conditions

Will the cable characteristics provide the desired data accuracy? Check:

- ✓ Low Noise
- ✓ Size and Weight
- ✓ Flexibility
- ✓ Is Sealed Connection Required?

Power Supply

Will the power supply operate satisfactorily in the measurement environment? Check:

- ✓ Temperature Range
- ✓ Maximum Shock and Vibration
- ✓ Humidity
- ✓ Pressure
- ✓ Acoustic Level
- ✓ Corrosive Gases
- ✓ Magnetic and RF Fields
- ✓ Nuclear Radiation
- ✓ Salt Spray

Is this the proper power supply for the application? Check:

- ✓ Voltage Regulation
- ✓ Current Regulation

Compliance Voltage

- ✓ Output Voltage Adjustable?
- ✓ Output Current Adjustable?
- ✓ Long Output Lines?
- ✓ Need for External Sensing
- ✓ Isolation

Will the power supply characteristics provide the desired data accuracy? Check:

- ✓ Load Regulation
- ✓ Line Regulation
- ✓ Temperature Stability
- ✓ Time Stability
- ✓ Ripple and Noise
- ✓ Output Impedance
- ✓ Line-Transient Response
- ✓ Noise to Ground
- ✓ DC Isolation

Amplifier

The amplifier must provide gain, impedance matching, output drive current, and other signal processing. Will the amplifier operate satisfactorily in the measurement environment? Check:

- ✓ Temperature Range
- ✓ Maximum Shock and Vibration
- ✓ Humidity
- ✓ Pressure
- ✓ Acoustic Level
- ✓ Corrosive Gases
- ✓ Magnetic and RF Fields
- ✓ Nuclear Radiation
- ✓ Salt Spray

Is this the proper amplifier for the application? Check:

- ✓ Long Input Lines?
  - ✓ Need for Charge Amplifier
  - ✓ Need for Remote Charge Amplifier
- ✓ Long Output Lines
  - ✓ Need for Power Amplifier
- ✓ Airborne
  - ✓ Size, Weight, Power Limitations

Will the amplifier characteristics provide the desired data accuracy? Check:

- ✓ Gain and Gain Stability
- ✓ Frequency Response
- ✓ Linearity
- ✓ Stability
- ✓ Phase Shift
- ✓ Output Current and Voltage
- ✓ Residual Noise
- ✓ Input Impedance
- ✓ Transient Response
- ✓ Overload Capability
- ✓ Common Mode Rejection
- ✓ Zero-Temperature Coefficient
- ✓ Gain-Temperature Coefficient

3.3.4 Data Acquisition and Readout

Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer. A DAQ **system** consists of sensors, DAQ measurement hardware, and a computer with programmable software.

Does the remainder of the system, including any additional *amplifiers, filters, data acquisition and readout devices*, introduce any limitation that will tend to degrade the sensor-amplifier characteristics?

Check: ALL of previous check items, plus Adequate Resolution.

3.3.5 Installation

Even the most carefully and thoughtfully selected and calibrated system can produce bad data if carelessly or ignorantly installed.

Sensor

Is the unit in good condition and ready to use? Check:

- ✓ Up-to-Date Calibration
- ✓ Physical Condition
  - o Case
  - o Mounting Surface
  - o Connector
  - o Mounting Hardware
- ✓ Inspect for Clean Connector
- ✓ Internal Resistance

Is the mounting hardware in good condition and ready to use? Check:

- ✓ Mounting Surface Condition
- ✓ Thread Condition
- ✓ Burred End Slots
- ✓ Insulated Stud
  - o Insulation Resistance
  - o Stud Damage by Over Torqueing
- ✓ Mounting Surface Clean and Flat
- ✓ Sensor Base Surface Clean and Flat
- ✓ Hole Drilled and Tapped Deep Enough
- ✓ Correct Tap Size
- ✓ Hole Properly Aligned Perpendicular to Mounting Surface
- ✓ Stud Threads Lubricated
- ✓ Sensor Mounted with Recommended Torque

Cement Mounting

Check:

- ✓ Mounting Surface Clean and Flat
- ✓ Dental Cement for Uneven Surfaces
- ✓ Cement Cured Properly
- ✓ Sensor Mounted to Cementing Stud with Recommended Torque

Cable

Is the cable in good condition and ready for use? Check:

- ✓ Physical Condition
  - Cable Kinked, Crushed
  - Connector Threads, Pins
- ✓ Inspect for Clean Connectors
- ✓ Continuity
- ✓ Insulation Resistance
- ✓ Capacitance
- ✓ All Cable Connections Secure
- ✓ Cable Properly restrained
- ✓ Excess Cable Coiled and Tied Down
- ✓ Drip Loop Provided
- ✓ Connectors Sealed and potted, if required

Power Supply, Amplifier, and Readout

Are the units in good condition and ready to use? Check:

- ✓ Up-to-Date Calibration
- ✓ Physical Condition
  - Connectors
  - Case
  - Output Cables
- ✓ Inspect for Clean Connectors
- ✓ Mounted Securely
- ✓ All Cable Connections Secure
- ✓ Gain Hole Cover Sealed, if Required
- ✓ Recommended Grounding in Use

When the above questions have been answered to the user's satisfaction, the measurement system has a high probability of providing accurate data.

3.4 *Measurement Issues and Criteria*

Sensors are most commonly used to make quantifiable measurements, as opposed to qualitative detection or presence sensing. Therefore, it should be obvious that the requirements of the measurement will determine the selection and application of the sensor.

How then can we quantify the requirements of the measurement?

First, we must consider what it is we want to measure. Sensors are available to measure almost anything you can think of, and many things you would never think of (but someone has!). Pressure, temperature and flow are probably the most common measurements as they are involved in monitoring and controlling many industrial processes and material transfers.

Second, we must consider the environment of the sensor. Environmental effects are perhaps the biggest contributor to measurement errors in most measurement systems. Sensors, and indeed whole measurement systems, respond to their total environment, not just to the measurand. In extreme cases, the response to the combination of environments may be greater than the response to the desired measurand. One of the sensor designer's greatest challenges is to minimize the response to the environment and maximize the response to the desired measurand. Assessing the environment and estimating its effect on the measurement system is an extremely important part of the selection and application process.

The environment includes not only such parameters as temperature, pressure and vibration, but also the mounting or attachment of the sensor, electromagnetic and electrostatic effects, and the rates of change of the various environments. For example, a sensor may be little affected by extreme temperatures, but may produce huge errors in a rapidly changing temperature ("thermal transient sensitivity").

Third, we must consider the requirements for accuracy (uncertainty) of the measurement. Often, we would like to achieve the lowest possible uncertainty, but that may not be economically feasible, or even necessary. How will the information derived from the measurement be used? Will it really make a difference, in the long run, whether the uncertainty is 1% or 1½%? Will highly accurate sensor data be obscured by inaccuracies in the signal conditioning or recording processes? On the other hand, many modern data acquisition systems are capable of much greater accuracy than the sensors making the measurement. A user must not be misled by thinking that high resolution in a data acquisition system will produce high accuracy data from a low accuracy sensor.

Last, but not least, the user must assure that the whole system is calibrated and traceable to a national standards organization (such as National Institute of Standards and Technology [NIST] in the United States). Without documented traceability, the uncertainty of any measurement is unknown. Either each part of the measurement system must be calibrated and an overall uncertainty calculated, or the total system must be calibrated as it will be used ("system calibration" or "end-to-end calibration").

Since most sensors do not have any adjustment capability for conventional "calibration", a characterization or evaluation of sensor parameters is most often required. For the lowest uncertainty in the measurement, the characterization should be done with mounting and environment as similar as possible to the actual measurement conditions. While this handbook concentrates on sensor technology, a properly selected, calibrated, and applied sensor is necessary but not sufficient to assure accurate measurements. The sensor must be carefully matched with, and integrated into, the total measurement system and its environment.

3.5 *Sensor Signal Conditioning*

Typically a sensor cannot be directly connected to the instruments that record, monitor, or process its signal, because the signal may be incompatible or may be too weak and/or noisy. The signal must be conditioned (i.e., cleaned up, amplified, and put into a compatible format).

3.5.1 Conditioning Bridge Circuits

Resistive elements are some of the most common sensors. They are inexpensive to manufacture and relatively easy to interface with signal conditioning circuits. Resistive elements can be made sensitive to temperature, strain (by pressure or by flex), and light. Using these basic elements, many complex physical phenomena can be measured, such as fluid or mass flow (by sensing the temperature difference between two calibrated resistances) and dew-point humidity (by measuring two different temperature points), etc. Bridge circuits are often incorporated into force, pressure and acceleration sensors.

Sensor elements resistances can range from less than 100 Ω to several hundred kΩ, depending on the sensor design and the physical environment to be measured (See table 3.2).

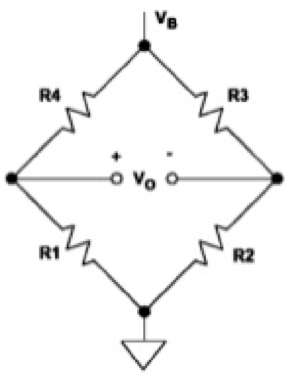
Table 3.2: Resistance of popular sensors.

Types of sensors	Typical resistance value
Strain gages	120Ω,320Ω,3500Ω
Weigh-scale load cells	350Ω-3500Ω
Pressure sensors	350Ω-3500Ω
Relative humidity	100KΩ-10MΩ
Resistance temperature devices (RTDs)	100Ω-1000Ω
Thermistors	100Ω-10MΩ

Bridge Circuits

Resistive sensors such as RTDs and strain gages produce small percentage changes in resistance in response to a change in a physical variable such as temperature or force.

Bridges offer an attractive alternative for measuring small resistance changes accurately. The basic Wheatstone bridge (actually developed by S. H. Christie in 1833) is shown in Figure 3.2. It consists of four resistors connected to form a quadrilateral, a source of excitation (voltage or current) connected across one of the diagonals, and a voltage detector connected across the other diagonal. The detector measures the difference between the outputs of two voltage dividers connected across the excitation.



$$V_O = \frac{R1}{R1+R4}V_B - \frac{R2}{R2+R3}V_B$$

$$= \frac{\frac{R1}{R4} - \frac{R2}{R3}}{\left(1+\frac{R1}{R4}\right)\left(1+\frac{R2}{R3}\right)}V_B$$

AT BALANCE,

$$V_O = 0 \quad \text{IF} \quad \frac{R1}{R4} = \frac{R2}{R3}$$

Figure 3.2: The Wheatstone bridge.

A bridge measures resistance indirectly by comparison with a similar resistance. The two principal ways of operating a bridge are as a null detector or as a device that reads a difference directly as voltage.

When R1/R4 = R2/R3, the resistance bridge is at *a null,* regardless of the mode of excitation (current or voltage, AC or DC), the magnitude of excitation, the mode of readout (current or voltage), or the impedance of the detector. Therefore, if the ratio of R2/R3 is fixed at K, a null is achieved when R1 = K·R4. If R1 is unknown and R4 is an accurately determined variable resistance, the magnitude of R1 can be found by adjusting R4 until null is achieved. Conversely, in sensor-type measurements, R4 may be a fixed reference, and a null occurs when the magnitude of the external variable (strain, temperature, etc.) is such that R1 = K·R4.

Null measurements are principally used in feedback systems involving electromechanical and/or human elements. Such systems seek to force the active element (strain gage, RTD, thermistor, etc.) to balance the bridge by influencing the parameter being measured.

For the majority of sensor applications employing bridges, however, the deviation of one or more resistors in a bridge from an initial value is measured as an indication of the magnitude (or a change) in the measured variable. In this case, the output voltage change is an indication of the resistance change. Because very small resistance changes are common, the output voltage change may be as small as tens of millivolts.

In many bridge applications, there may be two, or even four, elements that vary. Figure 3.3 shows the four commonly used bridges suitable for sensor applications and the corresponding equations which relate the bridge output voltage to the excitation voltage and the bridge resistance values. In this case, we assume a constant voltage drive, VB. Note that since the bridge output is directly proportional to VB, the measurement accuracy can be no better than that of the accuracy of the excitation voltage.

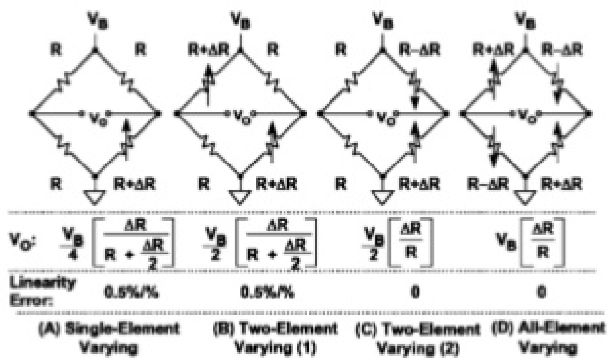


Figure 3.3: Output voltage & linearity error for constant voltage drive bridge configurations.

The ***single-element varying*** bridge is most suited for temperature sensing using RTDs or thermistors. This configuration is also used with a single resistive strain gage. All the resistances are nominally equal, but one of them (the sensor) is variable by an amount ΔR. As the equation indicates, the relationship between the bridge output and ΔR is not linear.

Single-Element Varying Bridge End-Point Linearity Error ≈ % Change in Resistance ÷ 2

It should be noted that the above nonlinearity refers to the nonlinearity of the bridge itself and not the sensor.

There are two possibilities to consider in the case of the ***two-element varying*** bridge. In the first, Case (1), both elements change in the ***same*** direction, such as two identical strain gages mounted adjacent to each other with their axes in parallel. The nonlinearity is the same as that of the single-element varying bridge, however the gain is twice that of the single-element varying bridge. The two-element varying bridge is commonly found in pressure sensors and flow meter systems.

A second configuration of the two-element varying bridge, Case (2), requires two identical elements that vary in ***opposite*** directions. This could correspond to two identical strain gages: one mounted on top of a flexing surface, and one on the bottom. Note that this configuration is linear, and like two-element Case (1), has twice the gain of the single-element configuration. Another way to view this configuration is to consider the terms $R + \Delta R$ and $R - \Delta R$ as comprising the two sections of a center tapped potentiometer.

The *all-element varying* bridge produces the most signal for a given resistance change and is inherently linear. It is an industry-standard configuration for load cells which are constructed from four identical strain gages.

In summary, there are many design issues relating to bridge circuits. After selecting the basic configuration, the excitation method must be determined. The value of the excitation voltage or current must first be determined. Recall that the full scale bridge output is directly proportional to the excitation voltage (or current).

3.5.2 Amplifiers for Signal Conditioning

The critical parameters of amplifiers for use in precision signal conditioning applications are:

- Offset voltages for precision IC op amps can be as low as 10 µV with corresponding temperature drifts of 0.1 µV/ºC.
- Chopper stabilized op amps provide offsets and offset voltage drifts which cannot be distinguished from noise.
- Open loop gains greater than 1 million are common, along with common mode and power supply rejection ratios of the same magnitude.

Applying these precision amplifiers while maintaining the amplifier performance can present significant challenges to a design engineer, i.e., external passive component selection and PC board layout.

It is important to understand that ***DC open-loop gain, offset voltage, power supply rejection (PSR), and common mode rejection (CMR)*** should not be the only considerations in selecting precision amplifiers. The AC performance of the amplifier is also important, even at "low" frequencies. Open-loop gain, PSR, and CMR all have relatively low corner frequencies, and therefore what may be considered "low" frequency may actually fall above these corner frequencies, increasing errors above the value predicted solely by the DC parameters. For example, an amplifier having a DC open-loop gain of 10 million and a unity gain crossover frequency of 1 MHz has a corresponding corner frequency of 0.1 Hz! One must therefore consider the open loop gain at the actual *signal* frequency

The challenge of selecting the right amplifier for a particular signal conditioning application has been complicated by the sheer proliferation of various types of amplifiers in various processes (Bipolar, Complementary Bipolar, BiFET, CMOS, BiCMOS, etc.) and architectures (traditional op amps, instrumentation amplifiers, chopper amplifiers, isolation amplifiers, etc.) In addition, a wide selection of precision amplifiers are now available which operate on single supply voltages, which complicates the design process even further because of the reduced signal swings and voltage input and output restrictions. Offset voltage and noise are now a more significant portion of the input signal.

In this section, we will first look at some key performance specifications for precision op amps. Other amplifiers will then be examined such as instrumentation amplifiers, chopper amplifiers, and isolation amplifiers.

Precision Op Amp Characteristics

Input Offset Voltage

Input offset voltage error is usually one of the largest error sources for precision amplifier circuit designs. However, it is a systemic error and can usually be dealt with by using a manual offset null trim or by system calibration techniques using a microcontroller or microprocessor. Both solutions carry a cost penalty, and today's precision op amps offer initial offset voltages as low as 10 µV for bipolar devices, and far less for chopper stabilized amplifiers. With low offset amplifiers, it is possible to eliminate the need for manual trims or system calibration routines.

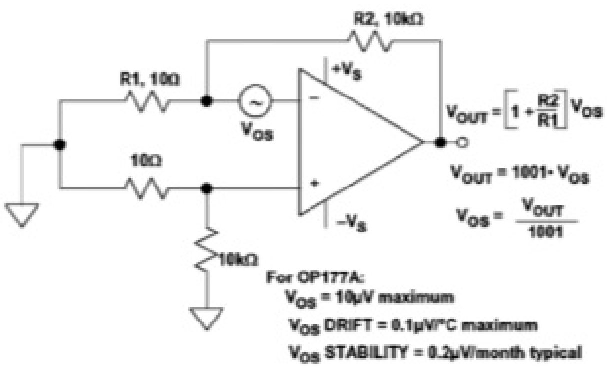


Figure 3.4: Measuring input offset voltage

Measuring input offset voltages of a few microvolts requires that the test circuit does not introduce more error than the offset voltage itself.

DC Open Loop Gain Nonlinearity

It is well understood that in order to maintain accuracy, a precision amplifier's DC open loop gain, A_{VOL}, should be high.

This can be seen by examining the equation for the closed loop gain:

$$\text{Closed Loop Gain} = A_{VCL} = \frac{NG}{1+\frac{NG}{A_{VOL}}}$$

Noise gain (NG) is simply the gain seen by a small voltage source in series with the op amp input and is also the amplifier signal gain in the non-inverting mode. If A_{VOL} in the above equation is infinite, the closed loop gain is exactly equal to the noise gain. However, for finite values of A_{VOL}, there is a closed loop gain error given by the equation:

$$\%\ \text{Gain Error} = \frac{NG}{NG+A_{VOL}} \times 100\% \approx \frac{NG}{A_{VOL}} \times 100\%,\ \text{for } NG << A_{VOL}$$

Notice from the equation that the percent gain error is directly proportional to the noise gain, therefore the effects of finite A_{VOL} are less for low gain. If the open loop gain stays constant over temperature and for various output loads and voltages, the gain error can be calibrated out of the measurement, and there is then no overall system gain error.

Op Amp Noise

The three noise sources in an op amp circuit are the voltage noise of the op amp, the current noise of the op amp (there are two uncorrelated sources, one in each input), and the Johnson noise of the resistances in the circuit. Op amp noise has two components, "white" noise at medium frequencies and low frequency "1/f" noise, whose spectral density is inversely proportional to the square root of the frequency. It should be noted that, though both the voltage and the current noise may have the same characteristic behavior, in a particular amplifier the 1/f corner frequency is not necessarily the same for voltage and current noise.

Common Mode Rejection and Power Supply Rejection

If a signal is applied equally to both inputs of an op amp so that the differential input voltage is unaffected, the output should not be affected. In practice, changes in common mode voltage will produce changes in the output. The *common mode rejection ratio* or CMRR is the ratio of the common mode gain to the differential- mode gain of an op amp.

For example, if a differential input change of Y volts will produce a change of 1 V at the output, and a common mode change of X volts produces a similar change of 1 V, then the CMRR is X/Y. It is normally expressed in dB, and typical LF values are between 70 and 120 dB. When expressed in dB, it is generally referred to as *common mode rejection* (CMR).

$$\mathbf{CMR=20log_{10}CMRR}$$

CMRR produces a corresponding output offset voltage error in op amps configured in the non-inverting mode. Op amps configured in the inverting mode have no CMRR output error because both inputs are at ground or virtual ground, so there is no common mode voltage, only the offset voltage of the amplifier if un-nulled.

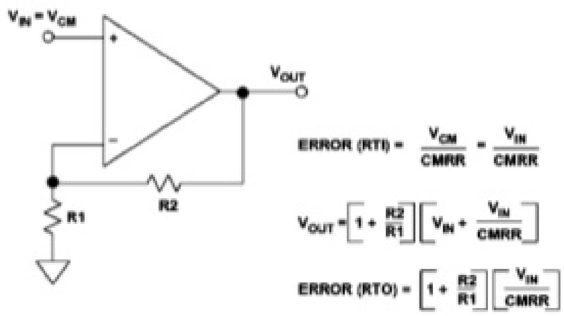


Figure 3.5: Calculating offset error due to common mode rejection ratio (CMRR)

If the supply of an op amp changes, its output should not, but it will. The specification of *power supply rejection ratio* or *PSRR* is defined similarly to the definition of CMRR. If a change of X volts in the supply produces the same output change as a differential input change of Y volts, then the PSRR on that supply is X/Y. When the ratio is expressed in dB, it is generally referred to as *power supply rejection*, or PSR.

The definition of PSRR assumes that both supplies are altered equally in opposite directions otherwise the change will introduce a common mode change as well as a supply change, and the analysis becomes considerably more complex. It is this effect which causes apparent differences in PSRR between the positive and negative supplies. In the case of single supply op amps, PSR is generally defined with respect to the change in the positive supply. Many single supply op amps have separate PSR specifications for the positive and negative supplies.

$$PSR = 20\log_{10} PSRR$$

Single Supply Op Amps

Over the last several years, single supply operation has become an increasingly important requirement because of market requirements. Automotive, set-top box, camera/camcorder, PC, and laptop computer applications are demanding IC vendors to supply an array of linear devices that operate on a single supply rail, with the same performance of dual supply parts.

Power consumption is now a key parameter for line or battery operated systems, and in some instances, more important than cost. This makes low-voltage/low supply current operation critical; at the same time, however, accuracy and precision requirements have forced IC manufacturers to meet the challenge of "doing more with less" in their amplifier designs.

In summary, the following points should be considered when selecting amplifiers for single-supply/rail-to-rail applications:

First, *input offset voltage and input bias currents are a function of the applied input common mode voltage (for true rail-to-rail input op amps)*. Circuits using this class of amplifiers should be designed to minimize resulting errors. An inverting amplifier configuration with a false ground reference at the non-inverting input prevents these errors by holding the input common mode voltage constant. If the inverting amplifier configuration cannot be used, then amplifiers do not exhibit any common mode crossover thresholds should be used.

Second*, since input bias currents are not always small and can exhibit different polarities, source impedance levels should be carefully matched to minimize additional input bias current-induced offset voltages and increased distortion*. Again, consider using amplifiers that exhibit a smooth input bias current transition throughout the applied input common mode voltage.

Third, *rail-to-rail amplifier output stages exhibit load-dependent gain which affects amplifier open-loop gain, and hence closed-loop gain accuracy*. Amplifiers with open-loop gains greater than 30,000 for resistive loads less than 10 kΩ are good choices in precision applications. For applications not requiring full rail-rail swings.

Lastly*, no matter what claims are made, rail-to-rail output voltage swings are functions of the amplifier's output stage devices and load current*. The saturation voltage (VCESAT), saturation resistance (RSAT) for bipolar output stages, and FET on-resistance for CMOS output stages, as well as load current all affect the amplifier output voltage swing.

3.6 Analog to Digital Converters for Signal Conditioning

The trend in ADCs and DACs is toward higher speeds and higher resolutions at reduced power levels. Modern data converters generally operate on ±5 V (dual supply) or +5 V (single supply). In fact, many new converters operate on a single +3 V supply. This trend has created a number of design and applications problems which were much less important in earlier data converters, where ±15 V supplies and ±10 V input ranges were the standard.

Lower supply voltages imply smaller input voltage ranges, and hence more susceptibility to noise from all potential sources: power supplies, references, digital signals, EMI/RFI, and probably most important, improper layout, grounding, and decoupling techniques. Single-supply ADCs often have an input range which is not referenced to ground. Finding compatible single-supply drive amplifiers and dealing with level shifting of the input signal in direct-coupled applications also becomes a challenge.

The most popular precision signal conditioning ADCs are based on two fundamental architectures:

- ***Successive approximation***
- ***Sigma-delta***.

The ***tracking*** ADC architecture is particularly suited for resolver-to-digital converters, but it is rarely used in other precision signal conditioning applications. The ***flash*** converter and the *sub-ranging (or pipelined)* converter architectures are widely used where sampling frequencies extend into the megahertz and hundreds of megahertz region, but are overkills in both speed and cost for low frequency precision signal conditioning applications.

Low power, low voltage ADC design issues

- Typical Supply Voltages: ±5V, +5V, +5/+3V, +3V
- Lower Signal Swings Increase Sensitivity to all Types of Noise (Device, Power Supply, Logic, etc.)
- Device Noise Increases at Low Currents
- Common Mode Input Voltage Restrictions
- Input Buffer Amplifier Selection Critical
- Auto-Calibration Modes Desirable at High Resolutions

ADCs for signal conditioning

- Successive Approximation
    - Resolutions to 16-bits
    - Minimal Throughput Delay Time
    - Used in Multiplexed Data Acquisition Systems

- Sigma-Delta
  - Resolutions to 24-bits
  - Excellent Differential Linearity
  - Internal Digital Filter, Excellent AC Line Rejection
  - Long Throughput Delay Time
  - Difficult to Multiplex Inputs Due to Digital Filter Settling Time
- High Speed Architectures:
  - Flash Converter
  - Sub ranging or Pipelined

3.6 Signal Conditioning High Impedance Sensors

Many popular sensors have output impedances greater than several MΩ, and the associated signal conditioning circuitry must be carefully designed to meet the challenges of low bias current, low noise, and high gain.

High impedance sensors

- *Photodiode preamplifiers*
- *Piezoelectric sensors*
  - *Accelerometers*
  - *Hydrophones*
- *Humidity monitors*
- *pH monitors*
- *chemical sensors*
- *smoke detectors*
- *charge coupled devices and contact image sensors for imaging*

Photodiode Preamplifier Design

Photodiodes generate a small current which is proportional to the level of illumination. They have many applications ranging from precision light meters to high-speed fiber optic receivers.

Photodiode applications

- Optical: light meter, auto-focus, flash controls
- Medical: CAT scanners (X-ray detection), blood particle analyzers
- Automotive: headlight dimmers, twilight detectors
- Communication: fiber optic receivers
- Industrial: bar code scanners, position sensors, laser printers

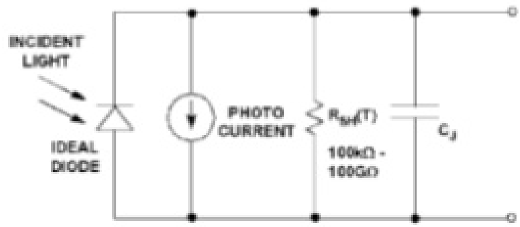


Figure 3.6: Photodiode equivalent circuit.

One of the standard methods for specifying the sensitivity of a photodiode is to state its short circuit photocurrent (Isc) at a given light level from a well-defined light source. The most commonly used source is an incandescent tungsten lamp running at a color temperature of 2850K. At 100 fc (foot-candles) illumination (approximately the light level on an overcast day), the short circuit current is usually in the Pico amps to hundreds of micro amps range for small area (less than $1mm^2$) diodes.

The short circuit current is very linear over 6 to 9 decades of light intensity, and is therefore often used as a measure of absolute light levels. The open circuit forward voltage drop across the photodiode varies logarithmically with light level, but, because of its large temperature coefficient, the diode voltage is seldom used as an accurate measure of light intensity.

The shunt resistance R_{SH} is usually in the order of 1000 MΩ at room temperature, and decreases by a factor of two for every 10ºC rise in temperature. Diode capacitance CJ is a function of junction area and the diode bias voltage. A value of 50 pF at zero bias is typical for small area diodes.

A convenient way to convert the photodiode current into a usable voltage is to use an op amp as a current-to-voltage converter.