

## ***Sensor Fundamentals***

### **1.1 Basic Sensor Technology**

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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.

Why do we care so much about this interface? In recent years, enormous capability for information processing has been developed within the electronics industry. The most significant example of this capability is the personal computer. In addition, the availability of inexpensive microprocessors is having a tremendous impact on the design of embedded computing products ranging from automobiles to microwave ovens to toys. In recent years, versions of these products that use microprocessors for control of functionality are becoming widely available. In automobiles, such capability is necessary to achieve compliance with pollution restrictions. In other cases, such capability simply offers an inexpensive performance advantage.

All of these microprocessors need electrical input voltages in order to receive instructions and information. So, along with the availability of inexpensive microprocessors has grown an opportunity for the use of sensors in a wide variety of products. In addition, since the output of the sensor is an electrical signal, sensors tend to be characterized in the same way as electronic devices. The data sheets for many sensors are formatted just like electronic product data sheets.

However, there are many formats in existence, and there is nothing close to an international standard for sensor specifications. The system designer will encounter a variety of interpretations of sensor performance parameters, and it can be confusing. It is important to realize that this confusion is not due to an inability to explain the meaning of the terms—rather it is a result of the fact that different parts of the sensor community have grown comfortable using these terms differently.

## **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. In many cases, the sensor has been designed to meet a particular performance specification for a specific customer, and the data sheet will concentrate on the performance parameters of greatest interest to this customer. In this case, the vendor and customer might have grown accustomed to unusual definitions for certain sensor performance parameters. Potential new users of such a sensor must recognize this situation and interpret things reasonably. Odd definitions may be encountered here and there, and most sensor data sheets are missing some pieces of information that are of interest to particular applications.

## **Sensor Performance Characteristics Definitions**

The following are some of the more important sensor characteristics:

### *Transfer Function*

The 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. For expensive sensors that are individually calibrated, this might take the form of the certified calibration curve.

### *Sensitivity*

The 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.

### *Span or Dynamic Range*

The range of input physical signals that may be converted to electrical signals by the sensor is the dynamic range or 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, newtons, etc.

### *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%.

### *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.

### *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.

### *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.

**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. Many sensors are limited by noise with a white spectral distribution. In these cases, the resolution may be specified in units of physical signal/root (Hz). Then, the actual resolution for a particular measurement may be obtained by multiplying this quantity by the square root of the measurement bandwidth. Sensor data sheets generally quote resolution in units of signal/root (Hz) or they give a minimum detectable signal for a specific measurement. If the shape of the noise distribution is also specified, it is possible to generalize these results to any measurement.

**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.

**Sensor Performance Characteristics of an Example Device**

To add substance to these definitions, we will identify the numerical values of these parameters for an off-the-shelf accelerometer, Analog Devices's ADXL150.

**Transfer Function**

The functional relationship between voltage and acceleration is stated as

$$V(Acc) = 1.5V + \left( Acc \times 167 \frac{mV}{g} \right)$$

This expression may be used to predict the behavior of the sensor, and contains information about the sensitivity and the offset at the output of the sensor.

**Sensitivity**

The sensitivity of the sensor is given by the derivative of the voltage with respect to acceleration at the initial operating point. For this device, the sensitivity is 167 mV/g.

### *Dynamic Range*

The stated dynamic range for the ADXL322 is  $\pm 2\text{g}$ . For signals outside this range, the signal will continue to rise or fall, but the sensitivity is not guaranteed to match 167 mV/g by the manufacturer. The sensor can withstand up to 3500g.

### *Hysteresis*

There is no fundamental source of hysteresis in this device. There is no mention of hysteresis in the data sheets.

### *Temperature Coefficient*

The sensitivity changes with temperature in this sensor, and this change is guaranteed to be less than 0.025%/C. The offset voltage for no acceleration (nominally 1.5 V) also changes by as much as 2 mg/C. Expressed in voltage, this offset change is no larger than 0.3 mV/C.

### *Linearity*

In this case, the linearity is the difference between the actual transfer function and the best straight line over the specified operating range. For this device, this is stated as less than 0.2% of the full-scale output. The data sheets show the expected deviation from linearity.

### *Noise*

Noise is expressed as a noise density and is no more than 300 microg/root Hz. To express this in voltage, we multiply by the sensitivity (167 mV/g) to get 0.5 microV/Rt Hz. Then, in a 10 Hz low-pass-filtered application, we'd have noise of about 1.5 microV RMS, and an acceleration error of about 1 milli g.

### *Resolution*

Resolution is 300 microG/RtHz as stated in the data sheet.

### *Bandwidth*

The bandwidth of this sensor depends on choices of external capacitors and resistors.

## **Introduction to Sensor Electronics**

The electronics that go along with the physical sensor element are often very important to the overall device. The sensor electronics can limit the performance, cost, and range of applicability. If carried out properly, the design of the sensor electronics can allow the optimal extraction of information from a noisy signal.

Most sensors do not directly produce voltages but rather act like passive devices, such as resistors, whose values change in response to external stimuli. In order to produce voltages suitable for input to microprocessors and their analog-to-digital converters, the resistor must be “biased” and the output signal needs to be “amplified.”

## Types of Sensors

### *Resistive sensor circuits*

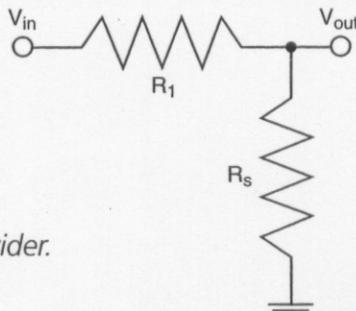


Figure 1.1.1: Voltage divider.

$$V_s = \frac{R_s}{R_1 + R_s} V_{in}$$

$$\text{if } R_1 \gg R_s, V_s = \frac{R_s}{R_1} V_{in}$$

Resistive devices obey Ohm's law, which states that the voltage across a resistor is equal to the product of the current flowing through it and the resistance value of the resistor. It is also required that all of the current entering a node in the circuit leave that same node. Taken together, these two rules are called Kirchhoff's Rules for Circuit Analysis, and these may be used to determine the currents and voltages throughout a circuit.

For the example shown in Figure 1.1.1, this analysis is straightforward. First, we recognize that the voltage across the sense resistor is equal to the resistance value times the current. Second, we note that the voltage drop across both resistors ( $V_{in}-0$ ) is equal to the sum of the resistances times the current. Taken together, we can solve these two equations for the voltage at the output. This general procedure applies to simple and complicated circuits; for each such circuit, there is an equation for the voltage between each pair of nodes, and another equation that sets the current into a node equal to the current leaving the node. Taken all together, it is always possible to solve this set of linear equations for all the voltages and currents. So, one way to

measure resistance is to force a current to flow and measure the voltage drop. Current sources can be built in number of ways. One of the easiest current sources to build consists of a voltage source and a stable resistor whose resistance is much larger than the one to be measured. The reference resistor is called a load resistor. Analyzing the connected load and sense resistors as shown in Figure 1.1.1, we can see that the current flowing through the circuit is nearly constant, since most of the resistance in the circuit is constant. Therefore, the voltage across the sense resistor is nearly proportional to the resistance of the sense resistor.

As stated, the load resistor must be much larger than the sense resistor for this circuit to offer good linearity. As a result, the output voltage will be much smaller than the input voltage. Therefore, some amplification will be needed.

A Wheatstone bridge circuit is a very common improvement on the simple voltage divider. It consists simply of the same voltage divider in Figure 1.1.1, combined with a second divider composed of fixed resistors only. The point of this additional divider is to make a reference voltage that is the same as the output of the sense voltage divider at some nominal value of the sense resistance. There are many complicated additional features that can be added to bridge circuits to more accurately compensate for particular effects, but for this discussion, we'll concentrate on the simplest designs—the ones with a single sense resistor, and three other bridge resistors that have resistance values that match the sense resistor at some nominal operating point.

The output of the sense divider and the reference divider are the same when the sense resistance is at its starting value, and changes in the sense resistance lead to small differences between these two voltages. A differential amplifier (such as an instrumentation amplifier) is used to produce the difference between these two voltages and amplify the result. The primary advantages are that there is very little offset voltage at the output of this differential amplifier, and that temperature or other effects that are common to all the resistors are automatically compensated out of the resulting signal. Eliminating the offset means that the small differential signal at the output can be amplified without also amplifying an offset voltage, which makes the design of the rest of the circuit easier.

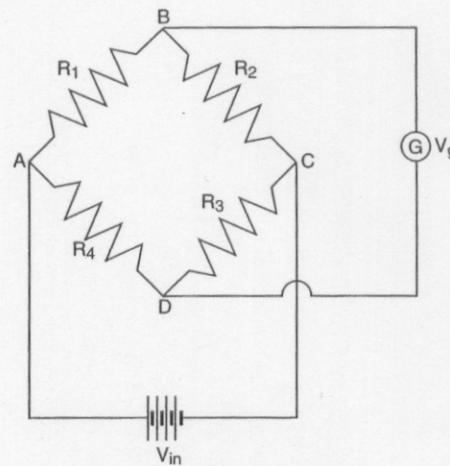


Figure 1.1.2: Wheatstone bridge circuit.

### *Capacitance measuring circuits*

Many sensors respond to physical signals by producing a change in capacitance. How is capacitance measured? Essentially, all capacitors have an impedance given by

$$\text{impedance} = \frac{1}{i\omega C} = \frac{1}{i2\pi fC}$$

where  $f$  is the oscillation frequency in Hz,  $\omega$  is in rad/sec, and  $C$  is the capacitance in farads. The  $i$  in this equation is the square root of  $-1$ , and signifies the phase shift between the current through a capacitor and the voltage across the capacitor.

Now, ideal capacitors cannot pass current at DC, since there is a physical separation between the conductive elements. However, oscillating voltages induce charge oscillations on the plates of the capacitor, which act as if there is physical charge flowing through the circuit. Since the oscillation reverses direction before substantial charges accumulate, there are no problems. The effective resistance of the capacitor is a meaningful characteristic, as long as we are talking about oscillating voltages.

With this in mind, the capacitor looks very much like a resistor. Therefore, we may measure capacitance by building voltage divider circuits as in Figure 1.1.1, and we may use either a resistor or a capacitor as the load resistance. It is generally easiest to use a resistor, since inexpensive resistors are available which have much smaller temperature coefficients than any reference capacitor. Following this analogy, we may build capacitance bridges as well. The only substantial difference is that these circuits must be biased with oscillating voltages. Since the “resistance” of the capacitor depends on the frequency of the AC bias, it is important to select this frequency carefully. By doing so, all of the advantages of bridges for resistance measurement are also available for capacitance measurement.

However, providing an AC bias can be problematic. Moreover, converting the AC signal to a DC signal for a microprocessor interface can be a substantial issue. On the other hand, the availability of a modulated signal creates an opportunity for use of some advanced sampling and processing techniques. Generally speaking, voltage oscillations must be used to bias the sensor. They can also be used to trigger voltage sampling circuits in a way that automatically subtracts the voltages from opposite clock phases. Such a technique is very valuable, because signals that oscillate at the correct frequency are added up, while any noise signals at all other frequencies are subtracted away. One reason these circuits have become popular in recent years is that they can be easily designed and fabricated using ordinary digital VLSI fabrication tools. Clocks and switches are easily made from transistors in CMOS circuits. Therefore, such designs can be included at very small additional cost—remember that the oscillator circuit has to be there to bias the sensor anyway.

Capacitance measuring circuits are increasingly implemented as integrated clock/sample circuits of various kinds. Such circuits are capable of good capacitance measurement, but not of very high performance measurement, since the clocked switches inject noise charges into the circuit. These injected charges result in voltage offsets and errors that are very difficult to eliminate entirely. Therefore, very accurate capacitance measurement still requires expensive precision circuitry.

Since most sensor capacitances are relatively small (100 pF is typical), and the measurement frequencies are in the 1–100 kHz range, these capacitors have impedances that are large ( $> 1$  megohm is common). With these high impedances, it is easy for parasitic signals to enter the circuit before the amplifiers and create problems for extracting the measured signal. For capacitive measuring circuits, it is therefore important to minimize the physical separation between the capacitor and the first amplifier. For microsensors made from silicon, this problem can be solved by integrating the measuring circuit and the capacitance element on the same chip, as is done for the ADXL311 mentioned above.

#### *Inductance measurement circuits*

Inductances are also essentially resistive elements. The “resistance” of an inductor is given by  $X_L = 2\pi fL$ , and this resistance may be compared with the resistance of any other passive element in a divider circuit or in a bridge circuit as shown in Figure 1.1.1. Inductive sensors generally require expensive techniques for the fabrication of the sensor mechanical structure, so inexpensive circuits are not generally of much use. In large part, this is because inductors are generally three-dimensional devices, consisting of a wire coiled around a form. As a result, inductive measuring circuits are most often of the traditional variety, relying on resistance divider approaches.

### Sensor Limitations

#### *Limitations in resistance measurement*

- Lead resistance – The wires leading from the resistive sensor element have a resistance of their own. These resistances may be large enough to add errors to the measurement, and they may have temperature dependencies that are large enough to matter. One useful solution to the problem is the use of the so-called 4-wire resistance approach (Figure 1.1.3). In this case, current (from a current source as in Figure 1.1.1) is passed through the leads and through the sensor element. A second pair of wires is independently attached to the sensor leads, and a voltage reading is made across these two wires alone.

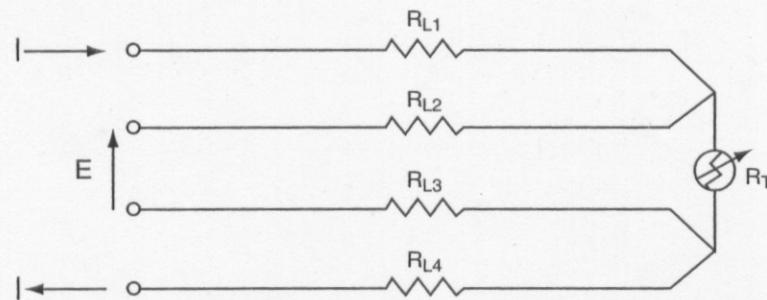


Figure 1.1.3: Lead compensation.

It is assumed that the voltage-measuring instrument does not draw significant current (see next point), so it simply measures the voltage drop across the sensor element alone. Such a 4-wire configuration is especially important when the sensor resistance is small, and the lead resistance is most likely to be a significant problem.

- Output impedance – The measuring network has a characteristic resistance which, simply put, places a lower limit on the value of a resistance which may be connected across the output terminals without changing the output voltage. For example, if the thermistor resistance is  $10\text{ k}\Omega$  and the load resistor resistance is  $1\text{ M}\Omega$ , the output impedance of this circuit is approximately  $10\text{ k}\Omega$ . If a  $1\text{ k}\Omega$  resistor is connected across the output leads, the output voltage would be reduced by about 90%. This is because the load applied to the circuit ( $1\text{ k}\Omega$ ) is much smaller than the output impedance of the circuit ( $10\text{ k}\Omega$ ), and the output is “loaded down.” So, we must be concerned with the effective resistance of any measuring instrument that we might attach to the output of such a circuit. This is a well-known problem, so measuring instruments are often designed to offer maximum input impedance, so as to minimize loading effects. In our discussions we must be careful to arrange for instrument input impedance to be much greater than sensor output impedance.

#### *Limitations to measurement of capacitance*

- Stray capacitance – Any wire in a real-world environment has a finite capacitance with respect to ground. If we have a sensor with an output that looks like a capacitor, we must be careful with the wires that run from the sensor to the rest of the circuit. These stray capacitances appear as additional capacitances in the measuring circuit, and can cause errors. One source of error is the changes in capacitance that result from these wires moving about with respect

to ground, causing capacitance fluctuations which might be confused with the signal. Since these effects can be due to acoustic pressure-induced vibrations in the positions of objects, they are often referred to as *microphonics*. An important way to minimize stray capacitances is to minimize the separation between the sensor element and the rest of the circuit. Another way to minimize the effects of stray capacitances is mentioned later—the virtual ground amplifier.

## Filters

Electronic filters are important for separating signals from noise in a measurement. The following sections contain descriptions of several simple filters used in sensor-based systems.

- *Low pass* – A low-pass filter (Figure 1.1.4) uses a resistor and a capacitor in a voltage divider configuration. In this case, the “resistance” of the capacitor decreases at high frequency, so the output voltage decreases as the input frequency increases. So, this circuit effectively filters out the high frequencies and “passes” the low frequencies.

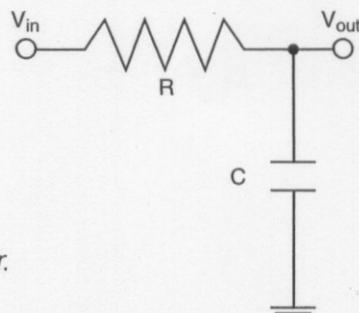


Figure 1.1.4: Low-pass filter.

The mathematical analysis is as follows:

Using the complex notation for the impedance, let

$$Z_1 = R, Z_2 = \frac{1}{i\omega C}$$

Using the voltage divider equation in Figure 1.1.1

$$V_{out} = \frac{Z_2}{Z_1 + Z_2} V_{in}$$