WHITE PAPER

Engineer’s Guide to Accurate Sensor Measurements

Overview

Sensors convert a physical phenomenon into a measurable electrical signal. But some sensors do not naturally respond to changing physical phenomena and require signal conditioning. Before the sensor output can be digitized, the signal may need additional components and circuitry to produce a signal that can take advantage of the full capabilities of the measurement hardware and reduce the effects of noise from external interference. This document covers best practices for connecting sensors to instrumentation, implementing proper signal conditioning, and reducing potential sources of error in your system.

CONTENTS

Thermocouples, RTDs, and Thermistors

Thermocouples, RTDs, and thermistors all operate on the principle that certain materials respond predictably and measurably to variations in temperature. In all three cases, the measured response is generally quite small and, as with all low-level measurements, difficult to measure accurately and reliably. Proper signal conditioning capabilities in the hardware and software components of your measurement system can greatly simplify the temperature measurement task. The following sections cover the recommended signal conditioning necessary for accurate thermocouple, RTD, and thermistor measurements.

Signal Conditioning Requirements

Filtering

Temperature measurements often must be taken far away from the measurement equipment. This means that sensor wires carrying the analog signal to the digitizer must span a long distance. Through the length of the cable, noise from the operating environment can seep into the analog signal and lead to inaccurate measurements. You need to minimize this problem by carefully considering where you run your cabling. Avoiding AC power lines, fluorescent lighting, and computer monitors can help avoid the 50/60 Hz power line noise they often emit.

You also can apply a lowpass filter to the incoming signal or incorporate one in the measurement hardware to help remove unwanted high-frequency signals.

Isolation

At their core, thermocouples, RTDs, and thermistors are made of electrically conductive materials. If you don't take isolation into consideration, you may inadvertently wire a measurement that is potentially dangerous to the measurement hardware or the user.

Consider applying thermocouples to the casing of a large electric motor. Large motors often require very high voltages and experience even larger voltage spikes during operation. If the casing of the motor is exposed to one of these high voltages due to an internal short, a voltage spike may travel to the measurement hardware through the thermocouple wiring. You can use isolated thermocouples to prevent this, but that leads to a slower response time and added cost.

Alternatively, a measurement device with channel isolation can help protect the analog-to-digital converter (ADC) circuitry as well as minimize noise from adjacent channels. You also can use an isolated measurement device to take accurate measurements when high-common-mode voltages are present by isolating the ADC circuitry from ground and allowing the measurement to float up to the signal of interest (within the limits of the device).

Linearization

The voltage output per unit temperature from a thermocouple, RTD, or thermistor is not a linear relationship. Because of this, you cannot simply apply a scaling coefficient to convert the measured voltage to a meaningful temperature output across the full range of the thermocouple. Figure 1, for example, shows the thermoelectric voltage output of various thermocouples across a range of temperatures. Note the nonlinear relationship.

THERMOCOUPLES AT VARYING TEMPERATURES

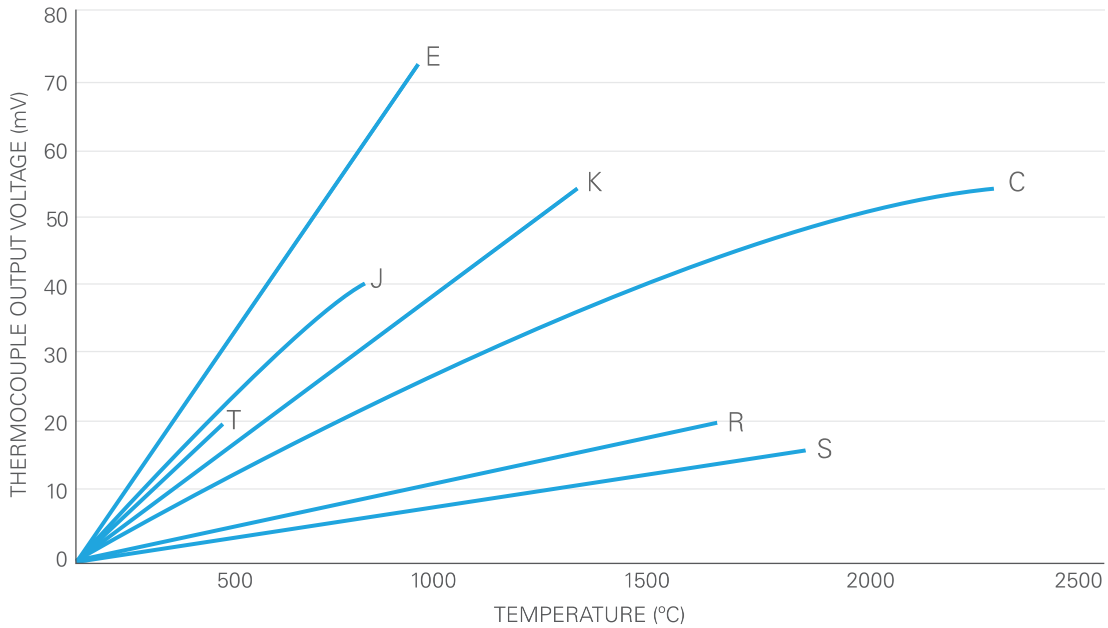

Figure 1. Thermocouple Output Voltage Versus Temperature[1]

You can choose from two options to accurately scale measurements and correct for this nonlinearity:

1. Use a lookup table and linear interpolation for measured voltages between data points in the table. This is fairly effective, but it requires coding a potentially large lookup table like the subset of one for type K thermocouples shown in Figure 2 and maintained by the National Institute of Standards and Technology (NIST).

[1] Digi-Key: http://www.digikey.com/en/articles/techzone/2011/may/designing-thermocouple-applications-with-a-sensor-afe

ITS-90 TABLE FOR TYPE K THERMOCOUPLE (THERMOELECTRIC VOLTAGE IN mV)

°C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293

Figure 2. NIST Type K Thermocouple Lookup Table[2]

2. Apply the voltage-to-temperature equation for the sensor type you are using to perform the measurement. For example, the high-order polynomial required for any given thermocouple is:

   $E = \sum_{i=0}^{n}(C_i t^i)$, where

   E = Thermoelectric voltage in μV
   C_i = Polynomial coefficients (provided by NIST for each temperature range)
   t^i = Temperature in °C

Thermistors also require a similarly complex equation to accurately convert the signals over a large range of temperatures. RTDs, on the other hand, deliver the most linear response of the three temperature measurement sensors. The relationship between resistance and temperature for RTDs is defined by the Callendar-Van Dusen equation as follows:

For <0 °C : $RT=R_0[1+AT+BT^2+CT^3(T-100\ °C)]$

For >0 °C : $RT=R_0[1+AT+BT^2]$

RT = RTD resistance at temperature T
R0 = RTD nominal resistance at 0 °C
A, B, and C = constants used to scale the RTD

[2]NIST ITS-90 Thermocouple Database: http://srdata.nist.gov/its90/main/

Note that performing these calculations in software may require significant computing power depending on the number of channels and sample rate as well as the temperature operating range. Having a software platform that integrates tightly with the measurement hardware can greatly simplify this scaling task by providing built-in scaling capabilities.

RTD/Thermistor-Specific Considerations

Current Excitation

Thermistors and RTDs are resistive sensors that require a current excitation to create a measurable voltage across the device. A constant and precise current source is critical to ensuring an accurate and consistent voltage for measurement. The DAQ system you select for your RTD and thermistor measurements should provide a current excitation source that is specified to be reliable, so you can achieve the most accurate and precise measurements.

Connecting to Hardware Using 2-, 3-, and 4-Wire Configurations (RTDs only)

You can purchase RTDs in three wiring configurations. The differences and benefits of each are discussed in detail in the RTD sensor reference. The measurement hardware you select for your system needs to be flexible enough to incorporate the types of RTDs your application requires. Some measurement hardware allows for 2-wire RTDs only, while other hardware offers automatic detection of 3- or 4-wire RTDs. You need to select a DAQ device that is designed for your RTD's level of resistance, for example, 100 Ω or 1000 Ω RTDs.

Thermocouple-Specific Considerations

Amplification

On their own, thermocouples output very small voltages for a given change in temperature that are typically on the order of millivolts and sometimes less. For example, type K thermocouples output only 40 μV per degree Celsius. Most conventional measurement hardware takes measurements within a given range, and the resolution of the device determines the smallest detectable change within that voltage range. Since the voltage you are measuring is so small in the case of a thermocouple, you may want to amplify the measured signal to take advantage of the full input range of the measurement device.

AMPLIFIED THERMOCOUPLE OUTPUTS

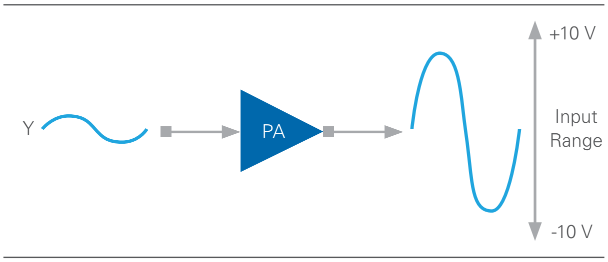

Figure 3. Amplify thermocouple outputs to detect smaller signal changes and use the full ADC input range.

In an ideal scenario, amplification occurs as close to the primary measurement as possible. This helps to avoid amplifying any noise injected into the signal along the length of the thermocouple wires. If external amplification is not possible or if you need to simplify the measurement system, you can use a measurement device with a 24-bit ADC. This type of device can provide measurement sensitivity on the order of 0.2 °C.

Cold-Junction Compensation (CJC)

The nature of a thermocouple measurement, as discussed in the overview of thermocouples, relies on the voltage differential created when two dissimilar metals are joined and exposed to some relative temperature. A problem arises when you consider the connection between the thermocouple and the terminals of your measurement hardware. At this connection, another junction of dissimilar metals is created, which also generates a voltage differential, depending on the environment. If you do not account for this secondary "parasitic thermocouple," it can skew the intended temperature measurement significantly enough to produce an invalid result.

To combat this, you can incorporate a reference measurement, or "cold-junction measurement," in your measurement hardware, as shown in Figure 4. You take this reference measurement some distance away from the primary measurement and ideally adjacent to the "parasitic thermocouple" caused by connecting the actual thermocouple to the measurement device's terminals. Use a direct-measuring temperature sensor (like an RTD or thermistor) and then subtract the resulting reference measurement from the primary measurement to remove, or compensate for, the parasitic component. This process is known as cold-junction compensation or CJC.

COLD-JUNCTION THERMOCOUPLE MEASUREMENT

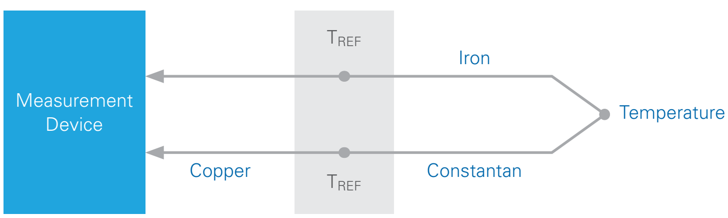

Figure 4. Cold-junction error adds more voltage to a thermocouple measurement.

Removing Offset Error

As discussed previously, CJC is important to correct the effect of the parasitic thermocouple created by connecting thermocouple wires to the metal terminals of your hardware. The parasitic thermocouple caused an offset in the measured voltage that led to inaccurate results. Similarly, the ambient temperature surrounding a measurement device can lead to an offset in the measured voltage from a thermocouple due to the induced voltages in the hardware itself. To correct for this, you should regularly measure the latent voltage without a thermocouple and subtract this value from each thermocouple measurement. To simplify this process, some measurement hardware provides an autozero function to regularly or semiregularly correct for any offset voltage caused by the ambient environment. This can greatly improve your overall measurement accuracy.

AUTOZERO COMPENSATION

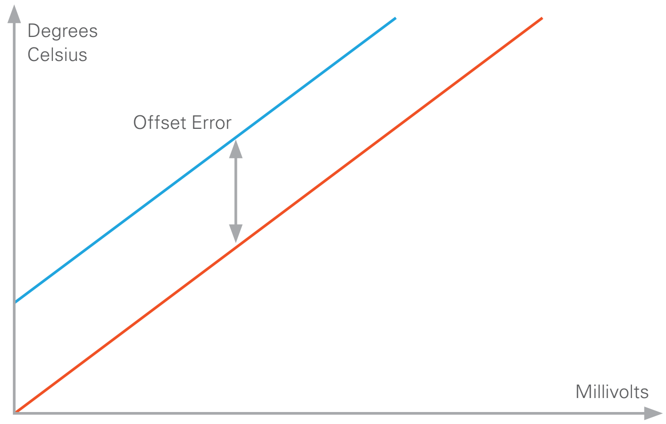

Figure 5. Autozero compensates for offset error.

Detecting Disconnected Thermocouples

Thermocouples can be susceptible to corrosion and wear over time because of their composition (dissimilar touching metals can cause corrosion in some environments) and the typical operating environment for this type of sensor. A broken or disconnected thermocouple may not be readily apparent to the user and may produce invalid data. Open thermocouple detection is a hardware feature that provides a small current to push the voltage input out of range when the hardware detects an open connection. You can easily check for this in software. When using this feature, remember that the small current can be a source of bias error in high-accuracy applications. To correct for this, you can pair open thermocouple detection with lead offset nulling, which takes the measured difference with and without the current applied and subtracts it from future measurements. This is effectively correcting for a user-induced offset error.

OPEN THERMOCOUPLE DETECTION

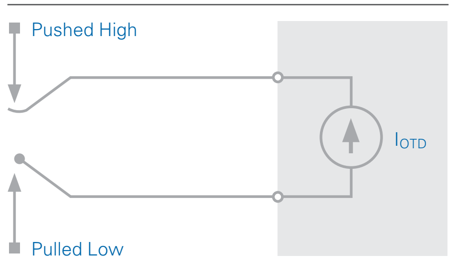

Figure 6. The open thermocouple detection circuit pushes the voltage high when the thermocouple breaks.

Conclusion

To obtain a reliable level of accuracy in your temperature measurements, you must progress through many layers of signal conditioning, some recommended and some required. When selecting a measurement system for thermocouples, RTDs, or thermistors, you should consider built-in filtering to remove noise, isolation to prevent ground loops, and linearization for scaling voltage to temperature. If you are using thermocouples as your temperature sensor, keep in mind these additional sources of error that can impact measurement accuracy:

- Cold-junction error—corrected by cold-junction compensation or CJC
- Offset error—corrected by autozero and lead offset nulling
- Open thermocouple detection for ensuring system reliability and uptime

Learn how to acquire accurate and reliable temperature measurements with NI hardware.

NI Thermocouple Measurement Systems

NI RTD Measurement Systems

Strain Gages and Bridge-Based Sensors

Strain gages are fundamental sensing devices that function as the building blocks of many other types of transducers, including pressure, load, and torque sensors, used extensively in structural test and monitoring applications. Even though strain gages are common, they are one of the most difficult types of sensors to use for conditioning and acquiring reliable data. Strain gage measurements operate by sensing minute changes in the length of a metal foil due to stress across a surface that is often smaller than 5 mm^2. Several factors can affect the measurement performance of your strain gages, including signal conditioning issues, electrical noise, temperature fluctuations, and improper calibration. Because pressure, load, and torque sensors are typically based on a full-bridge strain gage configuration, they are also affected by many of these factors. Consider the following recommendations to compensate for error and increase the accuracy of your bridge-based measurements.

Signal Conditioning Requirements

Bridge Completion

Unless you are using a full-bridge sensor, you must complete the bridge with reference resistors. Therefore, signal conditioners for bridge-based sensors typically provide half-bridge completion networks consisting of two high-precision reference resistors. The nominal resistance of the completion resistors is less important than how well the two resistors match. Ideally, the resistors match well and provide a stable reference voltage of $V_{EX}/2$ to the negative input lead of the measurement channel. The high resistance of the completion resistors helps minimize the current draw from the excitation voltage. However, using completion resistors that are too large can result in increased noise and errors due to bias currents.

SIGNAL CONDITIONING STRAIN GAGE CIRCUIT

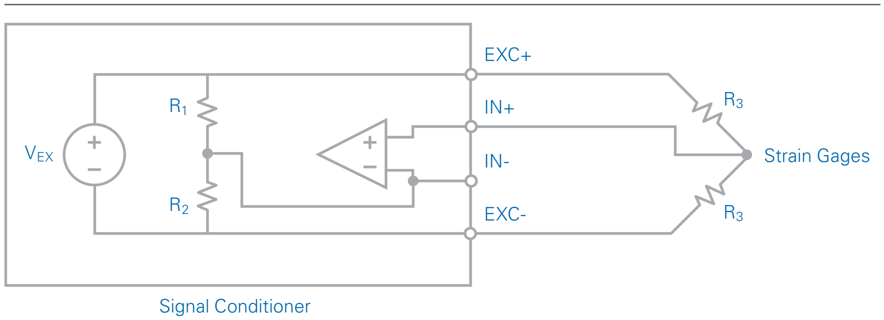

Figure 7. A signal conditioner provides excitation and bridge completion for a half-bridge strain gage circuit.

Excitation

Bridge-based sensors require a constant voltage to power the bridge. Bridge signal conditioners typically include a voltage source. No standard voltage level is recognized industry wide, but excitation voltage levels of around 3 V and 10 V are common. Though a higher excitation voltage generates a proportionately higher output voltage, it can also cause larger errors because of self-heating. Similarly, small fluctuations in the excitation voltage due to unstable excitation sources can affect the accuracy of your measurements. The next sections offer recommendations to minimize the effects of errors resulting from self-heating and unstable excitation sources.

Amplification

The output of strain gages is relatively small. For example, most strain gage bridges output less than 10 mV/V, or 10 millivolts of output per volt of excitation voltage. With 10 V excitation, the output signal is 100 mV. Therefore, signal conditioners for bridge-based sensors usually include amplifiers to boost the signal level, increase measurement resolution, and improve signal-to-noise ratios.

Load, pressure, and torque sensors can output low- or high-level voltages, depending on its excitation requirements. Low-level sensors are typically powered by a measurement device and output millivolt signals. High-level sensors (or conditioned sensors) require higher external power sources to operate, and output ±5 V, ±10 V, or 4–20 mA signals.

Choosing an Optimum Excitation Level

Selecting an optimum excitation level is a balance between achieving a strong signal-to-noise ratio and minimizing the effects of self-heating. In an ideal world, high excitation voltage levels are preferred because the change in output voltage for a given level of strain increases in direct proportion to the excitation voltage. Because of this, you can more easily and accurately measure the small voltages generated by strain gage bridges, especially in noisy environments or when long, noise-susceptible lead wires are used. However, because foil gages are essentially resistive electrical devices, higher excitation levels cause self-heating, which introduces multiple negative effects. Self-heating changes a bridge’s resistivity and sensitivity and the adhesive’s ability to transfer strain. Strain gages are rarely damaged by excessive excitation voltages. The usual result is performance degradation instead of gage failure.

Because many different factors can affect your ideal excitation level, you cannot standardize on a bridge excitation voltage level for a particular size and type of gage. In general, you can reduce self-heating by lowering the excitation level, but an optimum excitation voltage is best determined by an experimental procedure. With no load applied, you should examine the zero point of the channel while progressively raising the excitation level. When you see instability in the zero reading, you should lower the excitation until stability returns. You should perform this experiment at the highest temperature over which you are taking measurements. In noisy environments, you can still use low excitation levels by properly shielding the lead wires and placing the measurement device close to the sensors. Depending on your test configuration, consider measurement hardware with distributed form factors that give you maximum flexibility in the placement of the system.

Other Factors Affecting Optimum Excitation

- **Strain gage grid area.** You can reduce self-heating by selecting a strain gage with a bigger surface area (active gage length x active grid width) for better heat dissipation.
- **Strain gage nominal resistance.** Higher resistance gages, like 350 Ω instead of 120 Ω, decrease the power per unit area dissipated to make higher excitation voltage possible.
- **Heat-sink properties of the mounting surface.** High-thermal-conductivity metals, such as copper or aluminum, are excellent heat sinks, which draw heat away from the strain gage. Low-thermal-conductivity metals, such as stainless steel or titanium, are poor heat sinks. Strain measurement on plastic requires special consideration. Most plastics act as thermal insulators rather than heat sinks, so extremely low values of excitation are required to avoid serious self-heating effects. Plastics that are heavily loaded with inorganic fillers in powder or fibrous form present a lesser problem because such fillers help improve thermal conductivity.
- **Installation and wiring technique.** If the gage is damaged during installation, if solder tabs are partially unbonded due to soldering heat, or if any discontinuities form in the glue line, high levels of excitation can create serious problems. Proper technique is essential in obtaining consistent performance in all strain gage work but particularly under high-excitation conditions.

Compensating for Unstable Excitation Sources

The accuracy of a bridge-based measurement is directly proportional to the stability of the excitation source. Changes in the excitation source cause changes in the measured output of the bridge. As a result, small excitation source fluctuations translate to a misrepresentation in strain. Two methods can help you circumvent unstable and inaccurate excitation sources. You can measure the voltage actually supplied by the source to compensate for fluctuations when scaling the data in software or you can reference the measurement performed by the ADC against the excitation source. The first method requires additional measurements, thereby adding cost and complexity to the system.

CORRECTING FOR UNSTABLE POWER SOURCES

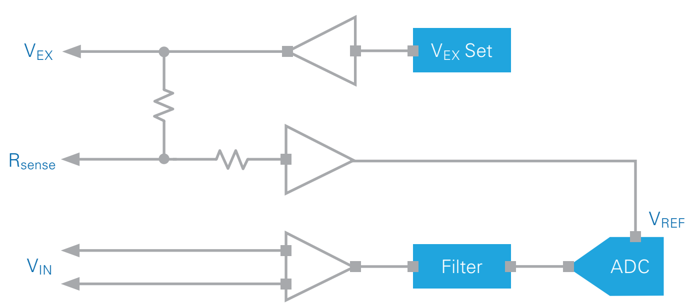

Figure 8. A ratiometric design uses excitation voltage as a reference to ADC to correct for unstable power sources.

The ratiometric approach removes your dependence on the accuracy of the excitation voltage by continuously sensing the excitation voltage and scaling the measurement directly in hardware. The excitation voltage is continuously sensed by precision circuitry on the modules and used to drive the reference input of the ADC. Using this implementation, as shown in Figure 8, the modules return data as a ratio of the bridge output voltage and the excitation voltage. This method continuously and automatically corrects for errors in the accuracy of the excitation voltage.

Minimizing Errors From Lead-Wire Resistance

Long lead wires and small gage wires, which present greater resistance than bridge-completion wiring, can be a major source of error in strain gage measurements. For example, suppose each wire in a 2-wire connection strain gage is 15 m long with a lead resistance R_L equal to 1 Ω. The lead resistance adds 2 Ω to the arm of the bridge, which adds an offset error and reduces the sensitivity of the bridge output. You can compensate for this error by measuring the lead resistance RL and accounting for it in the strain calculations. However, a more difficult problem arises from changes in the lead resistance due to temperature fluctuations. The temperature coefficient of copper lead wires is typically two orders of magnitude greater than the temperature coefficient of the gages. Therefore, a slight change in temperature can generate a measurement error of several microstrains (με).

Using a 3-wire connection can eliminate the effects of variable lead-wire resistance because the lead resistances affect adjacent legs of the bridge. As seen in Figure 9, changes in lead-wire resistance, RL2, do not change the ratio of the bridge legs R3 and RG. Therefore, any changes in resistance due to temperature cancel each other and the bridge remains balanced.

3-WIRE STRAIN GAGE

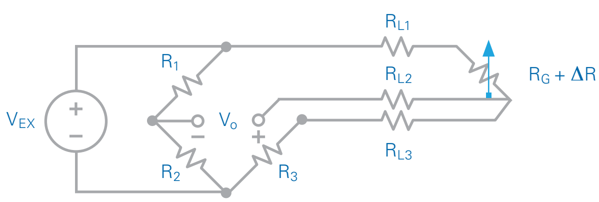

Figure 9. 3-Wire Strain Gage Configuration

Remote Sensing

If the strain gage circuit is far away from the signal conditioner and excitation source, another possible source of error is voltage drop caused by the resistance in the long lead wires connecting the excitation voltage to the bridge. This results in delivering a lower excitation voltage than originally intended across the sensing element. Some signal conditioners include a feature called remote sensing to compensate for this error. With feedback remote sensing, you connect extra sense wires to the point where the excitation voltage wires connect to the bridge circuit, as seen in Figure 10. The extra sense wires regulate the excitation supply through negative feedback amplifiers to compensate for lead losses and deliver the needed voltage at the bridge.

REMOTE SENSE MEASUREMENTS

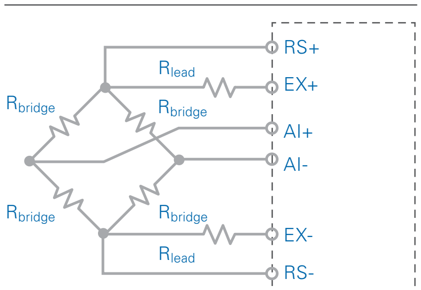

Figure 10. Remote sense measures the actual excitation voltage delivered to a bridge over long distances.

An alternative remote sensing scheme uses a separate measurement channel to directly measure the actual excitation voltage delivered across the bridge. Because the measurement channel leads carry very little current, the lead resistance has a negligible effect on the measurement. You then can use the measured excitation voltage in the voltage-to-strain conversion to compensate for lead losses.

Improving Signal-to-Noise Ratio

Strain gages and bridge-based sensors are often in electrically noisy environments. The signal-to-noise ratio (SNR) describes the ratio of the amplitude of the signal to the amplitude of the noise. A larger SNR typically results in a less noisy measurement, which enables better overall resolution. Noise in strain readings can be particularly troublesome because of the small signals in strain measurements. You can improve the SNR by either increasing the overall amplitude of the signal before the noise is introduced into it or by reducing the amplitude of the noise.

Noise introduced by an external source can often be associated with specific frequencies, so you can use software to filter it out if the frequency of the noise is predictable and does not interfere with the bandwidth of the signal of interest. The most common type of noise is power line interference, which shows up as 50 Hz or 60 Hz noise in the measurements.

Other techniques for rejecting external noise to improve SNR include:

- **Reduce lead-wire length and use twisted pairs or matched signal wires.** If possible, reduce the length of the strain gage's lead wire and keep the wire away from any potential noise sources. Using twisted pairs and matched signal wires also helps ensure that most of the environmental noise is conducted equally to the leads.
- **Use proper shielding techniques.** Connect the shield to the reference of the measurement device, which can be COM or EX- (refer to your device documentation), and make sure that you connect it at only one end of the cable. For isolated devices that have a floating ground, the shield needs to float at the same potential as the board's signals to be effective.
- **Increase the amplitude of the signal.** With strain measurements, you can accomplish this by either choosing a more sensitive strain gage or increasing the amplitude of the excitation voltage. Be careful if you are increasing the excitation voltage amplitude because if you increase it too much, self-heating errors in the strain gage may outweigh the SNR benefits achieved with the larger excitation.
- Features of the measurement device that can help improve SNR include:
  - **Dynamic range.** Dynamic range defines the noise level relative to the full input range of the measurement device, and it is often specified in decibels (dB). For example, a measurement device with a spurious-free dynamic range (SFDR) of 106 dB is equivalent to noise levels of about 0.0005 percent of the full input range. This means that the device itself contributes very little additional noise.
  - **Common-mode rejection ratio (CMRR).** Because noise from external sources is often conducted equally on all wires, a high-common-mode rejection ratio rejects a large percentage of the conducted noise.
  - **Remote sense.** When using remote sense, you cancel out any noise that is conducted to the excitation cables when you sample the data because the remote sense compensates for the noise.
  - **Anti-alias filters.** Anti-alias filters prevent high-frequency noise from being aliased at lower frequencies. This feature not only improves the overall noise performance of the device but also allows you to use software filters effectively for either filtering out specific frequencies (notch filter) or ranges of frequencies (lowpass/highpass filter).

Proper Calibration

Bridge Balancing

When you install a bridge for the first time, you probably won't read exactly zero volts when you don't apply any strain. Slight variations in resistance among the bridge arms and lead resistance and a prestrained installation condition generate some nonzero initial voltage offset. You can handle this initial offset voltage in the following ways:

1. **Software compensation.** With this method, you take an initial measurement before applying strain input and use this offset in the strain conversion equations to compensate for initial voltage offset in subsequent measurements. This simple and fast method requires no manual adjustments. The disadvantage of the software compensation method is that you don't remove the offset of the bridge. If the offset is large enough, it limits the amplifier gain you can apply to the output voltage, thus limiting the dynamic range of the measurement.

2. **Offset-nulling circuit.** The second balancing method uses an adjustable resistance, a potentiometer, to physically adjust the output of the bridge to zero. By varying the resistance of the potentiometer, you can control the level of the bridge output and set the initial output to zero volts.

3. **Buffered offset nulling.** The third method, like the software compensation method, does not affect the bridge directly. A nulling circuit adds an adjustable DC voltage, positive or negative, to the output of the instrumentation amplifier to compensate for initial bridge offset. Refer to the device documentation to determine the hardware nulling methods your measurement device provides.

NULL AND SHUNT CALIBRATION

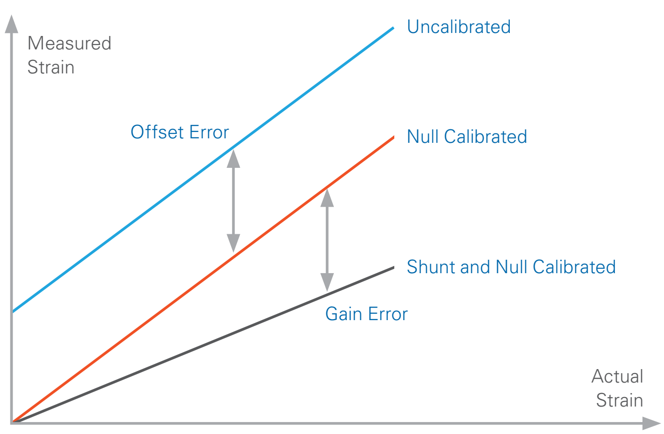

Figure 11. Null and shunt calibration adjust the offset and gain error of the measurement device.

Gain Adjustment

You can verify the output of a strain gage measurement system by comparing the measured strain with a predetermined or calculated mechanical input or strain. You can then use the difference (if any) between the calculated and the measured strain for each measurement as a gain adjustment factor or calibration factor. This procedure is called shunt calibration, and it simulates the input of strain by changing the resistance of the sensing arm in the bridge by some known amount. You accomplish this by shunting, or connecting, a large resistor of known value in parallel to one arm of the bridge to create a known change in resistance, as seen in Figure 12. Because the value of the shunt resistor is known, you can calculate the mechanical strain corresponding to the voltage drop of the resistor. You then measure the output of the bridge and compare it with the expected voltage value to correct gain errors in the entire measurement path.

SHUNT RESISTOR

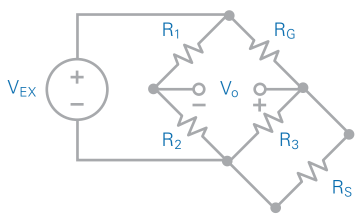

Figure 12. Shunt Resistor Connected Across R3

Scaling Electrical Measurements to Engineering Units

Once you have obtained a measurable voltage, you should convert the signal into actual units such as pounds (lb) for force or psi for pressure. You can scale these electrical values to the physical phenomenon that the sensor measures with the following methods:

- **Two-Point Linear**—Use two pairs of electrical values and their corresponding physical values to calculate the slope and y-intercept of a linear equation. You can then use this equation to scale electrical values to physical values, including measurements that fall outside the range of the values specified for calculating the slope and y-intercept.
- **Table**—Provide a set of electrical values and the corresponding physical values. The software that accompanies your measurement hardware must be able to perform linear scaling between each pair of electrical and physical values. The input limits must fall within the smallest and largest physical values.
- **Polynomial**—Provide the forward and reverse coefficients of a polynomial equation. Software then uses that equation to scale electrical values to physical values. Look for software that can compute one set of coefficients if you know only the other set.

Data sheets or calibration certificates from sensor manufacturers often include a table of electrical and physical values or a polynomial equation for scaling. If you do not have a table or polynomial equation for your sensor, use two-point linear scaling. Use the rated output of the sensor and the sensor capacity as one pair of electrical and physical values. Use zero for the other pair of electrical and physical values. For example, assume you have a conditioned pressure sensor that outputs a 0–5 V signal or 4–20 mA current. Both 0 V and 4 mA correspond to a 0 pressure measurement. Similarly, 5 V and 20 mA correspond to the full-scale capacity or the maximum pressure the transducer can measure.

Using TEDS Technology for Faster Connectivity and Configuration

As discussed in the previous section, bridge-based transducers, such as load cell, pressure, or torque sensors, require several inputs from the sensor data sheet to properly convert the output voltage from the sensor into engineering units. When you set up and configure a traditional measurement system, you must manually enter these important sensor parameters. You can reduce this setup time by outfitting your system with IEEE 1451.4 or Transducer Electronic Data Sheet (TEDS) smart sensors and actuators. These sensors store key data such as manufacturer, model, full-scale range, and sensitivity in an EEPROM in the sensor or sensor cable. With the setup information on the sensors, TEDS-compatible instrumentation can communicate directly with the sensor and perform the setup programmatically. TEDS-compatible software can also automatically scale from polynomial functions provided by the sensor manufacturer or calibration lab. For more information on the IEEE 1451.4 standard or how TEDS smart sensors work, refer to the TEDS section at the end of this document.

Conclusion

Reducing noise and increasing resolution are important for making accurate measurements from strain gages and nonconditioned bridge sensors because of the very small voltage levels that are involved. Selecting the right measurement device can greatly improve the integrity of your bridge measurements. In addition to gain and excitation level, you should consider a measurement device with a large dynamic range, excitation sensing, and a ratiometric architecture. Then if you take steps toward reducing the noise introduced into the system, you can decrease the excitation level to reduce self-heating errors and improve the accuracy of the signal from your bridge sensor. You should calibrate your strain gage periodically to account for changes in the physical characteristics of the strain gage variations in the lead-wire resistance and to compensate for imperfections in the measurement system.

Explore accurate bridge measurement systems using NI hardware.

Accelerometers and Microphones

Sound and vibration measurements are critical in a variety of applications such as environmental noise testing or machine condition monitoring. Accelerometers and microphones both measure oscillations but in different media. Therefore, they have similar signal conditioning requirements to produce a signal that measurement hardware can read properly. After acquiring the data, you typically need to perform additional signal processing to display the data in a more meaningful format. For example, vibration signals are commonly converted to the frequency spectrum for rotating equipment to detect unique signatures that can indicate a faulty mechanical part. The following sections cover recommendations for taking accurate accelerometer and microphone measurements and explore basic analysis techniques to help you gain insight from your data.

Signal Conditioning Requirements

Amplification

Because the charge produced by an accelerometer is very small, the electrical signal emitted by the sensor is susceptible to noise, and you must use sensitive electronics to amplify and condition the signal. Since piezoelectric accelerometers are high-impedance sources, you must design a charge-sensitive amplifier with low noise, a high input impedance, and a low output impedance.

Integrated Electronic Piezoelectric (IEPE) sensors integrate the charge amplifier or voltage amplifier close to the sensor to ensure better noise immunity and more convenient packaging. However, these sensors require 4–20 mA current excitation to operate the circuitry inside them.

Excitation

As mentioned in the previous section, IEPE sensors require an external current to power the amplifier. Common IEPE excitation values are 2.1 mA, 4 mA, and 10 mA. Refer to your device specifications for a list of the supported IEPE current values you need for your sensor.

Similar to accelerometers, microphones can be powered externally or internally. Externally polarized condenser microphones require 200 V from an external power supply. Make sure that the supply you use provides clean power at the rated voltage, and that you do not connect more microphones to the supply than its capacity. Prepolarized condenser microphones are powered by IEPE preamplifiers that require a constant current source.

AC Coupling

Enabling IEPE signal conditioning generates a DC voltage offset equal to the product of the excitation current and sensor impedance. The signal acquired from the sensor consists of both AC and DC components, and the DC component offsets the AC component from zero. As shown in Figure 13, this can lower the resolution of your measurement because amplification of the AC signal is limited to avoid saturating the input range of the ADC. You can solve this problem by implementing AC coupling. Also known as capacitive coupling, AC coupling uses a capacitor in series with the signal to filter out the DC component from a signal. When implemented in hardware, AC coupling can help you apply a more narrow input range to improve AC amplitude resolution and the usable dynamic range of the channel. When implemented in software, AC coupling can remove erroneous DC data that invalidates signal processing integration and measurement results like RMS and peak levels. AC coupling also attenuates the long-term DC drift that sensors have due to age and temperature effect.

AC AND DC COUPLING FILTERS

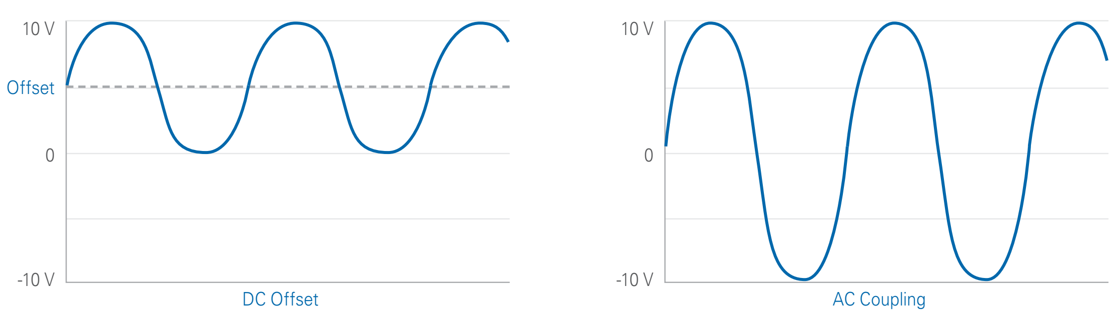

Figure 13. AC coupling filters out the DC component of a signal to increase measurement resolution.

Grounding

Improperly grounding your sensor can result in ground loops that create a source of noise in your measurement system. You can avoid this by ensuring that either the measurement system input or the sensor is grounded but not both. If the sensor is grounded, you must connect it differentially. If the sensor is floating, you should connect the inverting input of the measurement system to ground.

Source Reference	Channel Configuration
Floating	Pseudodifferential
Grounded	Differential or Pseudodifferential

Table 1. Analog Input Channel Configurations

Anti-alias Filters

Aliasing is a common concern when making sound and vibration measurements. According to the Nyquist-Shannon sampling theorem, the highest frequency that can be analyzed is the Nyquist frequency (fN), which is the sampling frequency of the ADC divided by two. Any analog frequency greater than the Nyquist frequency appears as a frequency between 0 and fN after sampling. Without detailed knowledge of the original signal, you cannot distinguish this alias frequency from frequencies that actually lie between 0 and fN.

A lowpass filter is usually sufficient to attenuate the high-frequency noise that is generated in aliasing. However, if the roll-off of the filter is not very steep, frequencies just above the Nyquist frequency may not be fully attenuated and can be aliased back into the valid portion of the signal. A form of lowpass filter, an anti-alias filter is characterized by a flat passband and fast roll-off. This filter helps preserve signals just below the Nyquist frequency and attenuate signals just above the Nyquist frequency. In Figure 14, two filters are used to eliminate high-frequency noise. The lowpass filter eliminates noise at f3, but the slow roll-off attenuates noise only at f2, which is aliased back into the signal. The anti-alias filter removes both frequency components from the acquired signal.

ANTI-ALIASING FILTERS

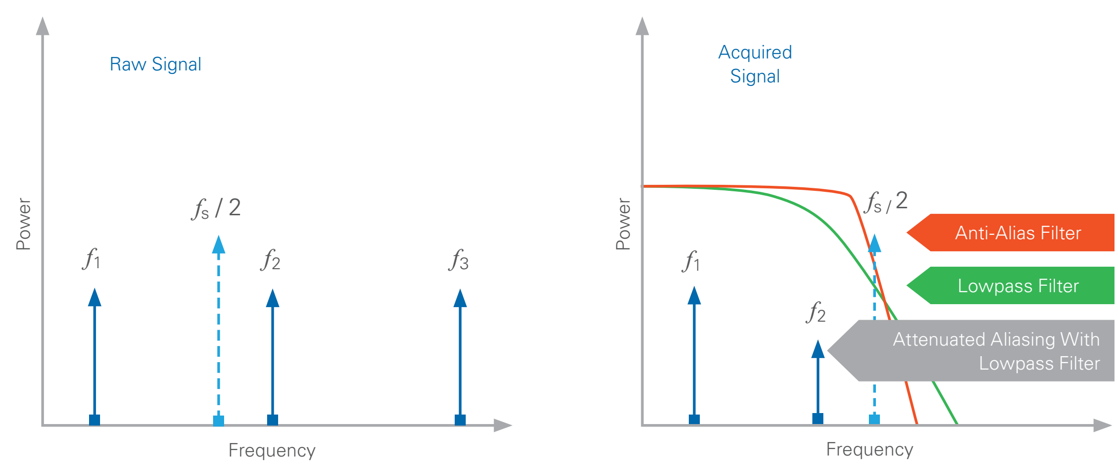

Figure 14. Anti-alias filters with steep roll-off help attenuate noise just above the Nyquist frequency.

Dynamic Range

Dynamic range is defined as the ratio between the largest and smallest signals a device can measure at the same time. Expressed in decibels, the dynamic range is 20 log (Vmax/Vmin). For example, a device with an input range of ±10 V and a dynamic range greater than 110 dB may have a voltage ratio of 106.

Traditional lower resolution ADCs generally have 16 bits, which gives you a dynamic range of roughly 90 dB. Most sensors offer 110 dB or more of dynamic range, so 16-bit devices cannot measure the full range of the sensor within the low-level signals buried in the electrical noise of the measurement. Instrumentation with 24-bit resolution can offer up to 120 dB of dynamic range, so you can detect smaller signals and get the most out of your sensors.

Simultaneous Sampling

In some applications such as noise mapping, impact testing, and sound intensity measurements, the phase information between two separate channels is crucial. In these cases, simultaneous sampling is required, which means you must perform the analog-to-digital conversion at the same instant for every channel.

Scaling Linear Units to Relative Units in Decibels

Use relative units, such as decibels (dB), to display scalar and spectrum results when you want to show large and small components on the same scale. For example, in Table 2, the sound power of a whisper is compared to that of a rocket engine. Comparing these values is more manageable using a logarithmic scale.

Source Reference	Sound Power (watt)	Sound Power (dB)
Whisper	0.00000000001 W	10 dB
Space Shuttle	100000000 W	200 dB

Table 2. Example Sound Power Comparison

Use the following equation to convert linear units to relative units in dB for amplitude values:

$$dB = 20\log\frac{V}{V_o}$$

Use the following equation to convert linear units to relative units in dB for power values:

$$dB = 20\log\frac{P}{P_o}$$

You typically use relative units of dB reference to the hearing threshold of 20 μPa to report acoustic measurements such as sound pressure level and fractional-octave spectra. For sound power measurements, the reference is 1 pW. For frequency response measurements, you often use a gain of one as the dB reference. In this case, negative dB values for the magnitude indicate attenuation, positive dB values indicate gain, and 0 dB is equivalent to a gain of one. Because each measurement domain might use a specific reference, you need to specify the dB reference when reporting results in dB.

Maintaining Signal Quality When Using Long Cables

When you use very long cables with IEPE sensors, the added capacitance in the cable can affect the frequency response of the sensor by filtering some of the high-frequency content. In addition, noise and distortion may seep into your measurement signal if you do not have sufficient current to drive cable capacitance. In general, you should be concerned about using long cable lengths with IEPE sensors only if you are interested in a frequency range of more than 10 kHz while using a cable longer than 100 ft (30 m).

To more accurately determine the effect of long cables, you should experimentally determine the high-frequency electrical characteristics. Use a function generator to supply the maximum amplitude of the expected signal into a unity-gain, low-output impedance amplifier in series with the sensor. Compare the ratio of the original signal to the ratio of the signal measured on the scope. If the signal is attenuated, then you must increase the current used to drive the signal until you have a 1:1 ratio. Be careful not to supply excessive current over short cable runs or when testing at elevated temperatures. Any current not used by the cable is used to power the internal electronics, and it creates heat that might cause the sensor to exceed its maximum temperature specification.

Reducing Configuration and Setup Time With TEDS Technology

TEDS-capable sensors carry a built-in, self-identification EEPROM that stores a table of parameters and sensor information. The EEPROM contains calibration, sensitivity, and manufacturer data for the sensor. With these parameters stored on the sensors, TEDS-compatible instrumentation can communicate directly with the sensor and perform the setup programmatically. TEDS-compatible software can also automatically scale from the polynomial functions provided by the sensor manufacturer or calibration lab. For more information on the IEEE 1451.4 standard or how TEDS works, refer to the TEDS section at the end of this document.

Additional Considerations for Microphones

Microphones are stable over long periods of time if they are handled properly. Components of the microphone are fragile and can get damaged by misuse. The following tips can help you maintain accurate measurements with microphones:

- Always calibrate the entire measurement chain, including the microphone, before starting the measurement. For highly critical measurements, as an extra precaution, you may want to perform a new calibration immediately after the measurements are completed to make sure the system is still within tolerances.
- For outdoor measurements, the microphone should be fitted with suitable protection against the environment. This may include rain caps, antibird spikes, and built-in heaters to prevent condensation.
- To prevent vibrations from influencing the measurement, you might need to shock mount the microphone. Check the microphone specifications for vibration sensitivity.
- For reproducible measurements, make sure the microphone is mounted firmly and at a precisely reproducible location compared to both the unit being tested and the environment.
- For handheld or tripod measurements, consider using a microphone extension arm to help reduce undesirable reflections.
- Carefully note the manufacturer's restrictions on cable lengths. Degradation of the signal first occurs at higher frequencies and high sound levels with long cables. Verify the SNR of the cable with the microphone connected. Check for hum and crosstalk and transients from nearby generators, electrical motors, air conditioning units, cells phones, radar installations, radio or TV transmitters, and other potential sources of interference.

Time-Domain Analysis Techniques

Level

Perhaps the most basic measurement analysis related to sound and vibration is level. You can perform sound- and vibration-level measurements with time-domain signals. Root mean square (RMS) measures the energy (thus the destructive potential) of dynamically varying sound and vibration signals. You compute RMS by squaring the signal, averaging it over a period of time, and then taking the square root of the result.

$$\text{Level}_{rms} = \sqrt{\frac{x_o + x_1^2 + \dots + x_n}{n}}$$

A common sound-level measurement is sound pressure level. This value is always expressed relative to a reference pressure of 20 μPa (threshold of human hearing).

The main problem with average-based measurements is that the result of your measurement changes based on the length you choose for your averaging interval. That is why measurements like sound pressure level have standard intervals. You can use two main methods to find RMS: linear averaging and exponential averaging.

Linear Averaging

Linear averaging, or equivalent continuous sound level (Leq), is one of the time-averaging processes for sound-level measurements. All points are weighted equally over a finite period of time in linear averaging. It is typically used to measure long-term exposure in a given environment (for example, measuring traffic noise at an intersection for an hour). You compute the Leq by integrating the square of the signal over a fixed-time interval and dividing by the time interval. The result represents an imaginary steady sound that has the same energy as the sound being measured.

MEASURING LONG-TERM SOUND EXPOSURE

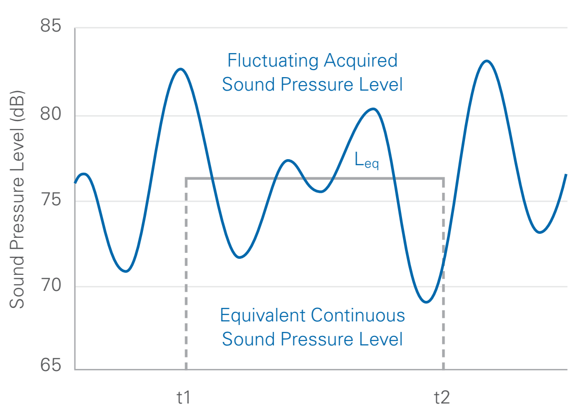

Figure 15. L_{eq} is used to quantify long-term exposure to sound in a given environment.

Exponential Averaging

Exponential averaging is a continuous averaging process that weights current and past data differently. The amount of weight given to past data compared to current data depends on the exponential time constant, which defines the slope of an exponentially decaying window.

The exponential averaging mode supports the following standard time constants:

- **Slow**—Uses a time constant of 1,000 ms. Slow averaging is useful for tracking the sound pressure levels of signals with sound pressure levels that vary slowly.
- **Fast**—Uses a time constant of 125 ms. Fast averaging is useful for tracking the sound pressure of signals with sound pressure levels that vary quickly.
- **Impulse**—Uses a very fast time constant of 35 ms if the signal is rising, but then a very slow time constant of 1,500 ms if the signal is falling. Impulse averaging is useful for tracking sudden increases in the sound pressure level (during an impact or a loud bang) and recording the increases so you have a record of the changes.

Frequency-Domain Analysis Techniques

Fourier Transform

Frequency analysis is most commonly used to analyze sound and vibration signals. A discrete time-domain signal shows how a signal evolves sample by sample over time. Any waveform in the time domain can be represented by the weighted sum of sines and cosines. This deconstruction of complex signals is the foundation of the Fourier transform and digital signal processing. The corresponding frequency-domain spectrum shows how much different frequencies contribute to the overall signal (Figure 16). This is useful for analyzing stationary signals whose frequency components do not change over time.

FREQUENCY AMPLITUDE SPECTRUMS

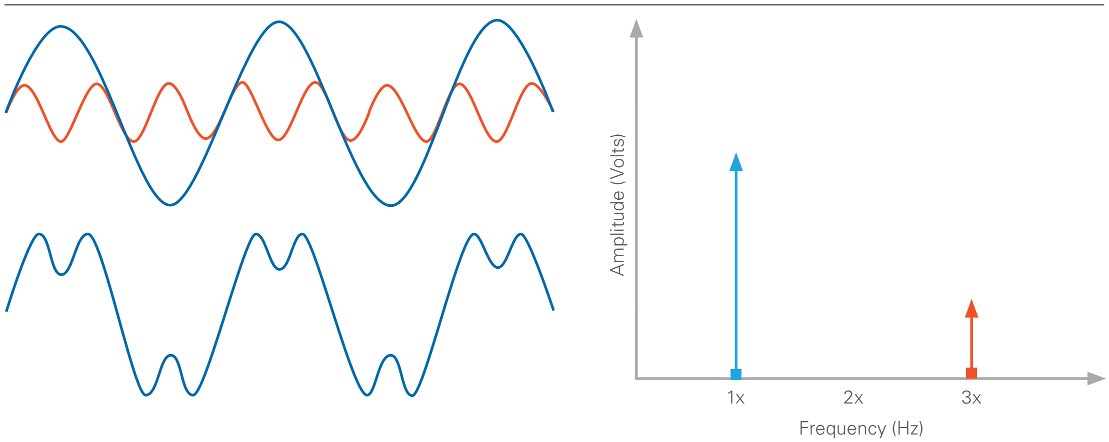

Figure 16. The frequency spectrum shows different amplitudes and frequencies of sinusoidal components.

The fast Fourier transform (FFT) resolves a continuous time waveform into its sinusoidal components. Because measurement devices sample waveforms and transform them into discrete values, you must use the discrete Fourier transform (DFT) to operate on signals using digital hardware. This algorithm produces frequency-domain components in discrete values, or bins. One of the DFT limitations is that it assumes it is operating on a periodic signal with an integer number of periods. Acquiring exactly an integer number of cycles while sampling a signal is difficult. When the number of periods is not an integer, the endpoints are discontinuous. This causes the energy at one frequency to leak into other frequencies, as shown in Figure 17.

MEASURING NONINTEGER PERIODS

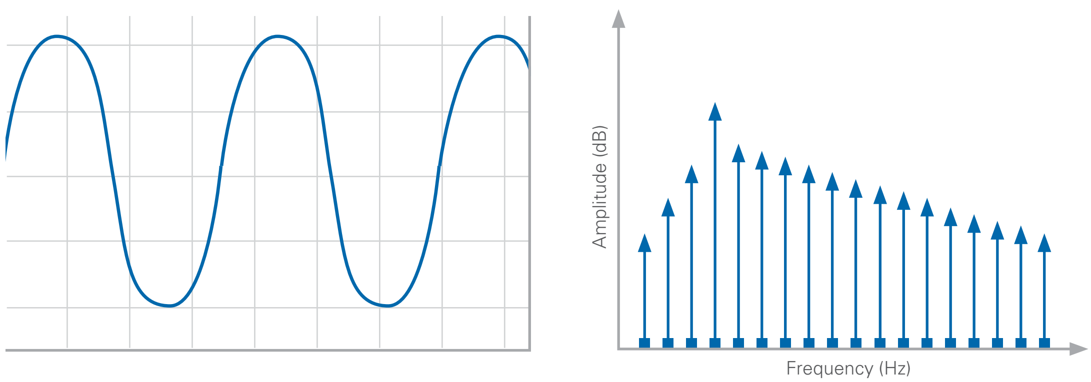

Figure 17. Measuring a noninteger number of periods results in spectral leakage in the frequency domain.

You can minimize the effects of spectral leakage by using a technique called windowing. Windowing consists of multiplying the time record by a finite-length window with an amplitude that varies smoothly and gradually toward zero at the edges. This makes the endpoints of the waveform meet and, therefore, results in a continuous waveform without sharp transitions.

MINIMIZING SPECTRAL LEAKAGE

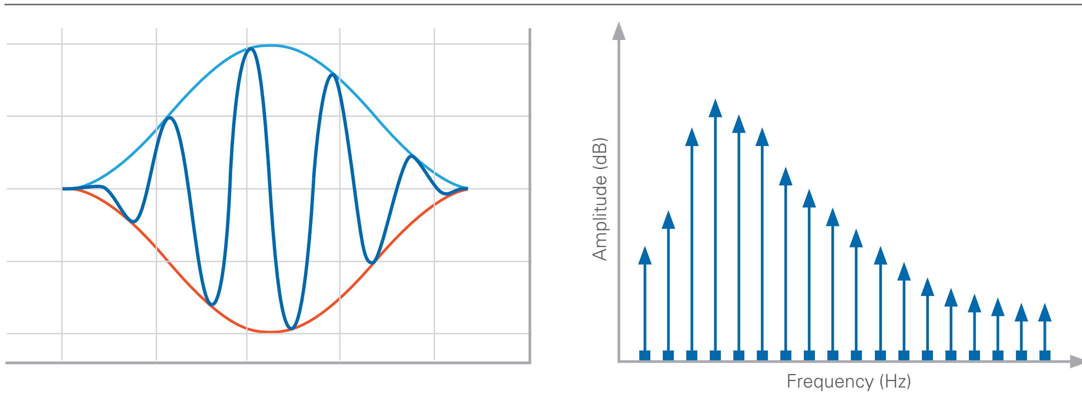

Figure 18. Applying a window minimizes the effects of spectral leakage.

The type of window you use depends on the type of signal you're acquiring. In many cases, you might not know enough about the signal, so you need to experiment with different windows to find the best one. In general, the Hanning (Hann) window is satisfactory for most applications. The Hann window has better frequency resolution than other windows and touches zero at both ends, which eliminates all discontinuities. Table 3 lists common window types, the appropriate signal types, and example applications.

Window	Characteristics	Signal Types and Applications
Rectangular (no window)	Transient signals that are shorter than the length of the window; truncates a window to within a finite time interval	Short duration transients such as impact Identification of closely spaced frequencies with almost equal amplitudes Order tracking
Hanning	Transient signals that are longer than the length of the window; sinusoidal shape with endpoints that reach zero	General processing on stationary signals Sine wave or a combination of sine waves
Hamming	Transient signals that are longer than the length of the window; a modified version of the Hanning window that is discontinuous at the edges	Closely spaced sine waves
Flat Top	The best amplitude accuracy of all the window types but limits frequency selectivity	Accurate, single-tone amplitude measurements with no nearby frequency components Dominant tone for which amplitude is a concern such as an imbalance

Table 3. Windows and Their Applications

Order Analysis

Another limitation of the FFT is that it does not contain any time information. Many mechanical characteristics of rotating or reciprocating machinery, such as engines, pumps, compressors, and turbines, change with speed. You can observe some mechanical faults, such as resonance, only as the rotational speed approaches or passes the critical speed. However, when the rotational speed changes, the frequency bandwidth of each harmonic gets wider. As a result, some frequency components might overlap. The resulting FFT power spectrum can no longer help you identify characteristic vibration components because no obvious peaks appear in the spectrum.

With order analysis, on the other hand, you can identify data at various orders, or harmonics, of the rotational speed. You perform order normalizing by resampling the data in the angular domain (points per revolutions) instead of the time domain (points per second). The first order refers to the speed at which the machine rotates. Each order thereafter is a corresponding multiple of the rotational speed. The second order is twice the rotational speed, the third order is three times the rotational speed, and so on. Using order analysis, you therefore can analyze signal variations due to changes in speed.

For example, Figure 19 uses an FFT power spectrum to identify and quantify the frequency components of the vibration of a PC fan. Notice that the overall vibration signal of the PC fan is the superposition of the vibration from the shaft, coils, and blades. The shaft rotates at the same rate as the rotational speed of the PC fan, whereas the rotational speeds of the coils and blades are four and seven times that of the PC fan, respectively.

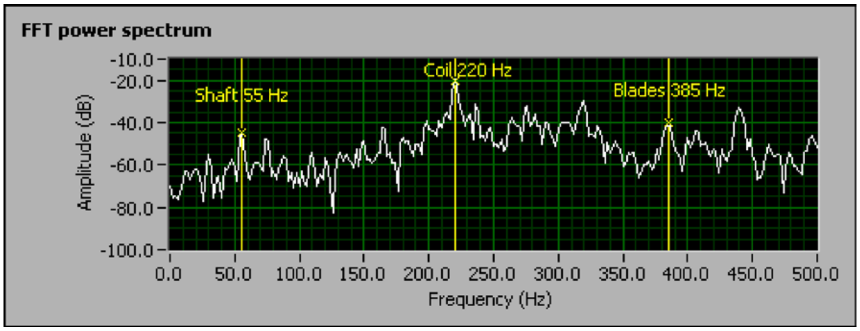

Figure 19. Frequency Components of a PC Fan Vibration Signal

Figure 20 shows the FFT power spectrum of the PC fan when the rotational speed changes from 1,000 to 4,000 revolutions per minute (rpm). Notice that you cannot identify any obvious peaks associated with the particular mechanical parts in the FFT power spectrum plot.

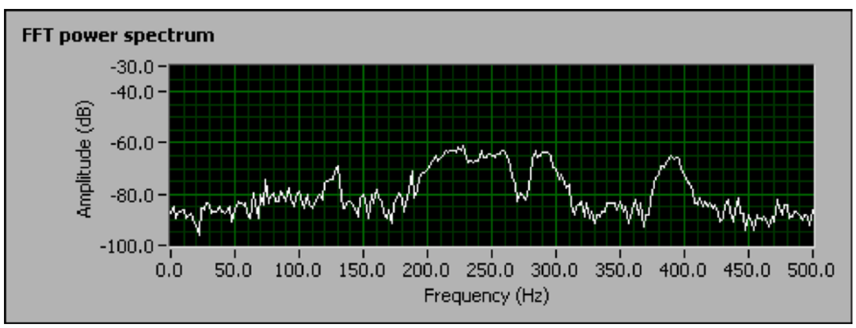

Figure 20. The FFT power spectrum shows no peaks as the rotational speed of the fan changes.

However, the order power spectrum plot in Figure 21 shows clearly defined peaks associated with different mechanical parts. The peak at the first order corresponds to the shaft vibration. The peak at the fourth order corresponds to the vibration of the coils. The peak at the seventh order corresponds to the vibration of the blades.

Figure 21. Order power spectrum identifies peaks by normalizing rotational speed.

Octave Analysis for Sound

Octave analysis is a technique for analyzing audio and acoustic signals. It measures the spectral energy with logarithmically spaced bandpass filters. The logarithmic scale emphasizes low to mid frequencies, and the grouping of frequency bands better emulates the human ear or how people perceive sound. For example, you typically cannot tell the difference between 350 Hz and 351 Hz. The power in each band is computed and displayed in a bar graph with a log scale for the x-axis, as shown in Figure 22.

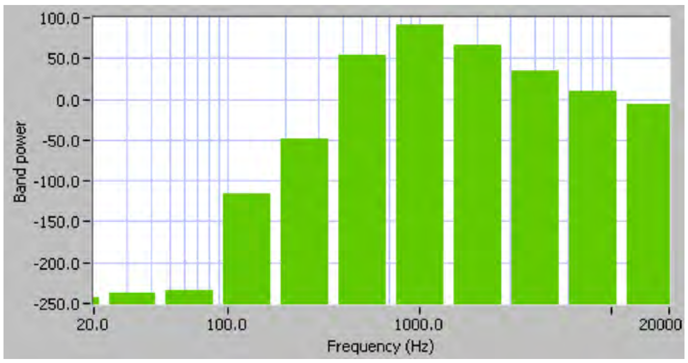

Figure 22. Octave analysis groups frequency bands on a logarithmic scale to emulate how humans perceive sound.

An octave is the interval between two frequencies, one of which is twice the length of the other. For example, frequencies of 250 Hz and 500 Hz are one octave apart, as are frequencies of 1 kHz and 2 kHz. Octave filter resolution is limited because the 16 Hz–16 kHz range has only 11 octaves. To overcome the limited resolution of octave filters, you can use other filters known as fractional-octave filters. Rather than covering one octave with a single filter, N filters are applied per octave to improve resolution, as shown in Figure 23. Typical fractional bands are 1/3 octave with three bands per octave, 1/12 octave with 12 bands per octave, and 1/24 octave with 24 bands per octave. ANSI and IEC standards define the specifications for these octave band and fractional-octave band filters.

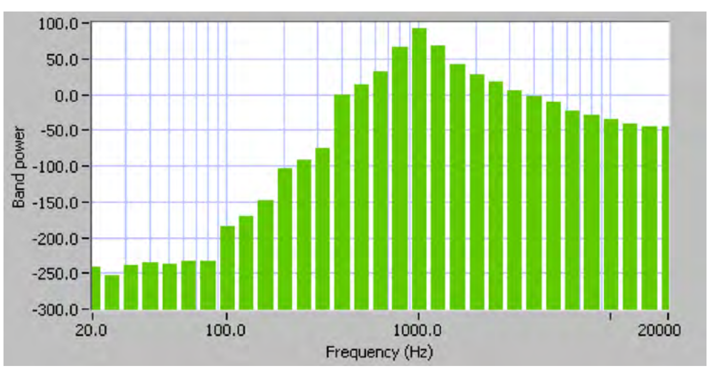

Figure 23. Fractional octave filters provide higher resolution.

Because it relies heavily on digital filtering, fractional octave analysis is a CPU-intensive operation. Increasing the number of filters applied to a signal increases the demands placed on the CPU and can result in increased computation time. In general, online third-octave analysis requires about 10 times as much processing power as FFT spectral calculations at the same sample rate.

Additional Signal Processing and Analysis

This guide has covered required signal conditioning and basic signal processing practices to take accurate sound and vibration measurements. The following list contains an overview of a few other analysis techniques that you may want to perform. Refer to your measurement software documentation to determine if these and other functions not listed are included or available with a separate analysis package.

- Short-time Fourier transform extracts frequency content from signals that change relatively slowly with time.
- Shock response spectrum characterizes a dynamic mechanical environment to help you estimate the damage potential of a specific shock to a component.
- Envelope detection extracts the modulating signal or envelope signal from an amplitude modulated signal to identify mechanical faults that have an amplitude modulating effect on the vibration signal of a machine.
- Acoustic weighting filters reflect the nonlinearities of the human ear or measure audio frequency noise on telephone or radio communications circuits.
- Tone detection identifies the tone with maximum amplitude or all tones with an amplitude that exceeds a specified threshold.
- Distortion analysis identifies total harmonic distortion (THD), THD plus noise, and the signal-to-noise and distortion ratio (SINAD).
- Swept sine wave generation and measurement characterizes the dynamic frequency response of a device under test.

Conclusion

Carefully review the specifications of your accelerometer or microphone to select a measurement device that has the appropriate dynamic range, gain, sample rate, and excitation level for your sensor. You also may want to consider simultaneous sampling if you are correlating measurements across different channels and built-in anti-alias filters to reduce the effects of high-frequency noise. Evaluating measurement software for signal processing techniques, such as averaging and windowing, can help provide a better representation of the vibration or acoustic phenomena that you are trying to measure.

Explore accurate sound and vibration measurement systems using NI hardware.

Transducer Electronic Data Sheet (TEDS)

When you connect a sensor to your measurement system, you must manually enter important sensor parameters, such as the range, sensitivity, and scale factors, for the software to properly use and scale the sensor data. Traditionally, you find these specifications by identifying the manufacturer and model number of the sensor and looking up the information you need in the corresponding data sheet. You can automate this configuration process by using Transducer Electronic Data Sheet (TEDS) smart sensors, which contain everything you need to know to make a measurement. TEDS-compatible instrumentation and software can then read this data to configure the acquisition and apply scaling factors.

The TEDS is deployed for a sensor in one of two ways. First, the TEDS can reside in embedded memory, typically an EEPROM, on the sensor itself or in the cable. Second, a Virtual TEDS can exist as a separate file that is downloadable from the Internet. A Virtual TEDS is used to store data for legacy sensors if the embedded memory or EEPROM is not available. A Virtual TEDS also is valuable in applications for which sensor operating conditions prevent the use of any electronics, such as EEPROMs, in the sensor.

The IEEE 1451.4 standard defines the method for encoding TEDS information for a broad range of senor types. At a minimum, an IEEE 1451.4 TEDS contains the manufacturer, model number, and serial number for the transducer. Usually a TEDS also describes the important attributes of the sensor or actuator, such as measurement range, sensitivity, temperature coefficients, and electrical interface. Table 4 shows an example of a TEDS for a load cell.

Basic TEDS	Manufacturer ID	21
	Model ID	19
	Version Letter	D
	Serial Number	8451
Standard and Extended TEDS *(fields vary according to transducer type)*	Calibration Date	10-Feb-14
	Measurement Range	±100 lb
	Electrical Output	±3 mV/V
	Bridge Impedance	350 Ω
	Excitation, Nominal	10 VDC
	Excitation, Minimum	7 VDC
	Excitation, Maximum	18 VDC
	Response Time	333.33 μs
User Area	Sensor Location	R32-1
	Cal. Record ID	543-0123

Table 4. Example TEDS for Load Cell

To cover such a broad range of sensors while keeping memory usage to a minimum, the IEEE 1451.4 standard uses templates that define the specific properties for different sensor types. Each type of sensor, from charge amplifiers to thermistors, has its own template. In addition to these 16 standard templates, sensors may have one of three possible calibration templates: a calibration table, calibration curve (polynomial), and frequency response table. For increased measurement accuracy, TEDS-compatible hardware and software can use the sensor calibration lookup table or a curve-fitting table to provide better characterization of the sensor. With prior agreement from the manufacturer, you can store up to 128 calibration points or the coefficients for a segmented multiorder polynomial.

Connecting to Measurement Hardware

The IEEE 1451.4 standard defines two types of mixed-mode interfaces: Class 1 two-wire and Class 2 multiwire. The Class 1 two-wire interface, shown in Figure 24, works with constant-current powered transducers, such as accelerometers. Class 1 transducers include diodes or analog switches you can use to multiplex the analog signal with the digital TEDS information on the single pair of wires.

TWO-WIRE INTERFACE

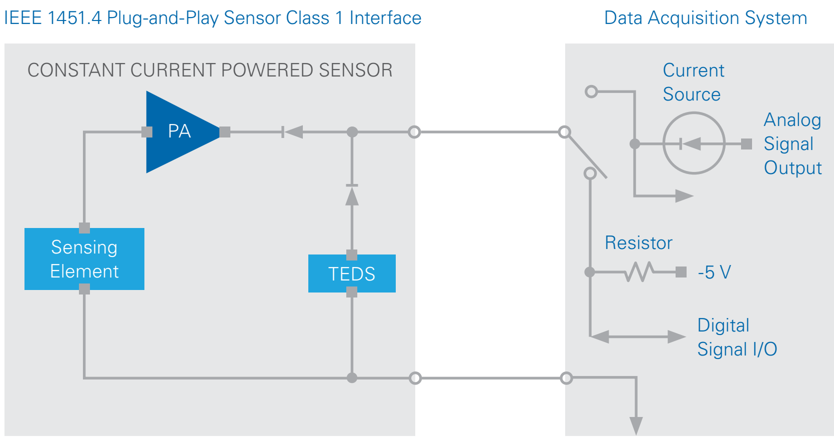

Figure 24. This Class 1 two-wire interface multiplexes analog measurement and digital TEDS data.

The Class 2 interface uses a separate connection for the analog and digital portions of the mixed-mode interface. The analog I/O of the sensors is left unmodified, and the digital TEDS circuit is added in parallel. You can then implement plug-and-play transducers with virtually any type of sensor or actuator, including thermocouples, RTDs, thermistors, bridge sensors, electrolytic chemical cells, and 4–20 mA current loop sensors. Figure 25 illustrates the implementation of a Class 2 mixed-mode interface.

MULTIWIRE INTERFACE

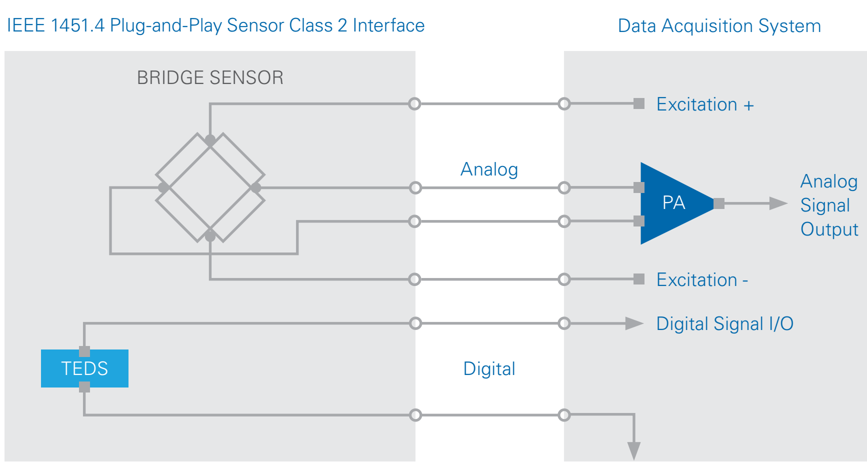

Figure 25. This Class 2 multiwire interface enables plug-and-play functionality.

Conclusion

You face little risk when adopting TEDS because the implementation of TEDS technology does not manipulate or change the analog output of the sensor, so it remains compatible with traditional analog interfaces. The plug-and-play capabilities offered with TEDS sensors and devices help reduce setup time by removing the need to review various manufacturers' data sheets and calibration certificates. In addition, they eliminate the possibility of error by the technician or engineer, who would otherwise have to manually set up the system and possibly configure the wrong sensor parameters by mistake.

Selecting a Sensor Measurement System

This guide has reviewed many requirements for making accurate sensor measurements. When configuring your measurement system, start with the source of your signal and consider any signal conditioning required for your sensor's electrical characteristics. Make sure that your instrumentation offers the resolution or dynamic range, sample rate, and input range that best fit your application needs. Lastly, choose the suite of software that most effectively helps you acquire, scale, and analyze your measurement data.

NI offers a wide variety of DAQ hardware ranging from single-measurement devices to high-performance, modular systems. The CompactDAQ and PXI platforms feature multichannel modules with built-in signal conditioning such as amplification, filtering, excitation, and isolation for direct connectivity and accurate sensor measurements. Sensor-specific I/O helps reduce total system cost and the likelihood of error because you don't have to build and maintain custom signal conditioning circuitry. Additionally, you can use NI hardware drivers along with application software such as LabVIEW to scale your data into desired units and perform analysis using built-in signal processing functions.

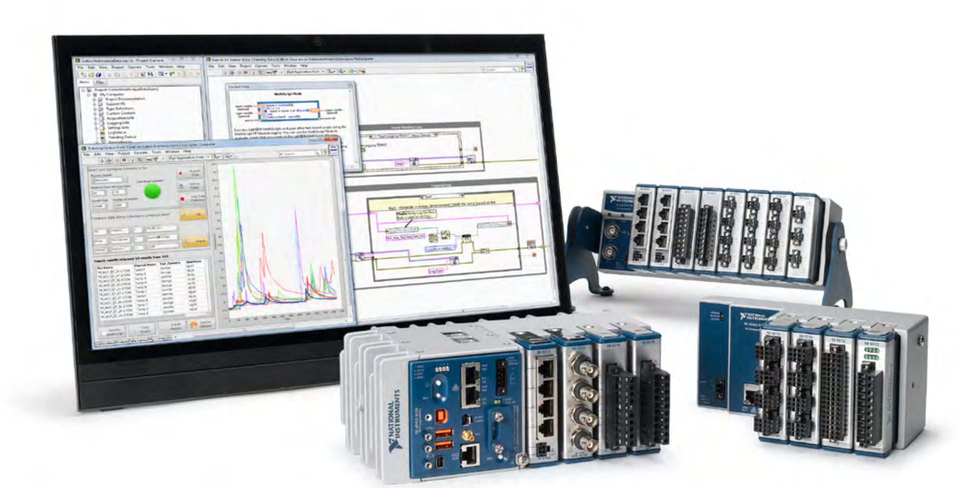

Figure 26. CompactDAQ hardware provides direct sensor connectivity in USB, Ethernet, Wi-Fi, and stand-alone form factors.