APPLICATION NOTE

An Engineer's Guide to Data Acquisition (DAQ)

EMERSON™

Contents

7 Lessons from a Former Test Engineer

(A Practical Welcome Letter)

Hi. My name is Kevin Sinkar. I am a senior product marketing engineer for the NI CompactDAQ modular data acquisition system. Previously, I worked as a test engineer creating NI LabVIEW and DAQ programs for product tests. And before that, I earned my degree in aerospace engineering from The University of Texas at Austin and a teaching certification from the UTeach program.

I'm writing this letter to share some of my personal engineering practical steps, precautions, and lessons learned over the past decade. My goal is to save you time and help you avoid missteps on your own test journey. Having been both user and developer (I used LabVIEW and DAQ as an engineer, and now work for the company that makes them), I offer these tips regardless of what vendor logo is on your instrumentation.

The Moment It Got Real

My first day as a test engineer felt like jumping into the deep end—owning multiple labs, picking sensors, writing acquisition code, and being accountable for data quality on systems that moved in milliseconds. I was excited, overwhelmed, and learning LabVIEW on the fly while deciding which measurements really needed kS/s and which absolutely didn't.

A few weeks in, I realized I needed to characterize each bench before I optimized anything: Which sensors were truly compatible, what their outputs were (voltage vs. current!), and what sampling and scaling actually matched the physics. That initial "click"—the realization that I had to read every spec that mattered—helped me manage my job, and it was first of many. Here are seven other "clicks" I'd share with my past self, if I could, and that I now share with you:

1) Characterize Before You Optimize

Bring every new setup to your desk first: Wire it, verify ranges, sanity-check scaling, and make sure your software drives it exactly like the lab rig will. Pushing a known-good executable to the stand beats walking back and forth hunting bugs without hardware.

2) Automate the Mundane (and Error-Prone) Stuff Early

My first project, hysteresis across temps and pressures, originally took three people and three days from acquisition to report. Rebuilding the flow in LabVIEW collapsed that to the run time of the test plus a few seconds for automated analysis and report generation. Later, I extended automation to step-response analysis: Autocursoring, 10–90% metrics, per-condition image capture, and rich filename-tagging so I could crunch thousands of runs in minutes.

3) Your Test System Is Important, so Keep It Reliable

Twice, I lost a long-running test thanks to power outages from a heat wave and a winter storm. After that, I implemented UPS on critical benches, monthly charge checks, quick "Are we in range?" health tests, and periodic runs with golden samples to catch drift. These habits save schedules! Mark them as recurring meetings in your calendar.

4) Metadata—or It Didn't Happen

Years later, stakeholders will ask, "Are you sure this is the right file and configuration?" Without consistent naming and embedded context (DUT, firmware, operator, conditions), you'll be rerunning tests just to remove doubt (trust me, I know). Even at the time, I wished our files carried query-able tags; hand-rolled naming helped, but true metadata would have saved hours of digging and lots of redundant testing.

Some specific data-centric pitfalls and potential fixes:

- **Using Excel for high-rate, multichannel time series:** Use NI DIAdem (or a time-series tool) for large files and interactive analysis. I wish I knew DIAdem existed in my former test engineer life.
- **Skipping metadata:** Standardize operator, DUT, firmware, conditions, and units; make them searchable.
- **Format chaos (.csv/.bin/.xlsx everywhere):** Consolidate on a universal model like TDM/TDMS with DataPlugins.
- **Manual file hunts:** Use a navigator with tags and advanced search to bypass retesting.
- **Static charts only:** Favor interactive visualization and multifile trending to quickly spot drifts.
- **Manual reports:** Script recurring analyses with Python/VB or LabVIEW for speed and consistency.
- **No standard data model:** TDM/TDMS file format is both binary (fast) and open (not proprietary and documented online). Open is important—if you win the lottery and need to leave, anyone can come in and read the file.

5) Preflight Every Wiring Job

Before you wheel anything onto a bench, confirm sensor excitation, termination, ranges, sample rates, and that the code you'll deploy is pointing at the right channels and units. That five-minute ritual prevents five-hour rabbit holes.

My 5-Minute Preflight (print this and post it on your bench):

1. **Sensors and Wiring:** Excitation, output type, termination, shield plan
2. **DAQ Config:** Sample rate, ranges, filters, channels → units
3. **Stimulus and Timing:** Setpoints, PWM/frequency details, triggers, log duration
4. **Health Checks:** Golden sample run, known-value sanity check
5. **Metadata:** DUT ID, firmware, operator, environmental conditions autotagged
6. **Power:** UPS status and recovery plan for long tests

6) Write Reports that Survive Time

Use a standard test method and report template for scope, setup (hardware, sensors, software stack), risks, data locations, analysis steps, and change logs with approvals. If you explore extras for a client, add them as an appendix so the core method remains auditable and repeatable. I automate a report using LabVIEW, DIAdem, and VB (and Python) as shown in this "**Automated Test with cDAQ and the LabVIEW+ Suite**" video. Add this to my list of "I wish I knew this existed."

7) Avoid Common Pitfalls that Prevent a Quality Measurement

- **Misreading sensor characteristics (DC vs. dynamic, excitation, output type):** Vet datasheets, match to your DAQ, and select sampling accordingly.
  Outcome: Correct scaling, fewer wild goose chases.
- **Wrong termination (RSE/NRSE/Diff):** Prefer differential in noisy environments; choose based on environment and signal type.
  Outcome: Better SNR, fewer ground-loop mysteries.
- **Ignoring common-mode and CMRR:** Know device limits; avoid shielding both ends to chassis.
  Outcome: Protected inputs, fewer distortions.
- **EMI and coupling blind spots:** Shield for E-fields, twist for B-fields, route away from aggressors.
  Outcome: Cleaner baselines, more stable thresholds.
- **Grounding by daisy-chain:** Use star grounding, isolate when needed.
  Outcome: Predictable measurements and safer rigs.
- **Cable and routing mistakes:** Use STP near drives/inverters; keep loop area small; don't bundle AC with sensitive DC.
  Outcome: Less crosstalk and fewer spikes.
- **Skipping ferrules/backshells and ignoring module thermals:** Protect terminations and respect slot placement.
  Outcome: Fewer intermittent faults and better accuracy.
- **Forgetting the environment:** Plan for humidity, shock, and vibration with mounting and immobilizers.
  Outcome: Less downtime in harsh conditions.

If you only do three things this week:

- **Automate one repetitive analysis** you run more than once a week. Your future self will thank you.
- **Define and enforce a minimal metadata schema** (DUT, firmware, operator, conditions). Then stick to it.
- **Run a bench-top dress rehearsal** for the next new test method, end-to-end. Push the same executable to the stand.

Gather Data with Intention

Good test engineering isn't just about collecting data, it's about collecting trustworthy data with intent. When you treat setup like a craft, automate the drudgery, and make your results findable years later, you earn the right kind of confidence: That which can explain every squiggle on a screen and back it up with an audit-ready report.

This document is a compliation of resources that I wish I had to help me gain a deeper understanding of my signals and get better data.

Happy Testing!

Kevin Sinkar

Analog Fundamentals

As part of the NI Measurement Fundamentals Series, this set of tutorials helps you learn about a specific common measurement application topic through theory explanations and practical examples.

Because a wide range of systems and applications incorporate analog devices and signals, advancing your analog fundamental knowledge is important for mastering many of today's test and measurement applications. This set of analog tutorials provides you with essential information about analog circuits, ground loops, noise, sampling, windowing, isolation, and proper connection schemes for measurements:

- Analog Circuits: Ohm's Law and Basic Concepts
- Analog Sample Quality: Accuracy, Sensitivity, Precision, and Noise
- Windowing: Optimizing FFTs Using Window Functions
- Dithering, Layout, and High-Quality Components: Tools to Decrease the Noise Floor
- Grounding for Improved Measurements
- High-Voltage Measurements and Isolation
- Frequency and DC Measurements

Analog Circuits: Ohm's Law and Basic Concepts

Let's discuss analog circuit fundamentals. We'll touch on Ohm's law and basic analog circuit concepts as well as how to make various calculations:

- Ohm's Law and Basic Analog Circuit Concepts
- Capacitance Calculations
- Inductance Calculations
- Analog Amplifier Circuits
- Analog RC Filters

Ohm's Law and Basic Analog Circuit Concepts

Resistance

Resistance is the characteristic of a medium that opposes flow of current through itself. The unit of resistance is ohms, which is represented by the Greek letter Ω (Omega). The power value associated with resistance is quantified as the amount of power that the resistor can dissipate as heat without overheating itself.

The current (I) through the resistor (R) is defined as:

$$I = \frac{V}{R}$$

$$V = I \cdot R$$

$$R = \frac{V}{I}$$

For a 1 MΩ resistance, the current resulting from the application of 10 V would be 10 µA.

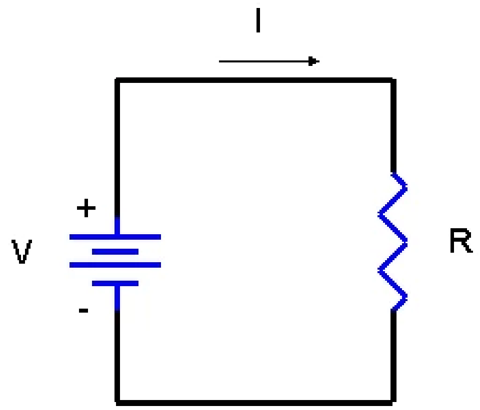


Figure 1. Simple Representation of Ohm's Law

Ohm's law is the fundamental equation that describes the above relationship between the voltage potential, the current flowing in the circuit, and the resistance of a circuit. The power dissipated in a load resistance (R) is defined as the product of the current and the voltage. Other relationships for power can be easily derived from this by applying Ohm's law using substitution.

The power (P) dissipated in (R) is defined as:

$$P = I \cdot V$$

$$P = \frac{V^2}{R}$$

$$P = I^2 \cdot R$$

To calculate the value of resistance that will result in 10 W with 10 V applied to it, we remember that P = V2/R. Transposing, R = V2/P. The resistance is 100/10, or 10 Ω. So 10 V applied to 10 Ω will yield 10 W. Whenever two of the parameters (V, R, or P) are numerically the same, the third one will be the same. A common way to measure resistance is by using a **digital multimeter (DMM)**.

Note: The power dissipation (P) is what sets the limit for how much voltage can be applied to the 50 Ω input of a digitizer. From the equations, we see that 10 V into 50 Ω will require the digitizer's input load to dissipate 2 W. If you are running two channels, that's 4 W. This amount of power dissipation is definitely notable. Also notice that, because of the square law effect, if you double that voltage into the digitizer, the power it must dissipate will QUADRUPLE.

Voltage Divider Calculation

When two resistors are connected in a series configuration, they must share the applied voltage, and the same current flows through both of them.

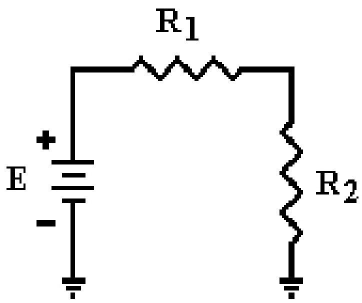


Figure 2. Voltage Divider Circuit Example

The formula used to calculate the applied voltage is:

$$E_1 = R_1 \cdot I$$

(E1 = Voltage drop across R1)

$$E_2 = R_2 \cdot I$$

(E2 = Voltage drop across R2)

$$R_{eq} = R_1 + R_2$$

$$I = \frac{E}{R_{eq}}$$

$$E = E_1 + E_2$$

$$E = I \cdot (R_1 + R_2)$$

To calculate the voltage across R2:

$$E_2 = R_2 \cdot I$$

$$E_2 = R_2 \cdot \frac{E}{R_{eq}}$$

$$E_2 = R_2 \cdot \frac{E}{R_1 + R_2}$$

$$E_2 = E \cdot \frac{R_2}{R_1 + R_2}$$

Note: Voltage divider is described by the equation above.

Current Divider Calculation

When two resistors are connected in parallel configuration, the same voltage is across each of them. The amount of current flowing through them depends on the value of the resistances.

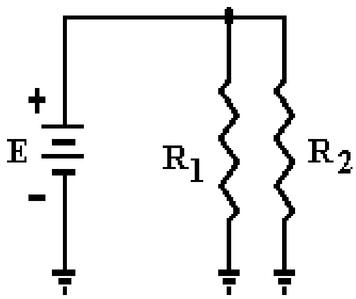


Figure 3. Current Divider Circuit Example

The above figure depicts two resistors in a parallel configuration.

$$I = I_1 + I_2$$

$$E = I_1 \cdot R_1$$

$$E = I_2 \cdot R_2$$

$$I = \frac{E}{R_1} + \frac{E}{R_2}$$

$$I = E\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$E = I \cdot R_{eq}$$

$$R_{eq} = \frac{1}{\left({}^{1}/_{R_1} + {}^{1}/_{R_2}\right)} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

Capacitance Calculations

Capacitors store energy in the form of electrical charge. The amount of charge that the capacitor can hold depends on the area of the two plates in the figure below and the distance between them. Large plates with a small distance between them have a higher capacity to hold charge. The electric field between the plates of a capacitor resists changes in applied voltage. Capacitors decrease their resistance with frequency.

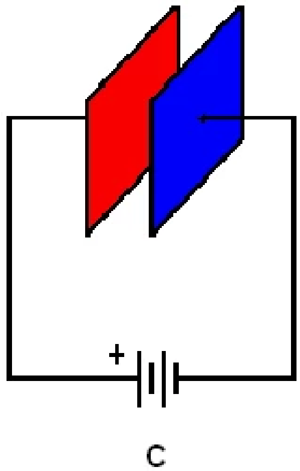


Figure 4. Capacitance Circuit Example

Reading Capacitor Values

The unit of capacitance is Farad, or F. The formula to calculate capacitance is:

$$C = \frac{Q}{V}$$

where
C = Capacitance in Farads
Q = Accumulated charge in Coulombs
V = Voltage difference between the plates

Series Configuration

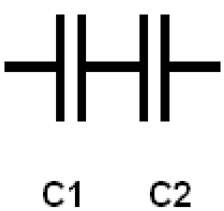


Figure 5. Series Capacitor Configuration

The above configuration represents two capacitors in series.

Since the capacitance of a capacitor is inversely proportional to the distance between the plates, the total capacitance (CT) of any number of capacitances can be calculated by the following:

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$$

For two capacitors connected in series,

$$C_1 = \frac{Q}{V_1}$$

$$C_2 = \frac{Q}{V_2}$$

$$V_1 = \frac{Q}{C_1}$$

$$V_2 = \frac{Q}{C_2}$$

$$V = V_1 + V_2$$

$$V = \frac{Q}{C_{eq}}$$

$$C_{eq} = \frac{1}{\left({}^{1}/_{C_1} + {}^{1}/_{C_2}\right)} = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

Parallel Configuration

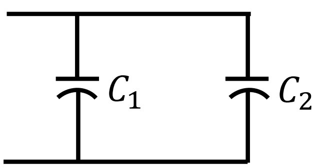


Figure 6. Parallel Capacitor Configuration

Each capacitor charges to the same applied voltage. Total capacitance equals the sum of the individual capacitances of the capacitors.
The formula used to calculate the capacitance is:

$$Q_1 = C_1 \cdot V$$

$$Q_2 = C_2 \cdot V$$

$$Q = Q_1 + Q_2$$

$$Q = V \cdot (C_1 + C_2)$$

$$C_{eq} = C_1 + C_2$$

Inductance Calculations

Inductance is the amount of voltage dropped across the inductor for a given rate of change of current flowing through it. Inductors increase their resistance with frequency. The unit of inductance is Henry, or H.

Series Configuration

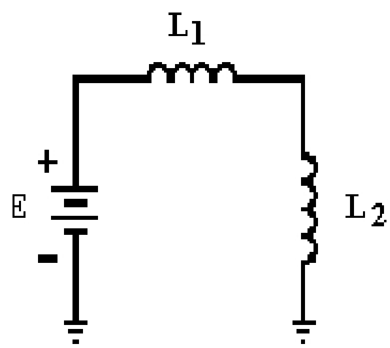


Figure 7. Series Inductor Configuration

Figure 7 shows a series configuration of two inductors. When two inductors are connected in series as shown, their total inductance equals the sum of individual inductances:

$$L_1 = E \cdot \frac{dI}{dt}$$

$$L_2 = E \cdot \frac{dI}{dt}$$

$$L_T = L_1 + L_2$$

where dI/dt is the change of current over time.

However, in the real world, if we consider mutual inductance where the magnetic field of each inductor affects the other coil, then the total inductance can be calculated using the formula below:

$$L_T = L_1 + L_2 \pm 2 \cdot M$$

where M is the mutual inductance between the two coils.

Parallel Configuration

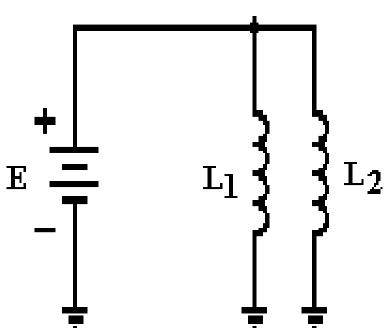


Figure 8. Parallel Inductor Configuration

Figure 8 is a parallel configuration of two inductors. When two inductors are connected in parallel configuration, mutual inductance is a factor. Also, mutual inductance will be either added or subtracted from the self-inductance of each coil, as current has two paths to flow in.

The total inductance can be calculated using the formula:

$$L_T = \frac{L_1 \cdot L_2 - M^2}{L_1 + L_2 - 2 \cdot M}$$

Impedance

Impedance (Z) is generally defined as the total opposition a device or circuit offers to the flow of an alternating current (AC) at a given frequency. Its value is equal to the ratio between the voltage and the current over an element of a circuit. Therefore, the unit of impedance is Ω.

Impedance is represented as a complex quantity which is graphically shown on a vector plane. An impedance vector consists of a real part (resistance, or R) and an imaginary part (reactance, or X). Impedance can be expressed using the rectangular coordinate form

R + jX

or in the polar form as a magnitude and phase angle: Z .

Admittance

Admittance (Y) is the reciprocal of impedance. It is also a complex quantity: The real part is conductance (C) and the imaginary part is susceptance (B).
The unit of admittance is siemens (S).

Y = G + jB

where Y is admittance, G represents conductance, and B represents susceptance.

Analog Amplifier Circuits

Figure 9 is a basic operational amplifier (op-amp) model that consists of three basic stages.

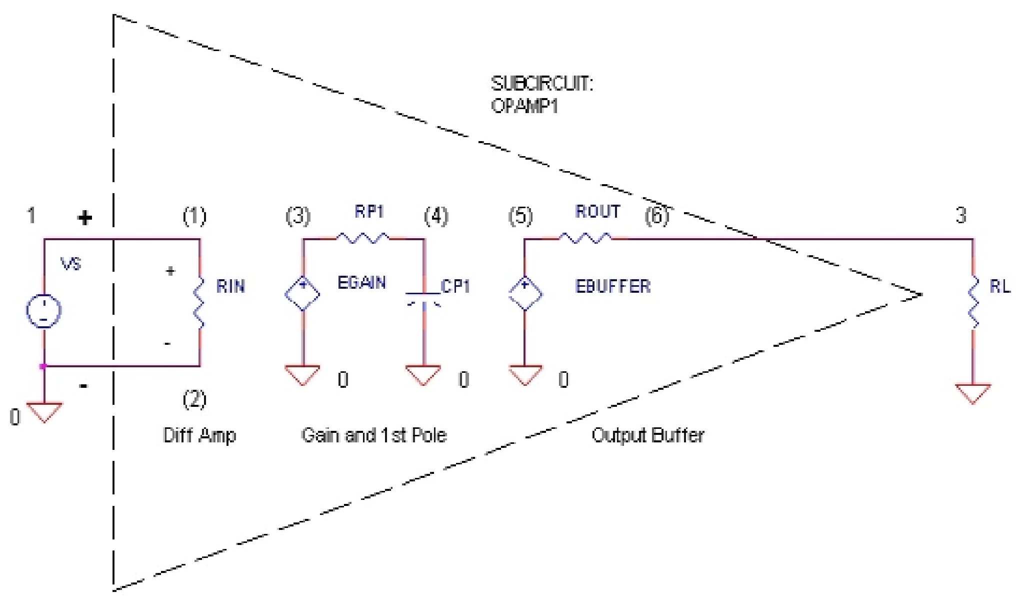


Figure 9. Basic Operational Amplifier (Op-Amp) Model

The stages include:

1) Differential Amplifier—An amplifier whose output is proportional to the difference between the input signals.

2) Gain/Frequency Response—A filter changes the amplitude or phase characteristics of a signal with respect to frequency. The frequency domain behavior of a filter is mathematically described in terms of a transfer function or a network function. The transfer function H(s) is described as a ratio between output and input signals.

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)}$$

where, $V_{out}(s)$ and $V_{in}(s)$ are the output and input voltage signals and s is the complex frequency variable.
The magnitude of transfer function is called amplitude response or frequency response, especially in radio applications.

3) Output Buffer

Inverting Amplifier

An inverting is as simple as it sounds; it reverses the polarity of the input signal. For example, if the voltage going into the amplifier is positive, it is negative when it comes out.

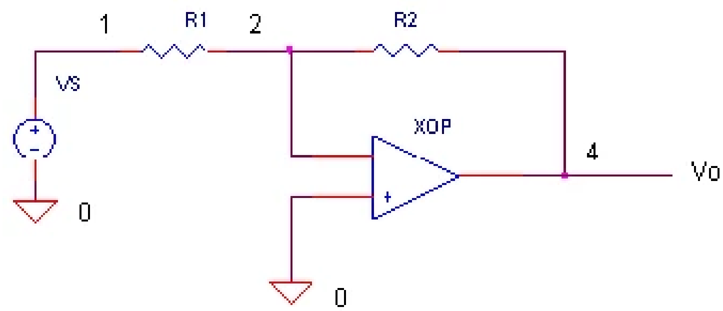


Figure 10. Basic Inverting Amplifier

Calculating the gain of an inverting amplifier is shown as:

$$\frac{V_s - V_1}{R_1} = \frac{V - V_0}{R_2}$$

because V_1 = V = 0 (virtual ground)

$$\frac{V_s}{R_1} = \frac{-V_0}{R_2}$$

$$Gain = \frac{V_0}{V_s} = \frac{-R_2}{R_1}$$

Noninverting Amplifier

Amplifier gain is determined by the ratio of R1 and R2.

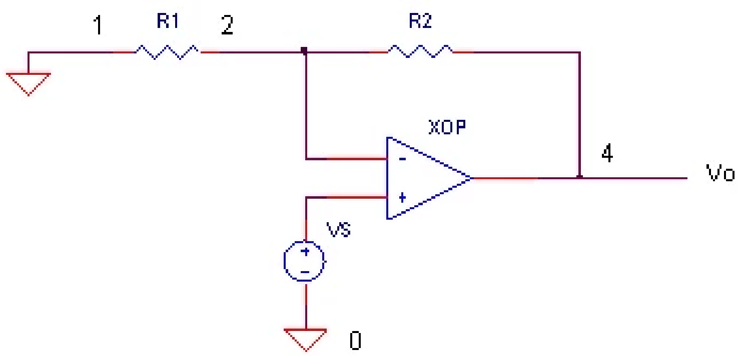


Figure 11. Basic Noninverting Amplifier

To calculate the gain of a noninverting amplifier:

$$V_0 \cdot R_1 = V_s \cdot R_1 + V_s \cdot R_2$$

$$R_1 \cdot (V_0 - V_s) = V_s \cdot R_2$$

$$\frac{V_0}{V_s} - 1 = \frac{R_2}{R_1}$$

$$Gain - 1 = \frac{R_2}{R_1}$$

$$Gain = 1 + \frac{R_2}{R_1}$$

where

$$Gain = \frac{V_0}{V_s}$$

Note: All NI DAQ products have built-in amplifiers.

Analog RC Filters

RC Lowpass Filter

A common circuit that attenuates high-frequency components in an analog signal is known as the RC lowpass filter. Examine the diagram below, where V_{in} is the applied voltage, and the voltage V_{out} across C1 is the output.

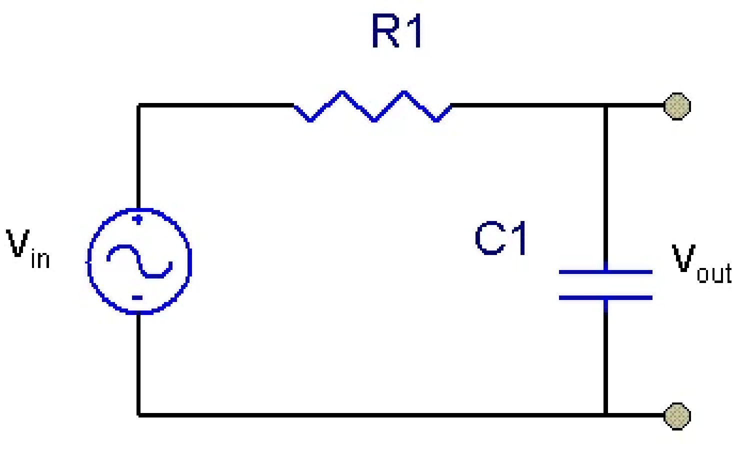


Figure 12. Simple RC Lowpass Filter

The RC lowpass filter passes low-frequency and DC signals to the output but attenuates high-frequency signals. You can get the equivalent of this circuit even when you don't explicitly design it. For example, **C** could be the input capacitance of a **digital multimeter** or **digitizer**, and **R** might be the source resistance of the device under test (DUT). The DUT has to charge and discharge **C** as the signal varies. As the signal frequency increases, the impedance of **C** decreases; once it becomes comparable to or smaller than **R**, the output signal starts to be attenuated.

The cutoff (or –3 dB) frequency is defined as the frequency where the output voltage amplitude drops to about 70.7% of the input:

$$V_{out} = \frac{V_{in}}{\sqrt{2}} \approx 0.707\, V_{in}$$

At this point, the output power is half of the input power, so this frequency is also called the half-power point.

Single-pole RC lowpass is shown as:

$$t = R \cdot C$$

$$f_c = \frac{1}{2 \cdot \pi \cdot t}$$

RC Highpass Filter

A circuit that attenuates low-frequency components in an analog signal is called a RC highpass filter. Notice that the circuit is similar to the one above, but V_{out} is now measured across R1.

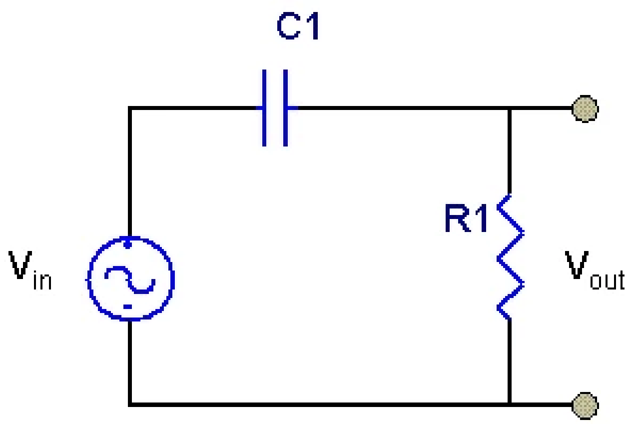


Figure 13. Simple RC Highpass Filter

A very important typical application of this circuit is in the input coupling circuits of a **digitizer** or **DMM**. With the capacitor in, it is "AC-coupled." With the capacitor shorted, it would be "DC-coupled."

Note: Lowpass and highpass filters also are used in **dynamic signal acquisition (DSA)** devices.

To summarize:

- Voltage, current, and resistance are interrelated through Ohm's Law. Power calculations help assess energy dissipation and input protection in DAQ devices.
- Divider circuits are used to scale signals and distribute current, enabling safe interfacing with measurement hardware.
- Capacitors resist voltage change; inductors resist current change. Their behavior in AC circuits affects filtering, timing, and energy storage.
- Impedance and admittance are complex quantities that describe how circuits respond to AC signals; crucial for frequency-domain analysis and signal integrity.
- Op-amps are versatile building blocks for amplification, filtering, and signal conditioning. Key configurations include inverting, noninverting, and differential amplifiers.
- Lowpass and highpass filters shape signal bandwidth, suppress noise, and isolate desired frequency components—vital for clean data acquisition.

Analog Sample Quality: Accuracy, Sensitivity, Precision, and Noise

The more you know about these factors, the more you can understand and improve your measurement sample quality:

- Measurement Sensitivity
- Accuracy
- Precision
- Noise and Noise Sources
- Noise-Reduction Strategies

Measurement Sensitivity

When referring sample to quality, you want to evaluate the accuracy and precision of your measurement. However, you must understand your oscilloscope's sensitivity first. Sensitivity is the smallest change in an input signal that can cause the measuring device to respond. In other words, if an input signal changes by a certain amount—by a certain sensitivity—then you can see a change in the digital data.

Note: Don't confuse sensitivity with resolution and **code width**. The resolution defines the code width; this is the discrete level at which the instrument displays values. However, the sensitivity defines the change in voltage needed for the instrument to register a change in value. For example, an instrument with a measurement range of 10 V may be able to detect signals with 1 mV resolution, but the smallest detectable voltage it can measure may be 15 mV. In this case, the instrument has a resolution of 1 mV, but a sensitivity of 15 mV.

In some cases, the sensitivity is greater than the code width. At first, this may seem counterintuitive—doesn't this mean that the voltage changes by an amount that can be displayed and yet not be registered? Yes! To understand the benefit, think about a constant DC voltage. Although it would be ideal if that voltage was exactly constant with no deviations, there is always some slight variation in a signal, which is represented in Figure 14. The sensitivity is denoted with red lines, and the code width is depicted, as well. In this example, because the voltage is never going above the sensitivity level, it is represented by the same digital value—even though it is greater than the code width. This is beneficial in that it doesn't pick up noise and more accurately represents the signal as a constant voltage.

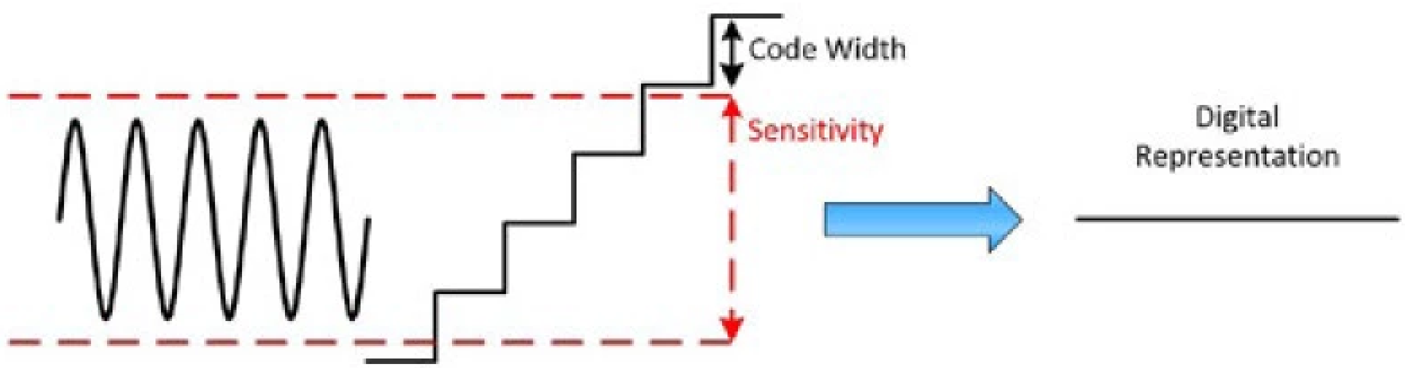


Figure 14. Sensitivity that is greater than the code width can help smooth out a noisy signal.

Once the signal actually starts to rise, it crosses the sensitivity level and is then represented by a different digital value (see Figure 15). Keep in mind that your measurement can never be more accurate than the sensitivity.

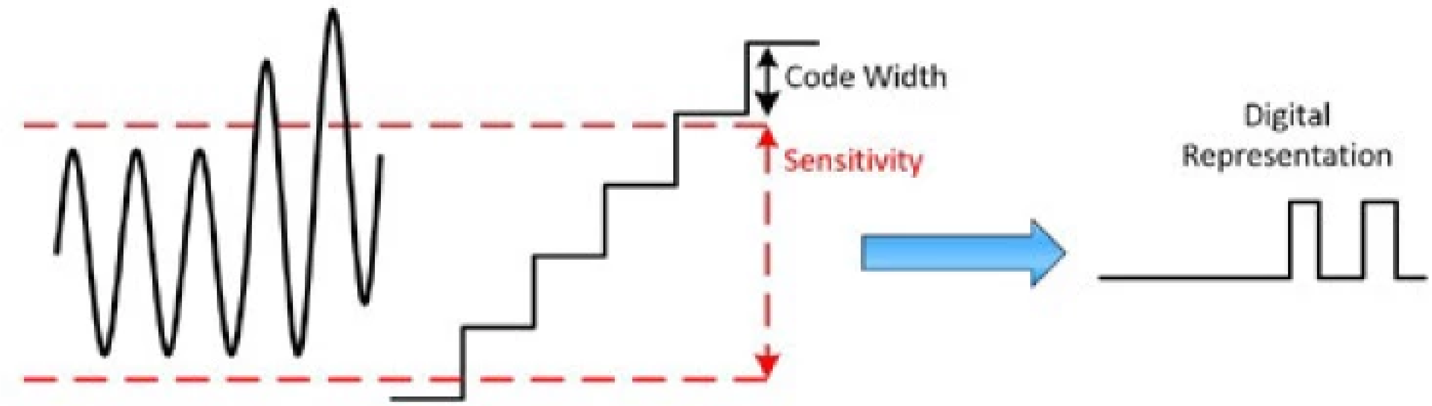


Figure 15. Once the signal crosses the sensitivity level, it is represented by a different digital value.

There is also some ambiguity in how the sensitivity of an instrument is defined. At times, it can be defined as a constant amount as in the example above. In this case, as soon as the input signal crosses the sensitivity level, the signal is represented by a different digital value. However, sometimes it is defined as a change in signal. After the signal has changed by the sensitivity amount specified, it is represented by a different signal. In this case, it doesn't matter the absolute voltage; rather, it's the **change** in voltage. In addition, some instruments define the sensitivity as around zero.

To add to the confusion, not only does the exact definition of the term "sensitivity" change from company to company, but different products from the same company could use it to mean something slightly different. It is important to check your instrument's specifications to see how sensitivity is defined; if it isn't well documented, contact the company for clarification.

Accuracy

Accuracy is defined as a measure of the capability of the instrument to faithfully indicate the value of the measured signal. This term is not related to resolution; however, the accuracy can never be better than the instrument's resolution.

Depending on the instrument or digitizer, there are different expectations for accuracy. For instance, in general, a DMM is expected to have higher accuracy than an oscilloscope. How accuracy is calculated also changes by device; always check your instrument's specifications to see how your particular instrument calculates accuracy.

DAQ Device Accuracy

DAQ devices often define accuracy as the deviation from an ideal transfer function. The following equation describes how a DAQ card might specify the accuracy:

$$Accuracy = (Reading * Gain\ Error) + (Reading * Offset\ Error) + (Noise\ Uncertainty)$$

It then defines the individual terms:

$$Gain\ Error = Residual\ AI\ Gain\ Error + (Gain\ Temperature\ Coefficient * Temperature\ Change\ From\ Last\ Internal\ Calibration) + (Reference\ Temperature\ Coefficient * Temperature\ Change\ From\ Last\ External\ Calibration)$$

$$Offset\ Error = Residual\ AI\ Offset\ Error + (Offset\ Temperature\ Coefficient * Temperature\ Change\ From\ Last\ Internal\ Calibration) + INL\_Error$$

The majority of these terms are defined in a table and based on the nominal range. The specifications also define the calculation for noise uncertainty. Noise uncertainty is the uncertainty of the measurement because of the effect of noise in the measurement and is factored into determining the accuracy.

In addition, there may be multiple accuracy tables for your device, depending on whether you are looking for the accuracy of analog in or analog out, or if a filter is enabled or disabled.

Precision

Accuracy and precision are often used interchangeably, but there is a subtle difference. Precision is defined as a measure of the stability of the instrument and its capability of resulting in the same measurement over and over again for the same input signal. Whereas accuracy refers to how closely a measured value is to the actual value, precision refers to how closely individual, repeated measurements agree with each other.

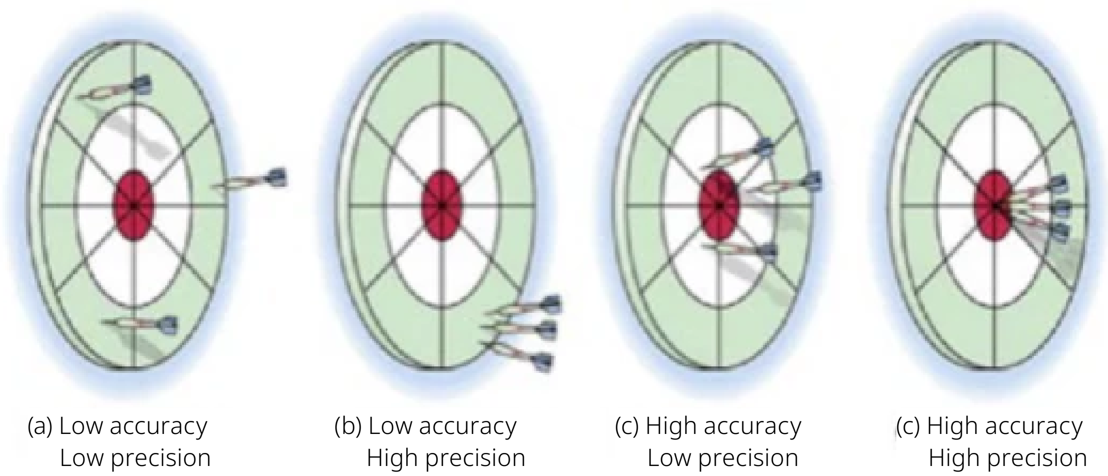


Figure 16. Precision and accuracy are related, but not identical.

Precision is most affected by noise and short-term drift on the instrument. The precision of an instrument is often not provided directly, but must be inferred from other specifications such as the transfer ratio specification, noise, and temperature drift. However, if you have a series of measurements, you can calculate the precision.

$$Precision = 1 - \frac{|Offset\ From\ Input\ Signal|}{|Input\ Signal|}$$

For instance, if you are monitoring a constant voltage of 1 V, and you notice that your measured value changes by 20 μV between measurements, then your measurement precision can be calculated as follows:

$$Precision = 1 - \frac{|20\mu V|}{|1V|} = 1 - \frac{|20\mu V|}{|1{,}000{,}000\mu V|} = 0.99998$$

Typically, precision is expressed as a percentage. In this example, the precision is 99.998 percent.

Precision is meaningful primarily when relative measurements (relative to a previous reading of the same value), such as device calibration, need to be taken.

Noise and Noise Sources

Don't confuse sensitivity with resolution and **code width**. The resolution defines the code width; this is the discrete level at which the instrument displays values. However, the sensitivity defines the change in voltage needed for the instrument to register a change in value. For example, an instrument with a measurement range of 10 V may be able to detect signals with 1 mV resolution, but the smallest detectable voltage it can measure may be 15 mV. In this case, the instrument has a resolution of 1 mV but a sensitivity of 15 mV.

Thermal Noise

An ideal electronic circuit produces no noise of its own, so the output signal from the ideal circuit contains only the noise that was in the original signal. But real electronic circuits and components do produce a certain level of inherent noise of their own. Even the simple fixed-value resistor is noisy.

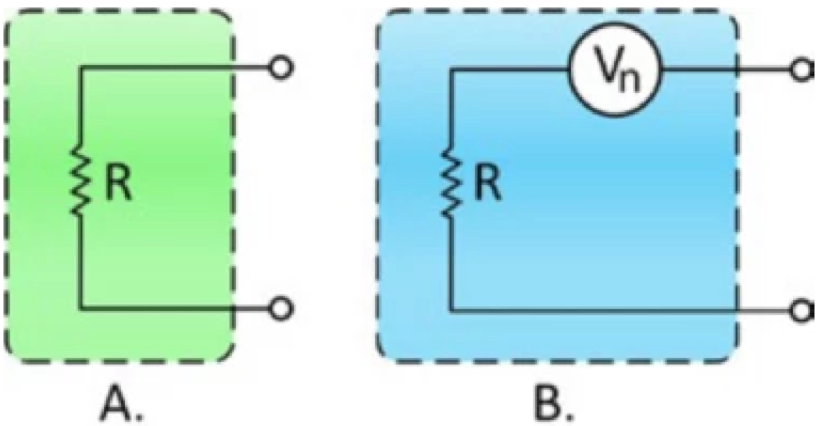


Figure 17. An ideal resistor is reflected in A, but, practically, resistors have internal thermal noise, as represented in B.

Item A in Figure 17 shows the equivalent circuit for an ideal, noise-free resistor. The inherent noise is represented in Figure 17 item B, by a noise voltage source V_n in series with the ideal, noise-free resistance R_i. At any temperature above absolute zero (0 °K, or about -273 °C), electrons in any material are in constant random motion. Because of the inherent randomness of that motion, however, there is no detectable current in any one direction. In other words, electron drift in any single direction is cancelled over short time periods by equal drift in the opposite direction. Electron motions are therefore statistically decorrelated. There is, however, a continuous series of random current pulses generated in the material, and those pulses are seen by the outside world as a noise signal. This signal is called by several names: Johnson noise, thermal agitation noise, or thermal noise. This noise increases with temperature and resistance, but as a square root function. This means you have to quadruple the resistance to double the noise of that resistor.

Flicker or $^1/_f$ Noise

Semiconductor devices tend to have noise that is not flat with frequency. It rises at the low end. This is called $^1/_f$ noise, pink noise, excess noise, or flicker noise. This type of noise also occurs in many physical systems other than electrical. Examples include proteins, reaction times of cognitive processes, and even earthquake activity. The chart below shows the most likely source of the noise, depending on the frequency the noise occurs for a particular voltage; knowing the cause of the noise goes a long way in reducing the noise.

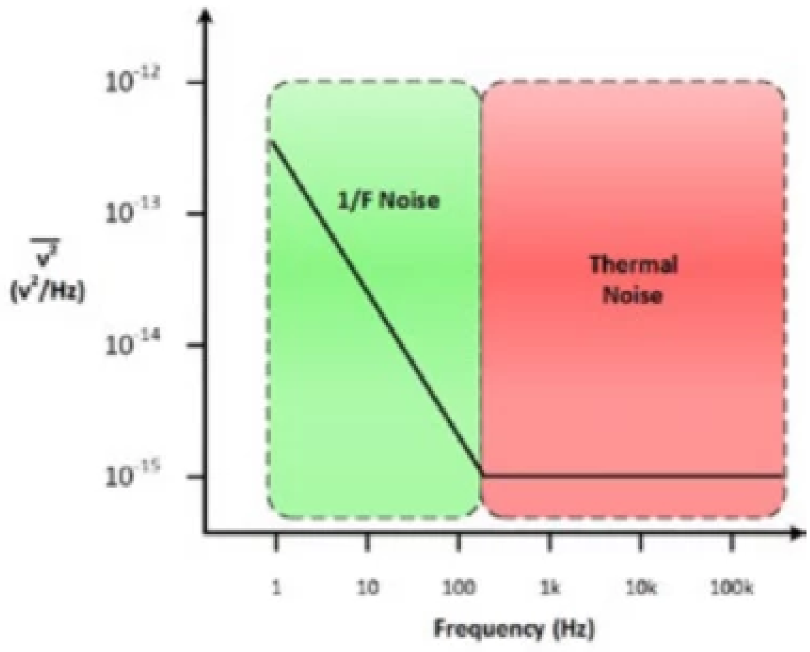


Figure 18. Noise as a Function of Voltage

Noise-Reduction Strategies

Although noise is a serious problem for a designer (especially when low signal levels are present), you can minimize the effects of noise on a system. Here are some strategies to help reduce noise:

- Keep the source resistance and the amplifier input resistance as low as possible. Using high-value resistances increases thermal noise proportionally.
- Total thermal noise is also a function of the bandwidth of the circuit. Therefore, reducing the bandwidth of the circuit to a minimum also minimizes noise. But this must be done mindfully, because signals have a Fourier spectrum that must be preserved for accurate measurement. The solution is to match the bandwidth to the frequency response required for the input signal.
- Prevent external noise from affecting the performance of the system by appropriate use of grounding, shielding, cabling, careful physical placement of wires, and filtering.
- Use a low-noise amplifier in the input stage of the system.
- For some semiconductor circuits, use the lowest DC power supply potential that does the job.

To summarize:

- Sensitivity is the smallest change in an input signal that causes the measuring device to respond.
- Accuracy is defined as a measure of the capability of the instrument to faithfully indicate the value of the measured signal.
- The accuracy and sensitivity are documented in the specifications; because different companies—and even different products from the same company—may use these terms differently, always check the documentation and contact the company for clarification, if needed.
- Precision is defined as a measure of the stability of the instrument and its capability of resulting in the same measurement repeatably for the same input signal.
- Noise is any unwanted signal that interferes with the wanted signal.
- There are different types of noise, and different strategies to help reduce noise.

Windowing: Optimizing FFTs Using Window Functions

Next, we'll discuss time and frequency domain, fast Fourier transforms (FFTs), and windowing, as well as how you can use them to improve your understanding of a signal:

- Time Domain, Frequency Domain, and FFT
- Windowing

Time Domain, Frequency Domain, and FFT

The FFT can be powerful in helping decode everyday signals and troubleshooting signal errors. Although the FFT is a complicated mathematical function, it isn't a complicated concept to relate to your measured signals. Essentially, it takes a signal and breaks it down into sine waves of different amplitudes and frequencies. Let's take a deeper look at what this means and why it is useful.

All Signals Are the Sum of Sines

When looking at real-world signals, you usually view them as a voltage changing over time. This is referred to as the time domain. Fourier's theorem states that any waveform in the time domain can be represented by the weighted sum of sines and cosines. For example, take two sine waves, where one is three times as fast as the other—or the frequency is 1/3 the first signal. When you add them, you get a different signal.

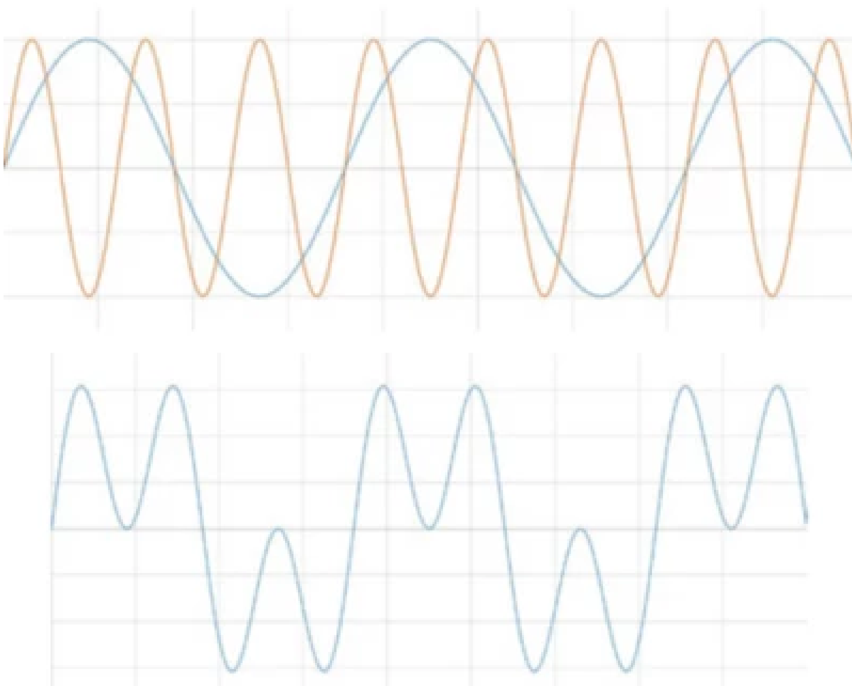


Figure 19. When you add two signals, you get a new signal.

Now imagine that second wave was also 1/3 the amplitude. This time, just the peaks are affected.

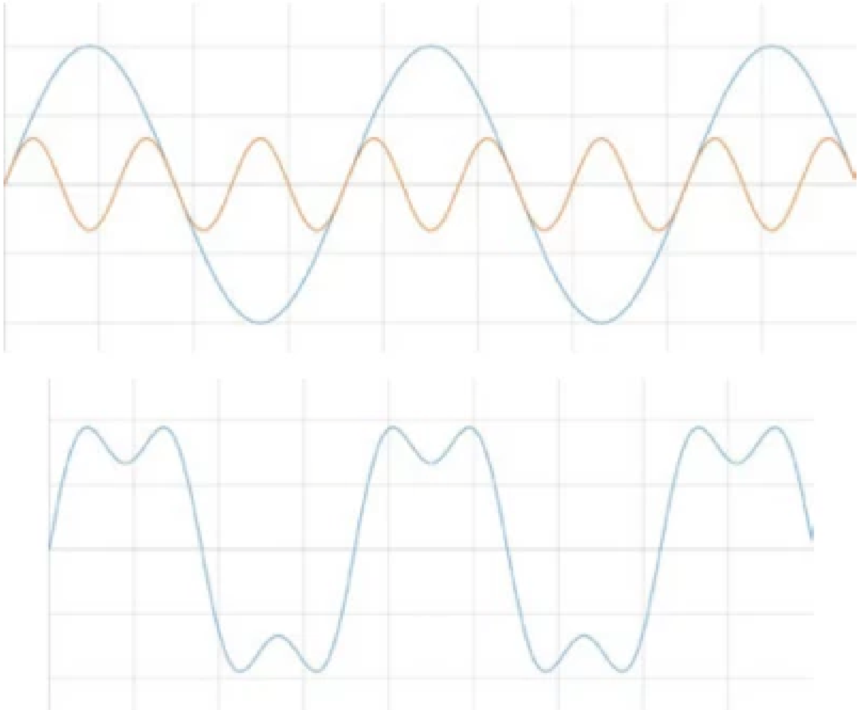


Figure 20. Adjusting the amplitude when adding signals affects the peaks.

Imagine you added a third signal that was 1/5 the amplitude and frequency of the original signal. If you continued in this fashion until you hit the noise floor, you might recognize the resulting waveform.

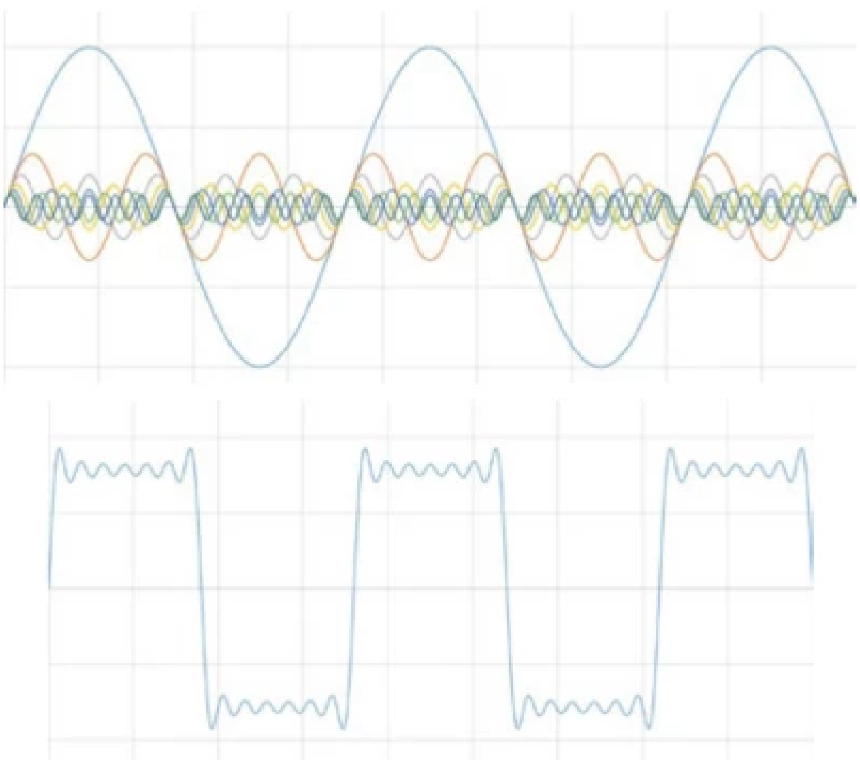


Figure 21. A square wave is the sum of sines.

You have created a square wave. In this way, all signals in the time domain can be represented by a series of sines.

Although it's interesting that you can construct signals in this fashion, why should you? Because if you can construct a signal using sines, you can also deconstruct signals into sines. Once a signal has been deconstructed, you can see and analyze the different frequencies present in the original signal. Let's examine a few examples in which deconstructing a signal could prove useful:

- If you deconstruct radio waves, you can choose which particular frequency—or station—you want to listen to.
- If you deconstruct audio waves into different frequencies such as bass and treble, you can alter the tones or frequencies to boost certain sounds and remove unwanted noise.
- If you deconstruct earthquake vibrations of varying speeds and strengths, you can optimize building designs to avoid the strongest vibrations.
- If you deconstruct computer data, you can ignore the least important frequencies and lead to more compact representations in memory, otherwise known as file compression.

Deconstructing Signals Using the FFT

The FFT deconstructs a time domain representation of a signal into the frequency domain representation. The frequency domain shows the voltages present at varying frequencies. It is a different way of looking at the same signal.

A digitizer samples a waveform and transforms it into discrete values. Because of this transformation, the FFT will not work on this data. Instead, the discrete Fourier transform (DFT) is used, which produces as its result the frequency domain components in discrete values, or bins. The FFT is an optimized implementation of a DFT that takes less computation to perform but essentially just deconstructs a signal.

Take a look at the signal from Figure 21 above. There are two signals at two different frequencies; in this case, the signal has two spikes in the frequency domain–one at each of the two frequencies of the sines that composed the signal in the first place.

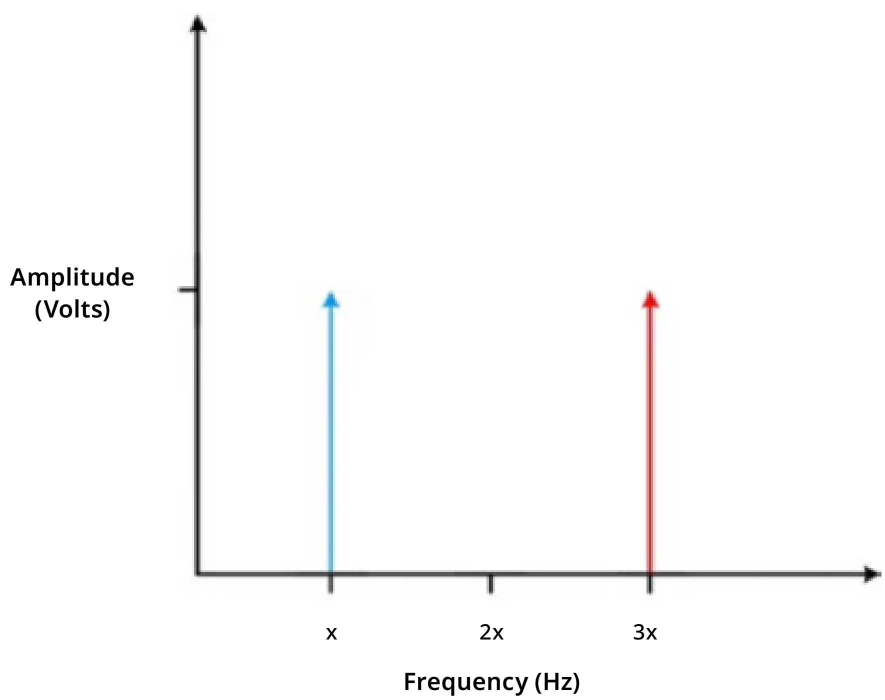


Figure 22. When two sine waves of equal amplitude are added, they result in two spikes in the frequency domain.

The amplitude of the original signal is represented on the vertical axis. If you look at the signal from Figure 22 above, where there are two different signals at different amplitudes, you can see that the most prominent spike corresponds to the frequency of the highest voltage sine signal. Looking at a signal in the time domain, you can get a good idea of the original signal by knowing at what frequencies the largest voltage signals occur.

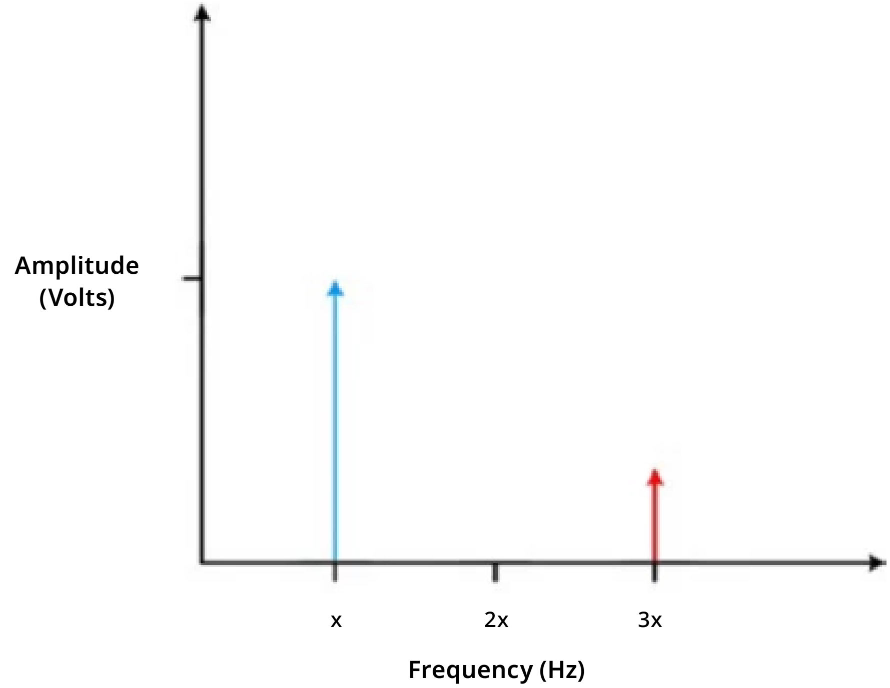


Figure 23. The highest spike is the frequency of the largest amplitude.

It can also be helpful to look at the shape of the signal in the frequency domain. For instance, let's look at the square wave in the frequency domain. We created the square wave using many sine waves at varying frequencies; as such, you would expect many spikes in the signal in the frequency domain—one for each signal added. If you see a nice ramp in the frequency domain, you know the original signal was a square wave.

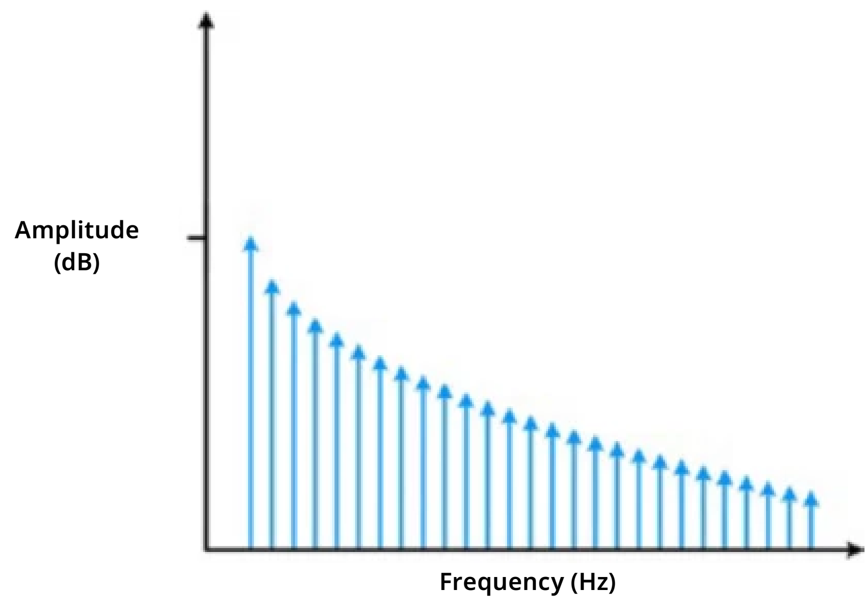


Figure 24. The frequency domain of a sine wave looks like a ramp.

So, what does this look like in the real world? Many mixed-signal oscilloscopes (MSOs) have an FFT function. Below, you can see what an FFT of a square wave looks like on a mixed-signal graph. If you zoom in, you can actually see the individual spikes in the frequency domain.

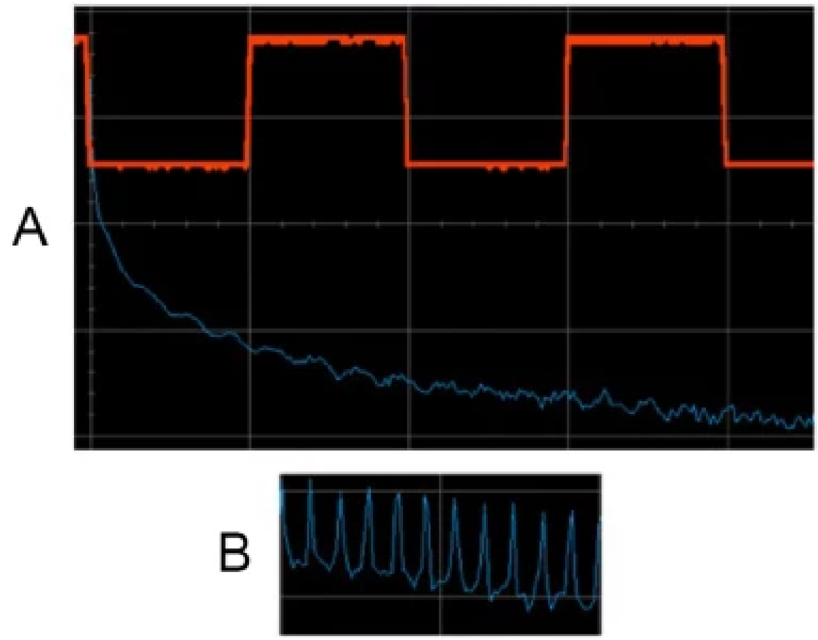


Figure 25. The original sine wave and its corresponding FFT are displayed in A, while B is a zoomed in portion of the FFT where you can see the individual spikes.

Looking at signals in the frequency domain can help when validating and troubleshooting signals. For instance, say you have a circuit that is supposed to output a sine wave. You can view the output signal on the oscilloscope in the time domain in Figure 26 below—nearly coherent!

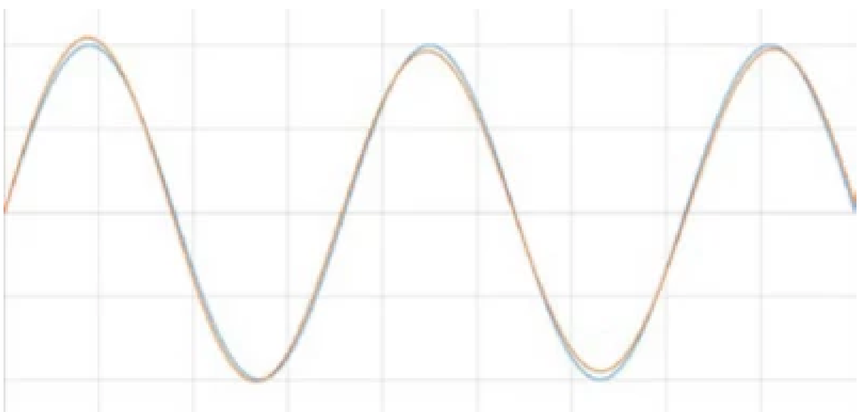


Figure 26. If these two waves were added, they would look like a perfect sine wave because they are so similar.

However, when you view the signal in the frequency domain, you expect only one spike because you are expecting to output a single sine wave at only one frequency. And, you can see that there is a smaller spike at a higher frequency; this is telling you that the sine wave isn't as good as you thought. You can work with the circuit to eliminate the cause of the noise added at that particular frequency. The frequency domain is great at showing if a clean signal in the time domain actually contains cross talk, noise, or jitter.

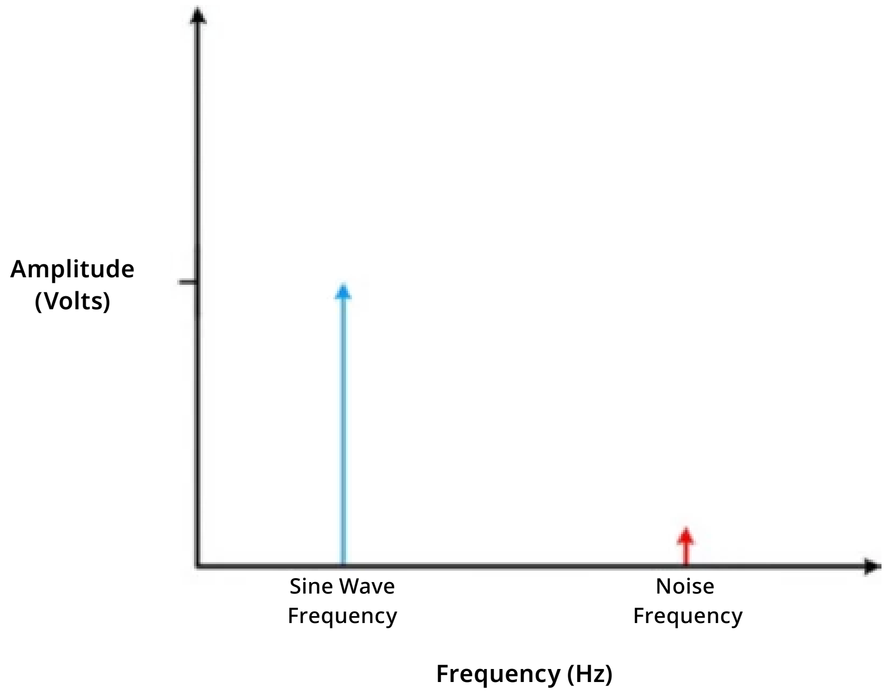


Figure 27. Looking at the seemingly perfect sine wave from Figure 26, you can see here that there is actually a glitch.

Windowing

Although performing an FFT on a signal can provide great insight, it is important to know the limitations of the FFT and how to improve the signal clarity using windowing.

How Windowing Works

When you use the FFT to measure the frequency component of a signal, you are basing the analysis on a finite set of data. The actual FFT transform assumes that it is a finite data set, a continuous spectrum that is one period of a periodic signal. For the FFT, both the time domain and the frequency domain are circular topologies, so the two endpoints of the time waveform are interpreted as though they were connected. When the measured signal is periodic, and an integer number of periods fill the acquisition time interval, the FFT turns out fine, as it matches this assumption.

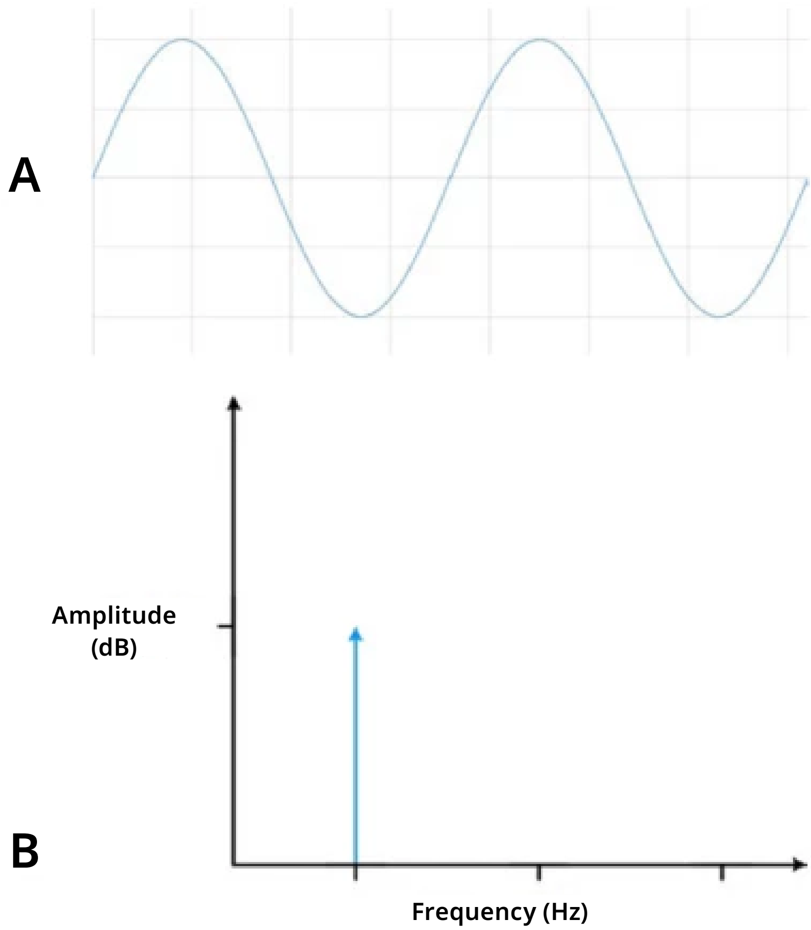


Figure 28. Measuring an integer number of periods (A) gives an ideal FFT (B).

However, many times, the measured signal isn't an integer number of periods. Therefore, the finiteness of the measured signal may result in a truncated waveform with different characteristics from the original continuous-time signal, and the finiteness can introduce sharp transition changes into the measured signal. The sharp transitions are discontinuities.

When the number of periods in the acquisition is not an integer, the endpoints are discontinuous. These artificial discontinuities show up in the FFT as high-frequency components not present in the original signal. These frequencies can be much higher than the Nyquist frequency and are aliased between 0 and half of your sampling rate. The spectrum you get by using an FFT, therefore, is not the actual spectrum of the original signal, but a smeared version. It appears as though energy at one frequency leaks into other frequencies. This phenomenon is known as spectral leakage, which causes the fine spectral lines to spread into wider signals.

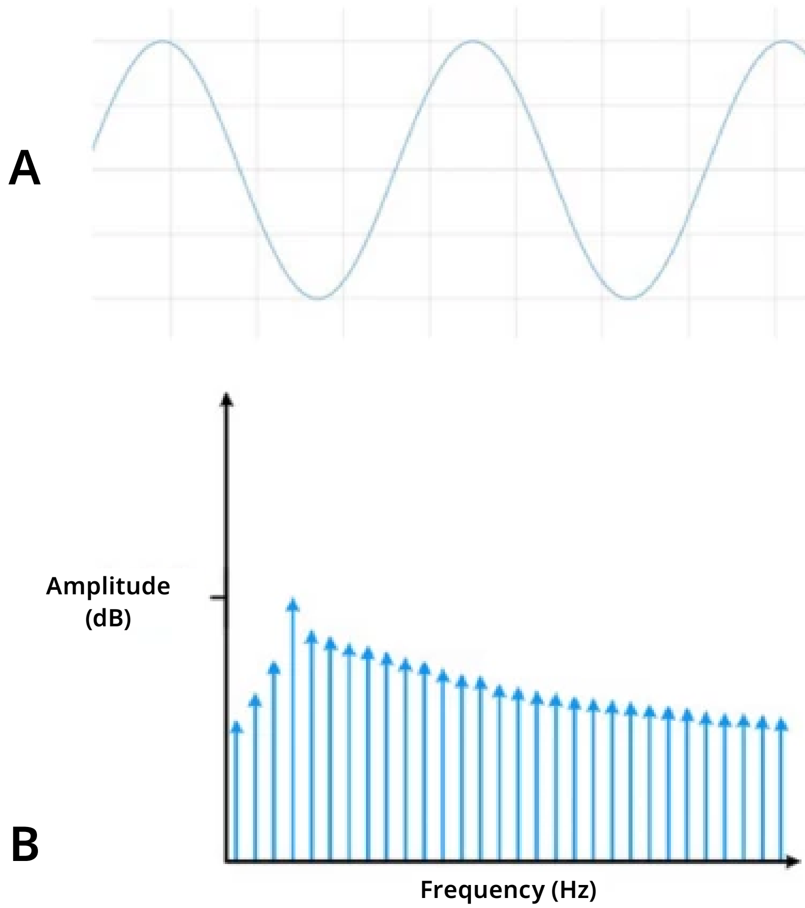


Figure 29. Measuring a noninteger number of periods (A) adds spectral leakage to the FFT (B).

You can minimize the effects of performing an FFT over a noninteger number of cycles by using a technique called windowing. Windowing reduces the amplitude of the discontinuities at the boundaries of each finite sequence acquired by the digitizer. 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. This technique is also referred to as applying a window.

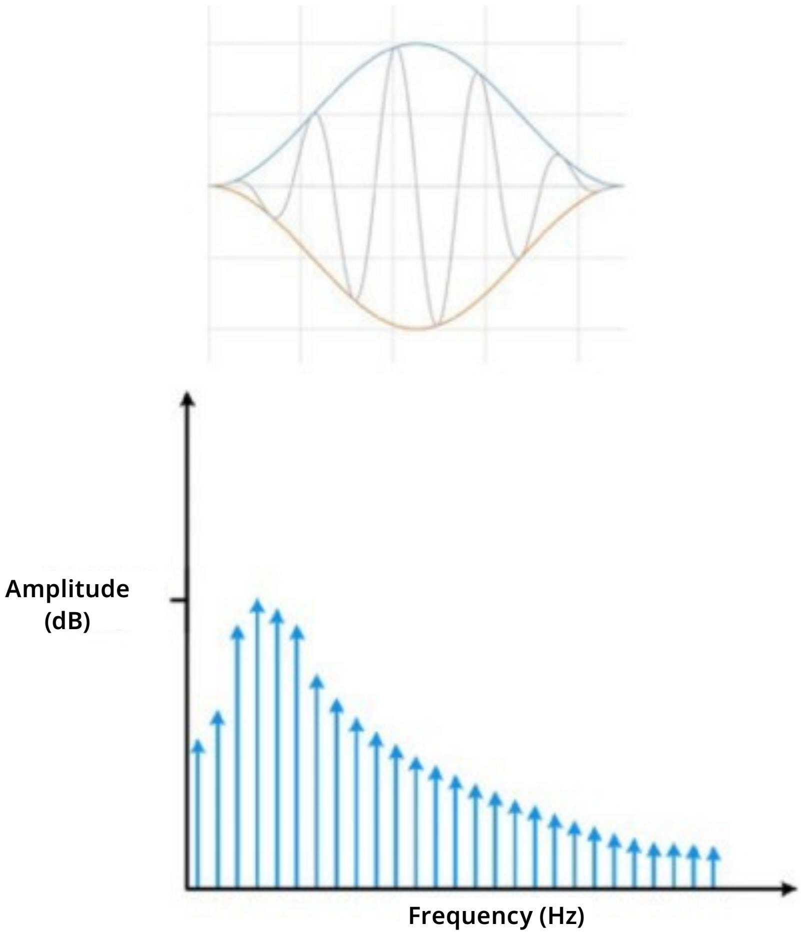


Figure 30. Applying a window minimizes the effect of spectral leakage.

Windowing Functions

There are several different window functions that you can apply, depending on the signal. To understand how a given window affects the frequency spectrum, you need to understand more about the frequency characteristics of windows.

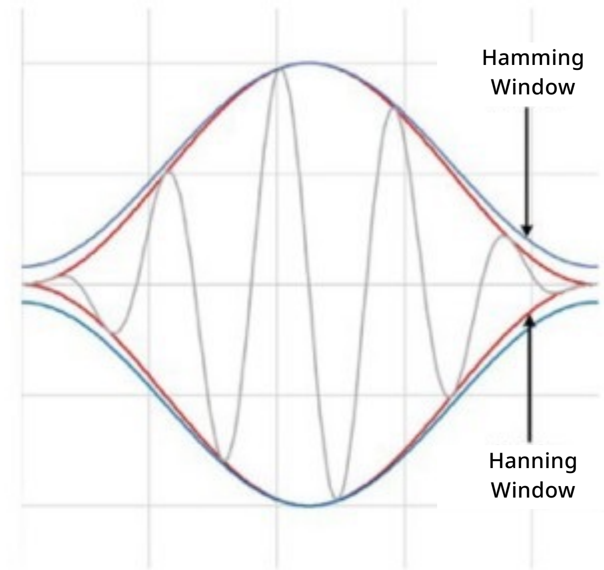
An actual plot of a window shows that the frequency characteristic of a window is a continuous spectrum with a main lobe and several side lobes. The main lobe is centered at each frequency component of the time-domain signal, and the side lobes approach zero. The height of the side lobes indicates the effect the windowing function has on frequencies around main lobes. The side lobe response of a strong sinusoidal signal can overpower the main lobe response of a nearby weak sinusoidal signal. Typically, lower side lobes reduce leakage in the measured FFT, but increase the bandwidth of the major lobe. The side lobe roll-off rate is the asymptotic decay rate of the side lobe peaks. By increasing the side lobe roll-off rate, you can reduce spectral leakage.

Selecting a window function is not a simple task. Each window function has its own characteristics suitable for specific applications. To choose a window function, you must estimate the frequency content of the signal:

- If the signal contains strong interfering frequency components distant from the frequency of interest, choose a smoothing window with a high side lobe roll-off rate.
- If the signal contains strong interfering signals near the frequency of interest, choose a window function with a low maximum side lobe level.
- If the frequency of interest contains two or more signals very near each other, spectral resolution is important. In this case, it is best to choose a smoothing window with a very narrow main lobe.
- If the amplitude accuracy of a single frequency component is more important than the exact location of the component in a given frequency bin, choose a window with a wide main lobe.
- If the signal spectrum is rather flat or broadband in frequency content, use the uniform window, or no window.
- In general, the Hanning (Hann) window is satisfactory in 95 percent of cases. It has good frequency resolution and reduced spectral leakage. If you do not know the nature of the signal but want to apply a smoothing window, start with the Hann window.

Even if you use no window, the signal is convolved with a rectangular-shaped window of uniform height, by the nature of taking a snapshot in time of the input signal and working with a discrete signal. This convolution has a sine function characteristic spectrum. For this reason, no window is often called the uniform or rectangular window because there is still a windowing effect.

The Hamming and Hann window functions both have a sinusoidal shape. Both windows result in a wide peak but low side lobes. However, the Hann window touches zero at both ends eliminating all discontinuity. The Hamming window doesn't quite reach zero, and thus still has a slight discontinuity in the signal. Because of this difference, the Hamming window does a better job of cancelling the nearest side lobe, but a poorer job of canceling any others. These window functions are useful for noise measurements where you desire better frequency resolution than some of the other windows, but moderate side lobes do not present a problem.



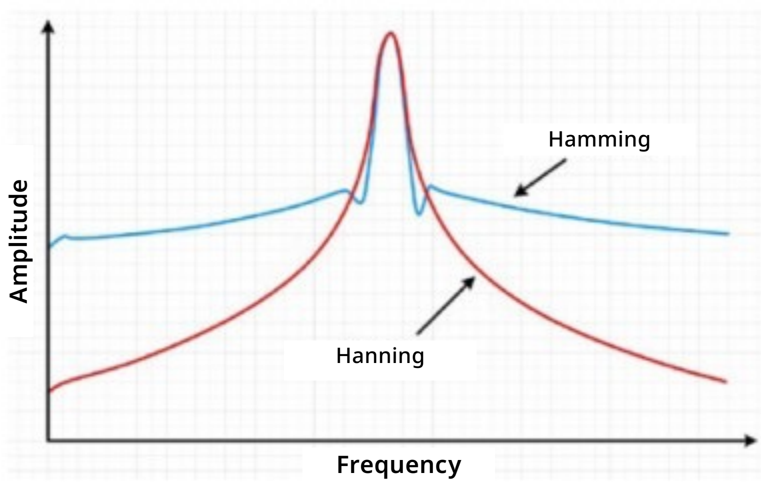
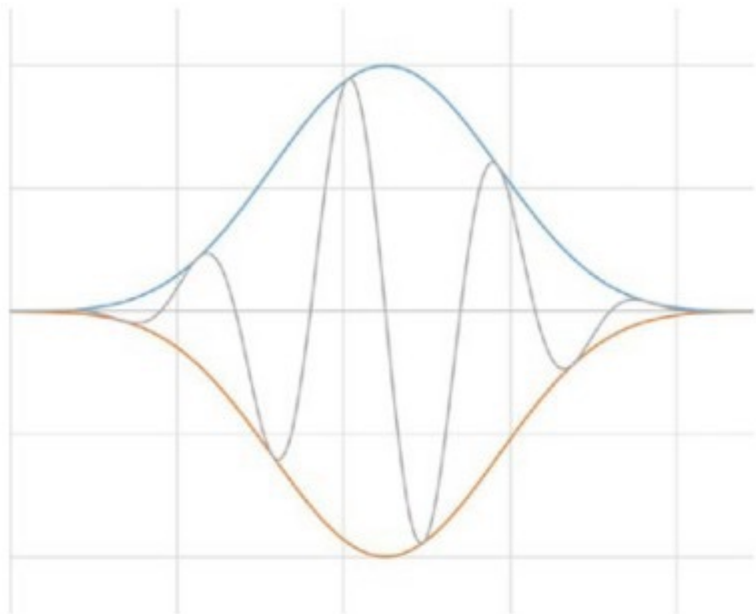


Figure 31. Hamming and Hann windowing result in a wide peak but nice low side lobes.

The Blackman-Harris window is similar to Hamming and Hann windows. The resulting spectrum has a wide peak, but good side-lobe compression. There are two main types of this window: The 4-term Blackman-Harris is a good general-purpose window, having side lobe rejection in the high 90s dB and a moderately wide main lobe. The 7-term Blackman-Harris window function has all the dynamic range you should ever need, but it comes with a wide main lobe.



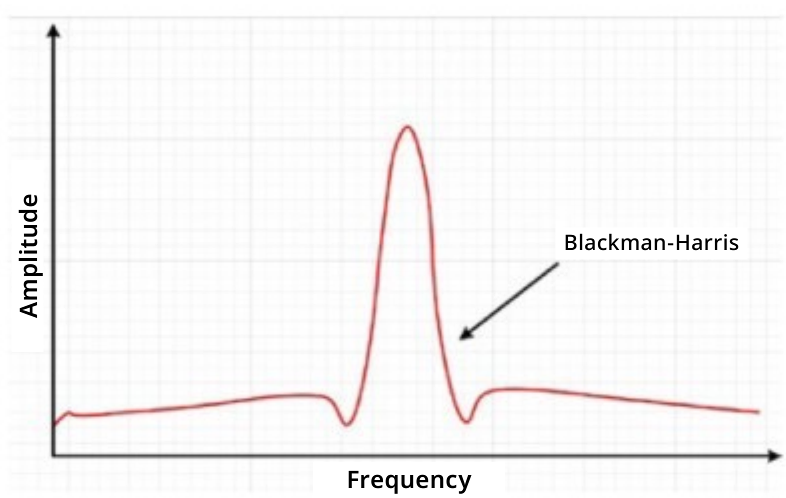


Figure 32. The Blackman-Harris results in a wide peak, but good side lobe compression.

A Kaiser-Bessel window strikes a balance among the various conflicting goals of amplitude accuracy, side lobe distance, and side lobe height. It compares roughly to the Blackman-Harris window functions, but for the same main lobe width, the near side lobes tend to be higher, while the further-out side lobes are lower. Choosing this window often reveals signals close to the noise floor.

The flat top window is sinusoidal, as well, but it actually crosses the zero line. This causes a much broader peak in the frequency domain, which is closer to the true amplitude of the signal than with other windows.

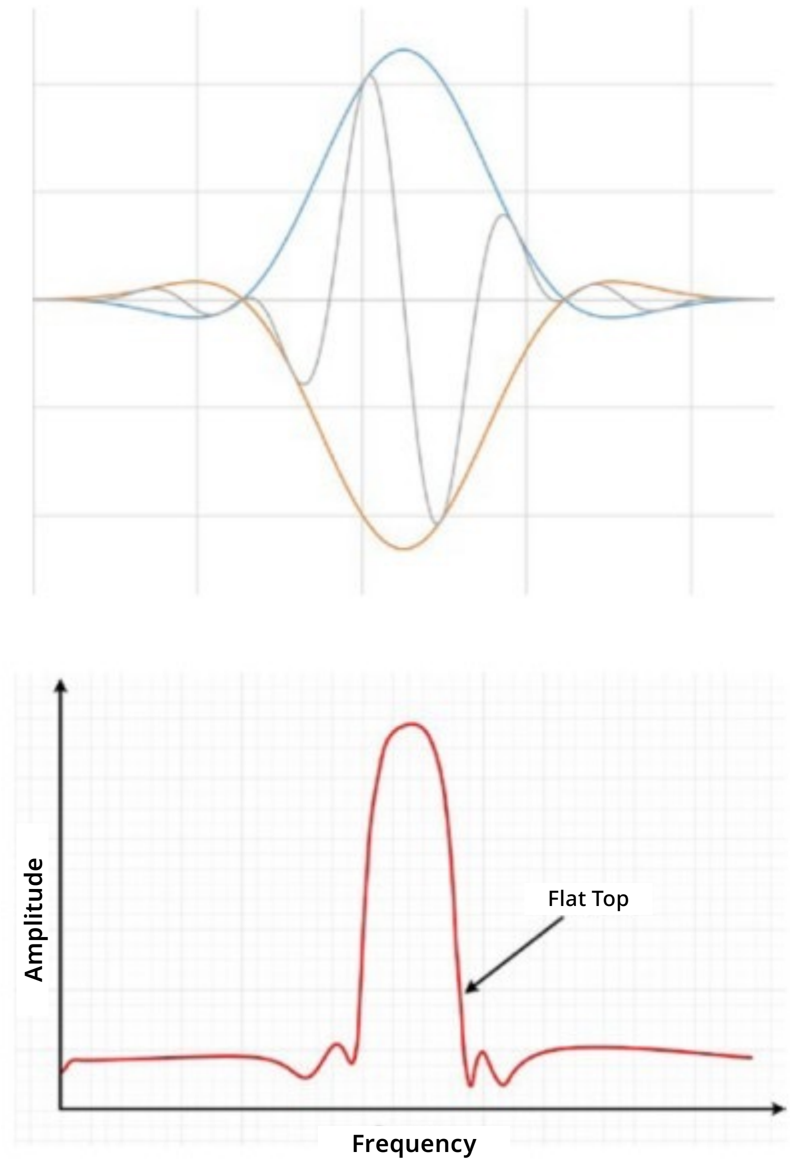


Figure 33. The flat top window results in more accurate amplitude information.

These are just a few of the possible window functions. There is no universal approach for selecting a window function. However, the table below can help you in your initial choice. Always compare the performance of different window functions to find the best one for your application.

Signal Content	Window
Sine wave or combination of sine waves	Hann
Sine wave (amplitude accuracy is important)	Flat Top
Narrowband random signal (vibration data)	Hann
Broadband random (white noise)	Uniform
Closely spaced sine waves	Uniform, Hamming
Excitation signals (hammer blow)	Force
Response signals	Exponential
Unknown content	Hann
Sine wave or combination of sine waves	Hann
Sine wave (amplitude accuracy is important)	Flat Top
Narrowband random signal (vibration data)	Hann
Broadband random (white noise)	Uniform
Two tones with frequencies close but amplitudes very different	Kaiser-Bessel
Two tones with frequencies close and almost equal amplitudes	Uniform
Accurate single tone amplitude measurements	Flat Top

To summarize:

- All signals in the time domain can be represented by a series of sines.
- An FFT transform deconstructs a time domain representation of a signal into the frequency domain representation to analyze the different frequencies in a signal.
- The frequency domain is great at showing you if a clean signal in the time domain actually contains cross talk, noise, or jitter.
- Spectral leakage is caused by discontinuities in the original, noninteger number of periods in a signal and can be improved using windowing.
- Windowing reduces the amplitude of the discontinuities at the boundaries of each finite sequence acquired by the digitizer.
- No window is often called the uniform or rectangular window because there is still a windowing effect.
- In general, the Hanning window is satisfactory in 95 percent of cases. It has good frequency resolution and reduced spectral leakage.
- You should compare the performance of different window functions to find the best one for the application.

Dithering, Layout, and High-Quality Components: Tools to Decrease the Noise Floor

Scientists and engineers taking analog measurements often use the term noise floor, but it is often misunderstood and, as a result, not used correctly. To reduce noise that occurs on your measurements, you need to have a firm understanding of the noise floor, its components, and what you can do to decrease it in your measurement system:

- Introducing Noise Floor
- Noise Floor Components
- Minimizing Noise Floor
- Further Decreasing Your Noise Floor

Introducing Noise Floor

The noise floor of a measurement device is the measured noise level with its inputs grounded.

You will usually see it expressed either as a noise density function with units of $^{V}/_{\sqrt{Hz}}$, or as a single number representing the total noise, expressed in V_{rms}. To convert from a noise density function to V_{rms}, you must integrate the noise density function over your bandwidth of interest. In the case of wide band (flat) noise, this integration breaks down into simple multiplication, where

$$V_{RMS} = \sqrt{Bandwidth} \times noise\ density$$

In general, you can derive the RMS noise of a device from the noise density function, but you cannot get the shape of a graph from a single number. The figure below illustrates a typical measurement device's noise density curve at low frequencies. This curve consists of the two sections in the figure. The steeply sloping portion to the left of the point, known as the $^{1}/_{f}$ corner is referred to as $^{1}/_{f}$ noise. To the right of the $^{1}/_{f}$ corner, the noise level flattens out and is known as wideband noise.

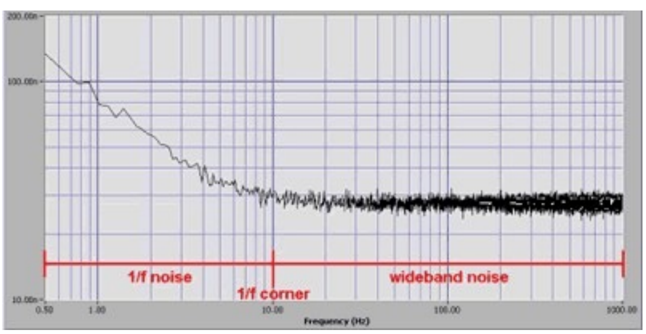


Figure 34. Noise Spectral Density Curve

Noise Floor Components

Wideband noise generally appears flat in the frequency domain, meaning that equal energy occurs in every Hz of bandwidth. This type of noise can result from almost every component in the measurement device, whether they reside in the signal path, or you use them for reference. These components include op amps, resistors, voltage references, and analog-to-digital converters (ADCs). Using post-processing techniques such as averaging helps minimize the effects of wide band noise on your measurement accuracy. We will discuss these techniques later.

$^{1}/_{f}$ noise, however, is more complex. It is referred to as $^{1}/_{f}$ noise because its voltage density is proportional the square root of frequency. You may also hear $^{1}/_{f}$ noise referred to as "flicker noise" because it causes the least significant bit on a DMM to flip or "flicker." Thermal gradients among board components and contamination during

IC manufacturing processes are the primary causes of this noise. These causes make $1/f$ noise difficult to predict and control, and IC manufacturers generally do not adequately specify the impact of $1/f$ noise. DAQ device end users may find this especially troublesome, because you cannot remove this uncertainty with any post-processing operations. For example, the longer you average, the more opportunity for drift. Therefore, depending on the $1/f$ slope, you may never converge on the "true" value, regardless of how much you average. In fact, as far as it has been proven, the $1/f$ spectrum continues its upward slope to the left, limited only by the aperture of your measurement. IC manufacturers have seen strong correlation between $1/f$ noise levels and the long- term drift of the voltage references they manufacture.

Minimizing Noise Floor

NI has minimized wideband noise on DAQ devices by designing them with high-quality amplifiers with a high common mode rejection ratio (CMRR). This means that the devices reject a significant portion of the noise experienced on both terminals of the amplifier, making your measurements less susceptible to common mode noise that can decrease accuracy.

NI designs **multifunction DAQ** devices with separated ground planes that connect to a single ground reference. Analog-to-digital and digital-to-analog converter chips are commonly designed with analog signals on one side of the chip and digital signals on the other. By placing the converter chips so they straddle the barrier between the analog and digital ground planes, noise generated on the digital side of the data acquisition board does not affect the analog side of the chip or the traces residing around the analog ground plane.

Thermal gradients in the measurement device can often induce $1/f$ noise. To combat this, NI measurement devices incorporate several features to experience minimal temperature drift. NI uses matched, temperature-tracking circuits, and custom resistor networks restrict temperature drift to 6 ppm/°C on all DAQ hardware. In addition, NI uses high-quality components with $1/f$ and drift characteristics that have been well-defined. Finally, NI self-calibration circuitry, accessible by a single function call, references a highly stable voltage source that drifts at a rate of only 0.6 ppm/°C.

Further Decreasing Your Noise Floor

While some types of noise result from imperfections in ICs, or environmental factors such as temperature, the device's resolution also can create noise. This is known as quantization error.

With NI **driver software**, you can take advantage of dithering. This adds approximately 0.5 LSB_{rms} of Gaussian white noise to the input signal. This noise is added to the signal before the input to the ADC. As a result, a signal that might fall somewhere in the smallest voltage difference that the board can detect (known as code width and defined by the formula $\frac{Range}{\#\ of\ codes}$) now randomly bounces above and below the boundaries of that code. When sampled, points now appear on both the top and bottom boundaries, and the number of points on either the top or bottom of the code width are weighted based on the location of the actual signal. You then can use averaging to essentially zoom in past the specified resolution of the board, providing more accurate measurements that are less influenced by wide band noise. For instance, a 12-bit board can perform with 14-bit resolution with dithering enabled. You can also disable dithering for high-speed applications that do not use averaging.

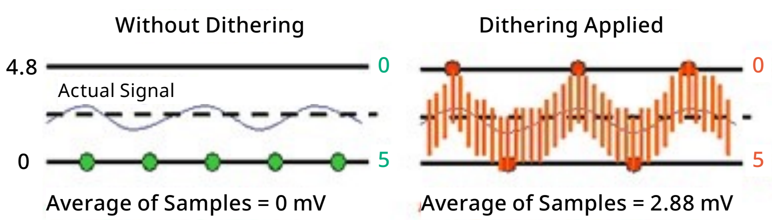


Figure 35. You can decrease quantization error on 12-bit devices using dithering.

These techniques not only reduce noise caused by nonideal components on the measurement device, but they also help reduce noise originating from other components of the measurement system. In addition, $^1/_f$ noise at the system level can result from the sensor, so choose a high-quality sensor to help ensure a lower noise floor for your overall system. The environment, long wires, nearby electromagnetic fields, and other sources also may induce noise on the system. To reduce noise from external sources, ground your system properly and use shielded cables.

To summarize:

- Noise floor is the baseline level of noise in a measurement system, typically expressed in V_{RMS} or as a noise density function; understanding its components is key to improving measurement accuracy.
- Wideband noise is flat across frequencies and originates from components including op amps, resistors, and ADCs; it can be reduced using techniques such as averaging.
- $^1/_f$ noise (flicker noise) increases at lower frequencies and is harder to control, as it is often caused by thermal gradients and IC manufacturing imperfections.
- NI minimizes noise through careful layout design, including separated analog and digital ground planes, high-CMRR amplifiers, and temperature-tracking circuits.
- Dithering adds controlled Gaussian noise before ADC conversion to reduce quantization error, effectively increasing resolution (e.g., 12-bit boards can behave like 14-bit).
- Self-calibration and component quality (for example, low drift voltage references) further reduce internal noise sources in NI DAQ devices.
- External noise from sensors, wiring, and environment can be mitigated with proper grounding, shielding, and sensor selection.

Grounding for Improved Measurements

Grounding helps determine how a measurement system should be connected for the most accurate measurements:

- Grounding and Measurements
- Signal Sources
- Measurement Systems
- Signal Source–Measurement System Configurations

Grounding and Measurements

Measurement systems vary in grounding configurations because signal sources also have different grounding configurations. This is essential to ensure accurate measurement; however, this flexibility adds some difficulty when choosing the grounding configuration of the measurement system.

Figure 36 shows a block diagram of components used to make a measurement. On the right, a measurement system is comprised of an instrument and signal conditioning (note that you can integrate signal conditioning in your instrument or keep it external to the instrument). On the left, we have the signal source, which could be a single transducer producing a voltage from physical phenomena or a DUT. We'll use this diagram to discuss grounding on the signal source, grounding on the measurement system, and finally, how to choose a measurement system configuration to ensure minimal measurement noise and error.

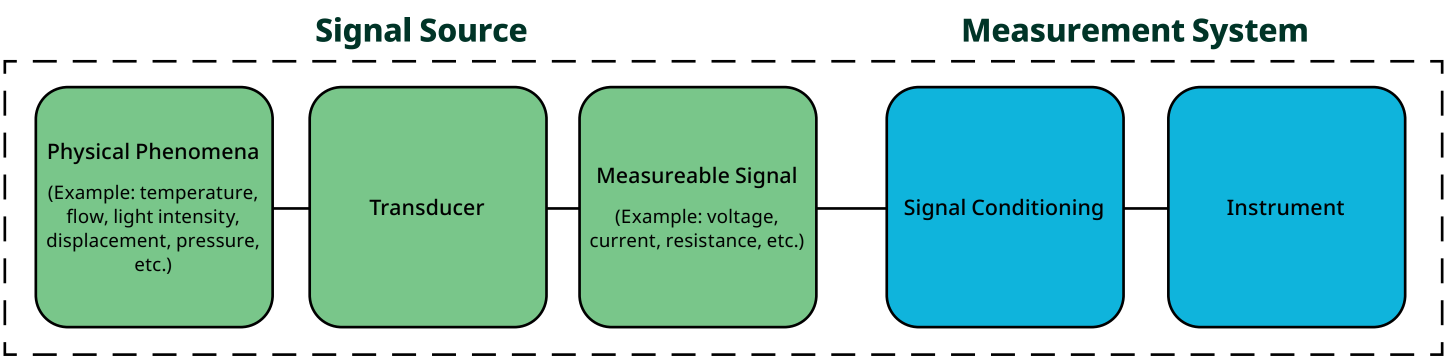


Figure 36. A signal source is fed into a measurement system that comprises an instrument and signal conditioning.

Signal Sources

There are two main signal sources we'll use for this discussion, both shown in schematic form in Figure 37.

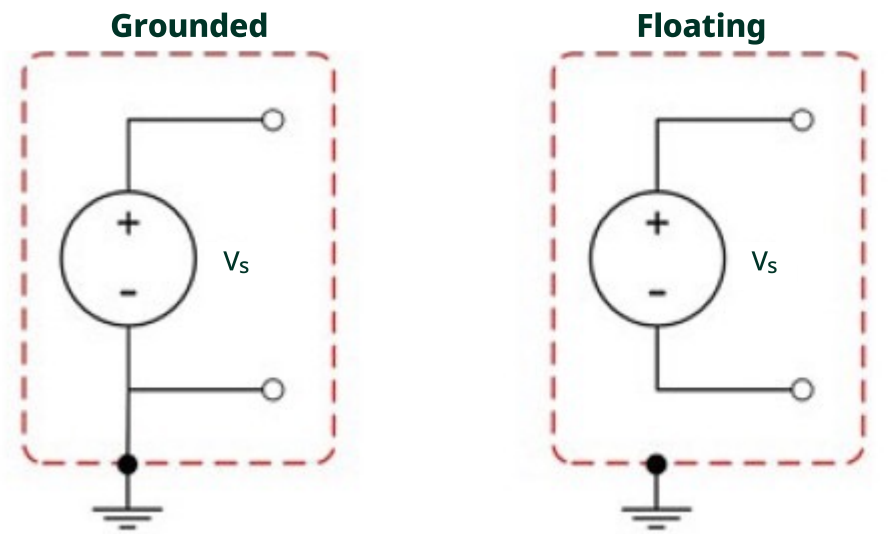


Figure 37. It is important to know if your signal is grounded or floating.

Grounded or Ground-Referenced Signal Sources

A grounded signal source occurs when a voltage signal is referenced to a system ground, such as earth or building ground. This is represented by the schematic on the left of Figure 37, because the voltage signal has a direct electrical path to the system ground. The most common examples of grounded sources are devices that plug into the building ground through three-pronged wall outlets such as signal generators and power supplies. It is important to know that the grounds of two independently grounded signal sources are typically not at the same potential. The difference in ground potential between two systems connected to the same building ground can be 10 mV, 200 mV, or more.

Ungrounded or Floating Signal Sources

An ungrounded or floating signal source is one in which the voltage signal is not referenced to a system ground, such as earth or building ground. This is represented on the right in Figure 37. Note that neither the positive nor negative terminal has a direct electrical path to a ground. Some common floating signal sources are batteries, thermocouples, and transformers.

Measurement Systems

You can configure instruments in one of three modes: differential (DIFF), referenced single-ended (RSE), or nonreferenced single-ended (NRSE).

Differential Measurement Systems

A differential instrument requires two inputs, where neither input to the instrumentation amplifier is referenced to a system ground. This is illustrated in Figure 38, where CH0+ and CH0- are wired into the positive and negative terminals of the instrumentation amplifier, respectively, but they are not connected to the measurement system ground (AI GND).

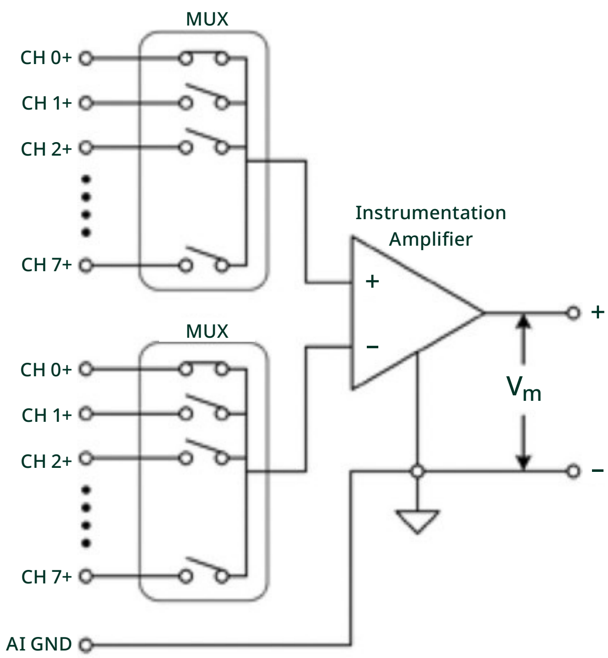


Figure 38. An ideal differential acquisition system responds to only the voltage difference between its two terminals.

An ideal differential acquisition system responds to only the voltage difference between its two terminals, the positive (+) and negative (-) inputs. The differential voltage across the circuit pair is the desired signal, yet an unwanted signal that is common to both sides of a differential circuit pair can exist. This voltage is known as common-mode voltage. An ideal differential measurement system completely rejects, instead of measures, the common-mode voltage for more accurate measurements. Practical devices, however, have limitations described by specifications such as common-mode voltage range and common-mode rejection ratio (CMRR).

The common-mode voltage range is the maximum allowable voltage swing on each input with respect to the instrument ground. To violate this constraint results in not only measurement error but also possible damage to instrument components. Here is the formula to calculate the common-mode voltage:

$$V_{CM} = \frac{V_{IN+} + V_{IN-}}{2}$$

where

V_{CM} = Common-mode voltage

V_{IN+} = Voltage at noninverting input terminal with respect to measurement ground

V_{IN-} = Voltage at inverting input terminal with respect to measurement ground

An example of violating the common-mode voltage range specification would be to attempt a differential measurement with one lead at 110 V and the other lead at 100 V. Although the differential measurement is 10 V, which may be within specification for the device, the common-mode voltage would be 105 V, and this may not be within the specification of the instrument.

CMRR describes the ability of a measurement system to reject common-mode voltages. Amplifiers with higher CMRRs are more effective at rejecting common-mode voltages and are, therefore, more desirable for accurate measurements. The CMRR can be described as a ratio of the differential gain over the common-mode gain, as seen in the first equation below. CMRR can also be described in dB, as shown in the second.

$$CMRR = \frac{|Differential\ Gain|}{|Common\ Mode\ Gain|}$$

$$CMRR_{dB} = 20log_{10}\left(\frac{Differential\ Gain}{Common\ Mode\ Gain}\right)$$

For example, if the instrument has a CMRR of 100,000:1 (or 100 dB) and the common-mode voltage is 5 V, you can distinguish voltage differences greater than 50 µV on the differential leads. Common-mode rejection is critical because noise sources from the environment are present on both lines of the differential measurement. However, if the noise is present on both lines, it is cancelled out by the differential measurement. For this reason, differential configurations lead to more accurate measurements in comparison to single-ended measurements, but differential measurements require double the channel count compared to single-ended measurements.

Single-Ended Measurement Systems

Single-ended configurations are commonly the default configuration for instruments. They differ from differential configurations because only one analog input channel is required for the measurement. All channels on the instrument use the negative input to the instrumentation amplifier as the common reference, shown in Figure 39. Because single-ended configurations use only one input, they can take twice the number of measurements compared to a differential configuration system with the same number of physical channels. On the other hand, this leaves single-ended measurements susceptible to ground loops, which can decrease the accuracy of the measurements.

Below are two different types of single-ended measurement systems:

- **Ground RSE (GRSE) or RSE systems** have the common reference channel connected to the instrument ground. In the example RSE system shown in Figure 39, the instrument ground channel is labeled AI GND.

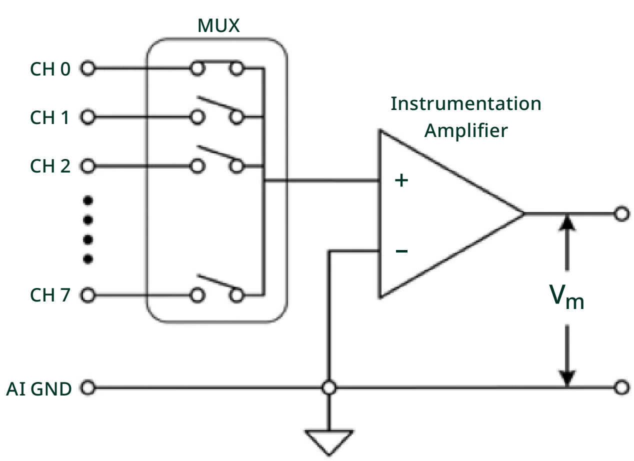


Figure 39. A GRSE or RSE system's common reference channel is connected to the instrument ground.

- **NRSE** instruments reference a common point; however, the common point is the voltage provided at the negative terminal of the instrumentation amplifier. In the NRSE example shown in Figure 40, the common reference is the AI SENSE line; therefore, the measured voltage is the potential difference between CH X and the voltage at the AI SENSE channel.

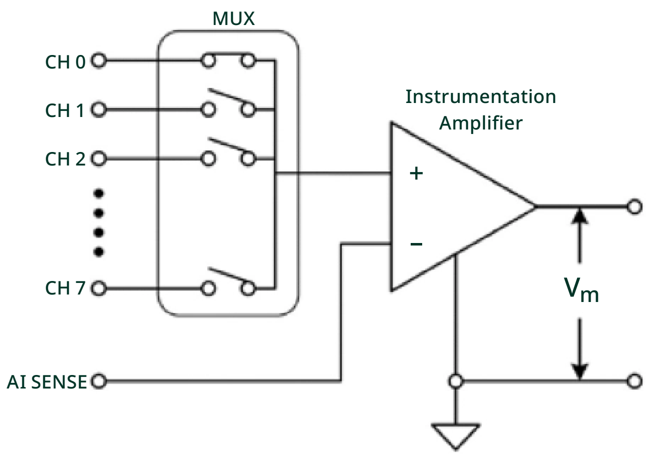


Figure 40. An NRSE instrument's common point is the voltage provided at the negative terminal of the instrumentation amplifier.

Signal Source–Measurement System Configurations

After characterizing both the signal source grounding types and the instrument configurations, let's discuss which combinations of signal sources and instrument configurations can yield the most accurate results.

Measuring Grounded Signal Sources

A grounded signal source is most accurately measured with a differential or NRSE instrument configuration because an additional ground is not introduced into the entire system. An additional ground added to the system can result in ground loops, which are common sources of noise in measurement applications.

Ground loops occur when two connected terminals in a circuit are at different ground potentials, causing current to flow between the two points. The ground of the signal source can be several volts above or below the ground of the instrument. This additional voltage can cause error in the measurement itself, and the flowing current can also induce voltages on nearby wires, causing additional measurement error. These errors can appear as scalar or periodic signals added to the measured signal. For example, if a ground loop is formed with a 60 Hz AC power line, the standard power line frequency in the United States and some other countries, the unwanted 60 Hz AC signal can appear as a periodic voltage error in the measurement.

To calculate the measured voltage, V_m, use the equation:

$$V_m = V_s + \Delta V_g$$

where

V_m = Measured Voltage

V_s = Signal Voltage

ΔV_g = Voltage difference between the signal source ground and the measurement system ground

Using the above equation mathematically gives you the measured voltage when a ground loop is present. If you continue to use the 60 Hz power line example, ΔV_g is a value that changes with time instead of a scalar offset. Therefore, the measured signal looks periodic instead of like a simple offset error for the measured voltage.

Figure 41 shows what a system with a ground loop looks like in schematic form. If you are measuring the voltage source V_s with an instrument using an RSE configuration, you can simplify the schematic on the left of the equation with the schematic on the right of the equation in Figure 41, which agrees with the calculations in the equation above.

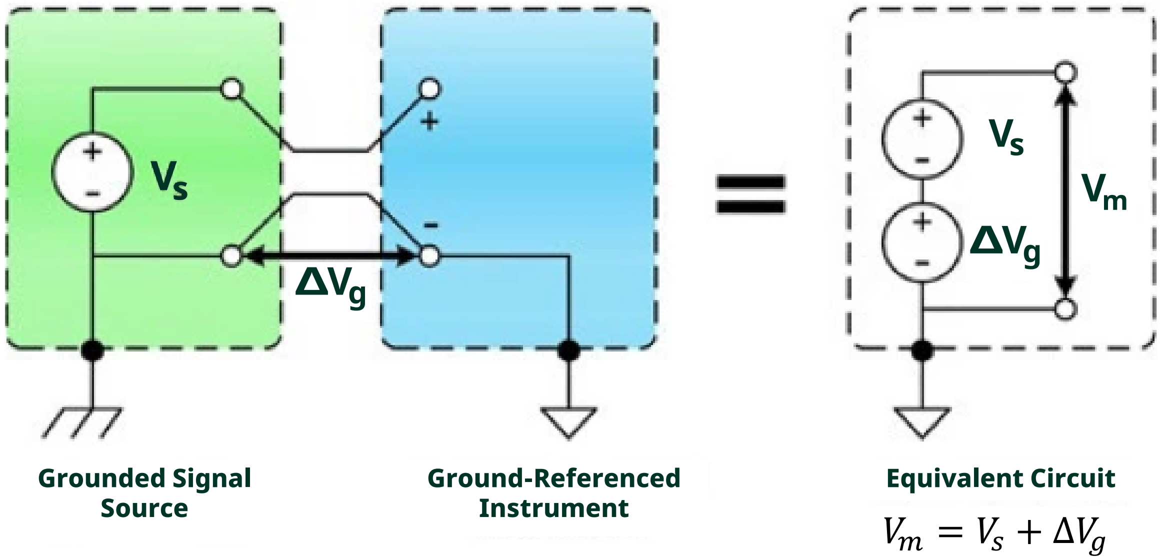


Figure 41. A grounded signal source measured with a ground-referenced system introduces ground loops and measurement error.

To avoid ground loops as shown in Figure 41, ensure only one ground reference exists in the signal source and the measurement system by using a differential or NRSE instrument configuration or by using isolated measurement hardware, which is discussed in the **Isolation Types and Considerations when Taking a Measurement** white paper of the Instrument Fundamentals Series.

Measuring Floating Signal Sources

You can measure floating signal sources with any of the measurement configurations discussed: Differential, GRSE/RSE, or NRSE. Note that, when using differential or NRSE measurement configurations with a floating source, you must include bias resistors from each lead, positive (+) and negative (-), to the instrument ground (see Figure 42).

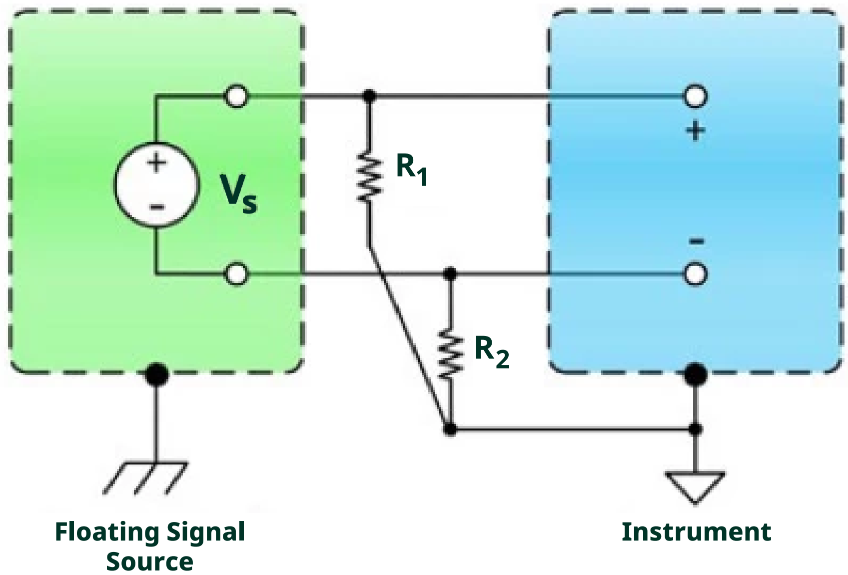


Figure 42. When measuring a floating signal source with a differential or NRSE instrument configuration, use bias resistors.

Bias resistors provide a DC path from the instrument amplifier inputs to the instrument amplifier ground. Bias resistors should have a high enough resistance to not load the signal source and to allow the signal source to float with respect to the instrument reference. However, the bias resistors should be small enough to keep the voltage within the range of the instrument. This typically results in bias resistors with a range of 10 kΩ to 100 kΩ to satisfy the conditions. You should always double-check the specifications guide of your device to ensure you use a bias resistor value that is within the suitable range.

If you do not use bias resistors in a differential or NRSE configuration when measuring floating signal sources, the measured signals can be unstable or at positive or negative full-scale range of the instrument.

When you use a GRSE/RSE configuration to measure a floating signal source, bias resistors are not necessary. To get the best measurement results when using single-ended instrument configurations, ensure that:

- Input signals are equal to or greater than 1 V.
- Signal cabling is relatively short and travels through a noise-free environment (or is properly shielded).
- All input signals can share a common, stable, and known reference signal–generally a point in the system where the voltage is at 0 V.

Figure 43 shows recommended combinations of signal sources and instrument configurations.

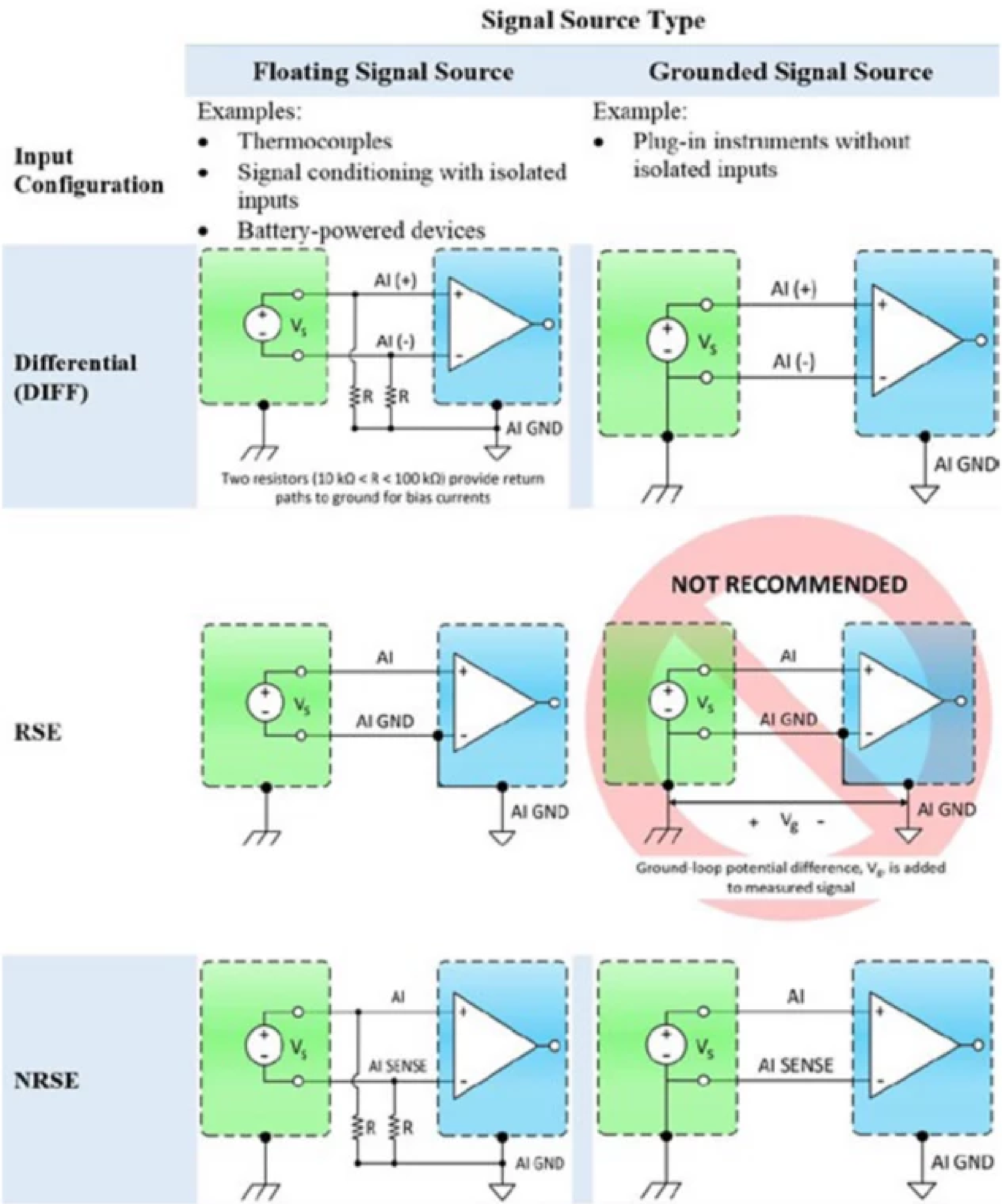


Figure 43. Instrument Configuration vs. Signal Source Type

To summarize:

- Measurement systems include an instrument and signal conditioning. Depending on the instrument, signal conditioning can be a part of the instrument or external to it.
- There are two main categories of signal sources:
  - **Grounded signal source—**Signal has a direct electrical path to ground.
  - **Floating signal source—**Signal does not have a direct electrical path to ground.
- Instruments can have three main measurement configurations:
  - **Differential**—A measurement that takes two input channels and is the most accurate configuration because it removes common-mode voltages.
  - **Ground referenced single-ended (GRSE)** or **referenced single-ended (RSE)**—A measurement that uses only one channel and the instrument ground; however, this single-ended measurement type is susceptible to noise.
  - Nonreferenced single-ended (NRSE)—A type of measurement that uses only one channel and a common reference point, which is not ground; however, this system is more susceptible to noise in comparison to differential measurements.
- Differential or NRSE instrument configurations are recommended to measure a grounded signal source.
- Differential, GRSE/RSE, or NRSE instrument configurations are recommended configurations to measure a floating signal source.
  - **Bias resistors** must be used in differential or NRSE instrument configurations to measure a floating signal source.

High-Voltage Measurements and Isolation

In this section, we'll discuss topologies used in instruments and the positive benefits that isolation can provide, including ground loops, common-mode voltage, isolation topologies, analog isolation, digital isolation, and isolation types:

- What Is Isolation?
- Isolation Topologies
- Analog versus Digital Isolation
- Isolation Types

What Is Isolation?

Isolation is a method of physically and electrically separating two distinct parts of an instrument. When the term isolation is used with instruments, it most likely refers to electrical isolation, which means that current does not flow between the two parts of the system that are isolated from each other. There are several advantages of electrical isolation but one of the largest advantages regarding measurement accuracy is that isolation breaks ground loops.

Isolation also uses the physical and electrical barriers to provide safety benefits by keeping high voltages or high transient voltages away from the user or away from important circuit components, and we'll discuss this later.

First, here's a quick review of ground loops, which are covered in more detail in the **Grounding Considerations for Improved Measurements** white paper in the Instrument Fundamental Series.

Ground Loops

Ground loops are the most common source of noise in acquisition applications. They occur when two connected terminals in a circuit are at different ground potentials, which causes current to flow between the two points. This potential difference causes error in the measured voltage, V_m, which can be calculated using the following calculation:

$$V_m = V_s + \Delta V_g$$

where

V_m = Measured voltage

V_s = Signal voltage

ΔV_g = Voltage difference between the signal source ground and the instrument ground

The Grounding Considerations for Measurements white paper discusses how to eliminate ground loops by ensuring only one ground reference exists in the signal source and measurement system setup. However, using isolated hardware also removes ground loops, because it eliminates the path for current to flow between the ground of the signal source and the ground of the measurement system.

Isolation Topologies

In general, there are three different types of isolation topologies, from a low level of protection to a high level of protection, respectively:

- Channel-to-earth isolation
- Bank (channel-to-bus) isolation
- Channel-to-channel isolation

Channel-to-Earth Isolation

This is the lowest protection level of isolation for an instrument. See Figure 44 for a schematic of channel-to-earth isolation. The voltages present at AI 1, AI 2, and AI ground are not isolated from each other; however, they are isolated from the instrument ground. This isolation topology breaks ground loops between AI 1 and the earth ground, but it is possible that a current present on AI 1 could induce a voltage on AI 2, because they are not isolated from each other.

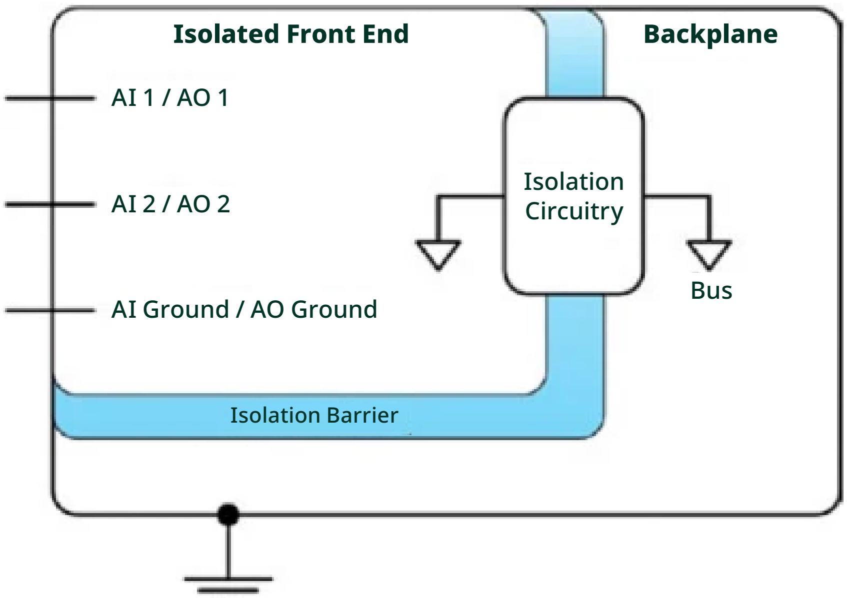


Figure 44. Channel-to-earth isolation does not isolate channels from each other but does isolate the channels from instrument ground.

Bank (Channel-to-Bus) Isolation

In bank isolation, also known as channel-to-bus isolation, several physical lines are built into groups called banks. See Figure 45 for this architecture. Because isolation barriers exist between channels in different banks, the ground loop protection is high between banks. However, it is still possible in this topology that signals on channels within a bank can affect each other.

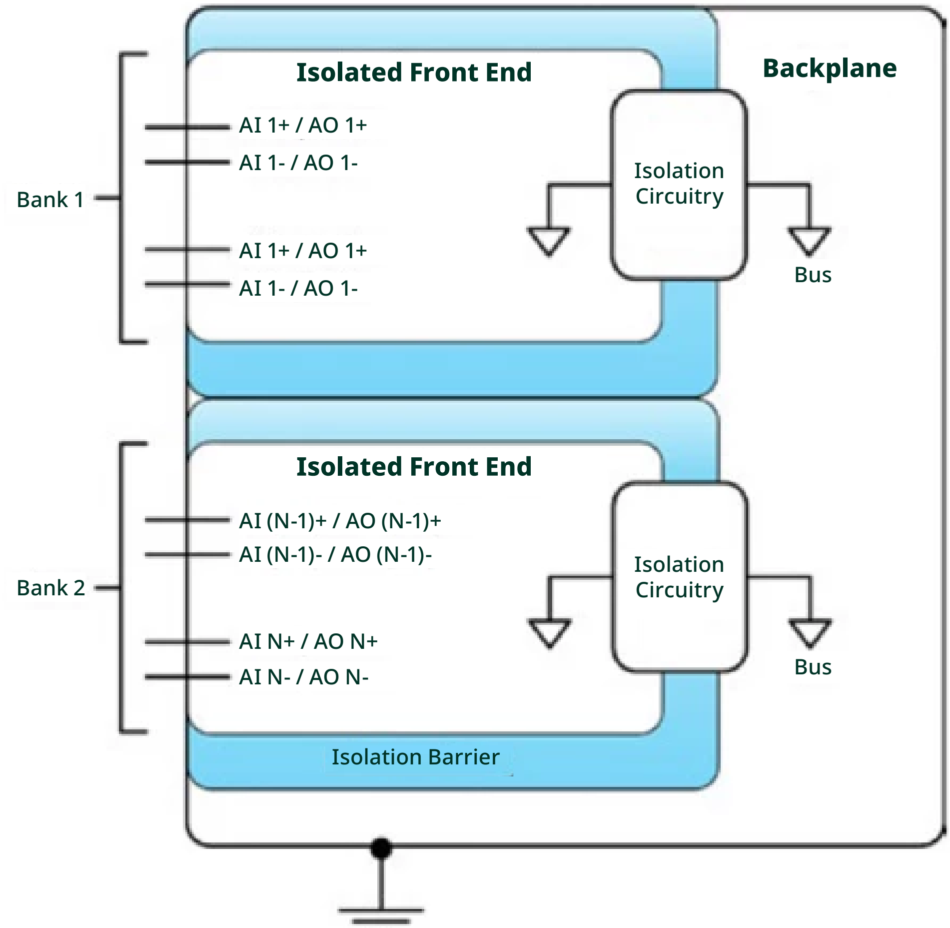


Figure 45. In bank isolation, the ground loop protection is high between different banks.

Channel-to-Channel Isolation

This topology provides the most comprehensive protection for the signals on the instrument lines because not only are all channels isolated from earth ground, but each channel is also isolated from all other individual channels. See this topology in Figure 46.

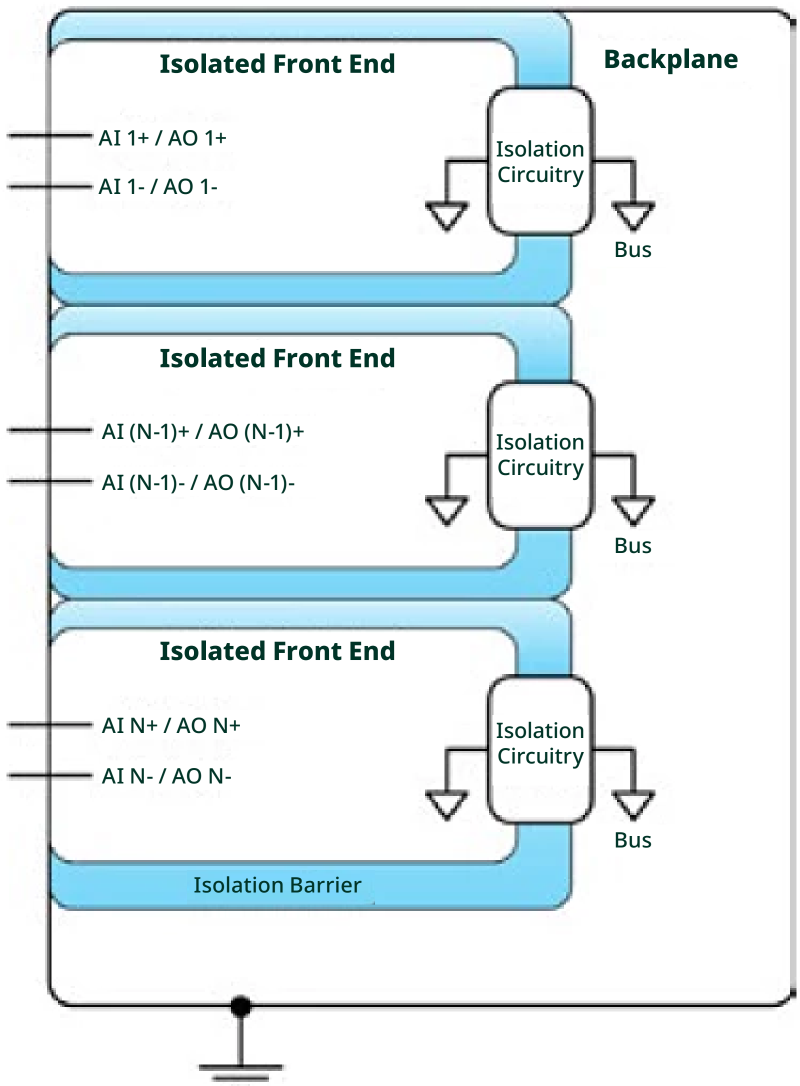


Figure 46. In channel-to-channel isolation, each channel is isolated from all other individual channels.

Analog versus Digital Isolation

Analog input or output channels can be isolated using two different methods regardless of the instrument isolation topology. The difference between the two methods lies in the location of the isolation circuitry in the instrument. Analog isolation is where the isolation circuitry is in the path prior to the analog-to-digital converter (ADC) and it acts on the analog signal. Digital isolation is where the isolation circuitry is after the ADC, because it acts on the newly digitized data.

Analog Isolation

An isolation amplifier is one of the more common parts used to provide isolation in the analog front end of an instrument. As shown in Figure 47, the analog data passes from the sensor into the I/O connector through the gain amplifier into the isolation amplifier and then to the ADC.

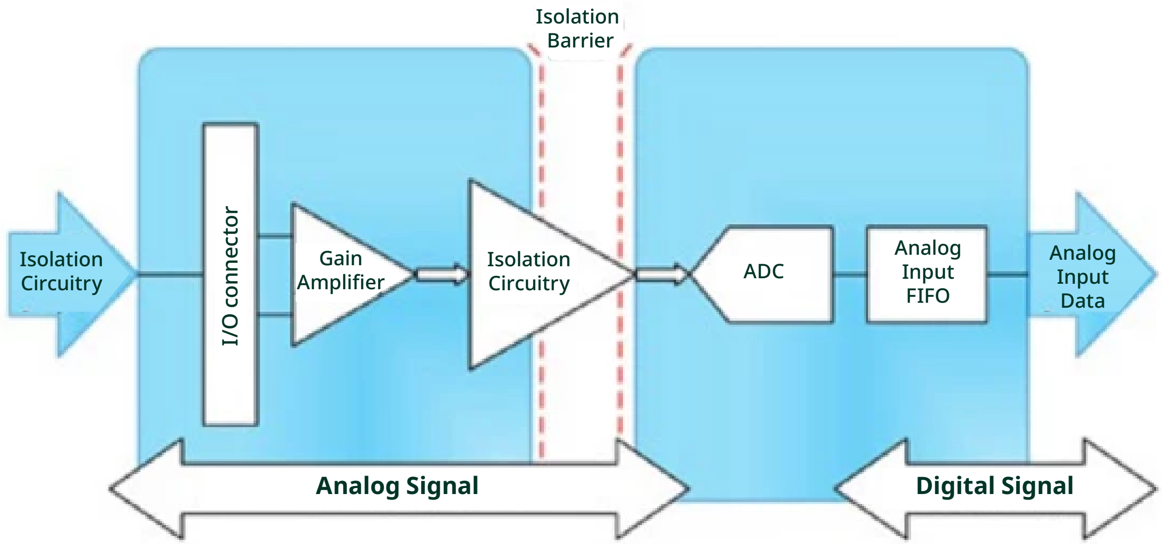


Figure 47. An isolation amplifier is one of the more common parts used to provide isolation in the analog front end of an instrument.

One large benefit of analog isolation is that it protects the ADC. Because the isolation is provided before the ADC, the ADC is less likely to be damaged by transient or high voltages. Analog isolation does, however, have disadvantages. First, because analog isolation is not perfect and it lies before the ADC, it can add gain, nonlinear, or offset error to the analog signal before it reaches the ADC. This is not ideal and can decrease the accuracy of the measurement. In addition, analog isolation components can introduce longer settling times and are often more expensive than their digital isolation counterparts.

Digital Isolation

As opposed to analog isolation, digital isolation circuitry is placed after the ADC in the instrument, as shown in Figure 48.

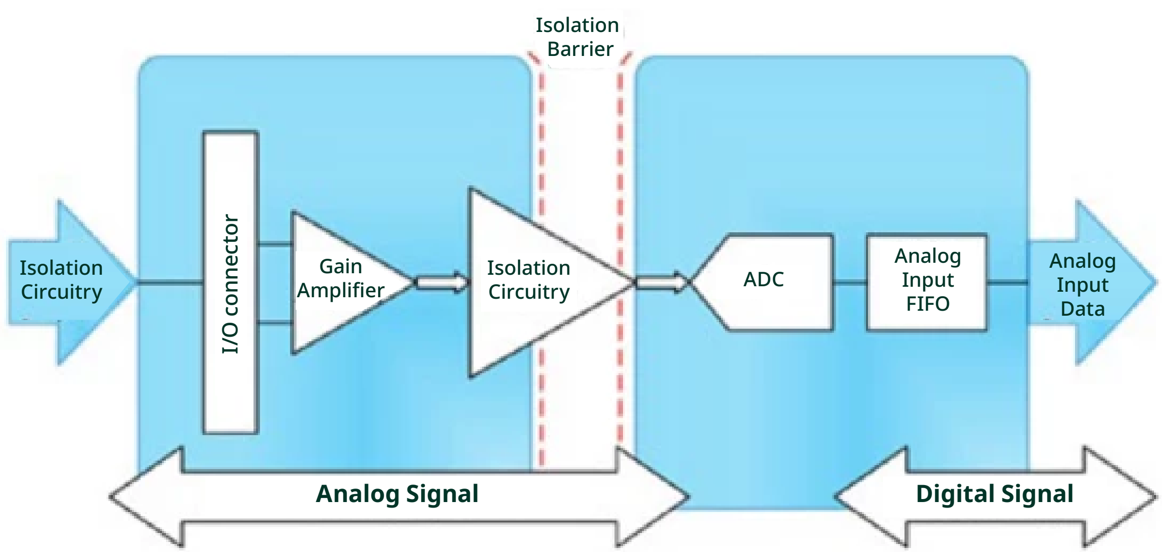


Figure 48. As opposed to analog isolation, digital isolation circuitry is placed after the ADC in the instrument.

Digital isolation can lead to better performance and accuracy, in comparison to analog isolation circuitry, because the measured signal is less altered before it is digitized by the ADC. Digital isolation circuitry also has advantages over analog isolation circuitry because it is typically lower in overall cost, and it performs at higher data transfer speeds. However, because digital isolation circuitry is after the ADC, the ADC is more susceptible to the damage a voltage spike can cause.

Isolation Types

We have talked about common isolation topologies for instruments and where the isolation can be applied to the signal within the instrument, but we have not talked about the isolation barrier itself or how the signal crosses the isolation barrier. In this section, we will cover the isolation barrier and then move into three common isolation types which use different techniques to transmit the signal data across the isolation barrier.

Physical isolation is the most basic form of isolation, meaning that there is a physical barrier between two electrical systems. This can be in the form of insulation, an air gap, or any nonconductive path between two electrical systems. With pure physical isolation, you can imply that no signal transfer exists between electrical systems. When dealing with isolated measurement systems, the signal of interest needs to cross the isolation barrier with the benefits of removing ground loops. Therefore, you must have a transfer, or coupling, of the signal's energy across the isolation barrier. Three common techniques of transferring the signal across the isolation are discussed below.

Capacitive Isolation

Capacitive isolation, as seen in Figure 49, uses an electrical field as the form of energy to transfer the signal across the isolation barrier. The electric field changes the level of charge on the capacitor. This charge is detected across the isolation barrier and the charge detected is proportional to the level of the measured signal.

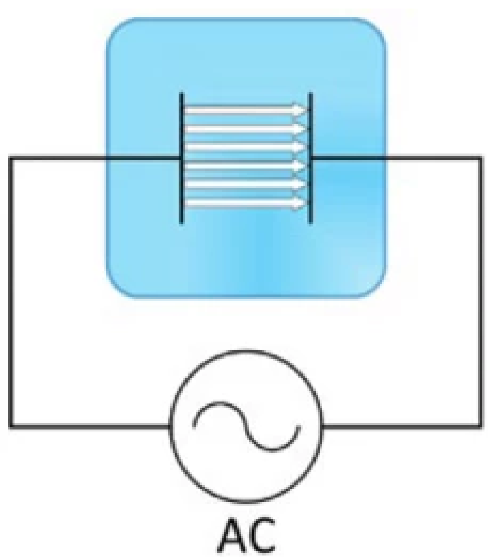


Figure 49. Capacitive isolation uses an electrical field as the form of energy to transfer the signal across the isolation barrier.

Inductive Isolation

Inductive isolation uses a transformer, shown in Figure 50, to transfer a signal across an isolation barrier. The transformer generates an electromagnetic field, proportional to the measured signal, as the form of energy to cross the isolation barrier.

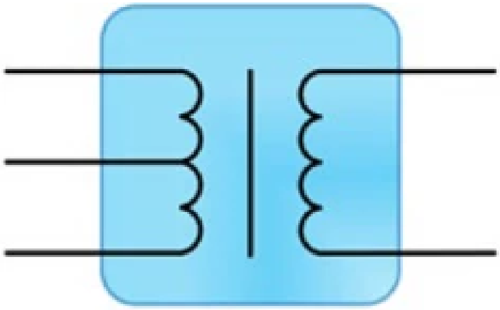


Figure 50. Inductive isolation uses a transformer, notated with the above symbol, to transfer a signal across an isolation barrier.

As in capacitive coupling, inductive isolation can provide relatively high-speed data transmission rates. In addition to high-speed transmission, inductive coupling uses low power for the data transmission. However, inductive coupling is susceptible to interference from surrounding magnetic fields because it uses electromagnetic fields as the method to cross the isolation barrier. If external magnetic fields do interfere with the electromagnetic field produced by the transformer, this could affect the accuracy of the measurement.

Optical Isolation

Optical isolation uses an LED and a photodetector to transmit the signal information across the isolation barrier. The isolation barrier in optical isolation typically is an air gap and the signal is transmitted using light. The light intensity produced by the LED is proportional to the measured signal.

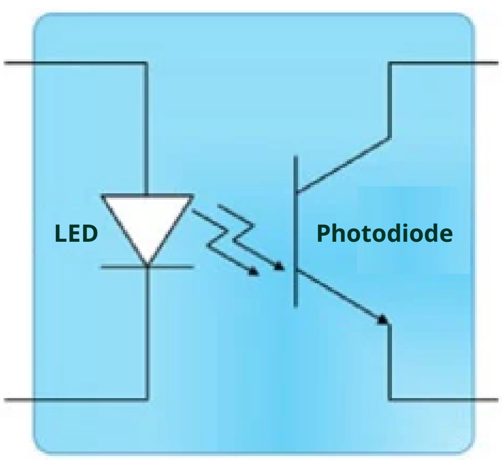


Figure 51. Optical isolation uses an LED and a photodetector to transmit the signal information across the isolation barrier.

Because optical isolation uses light as the energy to transfer the measured signal across the isolation barrier, it gains the advantage of immunity from electrical- and magnetic-field interference. This can make optical isolation an effective technique in industrial areas where strong electric or magnetic fields could be present. The advantages gained by using light are balanced by some disadvantages. Optical isolation typically has slower data transfer rates, which are limited to the LED switching speed. It also has relatively high power dissipation when compared to capacitive and inductive isolation.

To summarize:

- **Isolation** is a method of physically and electrically separating two distinct parts of an instrument.
- Breaking **ground loops** to measure the signal of interest more accurately is a main advantage of isolated measurement systems.
- Based on the application requirements, you can choose the isolation topology that best fits system needs:
  - **Channel-to-earth isolation** isolates the channels from the instrument ground.
  - **Bank (channel-to-bus) isolation** isolates groups (banks) of lines from other groups of lines as well as from the instrument ground.
  - **Channel-to-channel isolation** isolates every line from every other line present and from the instrument ground.
- **Analog isolation** circuitry protects the ADC from high voltages and transient voltages, but it can add gain, nonlinear, and offset errors to the signal before it reaches the ADC.
- **Digital isolation** circuitry does not protect the ADC, and its advantages over analog isolation include lower cost, higher data transmission speeds, and greater accuracy because the signal is less altered prior to reaching the ADC.
- Isolation types and their characteristics are summarized as:

Isolation Type	Advantages	Disadvantages
Capacitive	• Fast data transmission rate • Magnetic field interference immunity	• Susceptible to electric field interference
Inductive	• Fast data transmission rate • Electric field interference immunity	• Susceptible to magnetic field interference
Optical	• Electric field interference immunity • Magnetic field interference immunity	• Slower data transmission rates • Relatively high power dissipation

Tips to Reduce Measurement Noise

Introduction

Noise is a common challenge when working with analog signals, and identifying its source requires carefully considering multiple factors. This section explores how to diagnose noise sources and implement effective mitigation techniques to improve measurement accuracy. Many of these approaches can also serve as preventative measures when designing future systems to minimize unwanted noise from the start.

It's important to keep in mind that, although these are some of the most common sources of noise and strategies for reduction, your system may have more complex or unique sources of noise.

Diagnosing Noise

When trying to determine the source of noise in your signal, start with two quick diagnostic steps:

1. Create an FFT graph—This helps you visualize the frequency content of your signal and identify any frequency peaks that may stand out.
2. Survey your setup and environment—Nearby equipment, signal sources, or even the type of cable you're using can introduce noise.

By combining FFT analysis with a physical inspection of your setup, you'll gain the most comprehensive understanding of your signal behavior and potential noise sources. Below, you'll find guidance on interpreting frequency spikes and addressing common sources of interference, along with additional insights into environmental factors.

Sources of AC-Coupled Noise

Electrical AC signals and the magnetic fields they generate can couple onto your signal wires through cables, instruments, or even the infrastructure of your building.

Common-mode noise is a type of AC interference that appears equally on both conductors of a differential signal pair. It typically arises from external electromagnetic fields or differences in ground potential, and is often introduced through power lines, nearby equipment, or improper grounding. Although it affects both lines identically, it can still impact measurement accuracy if not properly rejected by the system.

Normal-mode noise refers to unwanted AC signals that appear as a voltage difference between the two conductors of a signal pair—essentially affecting the signal itself rather than both lines. This type of noise is typically introduced by external electromagnetic interference or coupling from nearby power sources and equipment. Unlike common-mode noise, normal-mode noise directly distorts the measured signal and is visible in the differential voltage.

Let's break these signals down into three categories based on their frequency:

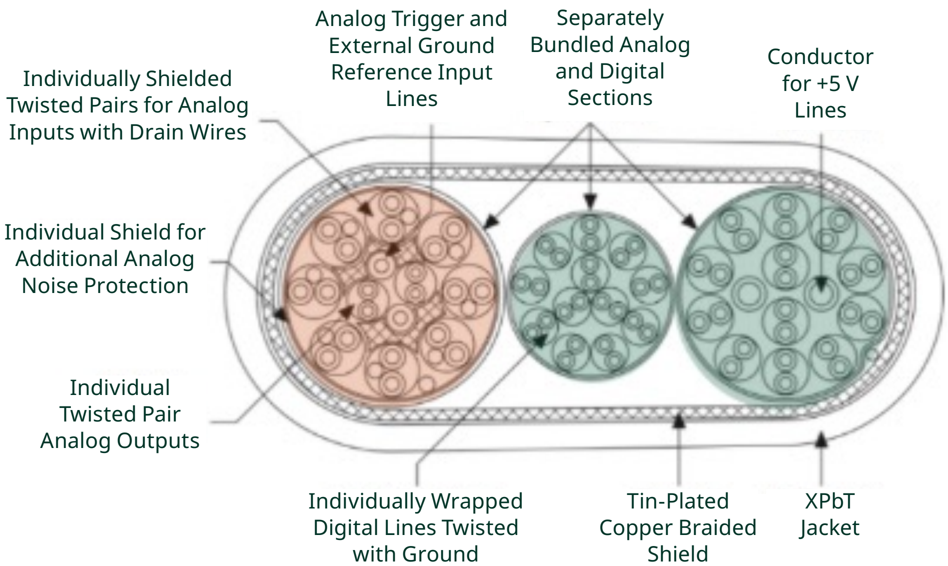
Low-Frequency (50 or 60 Hz)

An FFT of your signal showing a spike at 50 or 60 Hz (or even 100 or 120 Hz) can indicate that electrical or magnetic fields from power lines are being coupled onto your signal. This could be from the power lines themselves, synchronous rotating equipment, or even fluorescent lighting.

Ground loops may also cause low frequency spikes. Ground loops occur when multiple ground paths exist between the signal source and the DAQ device. This is a common issue in systems where the signal source and DAQ are powered from different outlets or grounding schemes.

Depending on the source, these cabling and setup techniques may be effective to reduce the impact of low-frequency noise and ground loops:

- Shielded EPM cables improve noise immunity by separating analog and digital signals and blocking external electromagnetic interference. When grounded, the shield prevents unwanted current from flowing through the signal path, helping maintain clean and accurate measurements.



- Twisted pair cables reduce electromagnetic interference by ensuring both conductors are equally affected by external noise. When paired with differential inputs, this common-mode noise is canceled out, improving signal integrity and minimizing magnetic field pickup.
- Use isolated DAQ hardware or differential inputs to eliminate the electrical connection between grounds. This may break the loop. Also, ensure that all equipment shares a single-point ground whenever possible, and avoid connecting grounds to multiple points in the system.

Medium- to High-Frequency (1 kHz to hundreds of kHz)

Medium- to high-frequency noise, typically in the range of 1 kHz to several-hundred kHz, can be difficult to diagnose because it often appears as an alias. In these cases, the frequency you observe may not reflect the actual source of the noise, which makes debugging more challenging. If you notice the noise shifting when you change your sample rate, that's a strong indication of aliasing. To better understand the true frequency content, try capturing the signal with as much bandwidth as possible.

This type of noise is commonly emitted by high-speed electronics such as switch-mode power supplies (SMPS). Even if these devices aren't directly connected to your system, they can still interfere with your signals by radiating energy through the air. Their presence in the vicinity of your setup can be enough to introduce unwanted noise.

To reduce the impact of this kind of interference, consider:

- Shielding the device emitting the noise to contain its electromagnetic output.
- Using shielded cables to prevent external noise from coupling onto your signal wires.
- Inspecting your system for unwanted current paths, as noise may be induced on the ground line—so you may need to check for ground loops or improper grounding.

- Keep in mind that even unconnected devices nearby can affect your signal.
- Adjusting your sample rate or applying filters can also help isolate and identify the true source of the noise.

Very-High-Frequency (MHz to GHz)

Very-high-frequency noise, typically in the MHz to GHZ range, can be especially difficult to manage, particularly if your lab is located near a radio or TV broadcast antenna. This type of RF noise interference could appear as broad-spectrum noise, raising the overall noise floor of your measurements.

Shielding may help, but it tends to be less effective at these higher frequencies compared to lower-frequency noise sources. Instead, consider the following techniques to reduce RF interference:

- Use twisted pair shielded cables and ground them properly to block RF pickup.
- Keep cables short and well-routed, away from power lines and noisy electronics.
- Try analog filtering to limit bandwidth to just what your signal needs.

If you're still seeing elevated noise levels, especially compared to your device's spec sheet, try disconnecting components one at a time or shorting the DAQ input to the device's ground to establish a baseline. This can help you isolate the source of interference without diving into more advanced techniques right away.

Sources of DC-Coupled Noise

DC-coupled noise will appear as an offset between the expected value and the measured value. If your application performs averaging, you may be unintentionally masking an AC source of noise, so it's important to confirm the offset by taking single-point measurements or plotting raw waveform data without any processing. Compare the offset to your device's accuracy and resolution specifications. If the offset is within spec, it may be a limitation of the hardware rather than external interference.

Keep in mind that DC-coupled noise could also be seen in the form of common-mode or normal-mode noise.

For DC-coupled noise, although there may be environmental causes such as cabling issues, it could be helpful look for direct paths where an unintended signal could couple onto your measurement system:

- Is your signal source grounded or floating? Match it with the correct DAQ input mode to reduce noise and improve accuracy.
  - Differential mode for floating sources
  - References single-ended or non-referenced single-ended for grounded sources
- If your sensor is mounted to a conductive surface (e.g., an accelerometer screwed to a metal chassis), ensure the monitored device has a solid path to ground. Poor grounding can introduce unwanted DC offsets. Also, avoid creating ground loops by ensuring the sensor and DAQ share a single ground reference.
- If your cable has exposed leads or connectors (such as a BNC cable plug), check that nothing conductive is touching it. Even incidental contact can introduce a DC bias.
- Verify that the DAQ or measurement instrument is properly grounded. Floating or poorly grounded instruments can cause DC offsets due to potential differences between the device and signal source.
- Minimize thermal drift by allowing equipment to warm up before taking measurements, especially in precision applications. Temperature changes can cause small shifts in voltage levels that appear as DC offsets over time.

To summarize:

- **Categorize the Noise by Frequency**
  Identify whether the noise is low (50/60 Hz), medium/high (kHz), very high (MHz–GHz), or DC-coupled—each has distinct sources and mitigation strategies.
- **Use Proper Cabling and Grounding**
  Twisted-pair shielded cables, single-point grounding, and avoiding ground loops are key to reducing both AC and DC noise.
- **Configure DAQ to Match Signal Source**
  Use differential inputs for floating sources and single-ended for grounded ones to prevent offsets and interference.
- **Apply Filtering and Isolation**
  Use analog/digital filters to suppress unwanted frequencies. Isolated DAQ devices help eliminate ground loops and common-mode noise.
- **Inspect and Troubleshoot Systematically**
  Check for exposed conductors, poor grounding, EMI sources, and thermal drift. Use FFTs and raw data to isolate and diagnose noise issues.

Sensor Fundamentals

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.

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 52, for example, shows the thermoelectric voltage output of various thermocouples across a range of temperatures. Note the nonlinear relationship.

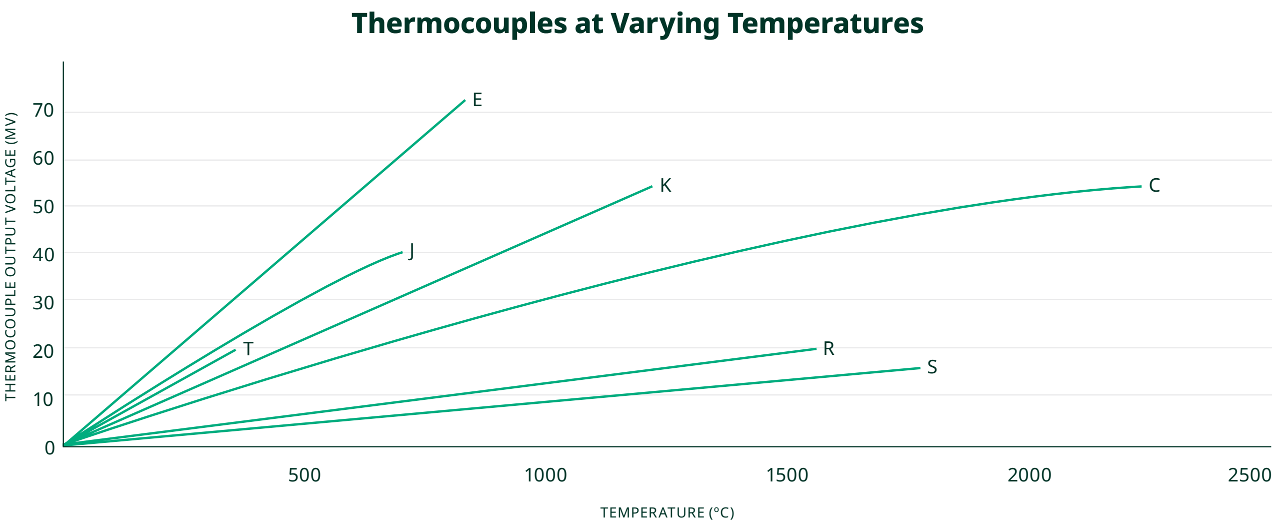


Figure 52. Thermocouple Output Voltage vs. Temperature: Digi-Key

You can choose from two options to accurately scale measurements 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 Table 1 and maintained by the National Institute of Standards and Technology (NIST).
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:

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

$$E = Thermoelectric\ voltage\ in\ \mu V$$

$$C_i = Polynomial\ coefficients\ (provided\ by\ NIST\ for\ each\ temperature\ range)$$

$$t^i = Temperature\ in\ °C$$

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:

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

$$R_T = R_0[1 + AT + BT^2]\ for\ T > 0°C$$

$$R_T = RTD\ resistance\ at\ temperature\ T$$

$$\mathrm{R_0 = RTD\ nominal\ resistance\ at\ 0°C}$$

$$A, B, and\ C = \ constants\ used\ to\ scale\ the\ RTD$$

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.

°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	0.038	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

Table 1. NIST Type K Thermocouple Lookup Table: NIST ITS-90 Thermocouple Database

RTD/Thermistor-Specific Considerations

Current Excitation

RTDs and thermistors 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 1,000 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

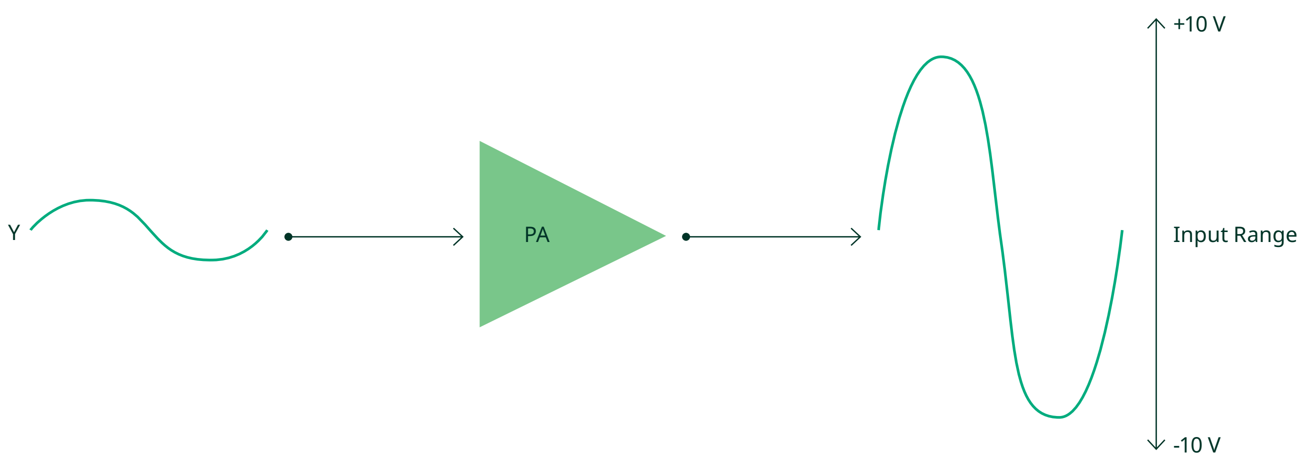


Figure 53. Amplify thermocouple outputs to detect smaller signal changes and use the full ADC input range.

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 54. 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

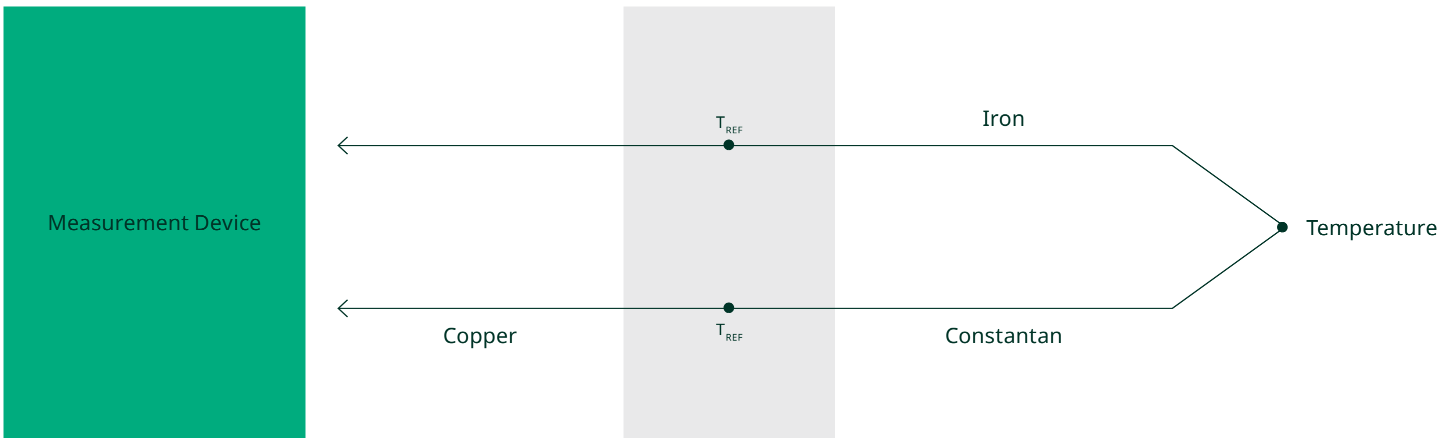


Figure 54. Cold-junction error adds more voltage to a thermocouple measurement.

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.

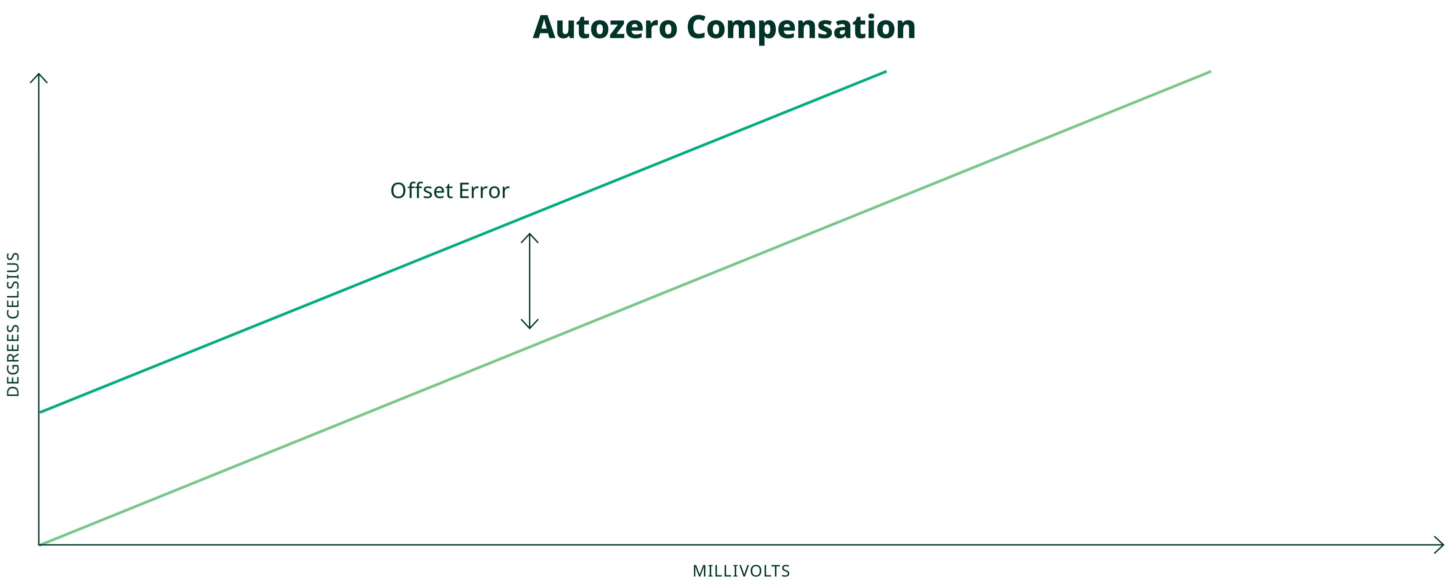


Figure 55. Autozero compensates for offset error.

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.

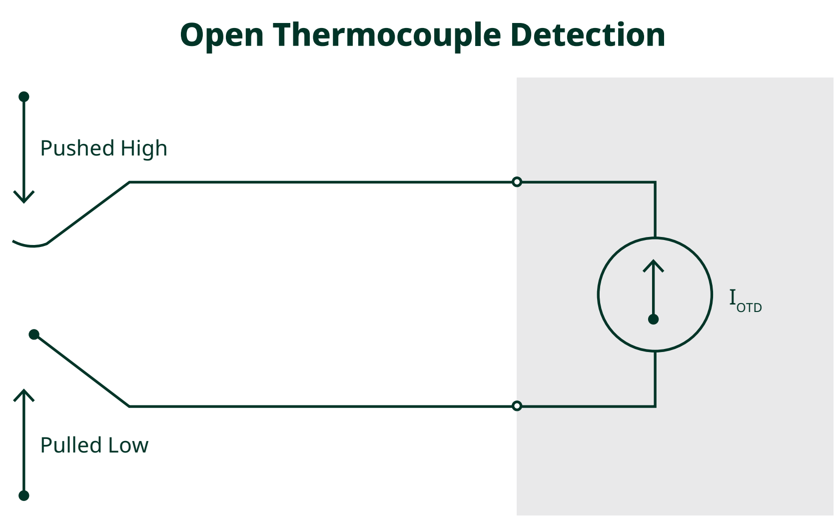


Figure 56. The open thermocouple detection circuit pushes the voltage high when the thermocouple breaks.

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

Strain Gages and Bridge-Based Sensors

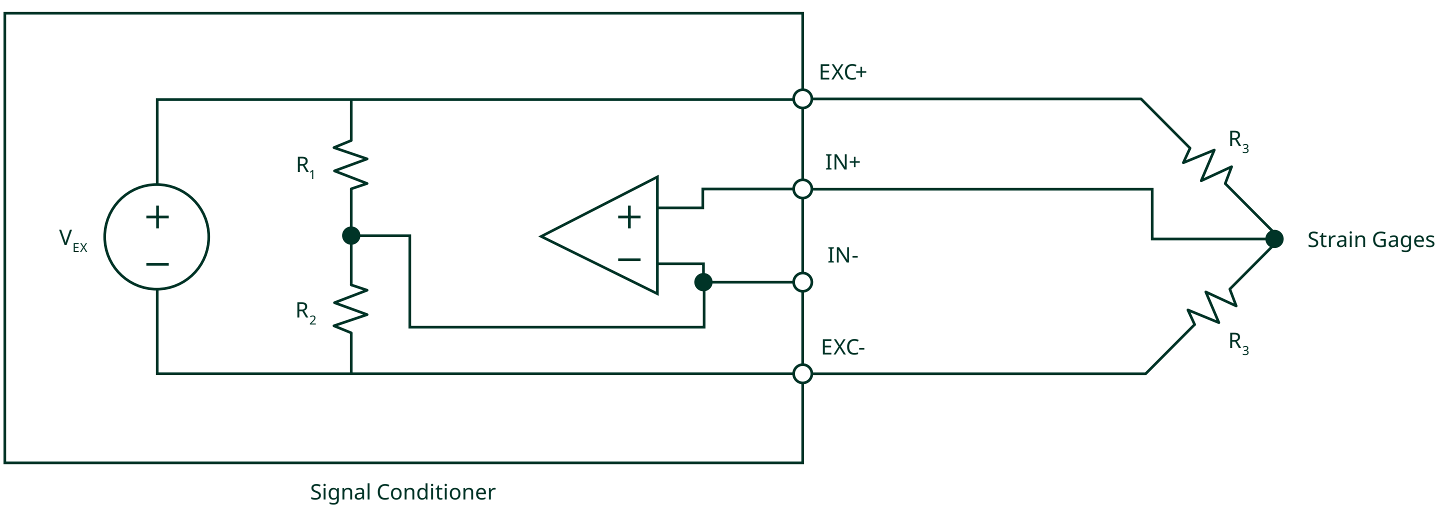
Strain gages are fundamental sensing devices that function as the building blocks of many other types of transducers, including pressure, load, and torque sensors, used extensively in structural test and monitoring applications. Even though strain gages are common, they are one of the most difficult 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 also are 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 VEX/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



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 universally recognized, 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 the sensor's 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 × 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

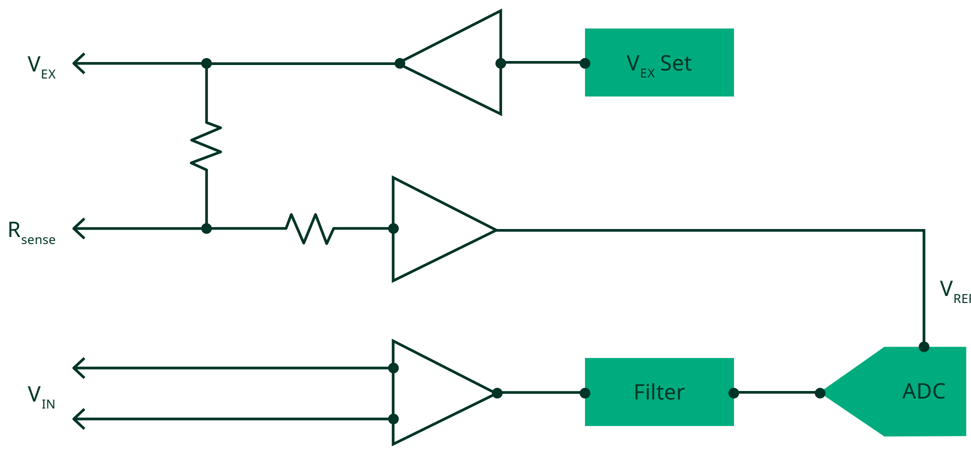


Figure 57. A ratiometric design uses excitation voltage as a reference to ADC to correct for unstable power sources.

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 57, 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 RL 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 58, 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

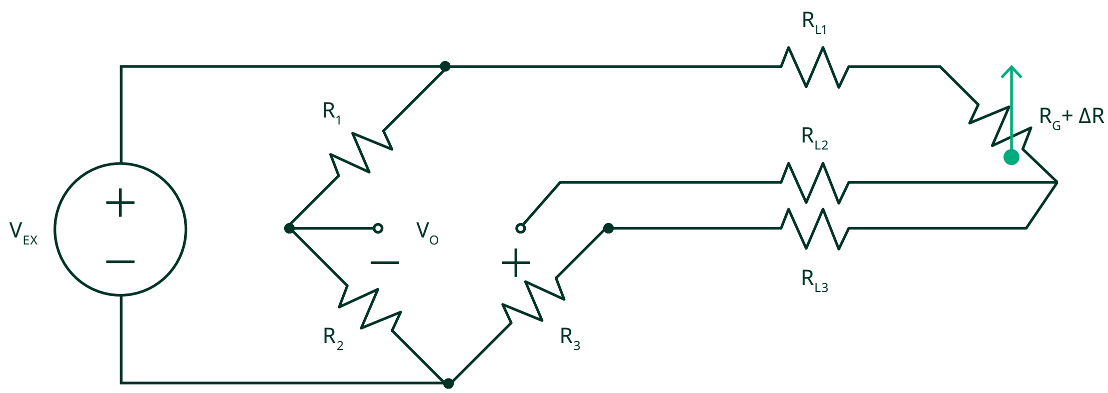


Figure 58. 3-Wire Strain Gage Configuration

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 59. 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.

3-Wire Strain Gage

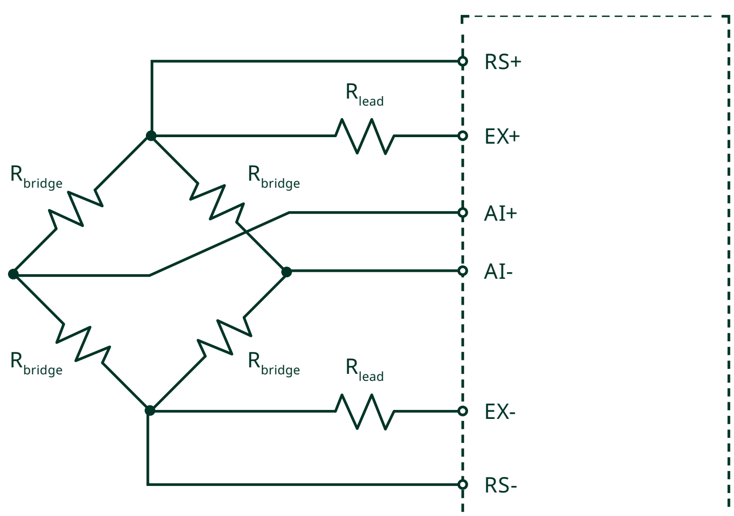


Figure 59. Remote sense measures the actual excitation voltage delivered to a bridge over long distances.

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:

- **Reducing 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.
- **Using 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.
- **Increasing 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.

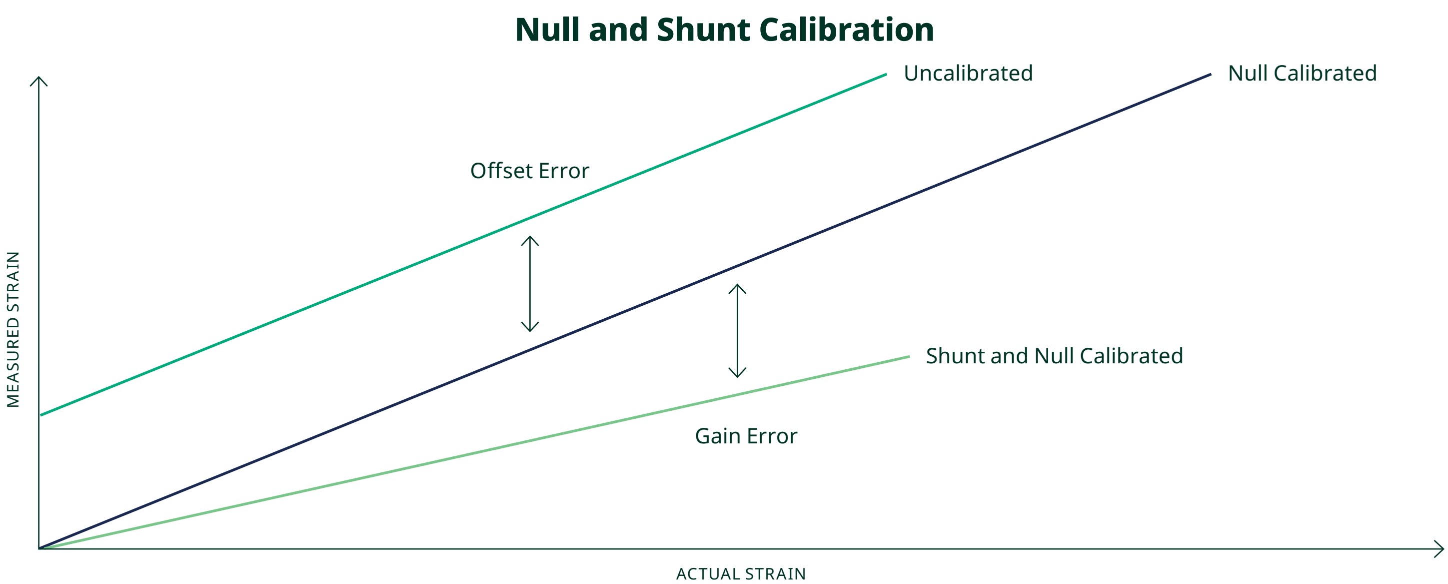


Figure 60. Null and shunt calibration adjust the offset and gain error of the measurement device.

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 61. 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.

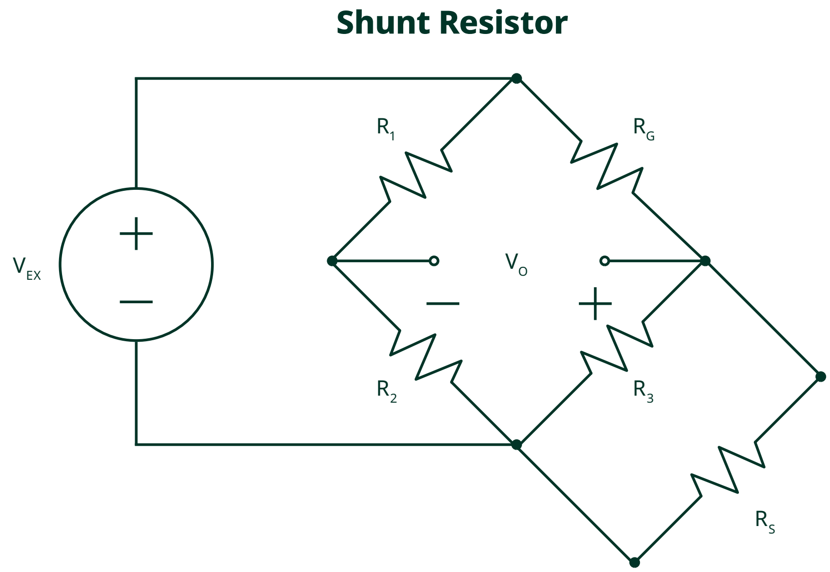


Figure 61. Shunt Resistor Connected Across R3

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 pounds per square inch 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.

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 Electronics 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 62, 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.

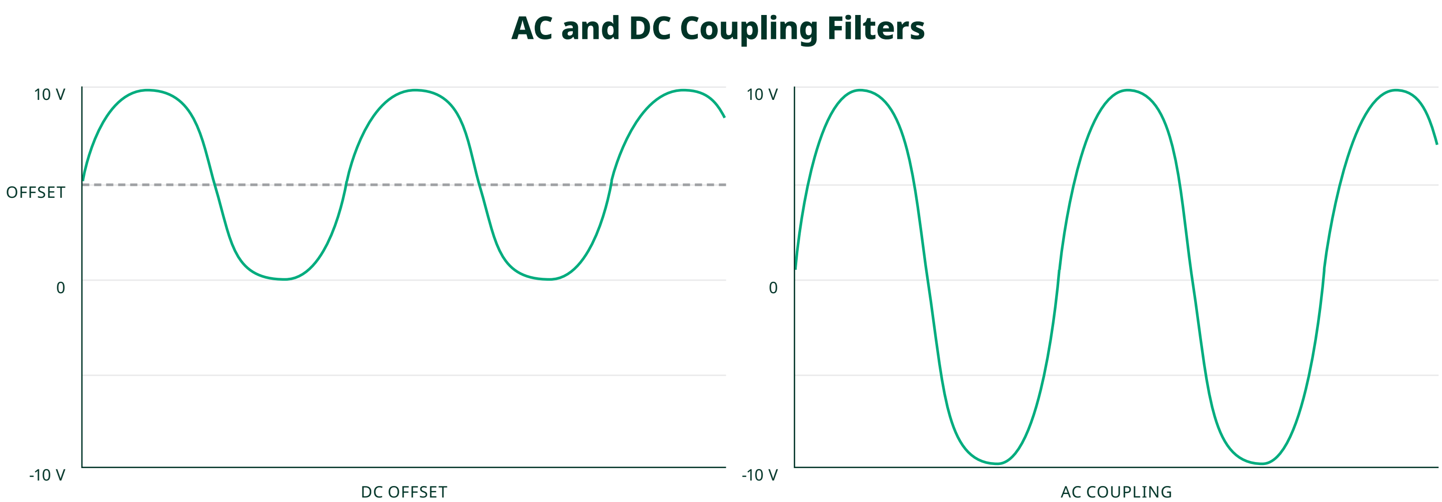


Figure 62. AC coupling filters out the DC component of a signal to increase measurement resolution.

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 2. 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 63, 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

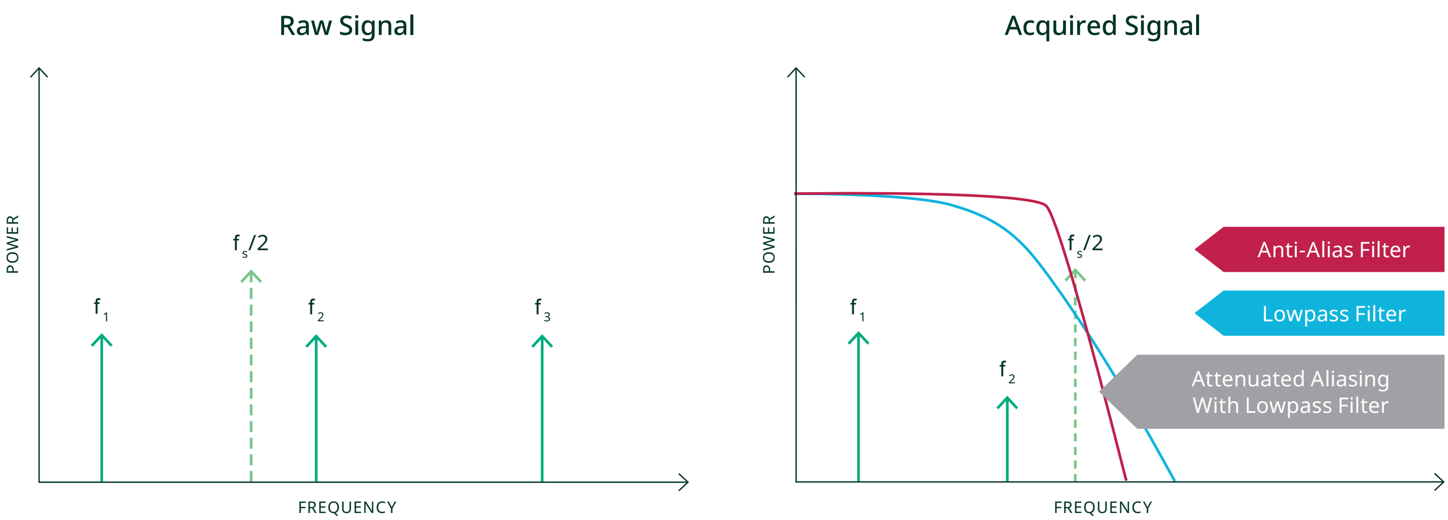


Figure 63. Anti-alias filters with steep roll-off help attenuate noise just above the Nyquist frequency.

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 (V_{max}/V_{min}). 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 3, 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	100.000,000 W	200 dB

Table 3. 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:

$$dB = 10 \log \frac{P}{P_o}$$

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, cellphones, 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.

$$\text{Level}_{rms} = \sqrt{\frac{x_1^2 + x_2^2 + \ldots + x_n^2}{n}}$$

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.

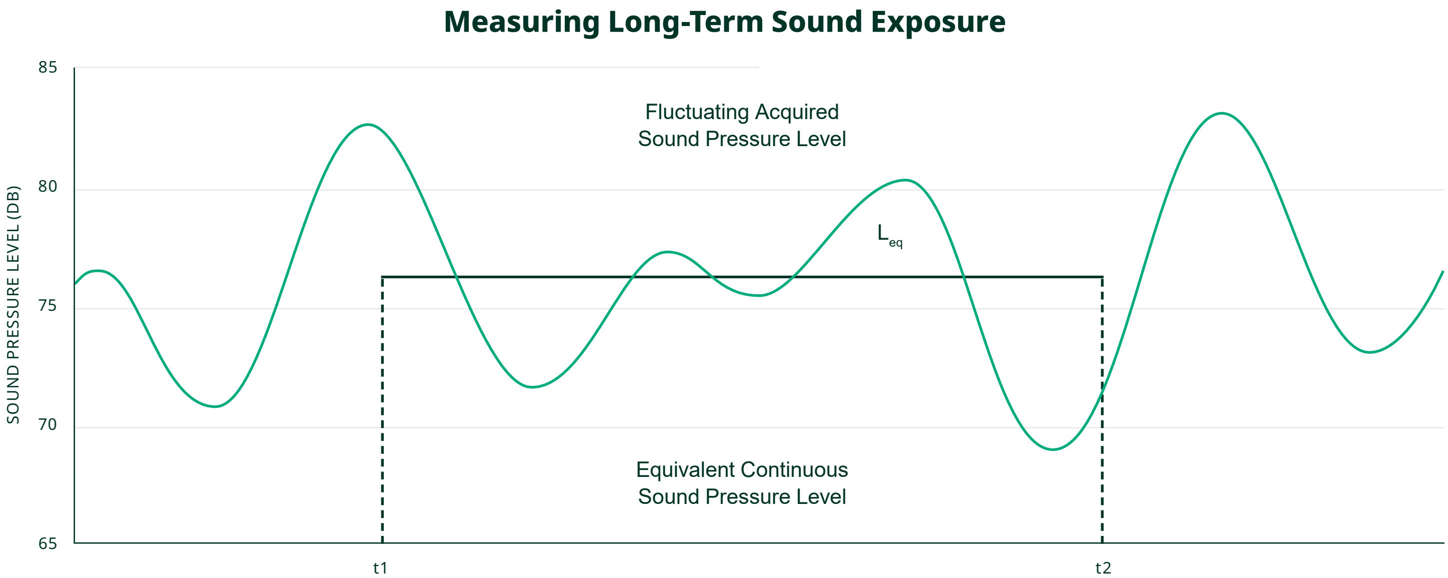


Figure 64. Leq is used to quantify long-term exposure to sound in a given environment.

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 65). This is useful for analyzing stationary signals whose frequency components do not change over time.

Frequency Amplitude Spectra

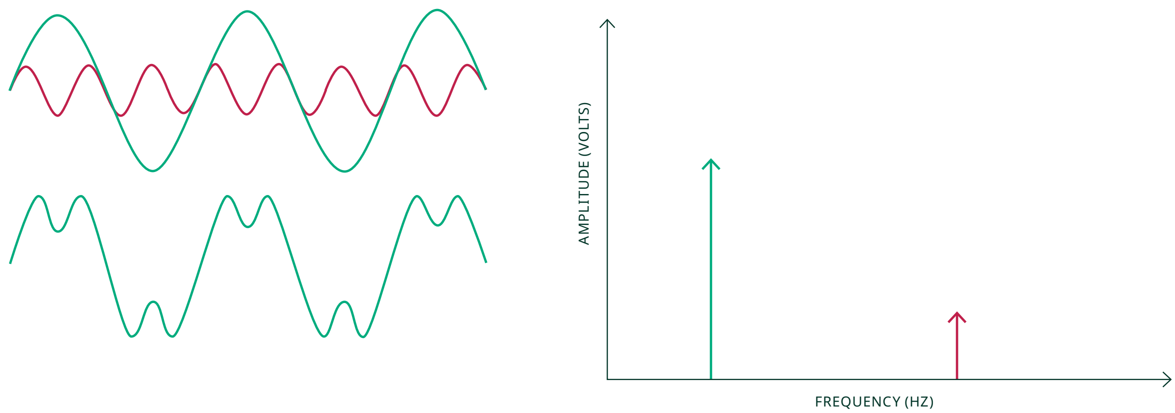


Figure 65. The frequency spectrum shows different amplitudes and frequencies of sinusoidal components.

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 66.

Measuring Noninteger Periods

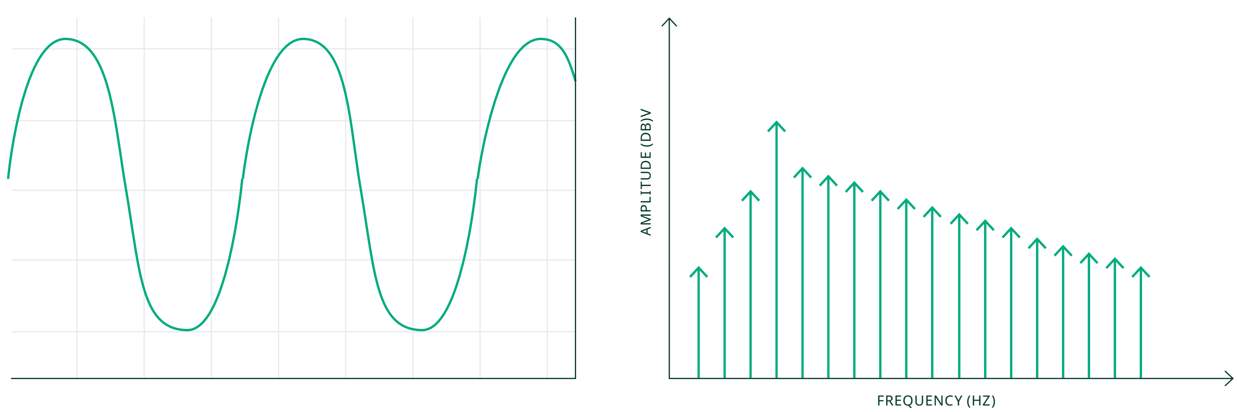


Figure 66. Measuring a noninteger number of periods results in spectral leakage in the frequency domain.

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

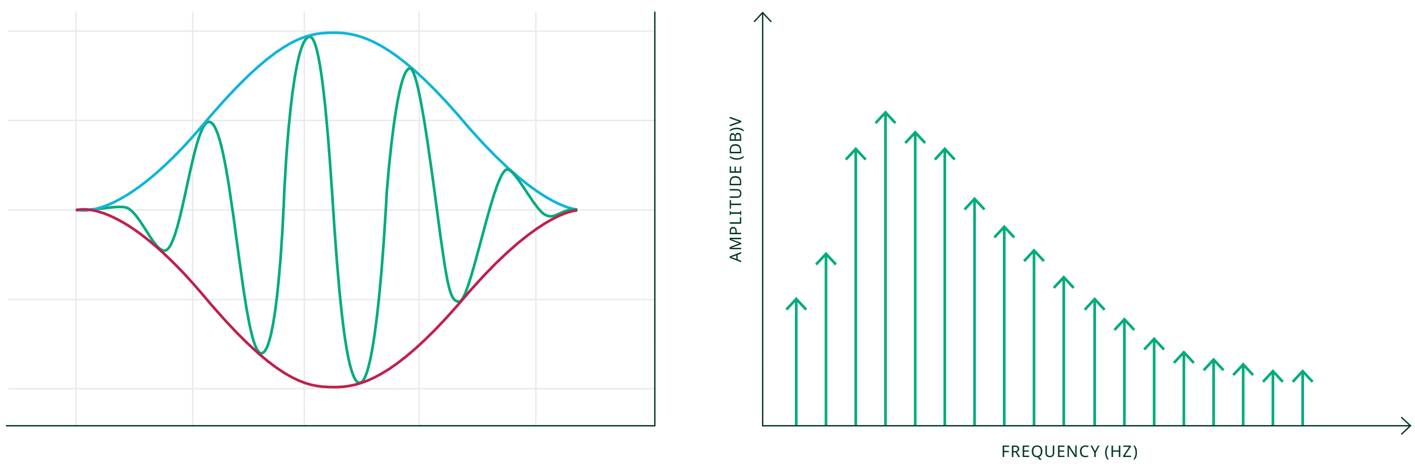


Figure 67. Applying a window minimizes the effects of spectral leakage.

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 4 lists common window types, the appropriate signal types, and example applications. For a deeper dive, refer back to the Windowing section.

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 4. 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 68 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.

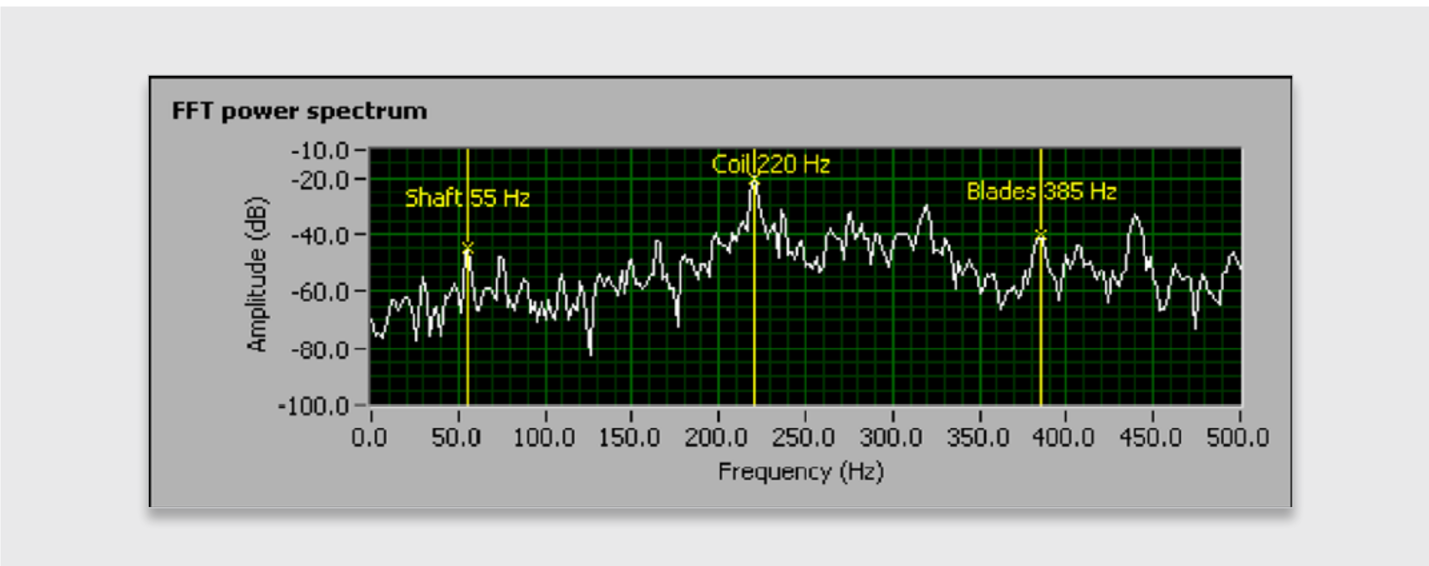


Figure 68. Frequency Components of a PC Fan Vibration Signal

Figure 69 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.

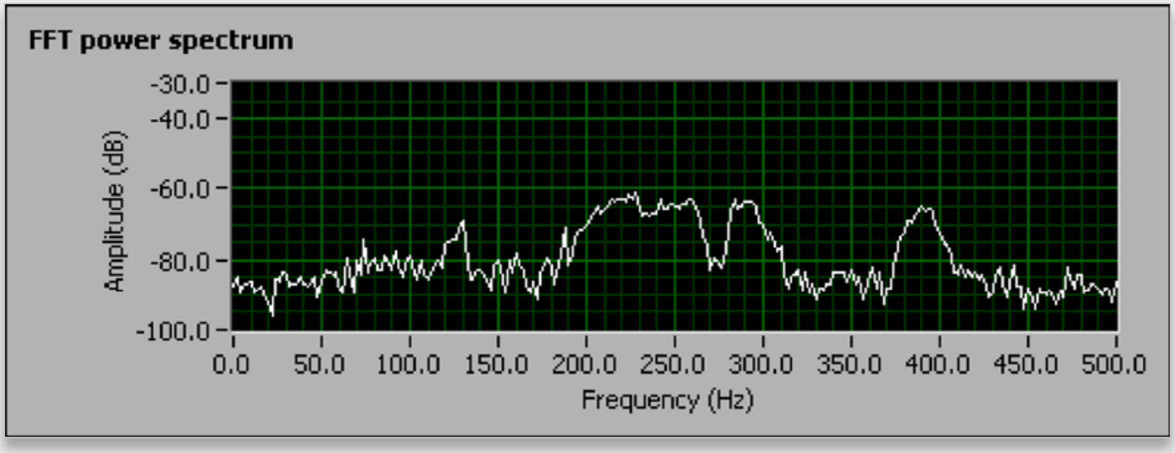


Figure 69. The FFT power spectrum shows no peaks as the rotational speed of the fan changes.

However, the order power spectrum plot in Figure 70 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 70. 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 71.

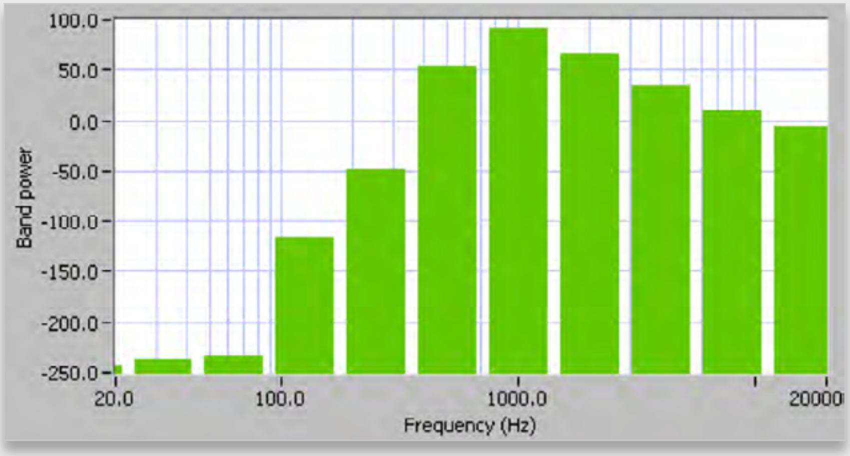


Figure 71. Octave analysis groups frequency bands on a logarithmic scale to emulate how humans perceive sound.

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 72. 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.

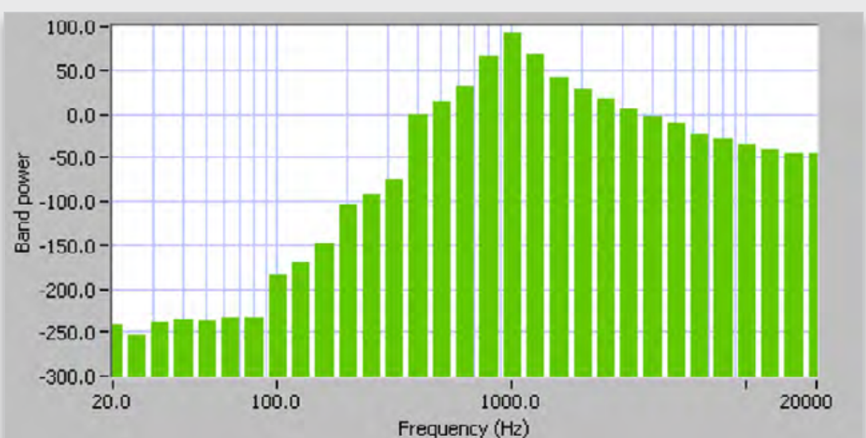


Figure 72. Fractional octave filters provide higher resolution.

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.

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 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 5 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-24
	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 5. 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 73, 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

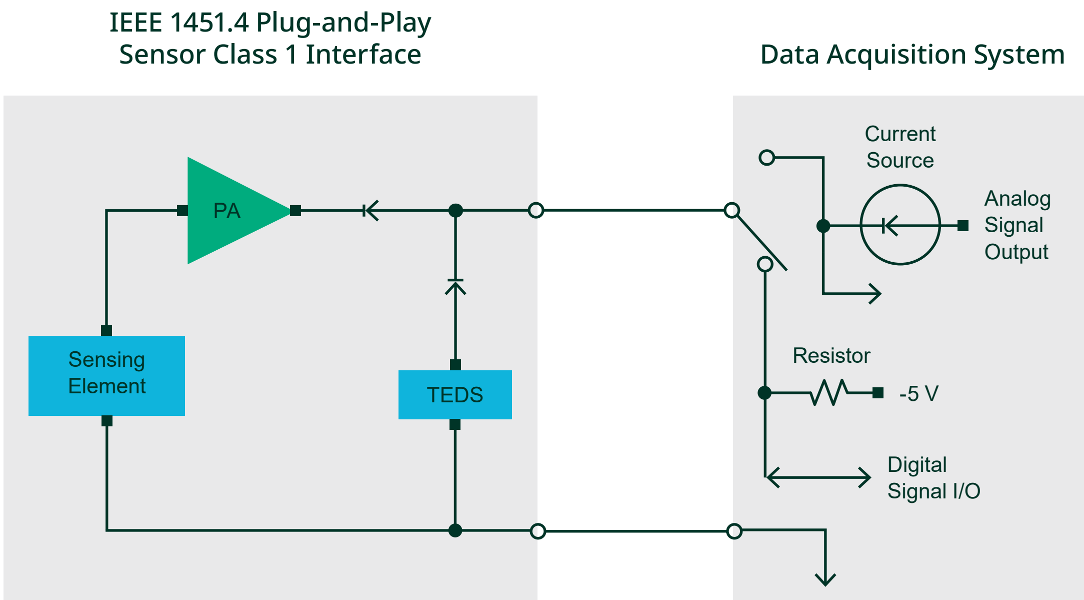


Figure 73. This Class 1 two-wire interface multiplexes analog measurement and digital TEDS data.

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 then can 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 74 illustrates the implementation of a Class 2 mixed-mode interface.

Multiwire Interface

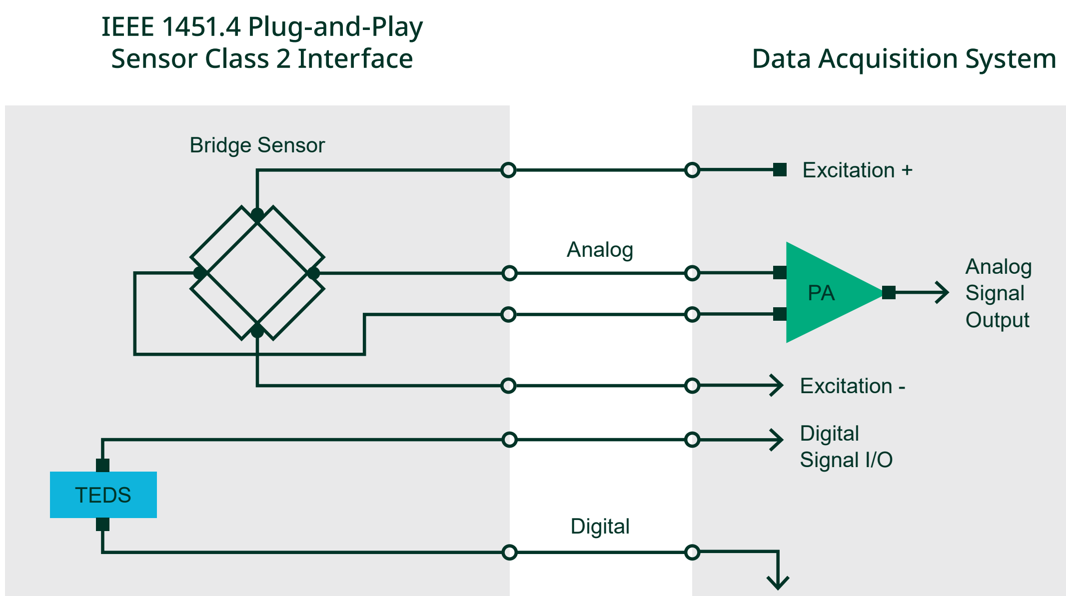


Figure 74. This Class 2 multiwire interface enables plug-and-play functionality.

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 **NI CompactDAQ** and **NI 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 **NI LabVIEW** to scale your data into desired units and perform analysis using built-in signal processing functions.

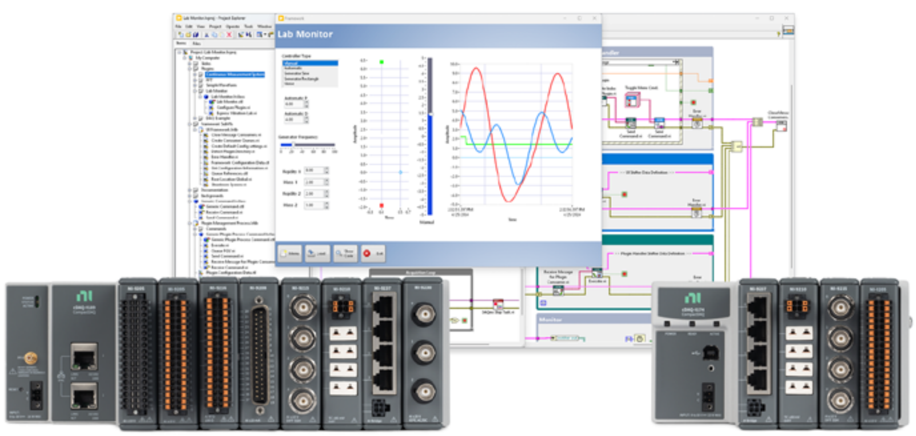


Figure 75. CompactDAQ hardware provides direct sensor connectivity in USB, Ethernet, and stand-alone form factors.

NI
11500 N Mopac Expwy
Austin, TX 78759-3504

758450

Linkedin.com/company/niglobal/

X.com/NIglobal

Youtube.com/@NIGlobalYoutube

Instagram.com/niglobal/

Facebook.com/NationalInstruments