

# Making Basic Strain Measurements

## using 24-Bit IOtech Hardware

### INTRODUCTION

Strain gages are sensing devices used in a variety of physical test and measurement applications. They change resistance at their output terminals when stretched or compressed. Because of this characteristic, the gages are typically bonded to the surface of a solid material and measure its minute dimensional changes when put in compression or tension. Strain gages and strain gage principles are often used in devices for measuring acceleration, pressure, tension, and force. Strain is a dimensionless unit, defined as a change in length per unit length.

For example, if a 1-m long bar stretches to 1.000002 m, the strain is defined as 2 microstrains. Strain gages have a characteristic gage factor, defined as the fractional change in resistance divided by the strain. For example, 2 microstrain applied to a gage with gage factor of 2 produces a fractional resistance change of  $(2 \times 2) \times 10^{-6} = 4 \times 10^{-6}$ , or  $4 \mu\Omega/\Omega$ . Common gage resistance values typically range from 120 to 350 $\Omega$ , but some devices are as low as 30 $\Omega$  or as high as 3 k $\Omega$ .

In the past, strain gage data acquisition hardware has typically provided 12- or 16-bit resolution. These devices must utilize every part of their 12- or 16-bit resolution to ensure accurate measurements. 24-bit analog-to-digital converters (ADC) offer 256 times the resolution of conventional 16-bit systems. Strain gage based DAQ systems such as the IOtech 6224, use a 24-bit ADC per channel and no longer operate with this disadvantage.

### DISCUSSION

#### STRAIN MEASUREMENT CONFIGURATIONS

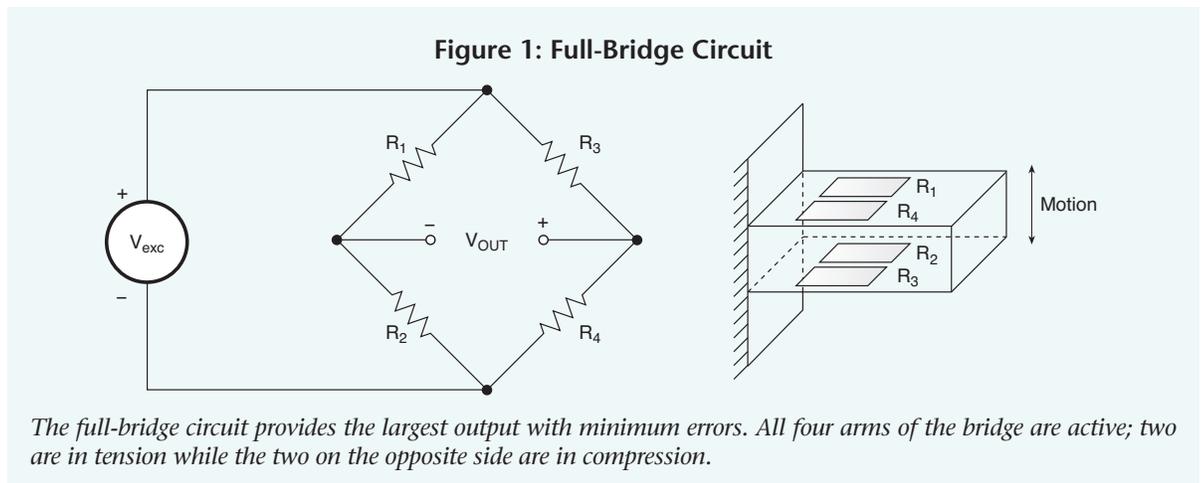
##### Wheatstone Bridge

To make an accurate strain measurement, extremely small resistance changes must be measured. The Wheatstone bridge circuit is widely used to convert the gage's microstrain into a voltage change that can be fed to the input of the ADC. (See Figure 1.)

When all four resistors in the bridge are absolutely equal, the bridge is perfectly balanced and  $V_{out} = 0$ . But when any one or more of the resistors change value by only a fractional amount, the bridge produces a significant, measurable voltage. When used with an instrument, a strain gage replaces one or more of the resistors in the bridge, and as the strain gage undergoes dimensional changes (because it is bonded to a test specimen), it unbalances the bridge and produces an output voltage proportional to the strain.

##### Full-Bridge Circuits

Although half-bridge and quarter-bridge circuits are often used, the full-bridge circuit is the optimal configuration for strain gages. It provides the highest sensitivity and the fewest error components, and because the full bridge produces the highest output, noise is a less significant factor in the measurement. For these reasons, the full bridge is recommended when possible.



An example of a full-bridge is the full bending bridge configuration containing four strain gages mounted on a test member shown in Figure 1. Two gages are mounted on the top surface to measure tension and the other two are mounted on the opposite surface to measure compression when the beam is forced downward. As the member deflects, the two gages in tension increase in resistance while the other two decrease, unbalancing the bridge and producing an output proportional to the displacement. Upward motion reverses the roles of the strain gages. The bridge output voltage is given by:

**Equation 1: Full-Bridge Output Voltage**

$$V_o = (V_{ex})(X)$$

Where:  $V_o$  = bridge output voltage, V

$V_{ex}$  = excitation voltage applied to the bridge, V

X = relative change in resistance,  $\Delta R/R$

The bridge nulls out potential error factors such as temperature changes because all four strain gages have the same temperature coefficient and are located in close proximity on the specimen. The resistance of the lead wire does not affect the accuracy of the measurement as long as the input amplifier has high input impedance, and the bridge excitation is remotely sensed. For example, an amplifier with a 100 M $\Omega$  input impedance produces negligible current flow through the measurement leads, minimizing voltage drops due to lead resistance.

**Half-Bridge Circuits**

When physical conditions do not allow mounting a full-bridge gage, a half- bridge might fit. Typically, two strain gages are mounted on a test member, and two highly stable discrete resistors or a highly stable resistor network complete the bridge. The output voltage is:

**Equation 2: Half-Bridge Output Voltage**

$$V_o = V_{ex} (X/2)$$

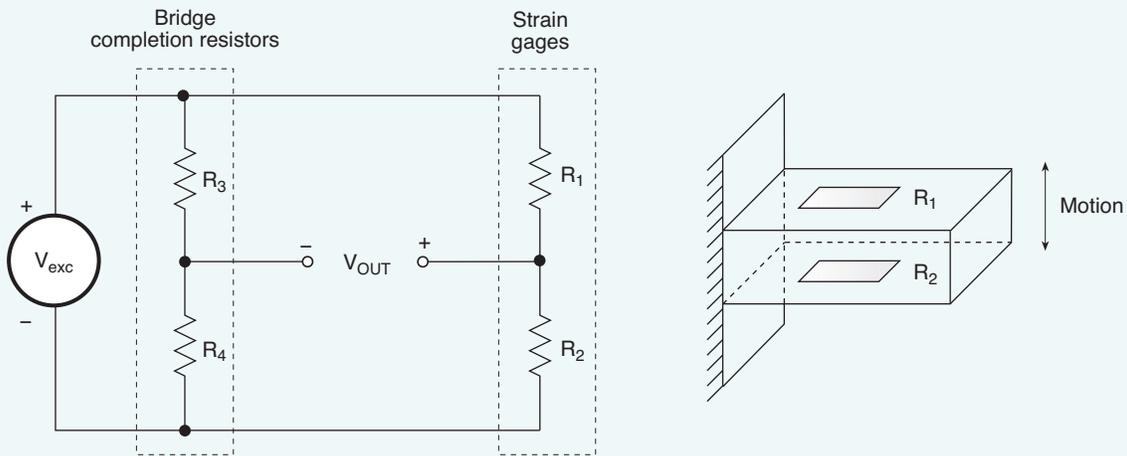
Where:  $V_o$  = bridge output voltage, V

$V_{ex}$  = excitation voltage applied to the bridge, V

X = relative change in resistance,  $\Delta R/R$

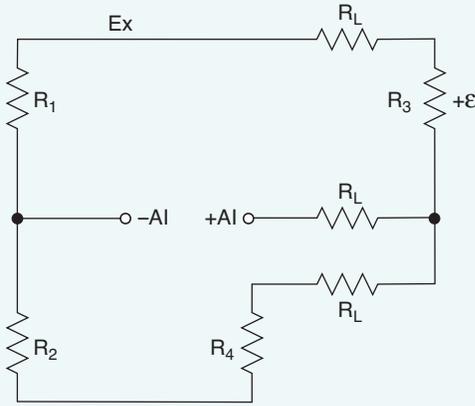
For a large  $\Delta R$ , half-bridge and quarter-bridge circuits can introduce an additional nonlinearity error. (See Figure 2.) Also, the readings are not accurate when the temperature coefficients among the bridge completion resistors and strain gages are different and the resistances do not change proportionally with temperature. Furthermore, bridge completion resistors are not usually located near the strain gages, so temperature differences contribute additional errors. In systems with long lead wires, the bridge completion resistors should be attached close to the gages. However, this may not always be practical due to test fixture limitations or other physical conditions.

**Figure 2: Half-Bridge Circuit**



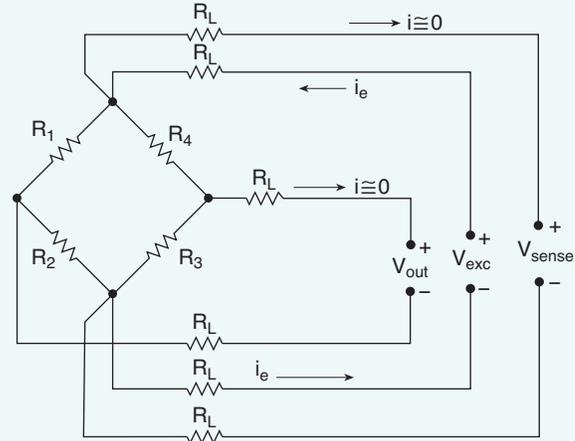
*In a half-bridge circuit, only two arms are active. Two strain gages are on the specimen while the two fixed resistors that complete the bridge are not.*

**Figure 3: Quarter-Bridge Circuit**



A quarter-bridge circuit uses only one active arm and is the least sensitive of the three types. It is also the most prone to noise and errors.

**Figure 4: Kelvin Strain Gage Bridge Circuit**



The Kelvin bridge circuit uses one pair of wires to provide the excitation voltage directly at the bridge, and another to sense the excitation voltage. A third pair of wires measures the bridge output voltage. This arrangement removes the voltage-drop error in the excitation wires from the measured strain signal.

### Quarter-Bridge Circuits

A quarter-bridge circuit uses one strain gage and three bridge completion resistors. The output voltage is:

#### Equation 3: Quarter-Bridge Output Voltage

$$V_o = V_{ex} (X/4) \text{ [approximate]}$$

Where:  $V_o$  = bridge output voltage,  $V$

$V_{ex}$  = excitation voltage applied to the bridge,  $V$

$X$  = relative change in resistance,  $\Delta R/R$

This arrangement has the smallest output, so noise is a potential problem. Furthermore, all the error sources and limitations in the half-bridge circuit apply to the quarter-bridge circuit. (See Figure 3).

## PROCEDURE

### Excitation Source

The Wheatstone bridge is a ratiometric transducer; its output voltage to excitation voltage ratio is proportional to the resistive bridge unbalance. The 6224 makes use of a true ratiometric measurement system; its measured output is proportional to the bridge output voltage to excitation voltage ratio. As such, this instrument is not sensitive to excitation voltage changes. The only excitation requirement is low short-term noise and the voltage is between 2 V and 10 VDC.

An ideal data acquisition system provides an excitation source for each channel, independently adjustable from 1.5 to 10.5 V with a current limit of 100 mA. An excitation voltage,  $V$ , used with a strain gage of resistance  $R$ , requires a current of  $I = V/R$ . The resistance of a Wheatstone bridge measured between any two

symmetrical terminals equals the value of one of the resistance arms. For example, four 350 Ohm arms make a 350 Ohm bridge. The load current equals the excitation voltage divided by the bridge resistance; in this case,  $10 \text{ V}/350 \Omega = 0.029 \text{ A} = 29 \text{ mA}$ .

### Heating

Resistive heating in strain gages also should be considered because the gages respond to temperature as well as stress. The excitation voltage must be coordinated with the gage and the material to which it is bonded. Like most engineering endeavors, strain measurement involves making compromises, in this case it is errors due to self-heating versus signal to noise ratio. Higher excitation results in a signal that is less affected by external electrical noise sources but will result in higher errors due to self-heating. Self-heating errors are more prevalent when the strain gage is bonded to a material that doesn't heat quickly, such as wood, plastic, or glass materials. Also, heat can become a problem when the strain gages are uncommonly small, or numerous gages occupy a limited space.

For full- and half-bridge configurations, consider a Kelvin connection for applying the excitation voltage. Because the excitation leads carry a small current, they drop a correspondingly small voltage;  $V = I/R_l$ , which reduces the voltage reaching the bridge terminals. As illustrated in Figure 4, Kelvin connections eliminate this drop with a pair of leads added at the excitation terminals to measure and regulate the bridge voltage. For example, when  $i_e = 50 \text{ mA}$ ,  $R_l = 5 \Omega$ , and the combined voltage drop in the two leads is 500 mV, no voltage drops in the sense wires.

An IOtech strain gage module uses a Kelvin connection to measure and regulate the voltage at the bridge. It supplies the voltage to the strain gage with one pair of leads and measures it with another pair as shown in Figure 5. The six wires are used in pairs for Sense, Excite, and Measure. The Sense lead is a feedback loop to ensure that the Excite voltage is constantly held within specifications.

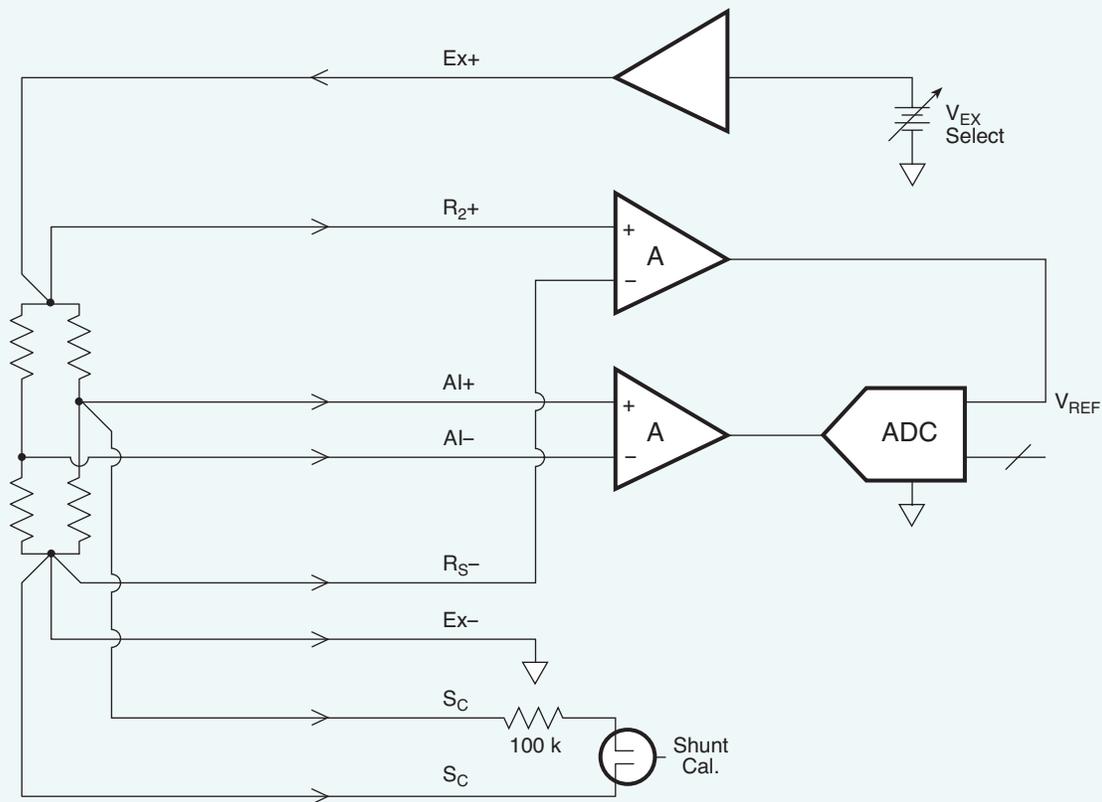
In the quarter-bridge configuration it is not possible to remotely sense around the lead wire resistances, so a three-wire connection is recommended. This configuration relies on the resistances of the lead wires being equal. Note, in Figure 3, that if  $R_1$  plus  $R_3$  equals  $R_1$  plus  $R_4$  and  $R_1$  equals  $R_2$ , then  $-AI$  equals  $+AI$  and the bridge will be balanced. The IOtech CN-269 and CN-270 provide the bridge completion resistor  $R_4$ . It is up to the user to run the three wires (denoted by RL) to the gage; do not tie pins 1 and 2 together at the CN unless the gage wires are extremely low resistance.

### Strain Gage Signal Conditioning

Most strain gage based transducers and load cells are assigned units of measure for weight, force, tension, pressure, torque, and deflection with a full-scale value measured in mV/V of excitation. For example, a load cell with a 10 V excitation supply and a 2 mV/V gain factor generates an output of 20 mV at full load, whether the load cell was designed to handle 10, 100, or 1,000 lbs. The difference is in the resolution of the system. That is, the small 10-lb load cell produces 0.5 lbs/mV, and the large 1,000-lb load cell produces 50 lbs/mV.

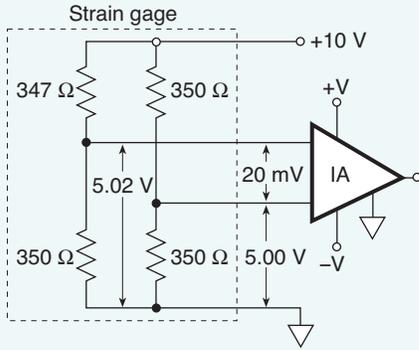
Conductors carrying such low level signals are susceptible to noise interference and should be shielded. Low-pass filters, differential voltage measurements, and signal averaging are also effective techniques for suppressing noise interference. Furthermore, instrumentation amplifiers usually condition the extremely low strain gage signals before feeding them to ADCs.

Figure 5: IOtech Strain Gage Module



*An IOtech strain-gage module provides adjustable excitation, gain, and offset for each channel. This lets it make use of the instrument's entire dynamic range.*

**Figure 6: Wheatstone Bridge Circuit**



Normally the strain gage signal in a Wheatstone bridge is superimposed on a common-mode voltage equal to half of the excitation voltage. Consequently, a high CMRR is necessary to reject the common-mode voltage and amplify the strain gage signal.

### Common-mode rejection ratio

A high common-mode rejection ratio (CMRR) is essential for strain gage amplifiers. A strain gage signal in a Wheatstone bridge is superimposed on a common-mode voltage equal to half the excitation voltage. CMRR is a measure of how well the amplifier rejects common-mode voltages. For example, consider a 10 V excitation supply ( $V_{\max} = 5 \text{ V}$ ) for a strain gage with  $2 \text{ mV/V}$  ( $V_s = 20 \text{ mV}$ ) at full scale and an amplifier with a CMRR of 90 dB. (See Figure 6.) The amplifier can introduce 0.158 mV of error, corresponding to about 0.80% full scale, which may not be acceptable:

#### Equation 4: Common-Mode Rejection Ratio

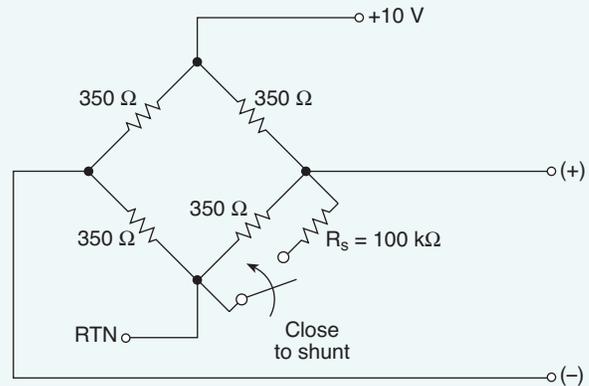
$$\begin{aligned} \text{dB} &= 20 \log_{10}(V_s/V_e) \\ V_{\max}/V_e &= \log_{10}^{-1}(\text{dB}/20) \\ &= \log_{10}^{-1}(90/20) \\ &= 31,622 \end{aligned}$$

$$\begin{aligned} V_e &= V_{\max}/\log_{10}^{-1}(\text{dB}/20) \\ &= 5.00/31,622 \\ &= 0.158 \text{ mV} \end{aligned}$$

$$\begin{aligned} \% \text{error} &= (V_e/V_s)100 \\ &= (0.158\text{mV}/20\text{mV})100 \\ &= 0.79\% \end{aligned}$$

Where:  $V_e$  = error voltage, V  
 $V_s$  = signal voltage, 20 mV  
 $V_{\max}$  = maximum voltage, 5V  
 CMRR = 90 dB

**Figure 7: Shunt Bridge Circuit**



A bridge may be calibrated with a shunt resistor, which is switched with a software command into either one of the two lower legs.

By comparison, a CMRR of 115 dB introduces only 9 mV of error, which corresponds to only 0.04% of full scale.

Strain gage signal conditioning modules usually provide a regulated excitation source with optional Kelvin excitation. Bridge completion resistors may be connected for quarter and half-bridge strain gages. Instrumentation amplifiers provide input and scaling gain.

The 6224 utilizes a 24-bit ADC, so the old practice of adjusting gain and offset voltages in hardware to pull out every last bit of a 16-bit ADC's resolution is no longer necessary. The old method had one very undesirable consequence; if one set the gain too close to the maximum, the ADC could limit out and valuable information would be lost. If the gain were set too low, low level signal information would be lost. The 24-bit ADC has 256 times the resolution of the 16-bit ADC, so software offset and gain adjustments can be employed providing great resolution and large overhead.

### CALIBRATION

The signal conditioning module also typically provides a shunt calibration feature. See Figure 7. It lets users switch in an extremely stable, internal shunt cal resistor. For example, a shunt resistor can be calculated to simulate a full load. Applying a shunt resistor is a convenient way to simulate an unbalance without having to apply a physical load.

### Transducers and Load Cells

Strain gages are commercially available in prefabricated modules such as load cells that measure force, tension, compression, and torque. Load cells typically use a full-bridge configuration and contain four leads for bridge excitation and measurement. The manufacturers provide calibration and accuracy information.

## Strain Diaphragm Pressure Gages

A strained diaphragm pressure gage consists of two or four strain gages mounted on a thin diaphragm. The gages are wired in a Wheatstone bridge circuit, including bridge completion resistors when needed, so the pressure gage is electrically equivalent to a load cell. The output voltage is specified in mV/V of excitation for a full-scale pressure differential across the diaphragm.

When one side of the diaphragm (called the reference pressure side) is open to the ambient atmosphere, the gage compares the inlet pressure to the ambient pressure, which is about 14.7 psi at sea level. When the gage measures ambient pressure, the reference chamber must be sealed with either a vacuum reference (near zero psi) or the sea-level reference.

Temperature variations can affect the accuracy of strained diaphragm pressure gages. A pressure gage with a sealed non-zero reference pressure exhibits temperature variations consistent with the ideal gas law. For example, a 5°C change in ambient temperature near normal room temp (25°C) produces an error of 1.7% in the pressure measurement. Temperature variations can also affect the performance

of the strain gages themselves. Transducers must contain temperature compensation circuits to maintain accurate pressure measurements in environments with widely varying temperatures.

All strained diaphragm pressure gages require a regulated excitation source. Some gages contain internal regulators, so users can connect an unregulated voltage from a power supply. Some strained diaphragm pressure gages also employ internal signal conditioning, which amplifies the mV signal output of the Wheatstone bridge to a full-scale voltage from 5 to 10 V. Gages of this type have low-impedance outputs. In contrast, other pressure gages have no internal signal conditioning so their output impedance equals the Wheatstone bridge resistance (several kΩ for semiconductor types), and their full-scale output is in mV.

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## IOtech 6224 Strain Measurement Module

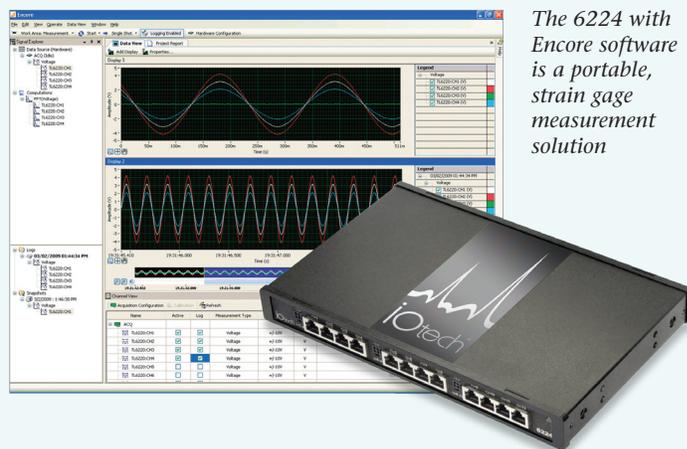
IOtech's 6224 module combines an accurate, instrument class, Ethernet-based module with powerful, easy-to-use software. It is a major advancement in ease-of-use and functionality. The 6224 features integrated signal conditioning and a modular design that allows for system expansion. Because it uses an Ethernet connection, modules can be connected directly to a PC or used in remote configurations utilizing multiple modules. Included with each module is Encore interactive measurement software, which couples ease-of-use with advanced functionality.

### Features

- 12 strain gage inputs
- 24-bit/delta-sigma ADC per channel
- 50-kHz per channel sample rate
- User programmable excitation
- Simultaneous sampling
- Remote sensing
- Shunt calibration
- Eight digital I/O
- Multiple trigger modes
- Compact, portable design
- Expandable using multiple modules

### Software

- Includes Encore interactive measurement software for *Out-of-the-Box* setup, acquisition, display, logging, analysis, and reporting
- Advanced feature set with no programming required
- True drag-and-drop functionality
- Easy-to-use set-up wizards
- Drag data directly to Excel®
- Included data analysis tools
- Playback mode
- Sophisticated test report capability
- Incorporate multiple 6224 devices into one application
- **Supported Operating Systems:**  
Windows 2000®, Windows Vista® x86 (32-bit), and Windows XP® (32-bit)



*The 6224 with Encore software is a portable, strain gage measurement solution*

### Software Overview

Encore is the premier *Out-of-the-Box* data acquisition software package and is included with each 6224 module. Encore combines ease of use with advanced functionality, including customizable data layouts, powerful analysis, and reporting capabilities. Instead of having a program to log data, another to analyze, and a third to develop report data, Encore includes the functionality of all three into one package, thus shortening the learning curve, and saving time and cost.

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