Measuring Strain with Strain Gages

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Overview

This tutorial is part of the National Instruments Measurement Fundamentals series. Each tutorial in this series will teach y
specific topic of common measurement applications by explaining theoretical concepts and providing practical examples.
tutorial introduces and explains the concepts and techniques of measuring strain with strain gages.

To find more information on the Measurement Fundamentals series, return to the NI Measurement Fundamentals Main F
http://zone.ni.com/devzone/cda/tut/p/id/4523).

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1. What Is Strain?

Strain is the amount of deformation of a body due to an applied force. More specifically, strain (e) is defined as the fractic
change in length, as shown in Figure 1.

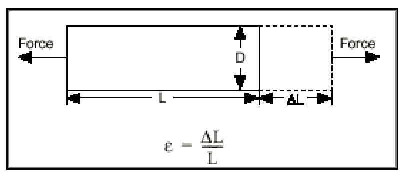

Figure 1. Definition of Strain

Strain can be positive (tensile) or negative (compressive). Although dimensionless, strain is sometimes expressed in unit
in./in. or mm/mm. In practice, the magnitude of measured strain is very small. Therefore, strain is often expressed as mic
(me), which is e x 10^{-6}.

When a bar is strained with a uniaxial force, as in Figure 1, a phenomenon known as Poisson Strain causes the girth of tl
to contract in the transverse, or perpendicular, direction. The magnitude of this transverse contraction is a material prope
indicated by its Poisson's Ratio. The Poisson's Ratio n of a material is defined as the negative ratio of the strain in the tra
direction (perpendicular to the force) to the strain in the axial direction (parallel to the force), or $n = e_T/e$. Poisson's Ratio f
for example, ranges from 0.25 to 0.3.

2. The Strain Gage

While there are several methods of measuring strain, the most common is with a strain gage, a device whose electrical re
varies in proportion to the amount of strain in the device. The most widely used gage is the bonded metallic strain gage.

The metallic strain gage consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern. The grid p
maximizes the amount of metallic wire or foil subject to strain in the parallel direction (Figure 2). The cross-sectional area
grid is minimized to reduce the effect of shear strain and Poisson Strain. The grid is bonded to a thin backing, called the c
which is attached directly to the test specimen. Therefore, the strain experienced by the test specimen is transferred direc
strain gage, which responds with a linear change in electrical resistance. Strain gages are available commercially with nc
resistance values from 30 to 3,000 Ω, with 120, 350, and 1,000 Ω being the most common values.

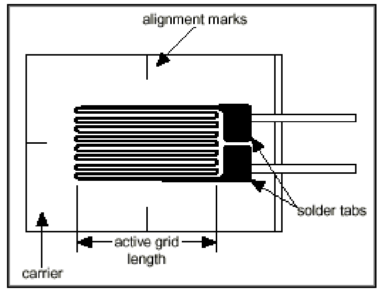

Figure 2. Bonded Metallic Strain Gage

It is very important that the strain gage be properly mounted onto the test specimen so that the strain is accurately transfe the test specimen, through the adhesive and strain gage backing, to the foil itself.

A fundamental parameter of the strain gage is its sensitivity to strain, expressed quantitatively as the gage factor (GF). G is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon}$$

The gage factor for metallic strain gages is typically around 2.

3. Strain Gage Measurement

In practice, strain measurements rarely involve quantities larger than a few millistrain (e x 10^{-3}). Therefore, to measure th requires accurate measurement of very small changes in resistance. For example, suppose a test specimen undergoes a 500 me. A strain gage with a gage factor of 2 will exhibit a change in electrical resistance of only 2 (500 x 10^{-6}) = 0.1%. F Ω gage, this is a change of only 0.12 Ω.

To measure such small changes in resistance, strain gages are almost always used in a bridge configuration with a volta excitation source. The general Wheatstone bridge, illustrated in Figure 3, consists of four resistive arms with an excitatior V_{EX}, that is applied across the bridge.

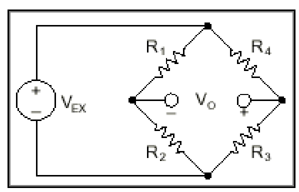

Figure 3. Wheatstone Bridge

The output voltage of the bridge, V_O, is equal to:

$$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right] \bullet V_{EX}$$

From this equation, it is apparent that when $R_1/R_2 = R_4/R_3$, the voltage output V_O is zero. Under these conditions, the bri said to be balanced. Any change in resistance in any arm of the bridge results in a nonzero output voltage.

Therefore, if you replace R_4 in Figure 3 with an active strain gage, any changes in the strain gage resistance will unbalan bridge and produce a nonzero output voltage. If the nominal resistance of the strain gage is designated as R_G, then the strain-induced change in resistance, DR, can be expressed as DR = R_G·GF·e, from the previously defined Gage Factor e Assuming that $R_1 = R_2$ and $R_3 = R_G$, the bridge equation above can be rewritten to express V_O/V_{EX} as a function of strair Figure 4). Note the presence of the 1/(1+GF·e/2) term that indicates the nonlinearity of the quarter-bridge output with resp strain.

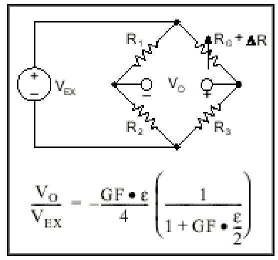

Figure 4. Quarter-Bridge Circuit

Ideally, you would like the resistance of the strain gage to change only in response to applied strain. However, strain gag material, as well as the specimen material to which the gage is applied, also responds to changes in temperature. Strain manufacturers attempt to minimize sensitivity to temperature by processing the gage material to compensate for the therı expansion of the specimen material for which the gage is intended. While compensated gages reduce the thermal sensiti do not totally remove it.

By using two strain gages in the bridge, you can further minimize the effect of temperature. For example, Figure 5 illustra strain gage configuration where one gage is active (R_G + DR) and a second gage is placed transverse to the applied stra Therefore, the strain has little effect on the second gage, called the dummy gage. However, any changes in temperature both gages in the same way. Because the temperature changes are identical in the two gages, the ratio of their resistanc not change, the voltage V_O does not change, and the effects of the temperature change are minimized. NOTE: In the Wh bridge configuration, the active gage and the dummy gage should be on the same vertical leg of the bridge.

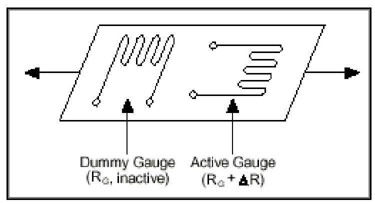

Figure 5. Use of Dummy Gage to Eliminate Temperature Effects

The sensitivity of the bridge to strain can be doubled by making both gages active in a half-bridge configuration. For exar Figure 6 illustrates a bending beam application with one bridge mounted in tension (R_G + DR) and the other mounted in compression (R_G - DR). This half-bridge configuration, whose circuit diagram is also illustrated in Figure 6, yields an outp that is linear and approximately doubles the output of the quarter-bridge circuit.

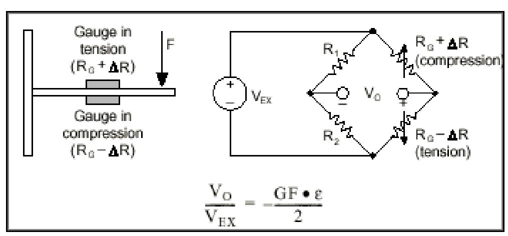

Figure 6. Half-Bridge Circuit

Finally, you can further increase the sensitivity of the circuit by making all four of the arms of the bridge active strain gage full-bridge configuration. The full-bridge circuit is shown in Figure 7.

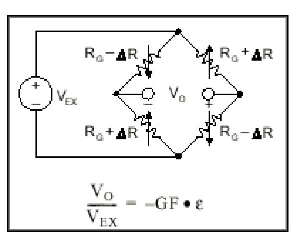

Figure 7. Full-Bridge Circuit

The equations given here for the Wheatstone bridge circuits assume an initially balanced bridge that generates zero outp no strain is applied. In practice, however, resistance tolerances and strain induced by gage application generate some in voltage. This initial offset voltage is typically handled in two ways. First, you can use a special offset-nulling, or balancing adjust the resistance in the bridge to rebalance the bridge to zero output. Alternatively, you can measure the initial unstra output of the circuit and compensate in software. This topic is discussed in greater detail later.

The equations given above for quarter-, half-, and full-bridge strain gage configurations assume that the lead wire resista negligible. While ignoring the lead resistance may be beneficial to understanding the basics of strain gage measurements so in practice can be a major source of error. For example, consider the 2-wire connection of a strain gage shown in Figu Suppose each lead wire connected to the strain gage is 15 m long with lead resistance R_L equal to 1 Ω. Therefore, the le resistance adds 2 Ω of resistance to that arm of the bridge. Besides adding an offset error, the lead resistance also dese the output of the bridge.

You can compensate for this error by measuring the lead resistance R_L and accounting for it in the strain calculations. Ho more difficult problem arises from changes in the lead resistance due to temperature fluctuations. Given typical temperat coefficients for copper wire, a slight change in temperature can generate a measurement error of several microstrain.

Using a 3-wire connection can eliminate the effects of variable lead wire resistance because the lead resistance affects a legs of the bridge. As seen in Figure 8b, changes in lead wire resistance, R_{L2}, do not change the ratio of the bridge legs I . Therefore, any changes in resistance due to temperature cancel out each other.

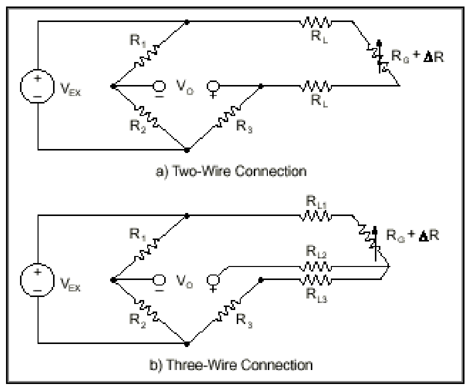

Figure 8. 2-Wire and 3-Wire Connections of Quarter-Bridge Circuit

4. Signal Conditioning for Strain Gages

Strain gage measurement involves sensing extremely small changes in resistance. Therefore, proper selection and use c bridge, signal conditioning, wiring, and data acquisition components are required for reliable measurements. To ensure a strain measurements, it is important to consider the following:

- Bridge completion
- Excitation
- Remote sensing
- Amplification
- Filtering
- Offset
- Shunt calibration

Bridge Completion – Unless you are using a full-bridge strain gage sensor with four active gages, you need to complete bridge with reference resistors. Therefore, strain gage signal conditioners typically provide half-bridge completion networ consisting of high-precision reference resistors. Figure 9a shows the wiring of a half-bridge strain gage circuit to a conditi completion resistors R_1 and R_2.

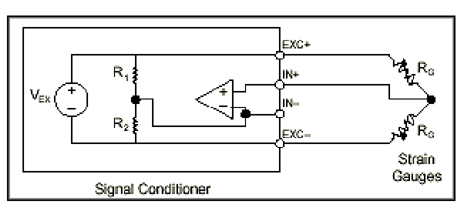

Figure 9a. Connection of Half-Bridge Strain Gage Circuit

Excitation – Strain gage signal conditioners typically provide a constant voltage source to power the bridge. While there standard voltage level that is recognized industry wide, excitation voltage levels of around 3 and 10 V are common. While excitation voltage generates a proportionately higher output voltage, the higher voltage can also cause larger errors beca self-heating.

Remote Sensing – If the strain gage circuit is located a distance away from the signal conditioner and excitation source, possible source of error is voltage drop caused by resistance in the wires connecting the excitation voltage to the bridge. Therefore, some signal conditioners include a feature called remote sensing to compensate for this error. Remote sense connected to the point where the excitation voltage wires connect to the bridge circuit, as seen in Figure 9b. The extra se serve to regulate the excitation supply through negative feedback amplifiers to compensate for lead losses and deliver th voltage at the bridge.

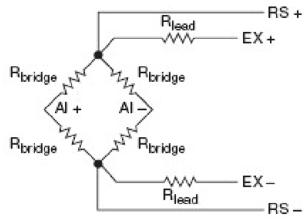

Figure 9b. Remote Sensor Error Compensation

Amplification – The output of strain gages and bridges is relatively small. In practice, most strain gage bridges and strai transducers output less than 10 mV/V (10 mV of output per volt of excitation voltage). With 10 V excitation, the output sig mV. Therefore, strain gage signal conditioners usually include amplifiers to boost the signal level to increase measureme resolution and improve signal-to-noise ratios.

Filtering – Strain gages are often located in electrically noisy environments. It is therefore essential to be able to eliminat that can couple to strain gages. Lowpass filters, when used with strain gages, can remove the high-frequency noise prev most environmental settings.

Offset Nulling – When a bridge is installed, it is very unlikely that the bridge will output exactly zero volts when no strain applied. Slight variations in resistance among the bridge arms and lead resistance will generate some nonzero initial offs voltage. Offset nulling can be performed by either hardware or software:

1. Software Compensation – With this method, you take an initial measurement before strain input is applied, and use thi compensate subsequent measurements. This method is simple, fast, and requires no manual adjustments. The disadvar the software compensation method is that the offset of the bridge is not removed. If the offset is large enough, it limits the 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 adj output of the bridge to zero. By varying the resistance of potentiometer, you can control the level of the bridge output and initial output to zero volts.

Shunt Calibration – The normal procedure to verify the output of a strain gage measurement system relative to some predetermined mechanical input or strain is called shunt calibration. Shunt calibration involves simulating the input of stra changing the resistance of an arm in the bridge by some known amount. This is accomplished by shunting, or connectinc resistor of known value (Rs) across one arm of the bridge, creating a known DR as seen in Figure 9c. The output of the b then be measured and compared to the expected voltage value. The results are used to correct span errors in the entire measurement path, or to simply verify general operation to gain confidence in the setup.

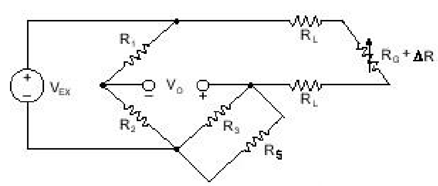

Figure 9c. Shunt Resistor Connected Across R3

5. Data Acquisition Systems for Strain Gage Measurements

Using CompactDAQ with Strain Gages

CompactDAQ is a portable, rugged DAQ platform that integrates connectivity and signal conditioning into modular I/O for interfacing to any sensor or signal. CompactDAQ delivers fast and accurate measurements with more than 60 different measurement modules available.

Figure 10. CompactDAQ chassis with C Series I/O Modules

The NI 9219 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/203423) is a 4-channel universal C Series module designed f multipurpose testing in any CompactDAQ or CompactRIO controller or chassis. With the NI 9219, you can measure seve signals from sensors such as strain gages, RTDs, thermocouples, load cells, and other powered sensors. The channels a individually selectable, so you can perform a different measurement type on each of the four channels. The NI 9219 uses six-position spring terminal connectors in each channel for direct signal connectivity and contains built-in quarter-, half-, a full-bridge support.

For C Series I/O modules specifically designed for the measurement of strain gages, National Instruments offers the NI 9 9236 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/205192), and the NI 9237 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/202632). These bridge modules contain all the signal conditioning required and measure bridge-based sensors simultaneously. The NI 9235 and NI 9236 have a higher channel count and include completion for quarter-bridge sensors. The NI 9237 supports up to four full- and half bridge sensors and can measure fro bridge strain gages using a completion accessory.

The NI 9237 can perform offset/null as well as shunt calibration and remote sense, making the module the best choice fo medium-channel-count strain and bridge measurements.

Recommended Starter Kit for Strain Gage CompactDAQ System:

1. CompactDAQ (http://www.ni.com/data-acquisition/compactdaq/) controller of chassis
2. NI 9237 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/202632) with an RJ50 cable and an NI 9949 (full and half bridge 9944/NI 9945 (quarter bridge)

Using PXI with Strain Gages

PXI is a rugged PC-based platform that offers a high-performance, low-cost deployment solution for measurement and au systems. PXI combines the PCI bus with the rugged, modular Eurocard mechanical packaging of CompactPCI and adds specialized synchronization buses and key software features. PXI can integrate a controller and provides up to 18 slots in chassis. There are timing and triggering lines on the backplane of the PXI chassis for tight synchronization of the various modules. PXI Express delivers PCI Express data transfer technology to the PXI platform, increasing backplane bandwid 132 MB/s to 6 GB/s.

Figure 11. PXI Express Chassis with SC Express Sensor Measurement Modules

The NI SC Express family (http://www.ni.com/sc-express/) features PXI Express data acquisition modules with integrated conditioning for sensor measurements, such as strain gages and other Wheatstone bridge-based transducers. The NI PX http://sine.ni.com/nips/cds/view/p/lang/en/nid/208289) 8-channel simultaneous bridge input module offers 24-bit resolutio accuracy and 25 kS/s per channel sample rate for high-performance strain measurements. The NI PXIe-4330 can perfor quarter-, half-, and full bridge-based measurements with automatic synchronization features; the included driver software tight synchronization across multiple modules and chassis with inter-channel skews as low as 5 parts per billion (PPB). T device offers per channel excitation from 0.625 to 10 V with remote sensing to compensate for error caused by resistanc wires connecting the voltage source to the bridge. For added flexibility, built-in bridge completion (120 Ω, 350 Ω, and 1 k shunt calibration (50 kΩ, 100 kΩ) are software-selectable on a per channel basis. The NI PXIe-4330 should be used with NI TB-4330 front-mounting terminal block for screw terminal connectivity.

Recommended Starter Kit for Strain Gage SC Express System:

1. NI PXIe-1073 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/207401) chassis
2. NI PXIe-4330 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/208289) universal bridge input module with TB-4330 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/208295) for connectivity

Using SCXI with Strain Gages

National Instruments SCXI (http://sine.ni.com/nips/cds/view/p/lang/en/nid/1604) is a signal conditioning system for PC-ba instrumentation applications. An SCXI system consists of a shielded chassis that houses a combination of signal conditio and output modules, which perform a variety of signal conditioning functions. You can connect many different types of se including strain gages, directly to SCXI modules. The SCXI system operates as a front-end signal conditioning system fo plug-in data acquisition (http://www.ni.com/data-acquisition/) devices (USB, PCI, and PCMCIA) or PXI data acquisition m

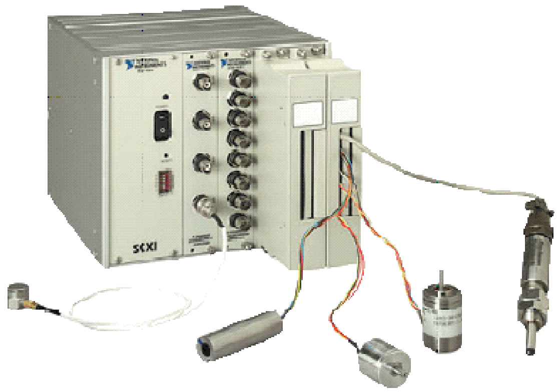

Figure 12. SCXI Signal Conditioning System

The NI SCXI-1520 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/4489) is an 8-channel universal strain gage input modu offers a variety of features for strain measurements. With this single module, signals from strain, force, torque, and press sensors can be easily read. The SCXI-1520 also offers a programmable amplifier and programmable four-pole Butterwor each channel, and simultaneous sampling with track-and-hold circuitry. In addition, the SCXI-1520 system offers a half-b completion resistor network in the module and a socketed 350 W quarter-bridge completion resistor. Table 1 summarizes additional features of the SCXI-1520 that relate to strain gage measurements.

Table 1. SCXI-1520 Features for Strain Gages

Number of channels	8
Multiplexer scan rate	Up to 333 kS/s[1]
Amplifier gain	1 to 1,000
Excitation voltage source	0.0 to 10.0 V in 0.635 V increments
Excitation current drive	29 mA throughout excitation voltage range
Half-bridge completion	Yes
Offset nulling	Yes
Shunt calibration	Yes
Remote excitation sensing	Yes

[1] Multiplexer scan rate depends on the data acquisition device.

Recommended Starter Kit for Strain Gage SCXI Data Acquisition System:

1. USB-1600 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/14235) USB Data Acquisition and Control Module for SCXI
2. NI SCXI-1000 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/10676) chassis
3. SCXI-1520 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/4489) with NI SCXI-1314 (http://sine.ni.com/nips/cds/view/p/lang/en/nid/3396) terminal block

6. Relevant NI Products

Customers interested in this topic were also interested in the following NI products:

- LabVIEW (http://www.ni.com/labview/)
- Data Acquisition (DAQ) (http://www.ni.com/data-acquisition/)
- Signal Conditioning (http://www.ni.com/signalconditioning/)

For more tutorials, return to the NI Measurement Fundamentals Main Page (http://zone.ni.com/devzone/cda/tut/p/id/4523

Download the Complete Guide to Building a Measurement System (https://lumen.ni.com/nicif/us/ekitdaqsys/content.xhtm checklist of questions to consider for your application.