

## Strain Gauge & Load Cell Input Transmitters

Whitepaper:

### INTRODUCTION TO STRAIN & STRAIN MEASUREMENT

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## About the Strain Gauge

*An “active” gauge is oriented in a direction to measure the effect of an applied force on a material (usually in the same direction as the force or lateral to it).*

This paper covers the topic of strain and load measurement as related to Acromag strain modules and transmitters, but may be extended to other strain gauge or load cell instruments. Acromag manufactures a complete line of I/O modules that support a wide range of sensor signal types. Please visit [www.acromag.com](http://www.acromag.com) to obtain the latest information about these products.

Strain gauges change resistance in proportion to applied forces that result from loading, torque, pressure, acceleration, and vibration. Because their change in resistance to force is very small, they often connect in a Wheatstone Bridge of four elements. You can wire a bridge with one active strain gauge and 3 resistors (quarter bridge), two active strain gauges and two resistors (half-bridge), or 4 active strain gauges (full-bridge). The number of active gauges in a bridge and how they are oriented relative to applied force will determine the bridge type, its application, and relative strain computation.

The load cell is a simpler form of a Wheatstone Bridge based sensor, but one whose output  $V_o$  is relative to percent of rated load and will correspond to the pressure or weight applied. Load cells are much simpler than strain gauge bridges because their relationship to load does not require additional detail of how its internal bridge elements are arranged, its Gauge Factor, or the Poisson's ratio of the material it is applied to. The only important considerations for resolving the load cell are its rated output (mV/V), excitation voltage, and rated capacity.

$$\text{micro-strain } (\mu\varepsilon) = \Delta L/L * 10^{-6}.$$

The output voltage of a Wheatstone Bridge is directly proportional to bridge excitation and very sensitive to the small mechanical deformations that drive resistance imbalances in one or more legs of a bridge. Because the mechanical deformation resulting from an applied force is a very small percentage, the corresponding strain it represents is often expressed as a multiple of  $10^{-6}$  or micro-strain (micro-strain =  $\Delta L/L * 10^{-6}$ ). Stress applied to an active bridge element will drive an unbalanced bridge condition that produces an offset in the bridge output voltage that can be related to the magnitude of the applied force. The *sensitivity* of a bridge network or load cell is how much the bridge output voltage changes relative to 1V of bridge excitation and expressed in millivolts of  $V_o$  per volt of excitation  $V_{ex}$  (mV/V). This is usually referred to as the gauge or cell Rated Output and denoted by  $V_r = V_o/V_{ex}$ . The full-scale output of a strain gauge bridge or load cell sensor at its full rated load (100%) is the product of the gauge Rated Output (mV/V) and applied excitation voltage  $V_{ex}$ .

## Strain Measurement

$$\varepsilon = \Delta L / L$$

*In most real-world applications, strain measurements are rarely encountered larger than a few milli-strain ( $\varepsilon = 0.003$  or about  $3000\mu\varepsilon$ ).*

Strain ( $\varepsilon$ ) is a measure of the mechanical deformation of a material and computed as a fractional change in dimension (length, width, or height) resulting from a force along that dimension ( $\varepsilon = \Delta L / L$ ). Strain may be positive (tensile  $+\varepsilon$ ), or negative (compressive  $-\varepsilon$ ) and the magnitude of deformation it represents is a very small percentage such that it is often expressed as an integer multiple of  $10^{-6}$ , or micro-strain ( $\mu\varepsilon$ ).

There are normally two sensor measurements used to resolve strain or load: the sensor bridge output signal  $V_o$  and the sensor bridge excitation  $V_{ex}$ . Using sensor specifications and these two measurements, the applied strain or load can be resolved from the bridge output signal.

## Strain Measurement...

$$GF = (\Delta R/R)/(\Delta L/L) = (\Delta R/R)/\epsilon$$

$$\Delta R = R * GF * \epsilon$$

$$\text{Poisson's Ratio } (\gamma) = -\epsilon_T / \epsilon.$$

$$\text{Poisson's Strain } (\epsilon_T) = -\gamma \epsilon.$$

$$-1.0 \leq \gamma \leq +0.5$$

*The effect of Poisson's strain is often ignored in strain calculations < 5000 $\mu\epsilon$  where it is small.*

*Example Calculation: If you measured 3000 $\mu\epsilon$  with a 120 $\Omega$  metallic strain gauge (GF=2.00), its corresponding fractional change in resistance  $\Delta R/R = 2.00 * 3000 * 10^{-6} = 0.006$ , implying that this 120 $\Omega$  gauge changed its resistance by only 0.6% or 0.72 $\Omega$ .*

Like the sensitivity of a bridge reflects how much the magnitude its full-scale output changes per volt of excitation, the sensitivity of a strain gauge or Gauge Factor GF is how much its resistance changes in proportion to applied strain (its ratio of fractional change in resistance to applied strain  $\epsilon$ ). For common metallic strain gauges, the Gauge Factor is *typically* around 2.0, meaning its resistance change is about 2x its dimension change to an applied force ( $\Delta R/R = 2x \Delta L/L$ ). However, GF varies slightly for most applications and this affects relative strain. For many instruments, sensor Gauge Factor will be used to compute *ideal* strain, but an Instrument Gauge Factor will be used to compute *indicated* strain.

A material subject to a tensile or compressive uniaxial force in one direction will coincide with a lateral force referred to as Poisson's Strain. Most materials that undergo a tensile force or positive strain (when stretched or elongated) will contract slightly due to coincident negative strain in the lateral/transverse dimension (when its Poisson's ratio  $\gamma = -\epsilon_T / \epsilon$  is a positive number). Less common, there are some materials with a negative Poisson's ratio that expand in the transverse direction ( $+\epsilon_T$ ) in response to being stretched ( $+\epsilon$ ) in the longitudinal direction. In general, the proportion of contraction or expansion is indicated by the application material's Poisson's Ratio. The Poisson's Ratio ( $\gamma$ ) is the negative ratio of the simultaneous transverse strain that occurs in the perpendicular direction to the main strain parallel to the applied force.

Strain gauge sensors typically consist of a very fine foil or wire grid that is bonded to an application material surface in the direction of an applied force (uniaxial) or lateral to it (bending force). These are referred to as a bonded metallic or resistance strain gauges. They are designed to change their resistance *slightly* in proportion to stress. Most strain gauges have nominal resistance values that vary from 30 to 3000 $\Omega$ , with 120 $\Omega$ , 350 $\Omega$ , and 1000 $\Omega$  being the most common. Their cross-sectional area is minimized by design to reduce the negative effect of the corresponding shear or Poisson's Strain coincident to applied strain.

The bonded metallic strain gauge has a foil grid attached to a thin backing material or carrier strip which is directly attached to the application material to help facilitate an efficient transfer of strain on the body to the foil grid of the gauge and allow it to respond with a linear or nearly-linear change in electrical resistance. Ideally, the strain gauge resistance should only change in response to applied strain, but unfortunately in practice, this is somewhat of an inexact science and it is difficult to make both the gauge material and application material expand and contract equally over temperature. As you can surmise, properly mounting the gauge is critical to ensure applied material strain is accurately transferred through the bonding adhesive and backing material to the gauge foil.

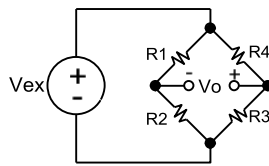
To curb potential problems caused by mismatched expansion and contraction rates between the gauge and application material, gauge manufacturers try to minimize sensitivity to temperature by selecting specific gauge materials for specific application materials. While this helps to minimize strain error, temperature remains a source of potential error and additional compensation is usually required. Adverse effects like this are the reason strain instruments provide additional parametric controls for rescaling their measurement as required, like utilizing Instrument Gauge Factor and Software Gain to help overcome application-induced skew in strain measurement.

## The Wheatstone Bridge

$\Delta R = R * GF * \epsilon$  implies that at  $3000\mu\epsilon$ ,  $\Delta R/R \sim 2.00 * 3000 * 10^{-6} = 0.006$  or 0.6%

We stated that because strain measurement requires the detection of very small resistance changes resulting from very small mechanical deformations, we wire strain gauges as elements of a Wheatstone bridge which converts the signal to a bipolar output voltage that can be conveniently measured in proportion to the applied stress and its direction. Note that the magnitude of most strain measurement in stress applications is commonly between  $2000\mu\epsilon$  and  $10000\mu\epsilon$ , and rarely larger than about  $3000\mu\epsilon$  or  $\sim 0.6\%$ . The Wheatstone Bridge offers an accurate method for measuring these very small changes in resistance and even provides an ability to compensate for the inherent sensitivity of the strain gauge relative to temperature.

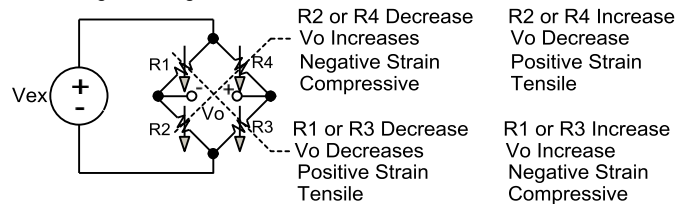
Figure 1: Wheatstone Bridge



The Wheatstone Bridge is comprised of four resistive arms or bridge elements arranged in the configuration of a diamond as shown at left. An excitation voltage  $V_{ex}$  is applied vertically across the diamond or bridge input and an output voltage  $V_o$  can be measured horizontally across the diamond as shown in Figure 1.

From Kirchoff's Voltage Law & Ohm's Law, the bridge output voltage  $V_o$  is the difference between two divided voltages with  $V_o = [R3/(R3+R4) - R2/(R2+R1)] * V_{ex}$ . If the adjacent resistors of each divider match their ratios such that  $R1/R2 = R4/R3$ , then  $V_o=0$  and the bridge is *balanced*. Note it is not required that  $R1=R4$  and  $R2=R3$  to achieve balance, just that the ratios of adjacent resistors  $R1:R2$  and  $R4:R3$  be equal (this also allows you to use half bridge completion resistors of a different value than the nominal gauge resistance). But for simplicity, if all four of the resistances in each leg of the bridge are equal, the two divider pairs will have equal ratios and the bridge will be balanced with a bridge output voltage  $V_o=0$ . Any change in resistance in any leg of the bridge will unbalance the bridge and produce  $V_o \neq 0$ . Remember that the same  $V_o$  can be obtained from adjacent pairs of different resistor values, if the ratios of the adjacent pairs are kept equal ( $R1/R2 = R4/R3$ ).

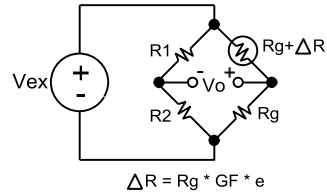
Figure 2: Sign Convention



As stated, if  $R1/R2 = R4/R3$ , then  $V_o=0$  and the bridge is balanced. Examine the two  $V_{ex}$  voltage dividers  $V_{o-} = R2/(R1+R2) * V_{ex}$  and  $V_{o+} = R3/(R4+R3) * V_{ex}$ . Note a decrease in  $R4$  or  $R2$  increases  $V_o$  by increasing the +node voltage and decreasing the -node voltage. Likewise, a decrease in  $R1$  or  $R3$  will decrease  $V_o$  by increasing the -node voltage and reducing the +node voltage. The strain due to a decrease in resistance  $R4$  or  $R2$  will be negative and increase  $V_o$  (convention is that negative strain is compressive and positive strain is tensile). Thus, bridge  $V_o$  will grow positive for a compressive stress on  $R4$  driving negative strain and decreasing its resistance. This is the convention used throughout this manual.

## Wheatstone Bridge...

Figure 3: Strain Bridge w/ Gauge Factor



If you replace R4 in the bridge with an active strain gauge ( $R_g$ ), then any change in the strain gauge resistance ( $\Delta R$ ) will unbalance the bridge and produce an offset in  $V_o$  proportional to the change in resistance  $\Delta R$ . Using Gauge Factor, the change in resistance due to the applied strain is  $\Delta R = R_g * GF * \epsilon$ .

From our divider equation  $V_o = V_{ex} * [R_3 / (R_4 + R_3) - R_2 / (R_1 + R_2)]$ , substituting  $R_1 = R_2$ ,  $R_3 = R_g$ , and  $R_4 = R_g + \Delta R$  yields:  $V_o / V_{ex} = -GF * \epsilon / 4 * [1 / (1 + GF * \epsilon / 2)]$ . This is the strain computation term  $V_r = V_o / V_{ex}$  in mV/V and represents the *sensitivity* of the bridge network in mV/V (not to be confused with strain gauge sensitivity or Gauge Factor). The presence of the extra term  $1 / (1 + GF * \epsilon / 2)$  is representative of a small non-linearity in the output of the quarter bridge network with respect to strain. But for quarter-bridge strain levels below ~5000 micro-strain, the effect of this non-linearity is small and can be ignored in most applications.

Strain sensors formed from a bridge network may employ multiple strain gauges in their construction with 1, 2, or 4 active gauges in a bridge possible. Note that one active strain gauge ( $R_g$ ) may occupy one leg of a four element Wheatstone Bridge (Quarter-Bridge), two legs of a bridge (Half-Bridge), or four legs of a bridge (Full-Bridge). Any remaining legs of a quarter or half bridge network are occupied by fixed resistors or "dummy" gauges, but it is the number of active gauges in the bridge that determines whether the bridge is a quarter (1), half (2), or full bridge (4) type.

Refer back to Figure 2 and note that tensile (positive) strain drives negative  $V_o$  for elements 1 and 3, and elements 4 and 2. Compressive (negative) strain drives  $V_o$  positive for 1 and 3, and elements 2 and 4. A change of resistance in the same direction for adjacent bridge resistors is subtractive and tends to cancel each other out, but a change of resistances in opposite directions for adjacent cells is additive and reinforces their effect on the output  $V_o$ . Similarly, resistance changes between diagonally opposite resistors are additive in same direction and reinforce their effect on output  $V_o$ , but subtractive in opposite directions and tend to cancel each other out.

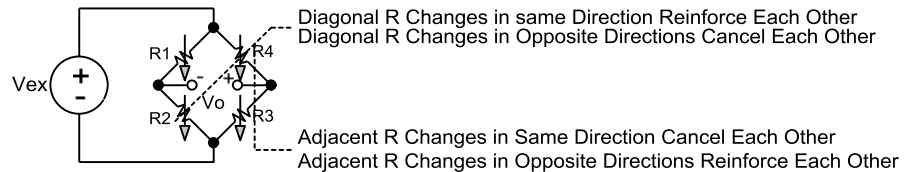
Because strain gauges are inherently sensitive to temperature, we can additionally arrange them in a bridge to compensate its  $V_o$  for temperature by making sure the adjacent element pair ratios  $R_1 : R_2$  and  $R_3 : R_4$  remain equal over temperature. Because opposite changes in resistance of adjacent bridge resistors  $R_1$  &  $R_2$  and  $R_3$  &  $R_4$  are numerically additive and reinforce each other, but numerically subtractive if in the same direction, then placing similar gauges and lead-wires in adjacent arms and exposing them to the same temperature will allow them to act together to null the net thermal effect on the bridge output  $V_o$  and effectively cancel temperature induced strain error.

That is, for an active strain gauge in one arm, use an identical strain gauge in the adjacent arm, subject to the same temperature but not the stress force. Then its temperature resistance change will track that of the primary gauge, and the ratio between them will stay the same, having no unbalancing effect on the bridge output  $V_o$  signal.

**Wheatstone Bridge...**

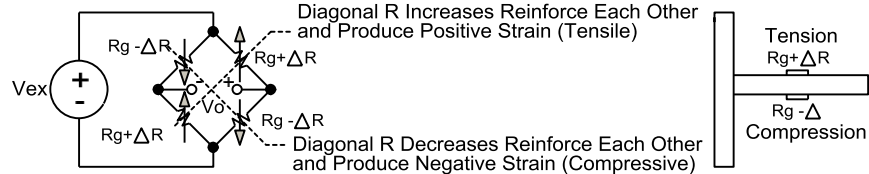
Returning to the prior example where we substituted  $R3=Rg$  and  $R4=Rg+\Delta R$  in the bridge, their net effect with temperature on  $V_o$  was avoided by carefully mounting both gauges such that they are subject to the same temperature, but the “dummy” gauge  $R3=Rg$  mounted transverse to the axial strain (perpendicular to applied strain) such that strain on  $R4=Rg+\Delta R$  has little or no effect on  $R3=Rg$ . Because the ambient temperature affects both gauges the same but not the force, they keep the same ratios and any temperature resistance changes cancel each other and  $V_o$  is not affected by temperature.

Figure 4: Effect of Resistance Changes on Bridge Output



Refer to Figure 4 and note opposite adjacent resistance changes reinforce each other. If you make the adjacent second gauge active by mounting it in the same axis as the applied strain, but of the opposite sign (e.g. one active gauge in tension, one active gauge in compression), you form a half-bridge configuration that doubles the sensitivity of the bridge to strain. That is, the output voltage  $V_o$  of the half-bridge is linear and approximately double the output of the quarter-bridge  $V_o$  for the same excitation  $V_{ex}$ .

Figure 5: Effect of Resistance on Bridge Output  $V_o$  for Balanced Beam



Consider one half of the balance beam bridge application in Figure 5. Solving for the sensitivity  $V_r$  in a half bridge application of two adjacent active gauges would yield:  $V_r = V_o/V_{ex} = -GF*\epsilon/2$ . In Figure 5, note that adjacent arrows are opposite to depict the two elements are mounted such that one is in compression, and the other in tension, for the same applied strain. Now this bridge sensitivity can be further increased by making all four arms of the bridge active strain gauges, with diagonally opposite legs combined such that two diagonal legs are in compression, and two diagonal legs in tension. This forms a full-bridge circuit that has double the sensitivity of the half-bridge circuit, and four times the sensitivity of the quarter bridge circuit. Solving for the sensitivity of a full-bridge balance beam application a shown, we get:  $V_r = V_o/V_{ex} = -GF*\epsilon$ , effectively twice that of the half-bridge circuit.

All the equations thus far have been simplified because they assume an initially balanced bridge with  $V_o=0$  with no strain applied. This is rarely achieved in practice where resistance tolerance and application strain errors usually result in  $V_o\neq 0$  with no strain applied. The equations also failed to account for lead wire resistance  $R_l$  in the measurement leads and connections to excitation. The equations that follow will be embellished to account for unloaded offset, sensor lead resistance, and material Poisson’s ratio where applicable using permutations of the three basic bridge configurations: quarter, half, and full, where applicable.

## Application

Strain gauge elements are arranged in bridge networks to measure strain or load on a material relative to bending, axial, shear, and torsion. A material under load that extends in the direction of applied stress normally exhibits longitudinal tensile strain and coincident strain in the transverse or lateral direction that is contractive for most materials (Poisson’s strain).

Bending stress results when a beam with a straight horizontal (longitudinal) axis is loaded by a lateral/transverse force such that its longitudinal axis bends into a curve. This strain is used to determine vertical loads.

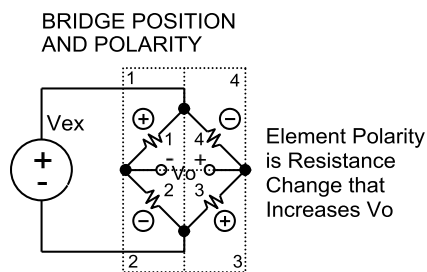
Axial stress/strain results when a body becomes shorter (compressive) or longer (tension) along the direction of an applied force. This strain is used to determine axial loads via material elongation.

Shear strain is the ratio of change in deformation to original dimensions along the length or axis perpendicular to the cross-section of the body (it’s the stress parallel to the cross section of the body). Shear stress drives deformation of a material by causing slippage along a cross-sectional plane parallel to the applied stress. For example, when a shear is used to cut a piece of material, the upper and lower parts of the shear exert lateral loads on the material that drives shear stress in it, causing it to separate into cross-sectional planes. Shear strain is defined as the tangent of the angle and is equal to the length of deformation at its maximum (45°) divided by the perpendicular length in the plane the force is applied. Torsional strain is a form of shear stress that results from an object twisted about an axis such that both tensile and compressive stresses are simultaneously imposed that can cause shear.

A detailed discussion of stress applications is beyond the scope of this document, except to say that specific bridge types are used for specific stress applications with bending and axial stress measurement the most common.

Most strain instruments will support all Wheatstone Bridge based sensor types incorporating separate strain gauges wired in a bridge for strain measurement, or simple load cells that utilize a Wheatstone Bridge internally and are used for measuring force (pressure transducers, torque converters, accelerometers, and vibration sensors). In general, the input to the strain instrument requires the input to be wired as a complete bridge circuit (4 wire nodes) plus remote sense lines to the bridge excitation nodes (6 wires total). But regardless of the sensor type, the strain module needs two measurements to resolve the corresponding strain or load: sensor output  $V_o$  and sensor excitation  $V_{ex}$ .

Load cell sensors may operate under compression and/or tension and will yield bipolar or unipolar millivolt output voltage  $V_o$  directly proportional to the applied force. Its output reading is often expressed in percent of span/full-load, and this can be easily scaled to other units using software gain. Load cells may already be internally compensated for temperature changes and their use does not require you to know additional details of its internal bridge, sensor Gauge Factor, or material Poisson’s ratio. Only the rated output and nominal excitation are considered for load cells.



- + Strain is Tensile (Elongation)
- Strain is Compressive (Contraction)
- Same Diagonal Polarity Adds to  $V_o$
- Opposite Adjacent Polarity Adds to  $V_o$

For a strain bridge, its formulation is more complex and requires knowledge of other parameters and the application. For any bridge, you must know the number of active load cells to determine whether it is a quarter (1), half (2), or full (4) bridge. Additionally, you must discern its specific type number by considering the way additional gauges are mounted in the bridge (their purpose), whether a “dummy” gauge is present, and whether half-bridge completion resistors are included or built into the sensor.

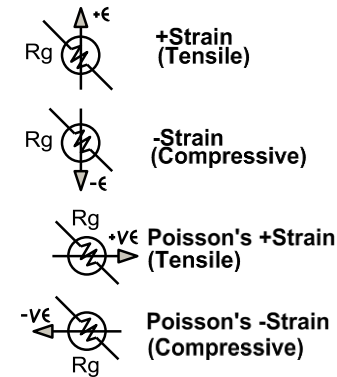
Generally, for connecting to a strain gauge bridge, the instrument is considered an *indicator* for measured strain and internally may refer to two values of strain—the ideal or simulated strain of which its computation uses the actual sensor Gauge Factor and a Software Gain of 1, and a calculated or indicated strain which substitutes your Instrument Gauge Factor and/or optional Software Gain that you control to rescale its indication for your

application. In most applications, simulated strain and indicated strain are driven to converge using calibration tools built into the instrument that adjust Instrument Gauge factor and/or gain to alter the indicated value.

## Strain Bridge Equations

The strain bridge formulas that follow are used to compute both *ideal or simulated strain* and *indicated strain*. For Indicated Strain, your Instrument Gauge Factor will be substituted for Gauge Factor (initial IGF ~ 2) and/or your result may be subject to software gain that you specify to rescale Indicated Strain or Load during shunt or load calibration, typically to resolve application inefficiencies between the ideal and indicated strain or load.

### Bridge Figure Key:



An active strain gauge measures axial strain when mounted in the same direction as the applied force and bending strain when mounted in a lateral direction to the applied force.

Table 1 reviews the terms and nomenclature used in the subsequent strain and load cell formulas for various strain gauge bridge configurations and for load cells.

**Table 1: Strain and Load Parameters**

Parameter	Definition
<b>Vo</b> <i>Bridge Output</i>	<u>ADC Measurement 1</u> – Sensor Bridge Output Voltage $V_o$ . To account for the non-balance $V_o \neq 0$ offset condition of an unstrained bridge, a distinction is made for $V_o$ via $V_{o\_strained}$ for the bridge output under load, and $V_{o\_unstrained}$ for the bridge output unloaded (initial bridge offset). Likewise, for any non-zero tare, $V_o = V_{o\_loaded} - V_{o\_unloaded} - V_{o\_tare}$ .
<b>Vex</b> <i>Bridge Excitation</i>	<u>ADC Measurement 2</u> - Bridge Excitation Voltage $V_{ex}$ . This is normally derived from a related ADC measurement.
<b>Vr</b> <i>Bridge Sensitivity</i>	Key strain computation term that represents the sensitivity of the strain bridge and is derived from ADC measurements of $V_o$ & $V_{ex}$ with $V_r = (V_o \text{ strained} - V_o \text{ unstrained}) / V_{ex}$ . It is equal to the bridge output signal per volt of excitation and expressed as mV/V.
<b>GF</b> (~2.00)	<i>Input Specification - Gauge Factor is the gauge specification for its sensitivity to strain (not the bridge sensitivity), ~2.00 for Metallic Gauges. <math>GF = (\Delta R/R) / (\Delta L/L) = (\Delta R/R) / \epsilon</math>, then <math>\Delta R = R * GF * \epsilon</math></i>
<b>RO</b> (1-10mV/V)	<i>Input Specification - Rated Output (1-10mV/V) is the gauge specification for its output voltage range under full-load (<math>\pm 100\%</math>) per volt of applied excitation voltage.</i>
$\epsilon$ Strain <b>+<math>\epsilon</math> Tensile<sup>1</sup></b> <b>-<math>\epsilon</math> Compr<sup>1</sup></b>	Strain ( $\epsilon = \Delta L / L$ , multiply by $10^6$ for equivalent micro-strain). <i>tensile Strain (<math>\epsilon = +\Delta L / L</math>) and compressive strain (<math>\epsilon = -\Delta L / L</math>)</i>
$\gamma$	Poisson's Ratio, material constant w/ $-1 < \gamma < 0.5$ ( $\gamma = -\epsilon_T / \epsilon$ )
<b><math>\epsilon_T = -\gamma \epsilon</math></b>	Transverse (Poisson's) Strain
<b>+<math>\gamma \epsilon</math></b>	A Tensile Poisson's strain $\gamma = -\epsilon_T / \epsilon$ & $\epsilon_T = -\gamma \epsilon$ .
<b>-<math>\gamma \epsilon</math></b>	A Compressive Poisson's strain $\gamma = -\epsilon_T / \epsilon$ & $\epsilon_T = -\gamma \epsilon$ .
<b>Rg</b>	Nominal Strain Gauge Resistance (120 $\Omega$ , 350 $\Omega$ , 1000 $\Omega$ common).
<b>RI</b>	Lead-Wire Resistance
<b>N</b>	Common Factor used to Account for Multiple Gauges in a Bridge (see Table 2 for N value)

In the following examples, the polarities indicated assume a positive strain + $\epsilon$  is tensile and negative strain -  $\epsilon$  is compressive, but you can reverse this convention by removing the negative sign from the strain formulas and flipping the polarity of the bridge output voltage  $V_o$ .

In the bridge, adjacent elements refer to the relationship between the two elements on the left, or the two elements on the right of a bridge. Diagonally opposite elements that measure strain in the same direction reinforce each other's effect on  $V_o$ , while adjacent strain gauges that measure in opposite directions reinforce each other's effect on  $V_o$  (they are additive to  $V_o$ ). Adjacent gauges that are mounted transverse to primary  $\pm \epsilon$  strain gauges normally measure the coincident Poisson's strain  $\pm \nu \epsilon$ .

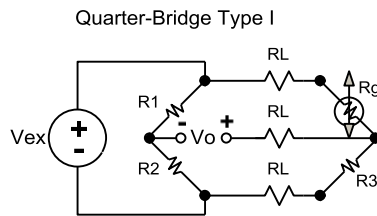


## Strain Bridge Equations...

### Quarter Bridge Type I, N=1 (For Axial or Bending Strain)

One Active Gauge  $R_g$  with Dummy Resistor  $R_3=R_g$  and Half-Bridge Completion Resistors  $R_1=R_2$  and  $R_1/R_2=R_g/R_3$ .

Not Temperature Compensated



A quarter-bridge uses one active gauge  $R_g$  to make a uniaxial tensile or compressive strain measurement with the gauge mounted in the direction of an axial strain or transverse to a bending strain.

The Quarter Bridge is Type I is most common in experimental stress analysis, where

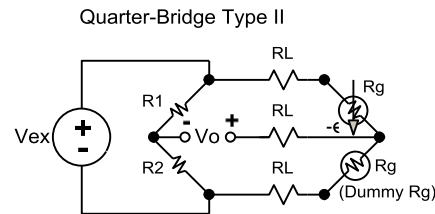
ambient temperature is relatively constant. It is not recommended for real world applications because it does not compensate for changes in temperature. In the Quarter bridge Type I configuration, the adjacent gauge resistor  $R_3$  is only selected to have the same resistance as the strain gauge ( $R_3=R_g$ ). The two resistors in the opposite half must equal each other ( $R_1=R_2$ ), but do not have to equal to the gauge resistor  $R_g$  or  $R_3$ , just their ratio ( $R_1/R_2=R_g/R_3$ ).

### Quarter-Bridge Type II, N=1 (For Axial or Bending Strain)

One Active Gauge  $R_g$  with Passive Gauge  $R_3=R_g$  and Half-Bridge Completion Resistors  $R_1=R_2$  and  $R_1/R_2=R_g/R_3$ .

Temperature Compensated

Good at lower levels of strain below  $\sim 5000\mu\epsilon$  where Poisson's Strain is small.



A second Quarter Bridge is Type II and often used to measure compression, common to weigh-scale applications.

This quarter bridge uses one active gauge  $R_g$ , plus a transverse mounted passive "dummy" gauge to compensate for temperature. The dummy gauge is

not subject to strain and only provided for temperature compensation. Applied strain has little effect on a dummy gauge because it is mounted transverse/perpendicular to the applied force and normally unbonded to the application material, but close enough to the active  $R_g$  such that the ambient temperature affects both gauges equally maintaining their ratio but not affecting output  $V_o$  over temperature.

Note that the temperature compensated Quarter-Bridge (Type II) is sometimes incorrectly referred to as a half-bridge configuration due to the presence of the second gauge. But because the second gauge matches its TC to  $R_g$  but does not measure strain (it is not active), it is in fact a Quarter-Bridge Type II circuit and the quarter-bridge formulation applies (note the absence of Poisson's ratio). No quarter bridge formulation can be used in an application where the direction of the stress field is unknown or changes.

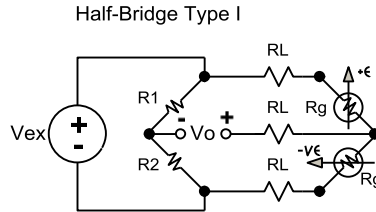
If any additional force is applied in the transverse direction of the dummy gauge, then the measurement of strain in the direction of the active gauge will be in error.

For Quarter-Bridge Type I or Type II, solving for the resultant strain will yield the following expression (note the absence of Poisson's Ratio because it is often ignored at lower levels of strain less than  $\sim 5000\mu\epsilon$ ):

$$\epsilon = (1 + R_l/R_g) * -4V_r/[GF*(1+2V_r)]$$

## Strain Bridge Equations...

**Half-Bridge Type I,  $N=1+\gamma$**   
**(Single-Axis Strain Measurement at higher levels of stress)**

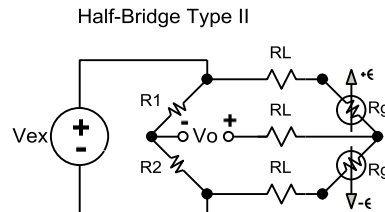


A Half-Bridge uses two active gauges in a single-axis (uniaxial) stress field to make strain measurements, one mounted in same direction as applied strain and the other mounted transverse to applied strain to capture the effect of Poisson's strain.

Solving for the strain of Half-Bridge Type I yields the following (note that Poisson's ratio is present because transverse strain is considered because of the generally higher stress levels):  $\epsilon = -4Vr * (1 + Rl / Rg) / [GF*(1+\gamma) - 2Vr*(\gamma - 1)]$

The Half Bridge Type I resembles the Quarter-Bridge Type II, except that the transverse mounted gauge measures the transverse strain that results from its higher applicable stress levels where Poisson's strain is more significant. The secondary gauge still corrects for changing temperatures because of its matching temperature coefficient which keeps R3/R4 ratio constant over temperature.

**Half-Bridge Type II,  $N=2$**   
**Bending Strain Only**  
**(Bending Beam Applications at Lower Strain Levels)**



The Half-Bridge Type II is typically used in bending beam applications. This bridge uses two active gauges with both subject to a bending stress, mounted to measure equal and opposite strain, one in compression (bottom of beam), one in tension (top of beam). Because the adjacent gauge pair

measures the same stress in opposite directions, their effect on Vo reinforces each other, doubling the output of the quarter bridge. The second gauge with a matching temperature coefficient also corrects for changes in temperature by keeping the gauge ratio R4/R3 constant. Solving for Half-Bridge Type II strain yields (note the absence of Poisson's Ratio suggests it is more applicable at lower levels of strain):  $\epsilon = -2Vr *(1 + Rl / Rg) / GF$

Another permutation of this arrangement would have the two diagonally opposite active gauges subject to equal strain in the same direction (also reinforcing each other). For example, each gauge could be mounted on opposite sides of a column with a low thermal gradient between them (both subject to same temperature). Recall that diagonally opposite gauges reinforce each other for resistance changes in the same direction, while adjacent gauges tend to cancel each other for strain in the same direction.

Two Active Gauges Rg with  
 R4 Meas Tensile Bending +ε  
 R3 Meas Compressive Bending -ε  
 R2 Half-Bridge Completion Res  
 R1 Half-Bridge Completion Res

Comp for Temperature  
 Good Sensitivity to Bending ε  
 No Comp for Poisson's (Lower ε)

## Strain Bridge Equations...

### Full-Bridge Type I, N=4

#### Bending Strain Only

(Bending Beams or Shafts Subject to Torsion at Lower Strain Levels)

Four Active Gauges  $R_g$  with

R4 Meas Tensile Bending  $+\epsilon$

R3 Meas Compressive Bending  $-\epsilon$

R2 Meas Tensile Bending  $+\epsilon$

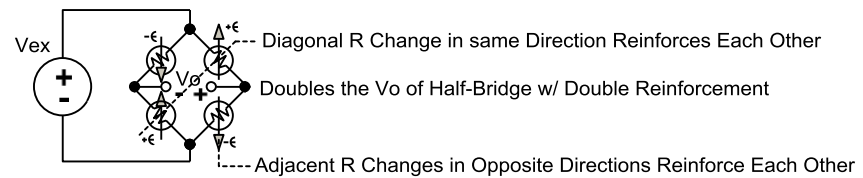
R1 Meas Compressive Bending  $-\epsilon$

Comp for Temperature

Higher Sensitivity to Bending  $\epsilon$

No Comp for Poisson's (Lower  $\epsilon$ )

Full-Bridge Type I



The Full-Bridge Type I is common to strain measurement of bending beams or shafts subject to torsion at lower levels of stress. This arrangement utilizes four active gauges with one diagonal pair measuring tensile bending strain and the opposite diagonal pair measuring compressive bending strain for the same applied stress (the diagonal gauge pairs in the same direction and adjacent gauge pairs in opposite directions reinforce each other making this bridge the most sensitive). While having greater sensitivity, it is generally used at lower levels of strain (no transverse mounted Poisson's strain gauges). The full-bridge is balanced with all gauges having the same resistance change, maintaining adjacent  $R1/R2=R3/R4$  ratios equivalent over temperature.

Because the four gauges are arranged to reinforce their effects on  $V_o$  both diagonally and adjacent, the Full-Bridge Type I doubles the  $V_o$  signal of a half-bridge and quadruples that of a quarter bridge. But its greater 2x sensitivity than the half-bridge makes it more expensive because of two additional gauges. Solving for the Full-Bridge Type I strain yields (note the absence of Poisson's strain):  $\epsilon = -V_r / GF$ .

### Full-Bridge Type II, N= 2(1+ $\gamma$ )

#### Bending Strain Only

(Bending Beam or Shaft Subject to Torsion at Higher Strain Levels)

Four Active Gauges  $R_g$  with

R4 Meas Tensile Bending  $+\epsilon$

R3 Meas Compressive Bending  $-\epsilon$

R2 Meas Tensile Poisson's  $+\epsilon$

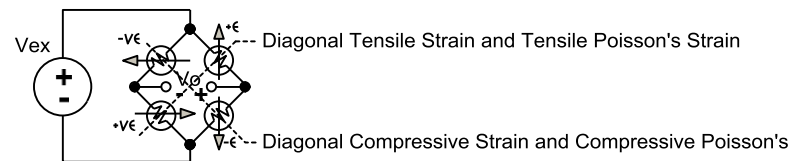
R1 Meas Compressive Poisson's  $-\epsilon$

Comp for Temperature

Less Sensitive to  $\epsilon$  than Type I

Comp for Poisson's (Higher  $\epsilon$ )

Full-Bridge Type II



Full-Bridge Type II is common to strain measurements for bending beams or shafts subject to torsion at higher stress levels (higher stress drives higher Poisson's strain). This arrangement utilizes four active gauges subject to bending stress, with one diagonal gauge pair aligned to measure tensile bending strain and transverse tensile Poisson's strain (i.e. top of beam), and the other diagonal pair aligned to measure the coincident compressive strain and transverse compressive Poisson's strain (i.e. bottom of beam). Solving for the Full-Bridge Type II strain yields:  $\epsilon = -2V_r / [GF*(\gamma + 1)]$ .

## Strain Bridge Equations...

### Full-Bridge Type III, $N = 2(1 + \gamma)$ Axial Strain Only (Single-Axis Column Strain)

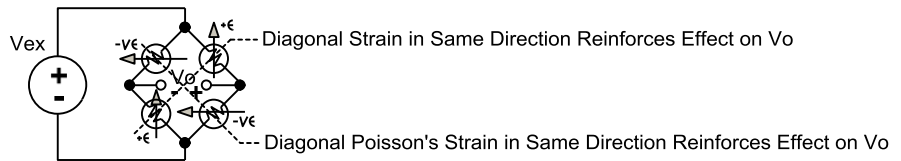
Four Active Gauges  $R_g$  with  
 R4 Meas Tensile  $+\epsilon$   
 R3 Meas Compressive Poisson's  $-\epsilon$   
 R2 Meas Tensile  $+\epsilon$   
 R1 Meas Compressive Poisson's  $-\epsilon$

Comp for Temperature  
 Comp for Poisson's (Higher  $\epsilon$ )

### Sensor Gauge Factor and Instrument Gauge Factor

**Example:** If measured strain  
 $\epsilon = 1000$  micro-strain and  $GF = 2.00$ .  
 Then,  $2.00 * 1000 * 10^{-6}$  strain  
 $= 0.002 = (\Delta R/R)$  and this implies a  
 $350\Omega$  gauge changes its resistance  
 by only 0.2%, equivalent to  $0.7\Omega$ .

Full-Bridge Type III



The Full-Bridge Type III is common to column stress measurement applications. This arrangement uses four active gauges subject to a uniaxial stress, with one diagonally opposite gauge pair measuring the principal axial strain in one direction (one mounted on top, one on bottom), and the other diagonal pair measuring the transverse Poisson's strain in the same direction (one mounted transverse on top and other transverse on bottom). Solving for the Full-Bridge Type III strain yields:

$$\epsilon = -2Vr / [GF*(\gamma + 1) - Vr*(\gamma - 1)].$$

Because the Full-Bridge Type III configuration includes measurement of coincident Poisson's strain, it is suitable for measurement at higher stress levels above  $5000\mu\epsilon$ .

The sensor Gauge Factor  $GF$  of a strain gauge is a characteristic transfer coefficient that relates the gauge element sensitivity to strain  $\epsilon$  relative to its change in resistance  $\Delta R$ . More specifically,  $GF$  is the ratio of the fractional change in resistance to the strain ( $GF = (\Delta R / R) / (\Delta L / L) = (\Delta R / R) / \epsilon$ ). The Gauge Factor for metallic strain gauges is typically around 2.00, but may vary with temperature, strain level, and gauge mounting, and these application effects will contribute to error in making ideal strain measurements. Think of  $GF$  as a built-in scaling factor for the computation of ideal strain that is generally fixed to a value by the gauge manufacturer.

You can think of Instrument Gauge Factor  $IGF$  similarly, except it is controlled by you and used to rescale the Indicated Strain of an instrument to help overcome less than ideal application sensor irregularities that may skew strain from its ideal. That is,  $IGF$  is usually adjusted as required to make the indicated strain of the instrument converge to an ideal or simulated strain during the process of strain gauge bridge shunt calibration. Optionally, a second means of rescaling Indicated Strain is by using Software Gain. The need to rescale the indicated value of an instrument is largely driven by the inherent lack of precision in applying the strain gauge and the wide variation incurred in the multitude of its applications, and sometimes even between sensors of the same type. Consider, the rated output (mV/V) of a strain gauge may vary by as much as  $\pm 10\%$  from its manufacturer specification and between sensors. Rescaling the instrument's indicated value for a given sensor by varying its Software Gain and/or Instrument Gauge Factor allows you to account for this tolerance by trimming your response to more accurately reflect ideal strain in your application. Typically, during shunt calibration, the indicated strain measurement is modified by varying Instrument Gauge Factor and/or software gain to make it reading match a calculated ideal or simulated strain. The simulated strain is calculated using the sensor Gauge Factor specification and a fixed gain of 1, while indicated strain uses the Instrument Gauge Factor and/or Software Gain other than 1. The Instrument Gauge Factor is initially set to 2 (roughly equivalent to the sensor Gauge Factor) and this makes indicated strain roughly equivalent to ideal strain, insofar as much as the application induced error is kept to a minimum.

## Resolving Strain or Load

How many active load cells?

One=Quarter Bridge QB  
Two=Half-Bridge HB  
Four=Full-Bridge FB

Is your strain measurement axial, bending, or torsional/shear?

Which Type best fits the application?

1 active/No Additional=**QB Type I**  
1 active+1 Dummy=**QB Type II**

The first step to determining which bridge formulation best fits your application is to identify the number of *active* load cells present or required. An “active” cell means the gauge is mounted so that it will measure tensile or compressive strain in the same direction as an applied force (or transverse for bending strain). A dummy gauge refers to an adjacent matching gauge mounted transverse to the applied force or unbonded to the material such that it is subject to the same temperature, but not mechanically stressed (the ratio of adjacent elements will stay the same over temperature and not affect  $V_o$ ). A bridge may have one, two, or four strain gauges present, but it is how they are positioned relative to one another and the applied force that will determine their application.

Next you may wish to consider the measurement environment and the relative level of stress you intend to measure. If the environment temperature varies, you can dismiss Quarter Bridge Type 1 which is not temperature compensated. If the strain level you intend to measure is high ( $> 5000\mu\epsilon$ ), then you will want to capture the negative effect of Poisson’s strain on your measurement and consider using Half-Bridge Type I, or Full-Bridge Type II or Type III, which take Poisson’s ratio into account. A simple uniaxial force in one direction may only require one active gauge at lower strain levels, unless the ambient varies, then an adjacent active gauge may be added to temperature compensate the bridge output  $V_o$ . If you choose to mount the second gauge transverse to axial strain, then it may additionally capture Poisson’s strain, which will be important at high levels of strain  $> 5000\mu\epsilon$  where its contribution becomes significant. If your application needs more output signal (and higher signal to noise ratio), note the Half-Bridge Type II has twice the sensitivity of a Quarter-Bridge, and a Full-Bridge has twice the sensitivity as a Half-Bridge. One active gauge will form a Quarter-Bridge, two active gauges may form a Half-Bridge, and four active load cells may form a Full-Bridge—but the more active gauges you require, the higher your cost.

To determine its Type designation, I, II, or III, you must consider how it is mounted.

If your bridge has one active gauge and no additional dummy gauges or resistive elements present, then you select a **Quarter-Bridge Type I** formulation. If your bridge has one active gauge plus a second passive or “dummy” gauge mounted transverse to the applied stress (for temperature compensation), then you select **Quarter Bridge Type II** formulation. Both Quarter-Bridge types use the same formula for calculating strain and their type distinction simply discerns whether the strain gauge is temperature compensated or not. Both quarter-bridge types also require half-bridge completion resistors (either external or internal) but Type I will require an adjacent fixed “dummy” resistor be connected, while Type II will require an adjacent “dummy” gauge be connected to closely match the temperature coefficient of the active gauge over temperature.

## **Resolving Strain or Load**

1 active+1 transverse= <b>HB Type I</b>	If your bridge has <u>two</u> active gauges, with the adjacent gauge mounted perpendicular to the applied force to measure coincident (Poisson's) strain <u>and</u> to temperature compensate the primary active gauge, then you would select a <b>Half-Bridge Type I</b> formulation, common for measuring uniaxial strain at higher stress levels where the Poisson's strain should be accounted for. Note that the Half-Bridge Type I circuit is like the Quarter-Bridge Type II, except that the transverse mounted gauge is mechanically linked to the material to measure Poisson's strain in addition to temperature compensating the primary active gauge.
1 active+1 opposite= <b>HB Type II</b>	If your bridge has <u>two</u> adjacent active gauges mounted such that they are subject to equal and opposite strains for the same applied force, you would select a <b>Half-Bridge Type II</b> formulation. This is common to bending-beam applications with one gauge is mounted to compress while the other undergoes tension for the same applied force. The presence of the second active gauge also temperature compensates $V_0$ but does not measure Poisson's strain, making it more accurate at lower levels of strain $< 5000\mu\epsilon$ where Poisson's contribution can usually be ignored.
4 active w/opposite pairs= <b>FB Type I</b>	If your bridge has <u>four</u> active gauges with both adjacent gauge pairs subject to equal and opposite strains for the same applied stress, then you would select a <b>Full-Bridge Type I</b> formulation. This arrangement offers the largest output signal, is inherently temperature compensated, and does not require bridge completion.
1 active $\pm$ pair & 1 transverse pair= <b>FB Type II</b>	If your bridge has <u>four</u> active gauges, with one half of the bridge (adjacent gauge pair) mounted to measure the tensile and compressive strain, and the opposite half mounted to measure their coincident transverse Poisson's Strains, then you would select a <b>Full-Bridge Type II</b> formulation. This type is commonly used to measure the uniaxial stress in bending beam applications. This arrangement is inherently temperature compensated and does not require bridge completion.
1 active tensile pair diagonal + 1 active transverse pair diagonal= <b>FB Type III</b>	If your bridge has <u>four</u> active gauges, with one diagonal gauge pair mounted to measure the principal tensile strain and the opposite diagonal pair mounted to measure its transverse (compressive) Poisson's Strain, then you would select a <b>Full-Bridge Type III</b> formulation. This is commonly selected to measure the strain in a column. This arrangement is inherently temperature compensated and does not require bridge completion and better suited for measuring higher levels of strain where Poisson's contribution is greater.

Table 2 summarizes important features of each of the seven strain gauge bridge types, their common application, the number of active gauges, bridge wiring, bridge sensitivity, any built-in compensation, applicable strain level, plus their strain formulation.

## Resolving Strain or Load

**Table 2: Salient Features of The Seven SG Bridge Types and Their Strain Formulas**

SUPPORT	QB Typ I	QB Typ II	HB Typ I	HB Typ II	FB Typ I	FB Typ II	FB Typ III
<b>Axial</b>	Yes	Yes	Yes	No	No	No	Yes
<b>Bending</b>	Yes	Yes	Yes	Yes	Yes	Yes	No
<b>Shear/Torsion</b>	No	No	No	Yes	Yes	Yes	No
<b>Active Gauges</b>	1	1	2	2	4	4	4
<b>Gauge R Positions &amp; Function</b>	R4 (+ε) R3 Fix R=Rg <sup>2</sup> R1,2 HB	R4 (+ε) R3=Dumb Rg <sup>1</sup> (Transverse) R1,2 HB	R4 (+ε) R3 (-γε) R1,2 HB	R4 (+ε) R3 (-ε) R1,2 HB	R1,3 (-ε) R2,4 (+ε)	R1 (-γε) R2 (+γε) R3 (-ε) R4 (+ε)	R1,3 (-γε) R2,4 (+ε)
<b><sup>3</sup>Sensitivity (Vr) @1000με</b>	~0.5mV/V	~0.5mV/V	~0.65/V	~1.0mV/V 2x QB	2.0mV/V 2x HB, 4x QB	1.3mV/V	1.3mV/V
<b>Comp Temp?</b>	No	Yes	Yes	Yes	Yes	Yes	Yes
<b>Comp Poisson's γ?</b>	No	No	Yes	No	No	Yes	Yes
<b>Strain High/Low</b>	Low<5000με	Low<5000με	High	Low<5000με	Low<5000με	High	High
<b>TYPE &amp; N</b>	<b>STRAIN FORMULA &amp; PRIMARY APPLICATION</b>						
<b>QB Typ I N=1</b>	$\epsilon = -4Vr * (1 + RI / Rg) / [GF*(1+2Vr)]$ , Axial or Bending strain in a constant temperature environment because its output is not temperature compensated.						
<b>QB Typ II N=1</b>	$\epsilon = -4Vr * (1 + RI / Rg) / [GF*(1+2Vr)]$ , Axial or Bending strain in a variable temperature environment, common use in weigh-scale load cells and at lower levels of strain where the effect of Poisson's strain is small.						
<b>HB Typ I, N=1+ γ</b>	$\epsilon = -4Vr * (1 + RI / Rg) / [GF*(1+ \gamma) - 2Vr*(\gamma - 1)]$ , Uniaxial tensile or compressive strain in a temperature variant environment and good for higher stress levels where Poisson's strain is more significant.						
<b>HB Typ II N=2</b>	$\epsilon = -2Vr *(1 + RI / Rg) / GF = -4Vr*(1 + RI / Rg) / N*GF$ , Bending beam strain with two strain gauges subject to equal and opposite strain for the same applied force.						
<b>FB Typ I N=4</b>	$\epsilon = -Vr / GF = -4Vr / (N*GF)$ , Bending beam strain or a shaft under torsion with 4 active gauges arranged to measure equal and opposite strains. 2x the sensitivity of a half bridge, 4x the sensitivity of a quarter bridge. Used at lower levels of strain where the Poisson's effect is small.						
<b>FB Typ II N= 2(1+ γ)</b>	$\epsilon = -2Vr / [GF*(\gamma + 1)] = -4Vr / (N*GF)$ , Axial column strain with one adjacent gauge pair measuring principal tensile and compressive strain and the opposite adjacent pair measuring the corresponding transverse Poisson's Strains, good for strain measurement at higher stress levels where Poisson's strain is significant.						
<b>FB Typ III N= 2(1+ γ)</b>	$\epsilon = -2Vr / [GF*(\gamma + 1) - Vr*(\gamma - 1)]$ , Axial column strain with diagonal gauge pairs measuring tensile strain and the diagonally opposite gauge pair measuring the coincident transverse compressive Poisson's strain.						

**Symbols:** +ε is positive or tensile strain and -vε is its compressive Poisson's strain, -ε is negative or compressive strain and +vε is its tensile Poisson's strain, HB refers to Half-Bridge completion resistors.

**Notes (Table 2):** <sup>1</sup>The quarter bridge resistor R3 is an inactive gauge that is mounted transverse or unbonded to the application material (thermally linked but not mechanically linked). <sup>2</sup>The quarter bridge resistor R3 matches the nominal active Rg resistance but is neither thermally linked or mechanically linked to the material that Rg attaches to. <sup>3</sup>The sensitivity of a bridge network is measured in mV/V and represents the full-scale output Vo with Vex=1V and is equivalent to Vr=Vo/Vex. Given strain, you can solve the strain equation for Vr to determine sensitivity. <sup>4</sup>Equations apply for output in the polarities shown. If HB completion is included, you can connect the bridge completion resistors to IN+ instead of IN- to flip the polarity of the bridge output Vo and remove the negative sign preceding each equation.

## Example Calculation for a Strain Gauge

A 120Ω strain gage is wired in a *quarter-bridge circuit* to measure the strain imposed on a beam under stress. The bridge excitation voltage is  $V_{ex}=10V$ . The sensor gauge Factor  $GF$  is 2.0. The bridge output is balanced with no load applied ( $V_{o\_unstrained} = 0$ ) and the gauge leads are short with negligible lead resistance. When loaded, the bridge output  $V_{o\_strained}=3.500mV$  and no tare applies. What is the strain imposed on this beam under load?

First, refer to Table 2 on page 15 to determine the Quarter-Bridge Type designation, I or II – A single gauge with no adjacent dummy gauge forms a Quarter-Bridge Type I circuit and strain  $\epsilon = -4V_r * (1 + R_l / R_g) / [GF*(1+2V_r)]$ .

Note  $R_g=120\Omega$ ,  $R_l=0$ , and  $GF=2.0$ . With  $V_o=0.0035$  and  $V_{ex}=10V$ , we can calculate the strain computation term  $V_r = V_o/V_{ex} = 0.0035/10 = 0.00035$  which represents the sensitivity of the strain bridge. That is, using  $V_r$ , the calculation of requisite strain is straight-forward using  $\epsilon = -4V_r * (1 + R_l / R_g) / [GF*(1+2V_r)] = -4*0.00035 / [2*1.0007] = -699.5$  micro-strain (negative strain is compressive).

**How would a digital instrument measure this strain?** A modern strain instrument would use an Analog-to-Digital Converter (ADC) and measure both the sensor bridge output  $V_o$  and the bridge excitation  $V_{ex}$  voltages, typically as 16-bit or greater bipolar digital counts. For the Acromag TT351, the  $V_{ex}$  voltage is determined by measuring it relative to a fixed voltage reference  $V_{ref2}$  at a gain of gain of 1. The ADC returns a digital count  $ex\_count$  for  $V_{ex}$  using 16-bit bipolar math with  $ex\_count = V_{ex}*32768/V_{ref2} + 32767$ , then solves the expression for the corresponding  $V_{ex}$  voltage.

The  $V_o$  voltage is measured similarly, but relative to a variable ratio-metric ADC reference  $V_{ref1}$  directly related to the  $V_{ex}$  voltage. The ADC returns a 16-bit bipolar count according to  $Vo\_count=V_o*GAIN*32768/V_{ref1} + 32767$ . The module sets GAIN to 1, 2, 4, 8, 16, 32, 64, or 128 ( $\pm V_{ref1}/\pm over-range$ ). One additional piece of information relative to the gauge is used to set over-range—its gauge Rated Output RO. For this example, the gauge RO is 5mV/V. This means that for a full load with  $V_{ex}=10V$ , the bipolar  $\pm 100\%$  input signal is  $\pm 10V*5mV/V=\pm 50mV$ . The Acromag module will set its over-range to 150% of this full-scale range, or by user specification up to 150%. It determine its GAIN by setting it  $< V_{ref1}/Over-range$ . Then the input count equation is solved for the  $V_o$  voltage that corresponds to the digital count returned.

With the  $V_r$  computation term for strain (bridge sensitivity) computed as  $V_r=V_o/V_{ex}$ , the module has all the terms it needs to compute the requisite strain for the Quarter-Bridge ( $R_g=120\Omega$ ,  $R_l=0$ , and  $GF=2.0$ ,  $V_o$ ,  $V_{ex}$ ). To resolve Indicated Strain, it will additionally use Instrument Gauge Factor in place of sensor Gauge Factor and apply any additional user-specified software gain instead of 1 to compute the Indicated value.

## Example Calculation for a Load Cell

*The load cell is a device principally used in weighing systems that utilizes strain gauge technology internally, but whose output is expressed in equivalent units of force or percent, not micro-strain.*

*Most load cells will have 4 or 6 leads and already have bridge completion and temperature compensation built-in. Internally, a load cell will contain some permutation of quarter, half, or full-bridge circuitry, but this detail is irrelevant to the load computation and is not usually provided by the load cell manufacturer.*

The load cell is a simpler form of Wheatstone Bridge based sensor, but one whose output reading is not expressed in micro-strain, but in common units of measure for pressure or weight (typically percent of full rated load). Unlike the SG input type, processing a load cell signal does not require additional detail of its internal bridge type, its gauge factor, or Poisson's ratio. The only important considerations for load cells are its Rated Output (mV/V), its Excitation level, and its rated capacity.

**Example:** A compression load cell with six connection wires: sense±, excitation±, and signal ±, is specified by its manufacturer as follows (bold specs are required):

- **Rated Output: 2.0mV/V**
- **Rated Excitation: 10V DC (15V Maximum)**
- **Rated Capacity: 50,000 lbs/square-inch**
- Safe Overload Level: 150% of Full-Scale
- Operating Temperature Range: -65 °F to 200 °F

*The cell output  $V_o = 0.0035V$  and this load contains no offset or tare, what is the indicated load?*



## Example Calculation for Load Cell...

**Note:** From the specifications above, you can additionally conclude the load cell is temperature compensated by its wide-ambient and based on its 6-lead wires, that it already includes half-bridge compensation resistors built-in.

**Manual Calculation:** The load cell's rated output is 2mV/V and its excitation is 10V. This means that 100% of load corresponds to  $10V * 2mV/V = 20mV$ . With a rated capacity = 50000lbs/in<sup>2</sup>, a  $V_o=20mV$  will correspond to 100% of load which will correspond to 50000psi with 10V of excitation. The load at  $V_o=3.5mV$  is simply  $3.5/20 * 50000psi = 8750lbs/square-inch$ . With software gain set to 1 the load in % and would indicate  $100% * (3.5mV/20mV$  or  $8750/50000$ ) or 17.50%. Additionally, this load cell may be over-loaded up to 75000psi (150% of full-scale) and  $V_o = 30mV$  for a load of 75000psi with 10V of excitation because its safe overload limit extends to 150%.

**IMPORTANT – NULL OFFSET:** Load cells commonly fail to indicate exactly 0% load with no load applied such that subsequent load measurements will be offset by this amount. Thus, you should Null the unloaded offset using module controls to remove it prior to taking measurements and prior to Load Calibration. Null offset will automatically remove the same offset from subsequent measurements. You should Null offsets after changing load cells or changing between Load Cell and Bridge input types. Additionally, do not combine Tare with Offset. If you erroneously use Null Offset to remove Tare weight, your subsequent load cell measurements will be in error.

**TARE:** Similar to Null Offset, modern instruments usually include a Tare control to automatically remove tare weight from the load cell measurement. That is, the sensor  $V_o$  will be automatically corrected for both non-zero offset and/or tare such that  $V_o = V_{o\_loaded} - V_{o\_offset} - V_{o\_tare}$ . Tare normally refers to a constant load of common/non-variable elements between loads, like the weight of its container or its shipping materials, and the instrument can subtract this "tare" from subsequent load cell measurements.

For the load cell, the load computation is straight-forward as shown and only Vex, Rated Output, and rated capacity were required to determine its percent load corresponding to a measured  $V_o$ . Be sure to null any unloaded offset indication before taking measurements. Optionally, you may automatically remove tare from the indicated load using its Tare controls.

**How would a digital instrument measure load?** Just as for strain gauge inputs, a modern instrument would take  $V_o$  and Vex voltage measurements to determine the load using its 16-bit or higher bipolar ADC to determine a count =  $V_{in} * Gain * 32768 / Reference + 32767$ . For example, the Acromag TT351-0700 first measures Vex relative to a fixed reference Vref2 and gain of 1. From the count expression, it solves for the excitation voltage  $V_{ex} = (count - 32767) * V_{ref2} / 32768$ .

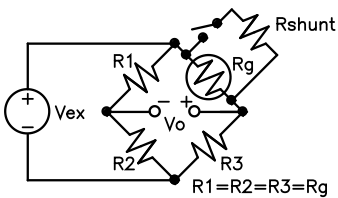
The instrument also measures the cell  $V_o$  relative to a variable ratio-metric reference Vref1 derived from Vex the same as it does for SG input. Using Vex and the cell Rated Output specification, it computes a full-scale  $V_o$  (100%). Unless otherwise specified, it adds overrange up to 150% of full-scale. With a rated output 2mV/V and overrange up to 150%, then  $V_{o\_max} = 1.5 * 2mV/V * V_{ex}$  and it will set Gain to the largest of 1, 2, 4, 8, 16, 32, 64, or  $128 < V_{ref1} / V_{o\_max}$ . The ADC also measures  $V_{o\_count} = V_o * Gain * 32768 / V_{ref1} + 32767$  and from the count, it solves for  $V_o = (V_{o\_count} - 32767) * V_{ref1} / (Gain * 32768)$ . With  $V_o$ , RO, Vex, it can compute the corresponding load.

## Shunt-Calibration of Strain Gauge Bridge

A strain gage instrument that utilizes constant voltage sensor excitation commonly uses Shunt-Calibration to affect its Indicated Strain measurement by adjusting Instrument Gauge Factor and/or Software Gain to make its reading converge with an ideal or simulated strain. This is accomplished by temporarily connecting a precision resistance in parallel with an arm of the Wheatstone Bridge (usually a dummy resistance) to stimulate the instrument’s response to a decrease in resistance corresponding to a known strain (or simulated ideal strain). The use of the term “calibration” is somewhat of a misnomer here because Shunt Calibration does not calibrate the measurement accuracy of the instrument itself to any known standard, but rather the strain bridge sensor it connects to, allowing its Indicated Strain to be scaled to correct engineering units and to overcome excitation and gain error due to tolerance, temperature changes, and other sources of measurement system error (the sensitivity of the sensor-transducer strain measurement system).

Shunt-calibration is the most common approach used to verify the operation of a strain measurement system to detect important changes that may occur over time. Traditionally, some strain gage instrument manufacturers collect and supply shunt calibration data for their instruments to a known shunt-resistor as a feature to facilitate monitoring the integrity of their measurement over time (this data/reference resistor is not a component of the sensor, but the instrument).

A key strain gauge parameter is its sensitivity to strain or Gauge Factor (GF) equivalent to its fractional change in resistance to fractional change in dimension (strain). The GF of common metallic strain gauges is typically ~2.0. Like sensor Gauge Factor represents a gauge’s sensitivity to strain, Instrument Gauge Factor is used to relate the instrument’s sensitivity to the sensor output. Initially, Instrument Gauge Factor is commonly set to 2.0, approximately equivalent to sensor Gauge Factor and its indicated strain will be roughly equal to ideal measured strain. Generally, if the strain sensor Gauge Factor  $GF \neq 2$  or its value changes, the Instrument Gauge Factor also changes accordingly. Adjustments are typically made to IGF to get the indicated strain to converge with an ideal or simulated value to help overcome application errors that result from less than ideal conditions in applied strain measurement.



Recall that an unloaded bridge is balanced with  $V_o=0$  when  $R_1/R_2 = R_g/R_3$ . Shunting a bridge element with  $R_{shunt}$  reduces its resistance. Likewise, a decrease in  $R_g$  or  $R_2$  will drive an increase in  $V_o$  (raising  $V_{o+}$  and reducing  $V_{o-}$ ) and simulate negative strain or compression (positive strain is tensile & negative strain compressive). At simulated strains  $\leq 2000$  micro-strain, the  $R_{shunt}$  value and its simulated micro-strain ( $E_s$ ) are related by the expression:  $R_s = [R_g * 10^6 / (GF * N * E_s)] - R_g$ .

Shunt-calibration does not have to shunt the active-gauge  $R_g$  of the bridge and it is often more convenient to shunt another bridge element, usually a dummy resistor. The magnitude of response is normally the same, but its sign varies according to the element (refer to Figure on page 7). If the indicated measurement differs from the ideal or simulated value for the applied reference-shunt, the instrument’s gain and/or sensitivity (Instrument Gauge Factor) is adjusted until the Indicated Value values converges with an ideal simulated value.

$R_g$  refers to the resistance of the shunted gauge arm. Nominal bridge resistances are typically  $120\Omega$ ,  $350\Omega$ , or  $1000\Omega$  and  $N$  is a factor used to account for the presence of multiple active gauges in a bridge circuit (see table below).  $E_s$  refers to the simulated strain in micro-strain units (its sign is often omitted because it’s always negative). Note that  $GF$  refers to the sensor Gauge Factor--not the Instrument Gauge Factor used to calculate indicated strain.

N	Bridge Type
1	Quarter Bridge Type I & II
$1 + \gamma$	Half-Bridge Type I
2	Half-Bridge Type II
$2 * (1 + \gamma)$	Full-Bridge Type II & III
4	Full-Bridge Type I

The factor  $N$  can be used to correct the strain simulated via a strain indicator calibrator (you typically divide the calibrator’s “dial” indication by  $N$  to get the actual strain seen by the module with its configuration set to the corresponding bridge type). To calculate **simulated strain** ( $E_s$ ) in micro-strain units, solve the equation for  $E_s$  as follows:

$$E_s \text{ (micro-strain)} = - R_g * 10^6 / (GF * N * (R_s + R_g)).$$

## Shunt Calibration of Strain Gauge Bridges...

If the lead-wire resistance  $R_l$  happens to be sufficiently large compared to shunt resistance  $R_s$  such that  $100 \cdot R_l / R_s > 0.1 \cdot$  (*required calibration precision in percent*), then the following calculation for  $R_s$  is more precise (note the additional term):  $R_s = [R_g \cdot 10^6 / (GF \cdot N \cdot Es)] - R_g - 2 \cdot R_l$ . For these equations to be used, it is assumed the resistance of each bridge leg is equal and the bridge is *balanced* prior to performing shunt calibration. Because simulated strain results from  $R_g$  shunted by  $R_s$  to lower its resistance, this simulates negative strain (compressive) and the sign is sometimes omitted.

**IMPORTANT:** Shunt Calibration should only be performed on unstrained sensors after nulling any unloaded offsets and without including tare. Unloaded bridge offsets should be nulled and the instrument allowed to warm up several minutes prior to performing shunt calibration.

## Sensor Load Cell Calibration

Much like Shunt-Calibration of Strain Gauge Bridge inputs, Load Calibration of Load Cells can be done. Load Calibration does not calibrate the instrument itself, but the load cell it connects to, by rescaling the indicated load using only Software Gain (load cells do not usually disclose their internal Gauge Factor).

Through Load Calibration, the ideal Simulated load and Indicated load are driven to converge by making small adjustments to Software Gain to compensate for gain and excitation tolerance and temperature error. It is the indicated value of load that drives the transmitter output current or voltage signal inclusive of any unloaded offset and tare correction.

**IMPORTANT-NULL FIRST:** Null any unloaded load cell offset to zero and allow the instrument module to warm-up several minutes prior to attempting Load Calibration. Note that load measurement during load calibration should not include any defined tare.

## About Acromag

Acromag is a leading manufacturer of signal transmitters and conditioners for use with many types of process sensors that will generally amplify and isolate the sensor signal and convert it into a proportional current or voltage output, or Modbus, Profibus, Ethernet message for interface to a PC, PLC, DCS, or other control equipment. Acromag has designed and manufactured measurement and control products for more than 50 years and are an AS9100 and ISO 9001-certified international corporation with their world headquarters near Detroit, Michigan serving a global network of sales representatives and distributors. Acromag offers a complete line of industrial I/O products including a variety of process instruments, signal conditioners, and distributed fieldbus I/O modules that are available with a 2-year warranty. Industries served include chemical processing, manufacturing, defense, energy, and water services.

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**Bruce Cyburt, Senior Design Engineer, Acromag, Inc., July 12, 2002**

## Revision History

Release Date	Version	EGR/DOC	Description of Revision
12-JUL-2002	A	BC/KK	Whitepaper: Introduction to Strain & Strain Measurement
26-FEB-2019	B	BC/AP	Update content and remove 851T references.