Measuring a Resistance Sensor with MadgeTech Bridge Products

This application Note demonstrates the use of resistive sensors with MadgeTech bridge products. The most common bridge sensors are based on strain gages, a sensor whose resistance changes with or [which] force applied. This note assumes the sensor is a strain gage; however the results will apply to all resistance output sensors. This note also covers resistor divider (single gage), Wheatstone bridge and packaged bridge applications.

Voltage Reference

MadgeTech Bridge data loggers provide a voltage reference to power a bridge circuit. In standard products, this reference voltage is 2.5 Volts. Because most of the calculations will be performed in Millivolts, the reference will be expressed as 2500 millivolts. Note: The reference voltage is turned on slightly prior to a measurement and turned off at the end of the measurement in order to reduce power requirements and extend the life of the battery.

Sensor Resistance

When choosing a strain gage or other resistive sensor to be measured, it is important to understand that the lowest resistance sensors require the highest amount of power to drive. In almost all circumstances, a higher resistance should be chosen over a lower one to maximum of 5000Ω. For example, strain gages are usually available in 120Ω, 350Ω and less frequently, 1000Ω types. In order of preference, 1000Ω types should be chosen over 350Ω types, if available, the 350Ω and the 120Ω .

Voltage Divider Configuration

The Voltage Divider configuration is a simple and frequently used setup to measure bridge strain. The voltage divider configuration is not the highest resolution configuration nor is it immune to the temperature coefficients of strain gages; however, its ease of use makes it an adaptable and user-friendly solution to most general bridge strain applications.

Voltage Divider configuration with 4 wire products

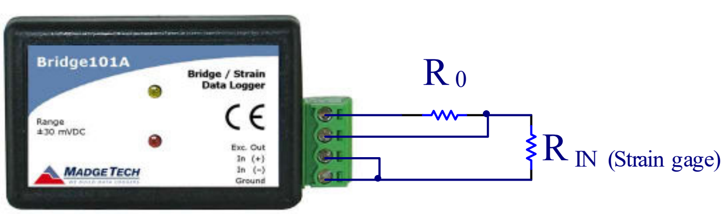

Figure 1, The voltage divider configuration for 4-wire Bridge products

$$V_{inmV} = mVref * \left(\frac{R_{in}}{R_{in} + R_0}\right)$$

Equation (1), The equation for the voltage at In (+)for 4-wire voltage divider configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV

R_0 should be chosen with R_{in} at its maximum value in order that the input range of the logger is not exceeded. For example, a Bridge101A-30mV has a maximum input range of 30mV. If a 350Ω strain gage has a maximum deviation of 7% combined strain, temperature change and initial tolerance, its maximum resistance in circuit will be 350Ω x 1.07 = 375.3Ω. R_0 needs to be at least 30,835Ω or (2500 / 30 - 1) * R_{IN} to guarantee that the input range will not be exceeded.

In this example, a commonly available resistor value of 30,900Ω should be chosen for R_0. With R_0 chosen at 30,900Ω, the combined deviations due to the strain gages initial value, its strain, changes with temperature and the tolerance of R_0 is 7% should be adequate for most installations. Check the datasheet on the strain gage to calculate your maximum R_{IN} to ensure your application will support the chosen value for R_0.

To set up the engineering units, calculate VINmV at two points and the desired output units into which the two values to be translated. For the above example when RIN = 350Ω and when RIN = 353.5 (1% over at rest):

$$V_{inmV} = 2500mV * \left(\frac{350}{350 + 30900}\right) = 28.000mV$$

$$V_{inmV} = 2500mV * \left(\frac{353.5}{353.5 + 30900}\right) = 28.277mV$$

The engineering units could then be set up in a number of different ways:

28.000mV is 350Ω and 28.277mV is 353.5Ω, for a direct ohms translation
28.000mV is 0Ω and 28.277mV is 3.5Ω, for a difference in ohms translation
28.000mV is 0Ω and 28.277mV is 1%, for a percentage in resistance translation

Converting voltage outputs to units of strain

A common unit of strain gage measurement is microstrains (με). Microstrain is mathematically expressed below:

$$\text{microstrain}(\mu\varepsilon) = \left[\left(\frac{\Delta R}{R}\right) \times 1{,}000{,}000\right] / \text{GageFactor}$$

Where ΔR/R is the ratio between the change in strain gage resistance (under stress) and the nominal strain gage resistance. The Gage Factor (GF) is specified by the manufacturer or vendor of the particular gage. Typically, GF values are 2 to 4.5 for metal and 50 to 200 for semiconductor strain gages.

In our example above and assuming that our gage factor is 2:

$$\text{microstrain}(\mu\varepsilon) = \left[\left(\frac{3.5}{350}\right) \times 1{,}000{,}000\right] / \text{GageFactor} = 5000$$

we can then set up engineering units:

28.000mV is 0 $\mu\varepsilon$ and 28.277mV is 5000 $\mu\varepsilon$, for a translation into units of microstrain

Another potentially useful equation is the 'slope of equation' (1) or the change in mV for a given change in ohms of the strain gage at a given point. The point where the slope is most useful to evaluate is the resistance of RIN where the strain gage is at rest, or RIN = 350Ω.

$$V_{inmV}' = mVref * \left(\frac{R_0}{{R_{in}}^2 + 2R_{in}R_0 + {R_0}^2}\right)$$

Equation (2), The equation for the slope of voltage at In (+)for 4-wire voltage divider configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV

Evaluating equation (2) in our example at 350Ω gives:

$$V'_{inmV} = mVref * \left(\frac{30{,}900}{350^2 + 2 * (350 * 30{,}900) + 30{,}900^2}\right) = 0.079104mV/\Omega$$

An important note is that the result of calculating the slope at one point will give a slightly different result than using the voltage equation at two points. This is due to a slight non-linearity in the voltage divider configuration. This non-linearity is negligible in this circuit but can become more significant in the quarter bridge circuit shown later in this document. In our example, 0.079104 * 3.5 = 0.276864mV,with our voltage equation expressed to 6 digits equals 28.276833mV, a difference of 0.000031mV. This result is about 30x smaller than the resolution of Bridge101A (which can be ignored) but the voltage equation is the preferred method when calculating engineering units.

In many real world applications, rather than mathematically calculating two points for engineering units, real world values can be used to set up the units. For instance, the logger can read the value unstrained for a zero value and then a known source of strain can be applied to get the second point. If a known source of strain is available, this is the preferred method of set- up since this accounts for all sources of error from variances in initial value, slope, temperature and tolerance of R_0.

Voltage Divider configuration with 6-wire Bridge products

The 6-wire loggers are equivalent to the 4-wire loggers except that the 4-wire loggers have the power pin internally connected to the REF+ pin (exc. Out) and the ground pin internally connected to the REF- pin (Ground). While the 4-wire loggers are sufficient for most applications and result in a smaller logger design, the 6-wire loggers offer two notable advantages.

One advantage of the 6-wire configuration is that when connecting a bridge with very fine gauge wires that can add large series resistances of greater which add error, the reference pins can be connected close to the bridge, also with fine gauge wire and the error term will disappear from the equation.

Another useful aspect of these pins is that they offer a unique voltage divider configuration simplifying the calculations: the R_{in} term is eliminated from the denominator of the equation leaving a simple linear equation. As a result, the slope equation will produce the exact same result as the voltage equation.

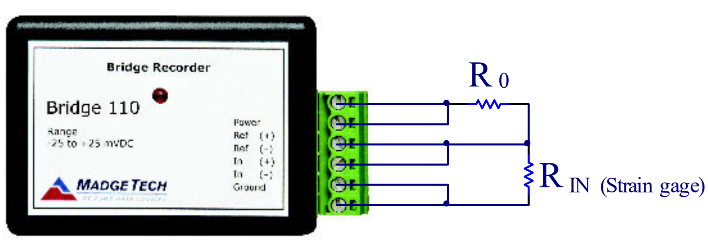

Figure 2, The voltage divider configuration for 6-wire Bridge products

$$V_{inmV} = mVref * \left(\frac{R_{in}}{R_0}\right)$$

Equation (3), The equation for the voltage differential at In (+) and In (-) for 4-wire voltage divider configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV

Using our example above with R_0 = 30,900Ω and RIN = 350Ω and 353.5Ω:

$$V_{inmV} = 2500mV * \left(\frac{350}{30900}\right) = 28.317mV$$

$$V_{inmV} = 2500mV * \left(\frac{353.5}{30900}\right) = 28.600mV$$

These values can then be entered into the engineering units set-up.

The slope of the voltage can also be evaluated:

$$V_{inmV}{}' = \left(\frac{mVref}{R_0}\right)$$

Equation (4), The equation for the slope of V_{inmV} *for 4-wire voltage divider configuration*
Note that the slope is not dependent on R_{IN}
All calculations are done in millivolts, V_{inmV} *is in mV,* $mVref$ *is 2500mV*

For the 6-wire voltage divider configuration, the equation for the slope will produce the exact same results as evaluating the voltage equation at two points.

As another example solving the above equation for an at rest (un-strained) 120Ω strain gage with a resistor R_0 = 12000Ω resolves to an at rest voltage of 25mV. The slope, or change in voltage for each ohm change in resistance, is 2500mV / 12000Ω = 0.2083mV/Ω.

Similar to the 4-wire configuration, R_0 should be greater than the value that resolves to V_{inmV} exceeding the range of the logger when the gage is at its maximum resistance, including all tolerances.

Wheatstone Bridge Configuration

If it is desired to make strain gage measurements with higher resolution, then a Wheatstone bridge configuration ought to be considered. The quarter bridge may be adequate for some applications; the half and full bridge configurations have better signal- to-noise ratio and excellent rejection of temperature coefficient and linearity errors.

The 4 and 6 wire logger configurations are essentially identical after [jumpering] POWER to REF (+) and GROUND to REF (-). The 6-wire does offer an advantage as the REF (+) and REF (-) pins can be connected closer to the bridge with fine gauge wires to reject error terms generated by series resistance in the wires.

Quarter Wheatstone Bridge Configuration

The one-quarter Wheatstone bridge is similar to the voltage divider configuration except that a second voltage divider of the same ratio is added to the other side driving the IN- pin. This effectively reduces the input voltage difference between the IN+ and IN- pin to zero when the strain gage is at rest. This allows for a much smaller Ro which can give a much greater gain and hence much better resolution.

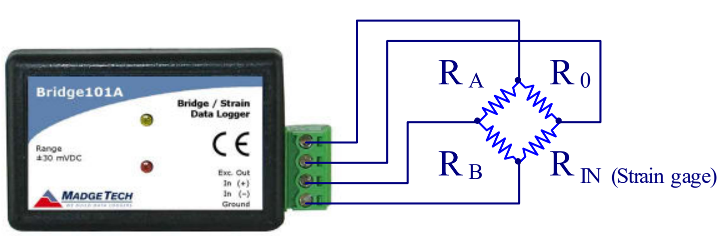

Figure 3, The quarter Wheatstone bridge configuration for 4-wire Bridge products

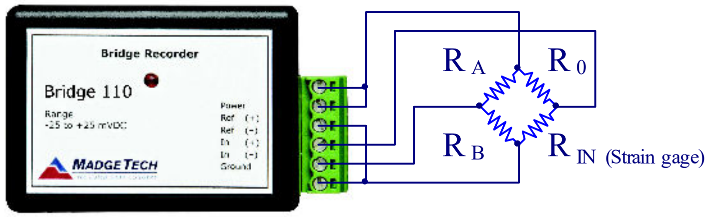

Figure 4, The quarter Wheatstone bridge configuration for 6-wire Bridge products

$$V_{inmV}(total) = mVref * [\left(\frac{R_{in}}{R_{in} + R_0}\right) - \left(\frac{R_B}{R_A + R_B}\right)]$$

Equation (5), The equation for the voltage differential at In (+) and In (-) for the quarter bridge configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV

Most "textbook" Wheatstone bridge circuits have $R_A = R_B = R_0 = R_{IN(at\ rest)}$. To save battery life, R_B should be chosen to be 4.99K and R_A should be chosen such that R_B / R_A = $R_{IN(at\ rest)}$/ R_0 can reduce the overall power load of the bridge. For the best resolution, choose $R_A = R_B$ = 4.99k and $R_0 = R_{IN(at\ rest)}$.

For some logger/strain gage combinations, the logger may not be able to drive the bridge properly. The Bridge101A can directly drive a bridge set-up with four 350Ω resistors, although it is preferred to use $R_A = R_B$ = 4.99k and $R_0 = R_{IN(at\ rest)}$ = 350Ω. It can't, however, directly drive $R_A = R_B$ = 4.99k with $R_0 = R_{IN(at\ rest)}$ = 120Ω. When you must use a 120Ω strain gage for the quarter bridge with Bridge101A, R_0 should be 240Ω, RA should be 10000Ω and RB should be 4.99K.

Similarly, Bridge120 can only directly drive a 1000Ω load. If you must use a 350Ω strain gage, then R_0 should be 700Ω, RA should be 10000Ω and RB should be 4.99K. If you must use a 120Ω strain gage, then R_0 should be 887Ω, RA should be 36500Ω and RB should be 4.99K.

The slope of equation (5) is the change in mV for a given change in ohms of the strain gage is the same as equation (2):?

$$V_{inmV}' = mVref * \left(\frac{R_0}{{R_{in}}^2 + 2R_{in}R_0 + {R_0}^2}\right)$$

Equation (6), The equation for the slope of voltage differential at In (+) and In (-) for quarter bridge configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV

Using the quarter-bridge circuit, the slope, or mV/Ω, can change more significantly with changes in R_{IN} resulting in a larger non-linearity than the voltage divider configuration. There are many resources available documenting this property of the quarter bridge circuit. It is also possible to use odd configurations such as R_B / R_A = R_0 / $R_{IN(at\ rest)}$ = 4, which result in better resolution than the voltage divider configuration but better linearity than the $R_0 = R_{IN(at\ rest)}$ configuration.

While the quarter-bridge circuit does have better resolution than the voltage divider circuit, it has significant disadvantages compared to the half and full-bridge circuits discussed later in this document. In addition to the non-linearity, all commercially available strain gages' initial resistance for R_{IN} changes with temperature which will then be interpreted as a change in strain.

In some applications where performance over temperature range is a requirement, but a half-bridge is not practical, a strain gage in the same environment that has the same temperature response as R_{IN} can be substituted for R_0 and the temperature error will cancel out. In this case, the substituted strain gage is not responding to actual strain but is merely there to cancel temperature error.

Half Wheatstone Bridge Configuration

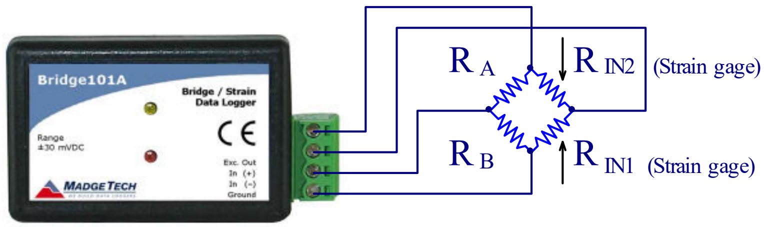

Figure 5, The half Wheatstone bridge configuration for 4-wire Bridge products

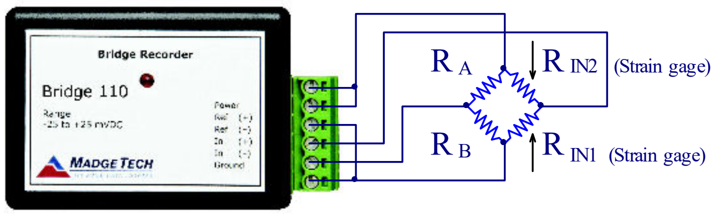

Figure 6, The half Wheatstone bridge configuration for 6-wire Bridge products

Note 1: The two strain gages need to bend in the opposite direction when stressed. Under this arrangement, the non-linear error is nulled out and temperature coefficients between the sensors will cancel.

Note 2: The tolerance of R_A and R_B resistors and the "matched" values of the strain gages affect the "null" reading which theoretically ought to be 0V. It is recommended to use 0.1% or better resistors and identical strain gages.

$$V_{inmV}(total) = mVref * [\left(\frac{R_{in1}}{R_{in1} + R_{IN}}\right) - \left(\frac{R_B}{R_A + R_B}\right)]$$

Equation (7), The equation for the voltage differential at In (+) and In (-) for the half bridge configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV

The half Wheatstone bridge is a very useful circuit with several distinct advantages over the quarter bridge. First, the opposing strain gages temperature error tends to cancel out. The error will completely cancel out if the initial value R_{IN1} and R_{IN2} are equivalent, and even for nearly equivalent values, the error will be insignificant.

A second advantage is that the denominator of the voltage equation is $R_{in1} + R_{IN2}$ which is near-constant. When R_{IN1} goes up 1Ω R_{IN2} goes down 1Ω, keeping the denominator constant. The non-linearity disappears completely if they have the same initial value.

A third advantage is that it provides twice the signal level and hence, twice the resolution of the quarter bridge.

The slope or derivative is the ohms/millivolt:

$$V'_{inmV} \approx mVref * \left(\frac{R_{in1} - R_{in2}}{R_{in1} + R_{in2}}\right)$$

Equation (8), The equation for the slope of voltage differential at In (+) and In (-) for half bridge configuration
All calculations are done in millivolts, V_{inmV} is in mV, $mVref$ is 2500mV
The equation is exact if $R_{in1} + R_{in2}$ remains constant.

The Bridge101A can drive the half bridge directly with $R_{IN1(at\ rest)} = R_{IN2(at\ rest)}$ = 350Ω. It cannot, however, directly drive when $R_{IN1(at\ rest)} = R_{IN2(at\ rest)}$ = 120Ω. In this situation, it is recommended to add a third 120Ω resistor in series with the bridge top and use $R_A = R_B$ = 4.99k. The third 120Ω will add an error term with temperature to the gain of the bridge and it is preferred if it is an actual unstrained strain gage of the same manufacture and in the same temperature environment to cancel this effect. It will also have the effect of reducing gain by 1/3. (See figure 10 for resistor placement.)

Bridge120 is not specified to directly drive even the $R_{IN1(at\ rest)} = R_{IN2(at\ rest)}$ = 350Ω and $R_A = R_B$ = 4.99k configuration. However, in this case, a 300Ω resistor can be added in series with the bridge top. By moving the REF (+) connection to the other end of the 300Ω, all temperature errors are removed so it is not an advantage to make this resistor from an unstrained strain gage. (See figure 9 for resistor placement.)

The Bridge120 can also handle the $R_{IN1(at\ rest)} = R_{IN2(at\ rest)}$ = 120Ω and $R_A = R_B$ = 4.99k configuration with the addition of a 665Ω resistor. Be sure to move the REF (+) connection to after the resistor to cancel temperature errors.

While adding series resistors to the Bridge120 and moving the REF (+) connection to the other side does not affect the voltage equation, it does have the effect of increasing noise levels. Adding the 300Ω to the 350Ω bridge circuit increases noise by 50%. Adding a 665Ω resistor to the 120Ω circuit increases noise by 150%. This is another reason besides power usage to consider using a higher resistance strain gage from the beginning.

Full Wheatstone Bridge Configuration

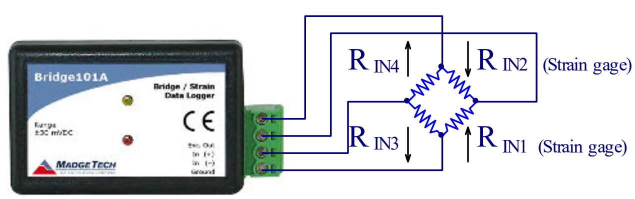

Figure 7, The full Wheatstone bridge configuration for 4-wire Bridge products

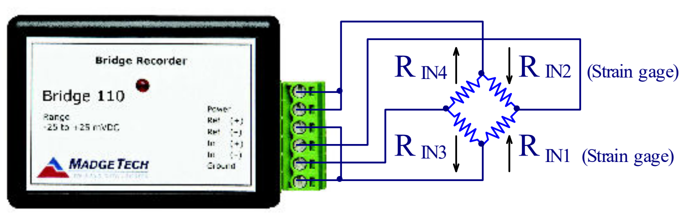

Figure 8, The full Wheatstone bridge configuration for 6-wire Bridge products

$$V_{inmV}(total) = mVref * [\left(\frac{R_{in1}}{R_{in1} + R_{IN}}\right) - \left(\frac{R_{in3}}{R_{in3} + R_{IN}}\right)]$$

Equation (9), The equation for the voltage differential at In (+) and In (-) for the full bridge configuration
All calculations are done in millivolts, V_{inmV} *is in mV,* $mVref$ *is 2500mV*

The full Wheatstone Bridge configuration has the same advantages as the half bridge configuration but provides twice the signal level. It does, however, require twice the power to drive it. A Bridge101A can drive a 350Ω full bridge directly but cannot drive the 120Ω configuration. It can drive the 120Ω configuration with a 240Ω resistor in series; however, this resistor should be made from two 120Ω unstrained strain gages in the same temperature environment to avoid gain changes with temperature. Also, the voltage equation needs to be multiplied by 1/3. (See figure 10 for resistor placement.)

Similarly, the Bridge110/120 cannot directly drive the 120Ω or 350Ω configurations and will require a 880Ω or 650Ω series resistor, respectively, and will increase noise 7x or 3x, respectively. Once again, by moving the REF (+) connection to the opposite side of the resistor, temperature errors and gain adjustments are avoided. (See figure 9 for resistor placement.)

$$V'_{inmV} \approx mVref * [\left(\frac{R_{in1} - R_{in2}}{R_{in} + R_{in2}}\right) - \left(\frac{R_{in} - R_{in4}}{R_{in3} + R_{in4}}\right)]$$

Equation (10), The equation for the slope of voltage differential at In (+) and In (-) for half bridge configuration
All calculations are done in millivolts, V'_{inmV} *is in mV/Ω,* $mVref$ *is 2500mV*
The equation is exact if $R_{in1} + R_{in2}$ *and* $R_{in3} + R_{in}$ *remain constant.*

Packaged Wheatstone Bridge Configuration

In some circumstances, you may wish to plug in a packaged Wheatstone Bridge sensor such as the Omega® PX170 differential pressure gage or Omega® LCGC series Load Cell gages; however, the internal resistive bridge cannot be altered.

When using a packaged Bridge sensor, check the specified bridge resistance. If it is less than the minimum drive resistance of the logger, then add a series resistor in the POWER line to bring the total resistance to the specification of the logger. Generally speaking, you may also increase the value of this resistor to conserve battery power; however, it will diminish the signal-to-noise ratio by a factor of R_S/R_{GAGE}. For a 6-wire logger, the REF (+) line should be brought to the power pin on the sensor as shown. For 4-wire loggers, it is impossible to avoid a difference in temperature response between the fixed resistor and the bridge which, in turn, can generate a temperature-related gain error.

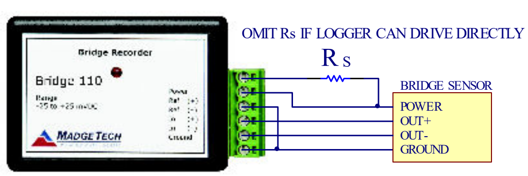

Figure 9, The packaged bridge configuration for 6-wire Bridge products

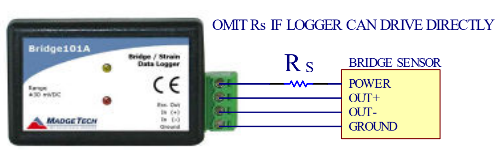

Figure 10, The packaged bridge configuration for 4-wire Bridge products

If you have any further questions about your application, please contact
MadgeTech Customer Support at 603.456.2011, or via e-mail: support@madgetech.com