What Is Strain?

Strain is a measure of the deformation of a body due to an applied force, and is defined as the fractional change in length, as shown in Figure 1 below.

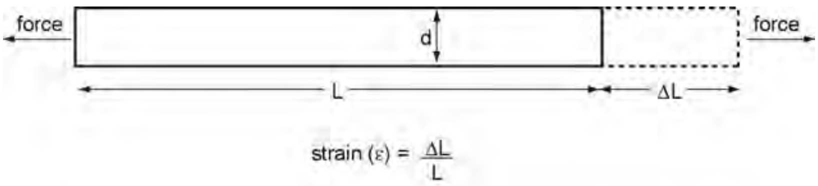

Figure 1. Definition of Strain

Strain can be tensile (positive) or compressive (negative), and can be expressed in units such as in/in. or mm/mm. However, the magnitude of measured strain is very small, and in practice, strain is usually expressed as microstrain (με), which is $\varepsilon \times 10^{-6}$.

The Strain Gauge

Although several ways of measuring strain exist, the most common method is to use a strain gauge, a device whose electrical resistance varies in proportion to the amount of deformation in the device. The most common gauge is the bonded metallic strain gauge.

The metallic strain gauge consists of a very fine wire or metallic foil, arranged in a grid pattern, which maximizes the amount of material subject to strain (see Figure 2). This grid is then bonded to the carrier, a thin backing which is attached directly to the measured object. Therefore, any strain experienced by the object is transferred directly to the strain gauge, which expands or contracts, causing a proportional change in electrical resistance.

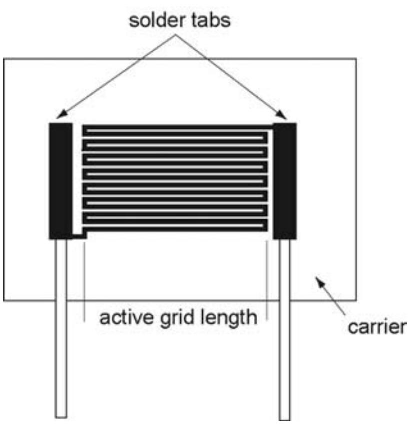

Figure 2. Bonded Metallic Strain Gauge

The sensitivity of a strain gauge is expressed by the gauge factor (GF) and is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \left[\frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} \right] = \frac{\frac{\Delta R}{R}}{\varepsilon}$$

The Gauge Factor for metallic strain gauges is typically around 2.

Strain Gauge Measurement

In practice, strain measurements involve very small quantities, i.e. a few microstrain ($\varepsilon \times 10^{-6}$). Therefore, to measure the strain requires accurate measurement of very small changes in resistance. For example, suppose an object undergoes a strain of 500 $\mu\varepsilon$. A strain gauge with a gauge factor of 2 will exhibit a change in electrical resistance of only $2 (500 \times 10^{-6}) = 0.1\%$. For a 350 Ω gauge, this is a change of only 0.35 Ω.

To measure such small changes in resistance, strain gauges are generally used in a bridge configuration with a voltage excitation source. The Wheatstone bridge (see Figure 3) consists of four resistive arms with an excitation voltage, V_{EX}, that is applied across the bridge.

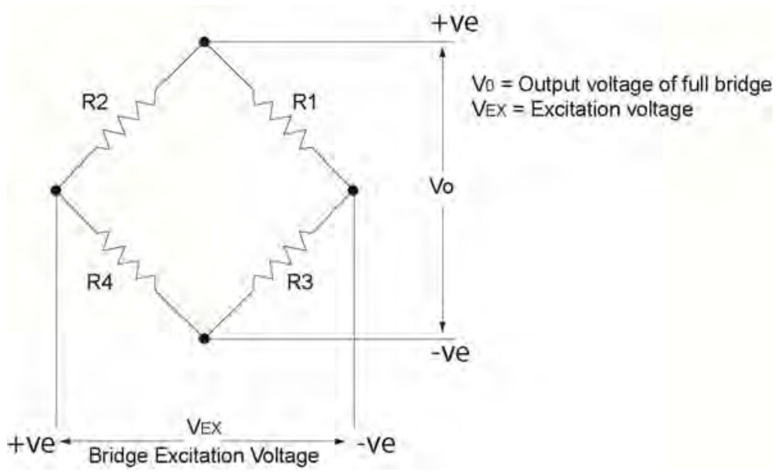

Figure 3. Wheatstone Bridge

The output voltage of the bridge, V_O, will be equal to:

$$V_0 = \left[\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4} \right] . V_{EX}$$

From the equation above, it is apparent that when $R_1/R_2 = R_3/R_4$, the voltage output V_O will be zero,and the bridge is said to be balanced. Any change in resistance in any arm of the bridge will result in a change to this zero output voltage.

Therefore, if we replace R_1 and R_4 in Figure 3 with active strain gauges, any changes in the strain gauge resistance will unbalance the bridge and produce an output voltage.

This change in resistance can then be expressed by the following formula:

$\Delta R = R_G \cdot G_F \cdot \varepsilon$.

Where

ΔR = the strain-induced change in resistance
R_G = the nominal resistance of the strain gauge
G_F = the Gauge Factor
ε = the strain (i.e. $\Delta L/L$)

Assuming that nominally, $R_2 = R_4$ and $R_1 = R_3 = R_G$, the bridge equation above can be rewritten to express V_O/V_{EX} as a function of strain (see Figure 4).

$$\frac{V_0}{V_{EX}} = \left[\frac{R_1 + \Delta R}{\Delta R + R_1 + R_2} - \frac{R_3}{R_3 + R_4 + \Delta R}\right]$$

$$= \left[\frac{R_G + \Delta R}{2R_G + \Delta R}\right] - \left[\frac{R_G}{2R_G + \Delta R}\right]$$

$$= \left[\frac{\Delta R}{2R_G + \Delta R}\right]$$

$$= \left[\frac{R_G \,.\, G_F \,.\, \varepsilon}{2R_G + R_G \,.\, G_F \,.\, \varepsilon}\right]$$

$$\frac{V_0}{V_{EX}} = \left[\frac{G_F \,.\, \varepsilon}{2 + G_F \,.\, \varepsilon}\right]$$

Ideally, the resistance of the strain gauge should change only in response to applied strain. However, the strain gauge material, (and the object to which the gauge is attached), also responds to temperature fluctuations.

By using a bridge arrangement, the effect of temperature can be minimized. For example, Figure 4 illustrates a strain gauge configuration where one gauge is active ($R_G + \Delta R$), and a second gauge (the dummy gauge) is placed transverse to the applied strain. The strain has little effect on the dummy gauge however, changes in temperature will affect both gauges equally. Because, the temperature changes in the two gauges are identical, the ratio of their resistance does not change. Therefore the voltage V_O does not change, and the effects of the temperature change are minimized.

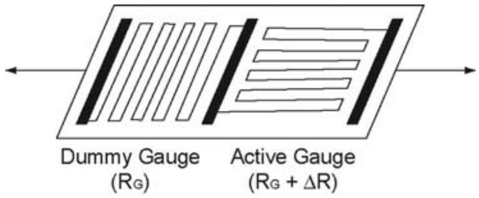

Figure 4. Use of Dummy Gauge to Eliminate Temperature Effects

The equations given here for the Wheatstone bridge circuits assume an initially balanced bridge, i.e. generates zero output when no strain is applied. In practice however, resistance tolerances and strain induced by gauge application will generate some initial offset voltage. This initial offset voltage can be handled in two ways. First, a special offset-nulling, or adjustment circuit can be used to adjust the resistance in the bridge until the bridge is balanced. Alternatively, the initial unstrained output of the circuit can be measured and compensated in software.

The equations also assume that the lead wire resistance is negligible. This is permissible when explaining the theory of strain gauge measurement, but could be a source of error if ignored in practise. This error can be compensated if the lead resistance R_L is measured and accounted for in the strain calculations. However, problems can also arise from changes in the lead resistance due to temperature fluctuations in unbalanced lead lengths.

A balanced 2-wire connection and low impedance measurement can help to eliminate the effects of variable lead wire resistance because the lead resistances affect adjacent legs of the bridge equally. Therefore, any changes in resistance due to temperature cancel each other. This 2-wire and full bridge approach also helps to improve common mode rejection of noise picked up by the bridge wire connections.

Signal Conditioning for Strain Gauges

As previously stated, strain gauge measurement involves sensing extremely small changes in resistance. Therefore, proper selection and use of a bridge, signal conditioning, wiring, and data acquisition components are required for reliable measurements. To ensure accurate strain measurements, it is important to consider the following parameters:

- Excitation
- Remote sensing
- Amplification
- Filtering
- Offset
- Calibration

Excitation – Typically, strain gauge signal conditioners provide a constant AC or DC voltage source to power the bridge. While there is no recognized industry standard voltage level, an excitation voltage level of between 2V and 10V is common. Although a higher excitation voltage generates a proportionately higher output voltage, the higher voltage can also cause larger errors because of self-heating.

Remote Sensing – The strain gauge circuit should be located as close as possible to the signal conditioner and excitation source. If not, voltage drop due to variable resistance in the wires connecting the excitation voltage to the bridge is a possible source of error.

Amplification – The output of strain gauges and bridges is relatively small. Typically, most strain gauge bridges and strain-based transducers output less than 10 mV per volt of excitation voltage. With 10V excitation, the output signal will be of the order of 100 mV. Therefore, strain gauge signal conditioners usually include amplifiers to boost the signal level to increase measurement resolution and improve signal-to-noise ratios.

Filtering – Strain gauges are often located in electrically noisy environments. It is essential to eliminate any noise that could couple to the strain gauges. Lowpass filters can be used in conjunction with strain gauges to remove high-frequency noise prevalent in most work environments.

Offset Nulling – When a bridge is installed, it is unlikely to be balanced (zero volts when no strain is applied). Slight variations in resistance among the bridge arms and lead resistance can generate some nitial offset voltage. Offset nulling can be performed by either hardware or software:

1. Software Compensation – An initial measurement is taken before strain input is applied. This offset can then be used to compensate subsequent measurements. This method is simple, fast, and requires no manual adjustments. The disadvantage of the software compensation method is that the offset of the bridge

is not removed. If the offset is large enough, it limits the amplifier gain which can be applied to the output voltage, thereby limiting the dynamic range of the measurement.

2. Offset-Nulling Circuit – This method uses an variable resistance to adjust the output of the bridge to zero. By varying the resistance, the level of the bridge output can be controlled and the initial output can be set to zero volts. Alternatively, the signal preamplifier used may have its own offset nulling adjustment.

Calibration – Calibration involves applying a known amount of strain or simulating the input of strain by changing the resistance of an arm in the bridge by some known amount. Simulation can be accomplished by shunting or connecting a large resistor of known value across one arm of the bridge, creating a known ΔR. The output of the bridge can then be measured and compared to the expected voltage value. The results are used to correct errors in the entire measurement path, or simply to verify general operation to gain confidence in the setup.

THORLABS
Thorlabs Ltd.
1 Saint Thomas Place
Ely
Cambridgeshire CB7 4EX, UK
Tel: +44 (0) 1353 654440
Fax: +44 (0) 1353 654444
www.thorlabs.com

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