Micron Optics, Inc.
Optical Strain Gage
Temperature Compensation Techniques

Wavelength to Strain Relation:

The basic relationship between Wavelength and strain for a Fiber Bragg grating based gage is:

$$\varepsilon = \frac{\Delta WL / WL_0}{F_G} \qquad \text{(Equation 1.0)}$$

Where:

ε	= Strain (m/m)
ΔWL	= Wavelength shift (nm)
WL_0	= Initial Reference Wavelength (nm)
F_G	= Gage factor (dimensionless)

Temperature Response:

Fiber Bragg grating based gages respond to temperature induced strain as well as mechanically induced strains. The temperature induced strain is a combination of two factors. First, the relative difference in coefficients of thermal expansion (CTE) between the gage and the substrate on which it is mounted causes a strain to be induced in the gage as temperature changes. Secondly, the index of refraction of the Bragg grating is a function of temperature causing the center wavelength to shift. Figure 1 shows response of typical gage mounted on steel.

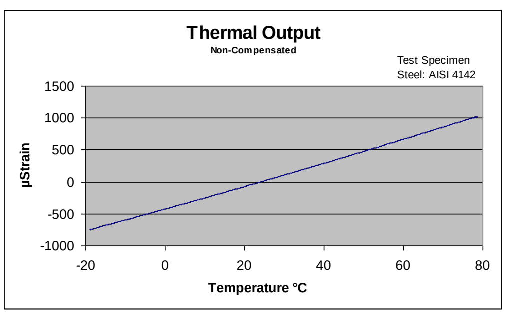

Figure 1

There are several methods of determining the thermal output of a gage. Once the thermal output is known, the mechanically induced strain can easily be calculated by subtracting the thermal output from the strain measured by the active gage as follows: (Note the introduction of a scaling factor that more conveniently expresses strain in units of µm/m)

ε = Stress Induced Strain (µm/m)
ΔWL = Wavelength shift (nm)
WL_0 = Initial Reference Wavelength (nm)
F_G = Gage factor (dimensionless)
ε_{T0} = Thermal output (µm/m)

$$\varepsilon = (10^6\ \mu m/m)\frac{\Delta WL/WL_0}{F_G} - \varepsilon_{T0} \qquad \text{(Equation 1.1)}$$

Method-I: Estimation of Thermal Output (ε_{TO}) for os3100 Strain Gages

ε_{TO} may be estimated if the CTE of the substrate and gage constants are known. This estimate can then be used in the equation 1.1 to compensate for temperature. This method requires that the temperature change be measured using a conventional electronic temperature sensor or an optical temperature sensor. See Method-IB for an example demonstrating the use of an os4100 optical temperature sensor to measure ΔT. Note that the constants in Equation 1.2 are themselves a function of temperature; therefore, equation 1.2 provides only an estimate of ε_{TO}.

ε_{TO} = Thermal Output (µm/m)
F_G = Gage factor (dimensionless)
C_1 = Gage Constant 1 (µm/m-°C)
C_2 = Gage Constant 2 (µm/m-°C)
ΔT = Temperature change, relative to initial reference temperature (°C)
CTE_S = Coefficient of thermal expansion-Substrate (µm/m-°C)

$$\varepsilon_{T0} = \Delta T\left[\frac{C_1}{F_G} + CTE_S - C_2\right] \qquad \text{(Equation 1.2)}$$

Example: An os3100 gage is applied to a substrate having a CTE of 11.5 µm/m-°C. The gage factor is listed as 0.890. The strained grating experiences a positive wavelength shift of 1.839 nm relative to reference conditions 1550.250 nm while the temperature decreases 18°C. The datasheet list C1 as 6.156 µm/m-°C. C2 is listed as 0.7 µm/m-°C.

F_G = 0.890
C_1 = 6.156 µm/m-°C
C_2 = 0.7 µm/m-°C
ΔT = -18°C
CTE_S = 11.5 µm/m-°C
ΔWL = 1.839 nm

(Equation 1.2)
$\varepsilon_{TO} = \Delta T\ [C_1 / F_G + CTE_S – C_2]$
ε_{TO} = -18°C [6.156 µm/m-°C / 0.890 + 11.5µm/m-°C - 0.7µm/m-°C]
ε_{TO} = -319 µm/m

(Equation 1.1)
$\varepsilon = (10^6\ \mu m/m)\ (\Delta WL / WL_0) / F_G - \varepsilon_{T0}$
$\varepsilon = (10^6\ \mu m/m)$ (1.839 nm /1550.250 nm) / 0.890 + 319 µm/m
ε = 1652 µm/m

Method-IB: Using os4100 Temperature Compensation Sensor to Measure ΔT

This section further expands on Method-I above and demonstrates the use of a Micron Optics os4100 temperature compensation sensor to optically measure ΔT. For an os4100 temperature sensor, the temperature change can be calculated using the following equation.

$$\Delta T = \frac{\Delta WL_{Temp}}{S_T} \qquad \text{(Equation 1.3)}$$

Subscript "Temp" or "Strain" will be added to the ΔWL term to indicate the change in wavelength of the Temperature sensor or Strain sensor respectively.

Plugging this into equation 1.2 results in:

ε_{TO} = Thermal Output (µm/m)
ΔWL_{Temp} = Wavelength shift [*os4100 Temp. Sensor*] (pm)
S_T = Temperature Sensitivity [*os4100 Temp. Sensor*] (pm/°C)
F_G = Gage factor [*os3100 Strain Sensor*] (dimensionless)
C_1 = Gage Constant 1 [*os3100 Strain Sensor*] (µm/m-°C)
C_2 = Gage Constant 2 [*os3100 Strain Sensor*] (µm/m-°C)
CTE_S = Coefficient of thermal expansion [*Substrate*] (µm/m-°C)

$$\varepsilon_{T0} = \frac{\Delta WL_{Temp}}{S_T}\left[\frac{C_1}{F_G} + CTE_S - C_2\right] \qquad \text{(Equation 1.4)}$$

Example: An os3100 gage is applied to a substrate having a CTE of 11.5 µm/m-°C. The gage factor is listed as 0.890. The strained grating experiences a positive wavelength shift of 1.839 nm relative to reference conditions 1550.250 nm while an os4100 temperature sensor experiences a negative wavelength shift of 0.520 nm (520 pm). The os3100 datasheet list C1 as 6.156 µm/m-°C. C2 is listed as 0.7 µm/m-°C. The os4100 datasheet list S_T as 28.9 pm/°C.

F_G = 0.890
C_1 = 6.156 µm/m-°C
C_2 = 0.7 µm/m-°C
CTE_S = 11.5 µm/m-°C
S_T = 28.9 pm/°C
ΔWL_{Strain} = 1.839 nm
ΔWL_{Temp} = -0.520 nm

(Equation 1.4)
$\varepsilon_{TO} = \Delta WL_{Temp} / S_T [C_1 / F_G + CTE_S - C_2]$
ε_{TO} = -520pm / 28.9pm/°C [6.156 µm/m-°C / 0.890 + 11.5µm/m-°C - 0.7µm/m-°C]
ε_{TO} = -319 µm/m

(Equation 1.1)
$\varepsilon = (10^6\ \mu m/m)\ (\Delta WL / WL_0) / F_G - \varepsilon_{T0}$
ε = (10^6 µm/m) (1.839nm / 1550.250nm) / 0.890 + 319 µm/m
ε = 1652 µm/m

Method-II: Experimental Measure of Thermal Output (ε_{T0})

Although it is often not feasible, ε_{T0} may be measured by placing the test article with mounted gage in an environmental chamber. The chamber is then slowly ramped through the temperature range of interest while recording temperature and $[(\Delta WL/WL_0) / F_G]$ to create a table of thermal output versus temperature. This information can be curve fit or used as a look-up table to correct for thermal output during test.

Once the test article is removed from the chamber, mechanically induced strain can be determined by simply correcting for temperature by using the thermal output from the look-up table in equation 1.1.

Method-III: Temperature Compensating Dummy Gage

A common method of temperature compensation involves the use of a second compensating "dummy gage" identical to the active gage. The dummy gage should be mounted to a stress-free piece of material identical to the material on which the active gage is mounted. The dummy gage should be located as close as possible to the active gage so that both gages experience the same temperature.

In this configuration, the dummy gage will respond to temperature in a similar way as the active gage providing a direct measurement of thermal output.

ε	= Stress Induced Strain (m/m)
ΔWL	= Wavelength shift
WL_0	= Initial Reference Wavelength
F_G	= Gage factor

$$\varepsilon = \left[\frac{\Delta WL/WL_0}{F_G}\right]_{Active} - \left[\frac{\Delta WL/WL_0}{F_G}\right]_{Dummy} \qquad \text{(Equation 3.1)}$$

Note: The resulting strain can be multiplied by a scaling factor (10^6 µm/m) that more conveniently expresses strain in units of µm/m.

Method-IV: Active Dummy Gage

In some applications, the compensating dummy gage can play an active role in the measurement of strain. In bending beam applications for example, one gage can be mounted on the top surface of the beam while a second gage is mounted on the bottom surface of the beam. When a bending load is applied to the beam, one gage will be in tension while the other gage is in equal but opposite compression. The difference in wavelength between the two gages provides a 2X reading of strain. Thermally induced strain will cause both gages to move in the same direction effectively canceling one another.

ε	= Stress Induced Strain (m/m)
ΔWL	= Wavelength shift
WL_0	= Initial Reference Wavelength
F_G	= Gage factor

$$\varepsilon = \left[\frac{\Delta WL/WL_0}{2F_G}\right]_{Active} - \left[\frac{\Delta WL/WL_0}{2F_G}\right]_{Dummy} \qquad \text{(Equation 4.1)}$$

Note: The resulting strain can be multiplied by a scaling factor (10^6 µm/m) that more conveniently expresses strain in units of µm/m.

Internally Compensated Strain Gage

Some optical strain gages such as the os3600 are “self compensating.” This gage includes a second Fiber Bragg Grating located inside the sensor that compensates for temperature. The gage is designed to compensate for temperature when mounted on a test specimen having a specific coefficient of thermal expansion (CTE), 10.1 µm/m-°C in the case of the os3600. If the gage is mounted on a test specimen having a different CTE, then a correction factor can be applied to reduce thermal effects.

Equation 5.1 is similar to equation 3.1 with the addition of a CTE correction term. We also included the scaling factor (10^6 µm/m) to expresses strain in units of µm/m. If the gage is mounted on a test specimen having a CTE that matches the gage, then the third term goes to zero and the equation is the same as equation 3.1.

ε = Stress Induced Strain
ΔWL_{Strain} = Wavelength shift [*Strain Grating*] (nm)
$WL_{0\text{-}Strain}$ = Initial Reference Wavelength [*Strain Grating*] (nm)
ΔWL_{Temp} = Wavelength shift [*Temp. Grating*] (nm)
$WL_{0\text{-}Temp}$ = Initial Reference Wavelength [*Temp. Grating*] (nm)
F_G = Gage factor
CTE_S = Coefficient of thermal expansion-Substrate (µm/m-°C)
C_1 = Gage Constant 1 [*Gage factor Temp. Grating*]
C_2 = Gage Constant 2 [*Specified Gage CTE*] (µm/m-°C)
S_T = Temperature Sensitivity [*Temp. Grating*] (pm/°C)

(Equation 5.1)

$$\varepsilon = (10^6\ \mu m/m)\left[\left[\frac{\Delta WL/WL_0}{F_G}\right]_{Strain} - \left[\frac{\Delta WL/WL_0}{C_1}\right]_{Temp}\right] - (CTE_S - C_2)\frac{(10^3 pm/nm)\,\Delta WL_{Temp}}{S_T}$$

Example: An os3600 gage is applied to a steel structure having a CTE of 11.5 µm/m-°C. The gage factor is listed as 0.815. The strained grating experiences a negative wavelength shift of 1.856 nm relative to reference conditions 1526 nm while the temperature grating experiences a positive wavelength shift of 0.320 nm relative to reference conditions 1522 nm. The os3600 datasheet list S_T as 23.8 pm/°C. C_1 is listed as 0.796 and C_2 is listed as 10.1 µm/m-°C. Note that in the above equation, the last two terms ΔWL_{Temp} and S_T both refer to wavelength. It is important that both terms express wavelength in the same units. Since S_T is expressed in terms of pm/°C, a scaling factor of (10^3 pm/nm) is included to convert ΔWL_{Temp} from nanometers to picometers.

ΔWL_{Strain} = -1.856 nm
$WL_{0\text{-}Strain}$ = 1526 nm
ΔWL_{Temp} = 0.320 nm
$WL_{0\text{-}Temp}$ = 1522 nm
$F_{G\ Strain}$ = 0.815
CTE_S = 11.5 µm/m-°C
C_1 = 0.796
C_2 = 10.1 µm/m-°C
S_T = 23.8 pm/°C

(Equation 5.1)
$\varepsilon = (10^6\ \mu m/m)\{[\Delta WL/WL_0 / F_G]_{Strain} - [\Delta WL/WL_0 / C_1]_{Temp}\} - (CTE_S - C_2)\ (10^3\ pm/nm)\ \Delta WL_{Temp} / S_T$
$\varepsilon = (10^6\ \mu m/m)\{[-1.856nm/1526nm / 0.815]_{Strain} - [0.320nm/1522nm / 0.796]_{Temp}\} - (11.5\mu m/m\text{-}°C - 10.1\mu m/m\text{-}°C)\ 320pm / 23.8pm/°C$
$\varepsilon = -1775\ \mu m/m$