Distributed Fiber Optic Sensing: Temperature Compensation of Strain Measurement

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Introduction

Ideally, a fiber optic strain sensor bonded to a test article would respond only to the external load applied to the article, and remain unaffected by other variables in the environment. However, similar to electrical foil gages, the optical fiber is sensitive to both strain as well as changes in temperature. In the instance where the strain being measured is large (thousands of microstrain) compared to temperature variations throughout the test (a few °C), this effect can potentially be safely ignored. However, in circumstances where temperature variations are large compared to the expected strain output, these deviations can cause significant errors if not properly accounted for. This Engineering Note describes some methods that can be employed to correct for this temperature-induced apparent strain.

1. Distributed Sensing Parameters

Luna utilizes swept-wavelength interferometry to interrogate fiber optic sensors. Physical changes in the sensors create a measurable change to the light that is scattered in the fiber (Rayleigh scatter). By comparing the scattered light of a sensor to a reference measurement that was recorded with the fiber in a known state one can determine the physical state of the fiber at the time of measurement. The state of the fiber is coupled to the local environmental temperature and strain.

The physical length and index of refraction of the fiber are intrinsically sensitive to environmental parameters: temperature and strain, and to a lesser extent, pressure, humidity (if the fiber coating is hydroscopic), electromagnetic fields, etc. In most practical cases the effects of temperature and strain will dominate the spectral response of the Rayleigh backscatter. Changes in the local period of the Rayleigh scatter cause temporal and spectral shifts in the locally-reflected spectrum. These shifts can be scaled to form a distributed sensor.

A change in temperature or strain from the baseline condition results in a shift in the spectrum of light scattered in the fiber. The strain response arises due to both the physical elongation of the sensor, and the change in fiber index due to photoelastic effects. The thermal response arises due to the inherent thermal expansion of the fiber material and the temperature dependence of the refractive index, n. The thermal response is dominated by the dn/dT effect, which accounts for ~95% of the observed shift. [1]

The shift in the spectrum of light scattered in the fiber in response to strain or temperature is analogous to a shift in the resonance wavelength Δλ or the spectral shift, Δν, of a Bragg grating:

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} = K_T\Delta T + K_\varepsilon\varepsilon$$

where λ and υ are the mean optical wavelength and frequency, and K_T and K_ε are the temperature and strain calibration constants, respectively. The default values for these constants are set at values common for most germanosilicate core fibers: K_T = 6.45 x 10-6 °C-1 and K_ε = 0.780. The values for K_T and K_ε are somewhat dependent on the dopant species and concentration in the core of the fiber, but also to a lesser extent on the composition of the cladding and coating. Variations of 10% in K_T and K_ε between standard telecom fibers are common.

In the absence of strain the temperature change can be written as:

Temperature Change, $\Delta T = -\frac{\bar{\lambda}}{cK_T}\Delta\nu$,

where $\bar{\lambda}$ is the center wavelength of the scan and c is the speed of light. Similarly, in the absence of a temperature change, the strain can be written as:

Strain, $\Delta\varepsilon = -\frac{\bar{\lambda}}{cK_\varepsilon}\Delta\nu$.

Assuming a scan center wavelength of 1550 nm, the constants K_T and K_ε can be substituted in to yield the following conversion factors: ε=(−6.67με/GHz)Δν and ΔT=(−0.801°C/GHz)Δν. These conversion factors are denoted k_ε and k_T respectively.

Thus the distributed temperature and strain curves are merely rescaled copies of the spectral shift distribution.

In the presence of both strain and temperature changes, judicious experimental planning is necessary in order to decouple these measurements.

2. Fiber Thermal Output

We define here the fiber thermal output as changes in spectrum due to temperature changes. As previously mentioned, the fiber thermal response is caused by two concurrent and algebraically additive effects in the fiber installation. The first is the temperature dependence of the refractive index. The second is the thermal expansion of the fiber. The fiber's coefficient of thermal expansion (CTE) is 0.55 ppm/°C for fused silica. When the fiber sensor is bonded onto a substrate, the second term is now the differential of the thermal expansion between the fiber and the substrate to which the fiber is bonded. Due to the small CTE of the fiber, in many instances, the CTE of the substrate dominates and the fiber is forced to undergo the same expansion or contraction as the substrate. For comparison purposes, the CTE for Aluminum, Steel, and E-glass are 22.2, 13, and 5.4 ppm/°C respectively.

The net fiber thermal output is therefore the algebraic sum of these. Expressed in terms of spectral shift, the thermal output, $\Delta\nu_T$ becomes:

$$\Delta\nu_T = \Delta\nu_n + \Delta\nu_S$$

where $\Delta\nu_n$ is the refractive index-dependent spectral shift and $\Delta\nu_S$ is the CTE-dependent spectral shift.

3. Compensation for Thermal Output

When carrying out strain measurements in an environment where the environmental temperature is also changing, the error due to fiber thermal output can be either controlled, or compensated for using one of the methods outlined below.

3.1 Unbonded Fiber

3.1.1 Single fiber loop

In a test where the temperature of the whole active test article varies without any local temperature gradients, a single fiber measurement can be used for compensation. A compensating fiber loop can be created by leaving a short segment of the fiber sensor unbonded but resting on the test article (Figure 1). Under this condition, the thermal output of the fiber loop can be used to compensate the mechanical strain measurements of the bonded fiber in the following way:

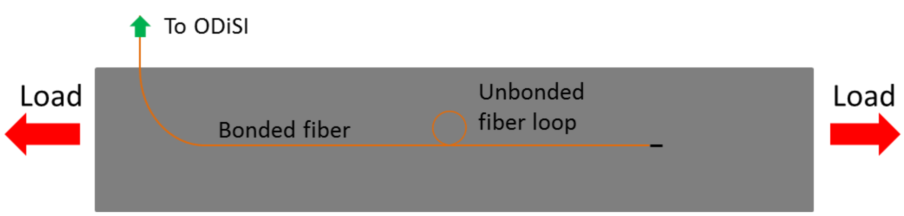

Figure 1: Single unbonded fiber loop

Mechanical strain in bonded fiber $_i$ = Strain measured in bonded fiber $_i$ – (Index-dependent apparent strain + CTE-dependent apparent strain)

$$\varepsilon_{L_i} = (\Delta\nu_{B_i} * k_\varepsilon) - ((k_{nT} * \Delta\nu_U * k_\varepsilon) + (\Delta\nu_U * k_T * \alpha_S))$$

$$\Delta\nu_B = Spectral\ shift\ in\ bonded\ fiber$$
$$\Delta\nu_U = Spectral\ shift\ in\ unboned\ fiber\ loop$$

$k_{nT} = \frac{dn}{dT} effect, approximately\ 0.95$
$k_{\varepsilon} = Strain\ conversion\ factor$
$k_T = Temperature\ conversion\ factor$
$\alpha_S = Substrate\ CTE$

Subscript *i* denotes individual sensing points along the fiber

In this method, it is assumed that the temperature of the fiber loop is always identical to the temperature of the whole active test article. This is not always true, especially if there are temperature gradients within the test environment.

3.1.2 Point-to-point compensation

In a test where temperature gradients are expected across the active test article, an unbonded fiber segment can be floated in a tube beside the bonded fiber (Figure 2). Under this condition, the thermal output of the fiber segment can be used for point-to-point compensation of the mechanical strain measurements of the bonded fiber in the following way:

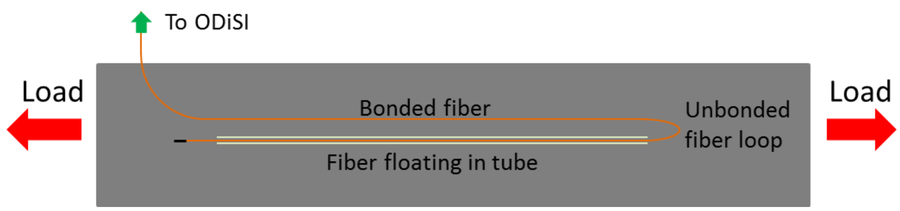

Figure 2: Unbonded fiber segment

Mechanical strain in bonded fiber $_i$ = Strain measured in bonded fiber $_i$ – (Index-dependent apparent strain $_i$ + CTE-dependent apparent strain $_i$)

$$\varepsilon_{L_i} = (\Delta\nu_{B_i} * k_{\varepsilon}) - ((k_{nT} * \Delta\nu_{U_i} * k_{\varepsilon}) + (\Delta\nu_{U_i} * k_T * \alpha_S))$$

$\Delta\nu_B = Spectral\ shift\ in\ bonded\ fiber$
$\Delta\nu_U = Spectral\ shift\ in\ unboned\ fiber\ loop$
$k_{nT} = \frac{dn}{dT} effect, approximately\ 0.95$
$k_{\varepsilon} = Strain\ conversion\ factor$
$k_T = Temperature\ conversion\ factor$
$\alpha_S = Substrate\ CTE$

Subscript *i* denotes individual sensing points along the fiber

3.2 Bonded fiber

3.2.1 Extrinsic specimen

A compensating or 'dummy' gage can be created by bonding the fiber on an unstrained specimen made from the identical material as the test article (Figure 3), and subjected always to the same temperature as the test article. Under this condition, the thermal outputs of both bonded fiber segments should be identical. Therefore the stress-induced strain in the test article can be calculated by taking a difference of these measurements.

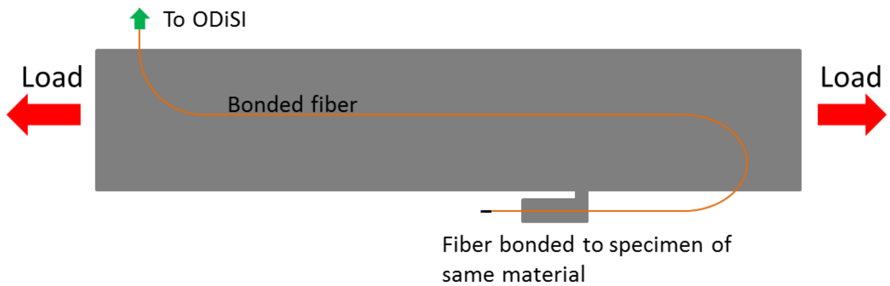

Figure 3: Fiber bonded on 'dummy' gage

Mechanical strain in bonded fiber $_i$ = Strain measured in bonded fiber $_i$ – (Thermal output from 'dummy' gage)

$$\varepsilon_{L_i} = (\Delta\nu_{B_i} * k_\varepsilon) - (\Delta\nu_D * k_\varepsilon)$$

$$\Delta\nu_B = Spectral\ shift\ in\ bonded\ fiber$$
$$\Delta\nu_D = Spectral\ shift\ from\ 'dummy'\ gage$$
$$k_\varepsilon = Strain\ conversion\ factor$$

Subscript *i* denotes individual sensing points along the fiber

This method assumes that the dummy gage remains unstrained under all test conditions. Similarly to 3.1, it is also assumed that the temperature of the dummy gage is always identical to the temperature of the whole active test article. It is not always possible to ensure this, especially if there are temperature gradients within the test environment.

3.2.2 Test article with known relative strains

In some applications, the ratio of strains at two different locations on the test object is known a *priori*. Examples include bars in pure torsion and beams in bending, stressed within their proportional limits. In these applications, the fiber sensor can be routed strategically to exploit these relationships (Figure 4).

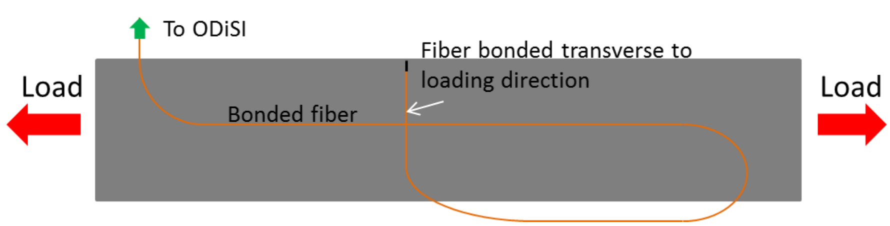

Figure 4: Fiber bonded strategically on test article

In this example, at the crossover point, the strain in the transverse direction is related to the strain in the axial direction by Poisson's ratio, υ.

Thermal output for compensation, $\Delta\nu_C = \Delta\nu_T - \frac{(\Delta\nu_A - \Delta\nu_T)}{(1-\upsilon)} * \upsilon$

Mechanical strain in bonded fiber $_i$ = Strain measured in bonded fiber $_i$ – (Thermal output)

$$\varepsilon_{L_i} = (\Delta\nu_{B_i} * k_\varepsilon) - (\Delta\nu_C * k_\varepsilon)$$

$$\Delta\nu_T = Spectral\ shift\ in\ transverse\ fiber\ at\ crossover\ point$$
$$\Delta\nu_A = Spectral\ shift\ in\ axial\ fiber\ at\ crossover\ point$$
$$k_\varepsilon = Strain\ conversion\ factor$$

Subscript *i* denotes individual sensing points along the fiber

3.3 Event Time Scale

In applications where strain is varying quickly while temperature varies on a longer time scale, the fact that these events are occurring on different time scales can be used to decouple the effect of temperature from strain. High pass filters can be applied to the measurement data to pass the high-frequency strain signal through, but attenuate the low frequency signal from the thermal output.

Summary

This Engineering Note describes some methods that can be employed to correct for this temperature-induced apparent strain. Various compensation schemes are discussed, based on fiber layout and environmental conditions.

References

1 Kersey et. al. "Fiber Grating Sensors". *Journal of Lightwave Technology*, Vol. 15, No. 8. 1997

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