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Spectral profile tracking of multiplexed fiber Bragg grating sensors

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ABSTRACT

This paper outlines a demodulation technique for fiber Bragg grating (FBG) sensors based on combined spectral profile division multiplexing and wavelength division multiplexing. The advantage to this technique is that more FBG sensors can be compressed in a fixed bandwidth, as compared to pure wavelength division multiplexing, in which separate wavelength window is required for each sensor. To identify each FBG sensor, the cross-correlation algorithm of the original sensor spectral profile with the measured full-spectrum from the sensor array is calculated for rapid signal processing. The demodulation method is tested on simulated and experimental data. The demodulation generally performed well, except for cases where a significant amount of spectral distortion due to multiplexing was present. Finally, a correction factor based on the prior location of each sensor at the previous time step is added to compensate for inherent uncertainties in the cross-correlation algorithm. The correction factor improved some predictions, but made others worse, and therefore needs further investigation for practical applications.

1. Introduction

The spectral encoding of fiber Bragg grating (FBG) sensor information allows FBGs to be multiplexed to form sensor networks with a few measurement channels. The benefits of high density multiplexing are particularly strong when FBG sensor networks are applied to monitor large structural systems such as aircraft, wind turbines or civil infrastructure systems [1–3]. The challenge associated with multiplexing is to be able to identify and track each separate FBG sensor. The difficulty of this task is increased whenever a large number of FBG sensors are to be tracked at high sampling rates.

Classical multiplexing strategies are wavelength division multiplexing (WDM), time division multiplexing (TDM), or a combination thereof. In WDM the number of sensors that can be multiplexed is limited by the available bandwidth from the source and the needed width of each sensor window. For low speed systems, large numbers of sensors have been multiplexed [4,5]. For higher speed systems, wavelength scanning is typically performed by scanning a tunable filter. For tunable filter based systems, the bandwidth of the source decreases with tuning speed, limiting the number of sensors that can be tracked with high-scanning rate systems [6,7].

The second approach, TDM, separates the individual sensors through the time of arrival of a particular peak wavelength. For dynamic systems, the limiting factor to TDM is the minimum time of arrival difference between the sensors, limiting the sampling rate and minimum distance between individual sensors, often on the order of several meters [8]. Researchers have also successfully combined WDM and TDM to produce highly multiplexed sensor arrays of up to 1000 FBG sensors for quasi-static measurements [9]. Other multiplexing techniques including super-structuring FBG sensors, or monitoring the polarization state of each sensor have also been demonstrated, as reviewed in [10]. Each of these techniques has been demonstrated for a few sensors, however the highly specialized nature of each individual FBG sensor prevents these from being expanded to the fabrication of large sensor networks.

In this paper, we apply the concept of spectral profile division multiplexing (SDM), combined with WDM. SDM is based on each FBG sensor having a distinct reflected spectral shape in the wavelength domain. We assume that each FBG begins with a unique Bragg wavelength, enabling their profile to be characterized. As each FBG can then be uniquely identified by its spectral profile, a distinct wavelength window does not need to be reserved for each sensor. Over the course of the experiment, the Bragg wavelengths of one more sensors can be allowed to overlap. Therefore more FBG sensors can be monitored within the source bandwidth.

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However, the combined WDM–SDM system must be able to treat the case of spectral overlapping between two or more FBG sensors.

We also address the issue of scalability of the multiplexing approach to a large number of sensors by varying the length of each FBG while keeping the other writing parameters the same. This technique could also be easily implemented into draw tower fabrication of FBG sensor arrays [11]. To address the issue of data processing speed, we apply a cross-correlation algorithm to identify the wavelength location of each individual spectrum. While the cross-correlation algorithm produces rapid processing benefits, the approach also produces uncertainties when a significant number of sensors are present. The sources of this uncertainty are due to the small differences in spectral shape, as compared to the noise level, and distortion due to the combined output reflected spectra from multiple FBG sensors overlap in the wavelength domain. A correction factor, based on previous time steps, is therefore added to the cross-correlation algorithm to reduce these uncertainties.

2. Theory

In the combined SDM–WDM approach, each sensor spectral profile is tracked by cross-correlating the measured sensor network output with the reference profile of each individual FBG sensor [12]. The cross-correlation algorithm was chosen to maximize the calculation speed. The cross-correlation algorithm is often applied to identify the peak wavelength location of a single FBG sensor, with high accuracy [13]. Previous researchers have applied evolutionary optimization algorithms to identify the current peak wavelength location of two FBG sensors with distinct spectral profiles [14]. While evolutionary algorithms are good for searching wide, poorly behaved domains, they are not scalable to semi-real time processing of large sensor network data. The computational requirements for evolutionary optimization algorithms increase exponentially with the number of sensors to be identified.

Mathematically the requirements of the cross-correlation calculation increase linearly with the number of FBG sensors. However, the cost of this efficiency is that uncertainties in the wavelength location of each sensor arise due to distortions in the combined spectral shape when the two spectra are located close to one another in the wavelength domain. This distortion depends on how the sensors are multiplexed (i.e. through serial or parallel multiplexing).

2.1. Cross-correlation algorithm

The cross-correlation algorithm calculates the overlap area between a measured FBG spectrum defined by the vector $R'(\lambda_i)$ ($i = 1, 2, 3 \ldots N$), and a reference FBG spectrum, $R(\lambda_i)$, as a function of the relative wavelength shift between the two spectra, $\Delta\lambda$ [13]. λ_i are the wavelengths at which the reflectivity is measured. Outside of this range it is assumed that $R = R' = 0$. The equation for the cross-correlation coefficient is

$$C_j = \sum_{i=1}^{N} R(\lambda_i) R'(\lambda_{j-N+i}) \tag{1}$$

C_j is a vector of length $j = 1, 2, 3, \ldots (2N - 1)$. Eq. (1) assumes that the FBG sensor profile maintains a constant shape while moving through the spectrum. The maximum value of C indicates the location of the FBG in the spectrum. The shift in wavelength between the reference and measured signals can then be expressed as

$$\Delta\lambda = (p - N)\delta\lambda \tag{2}$$

where p is the index of the vector C_j corresponding to the maximum value of C. $\delta\lambda$ is the wavelength resolution of the FBG interrogator. $\Delta\lambda$ can be used to calculate the axial strain applied to the FBG sensor, ϵ,

$$\epsilon = \frac{\Delta\lambda_B}{\lambda_B(1 - p_e)} \tag{3}$$

where p_e is the optical fiber photoelastic constant for axial strain and λ_B is the unloaded Bragg wavelength of the sensor [15].

For multiplexed sensors, the algorithm is repeated using the reference spectrum for each FBG. However, a condition of non-uniqueness can exist when a smaller FBG spectral profile can be completely encompassed by a larger FBG profile. In this case, the cross-correlation produces the same result when the smaller FBG profile is overlapped with its own spectra or with the larger FBG profile. Therefore, in this work, the cross-correlation algorithm is first applied to the FBG with the largest area under the reflectivity–wavelength curve. Once the peak location of this FBG has been identified, the spectrum contribution of that FBG is subtracted from the measured spectrum. This reveals the previously hidden, smaller FBG profile. Then the identification is performed for the FBG with the next largest area under the curve and repeated until the peak wavelength of the last FBG has been identified.

3. Simulations

Simulation of a two FBG sensor network was conducted. The FBG profiles in reflection were simulated using the exact solution for the reflected spectrum of an FBG [15],

$$r = \frac{\sinh^2(L\sqrt{\kappa^2 - \hat{\sigma}^2})}{\cosh^2(L\sqrt{\kappa^2 - \hat{\sigma}^2}) - \dfrac{\hat{\sigma}^2}{\kappa^2}} \tag{4}$$

where L is the length of the grating. κ is the AC coupling coefficient and $\hat{\sigma}$ is the DC coupling coefficient, defined as,

$$\kappa = \frac{\pi}{\lambda} \nu \overline{\delta n_{\mathrm{eff}}} \tag{5}$$

$$\hat{\sigma} = \frac{2\pi}{\lambda}(n_{\mathrm{eff}} + \overline{\delta n_{\mathrm{eff}}}) - \frac{\pi}{\Lambda} \tag{6}$$

$\overline{\delta n_{\mathrm{eff}}}$ is the average amplitude of the modulation in the fiber index of refraction and ν is the fringe visibility of the index modulation. Λ is the period of the grating and n_{eff} is the effective index of refraction of the optical fiber fundamental mode.

The total reflectivity, R, was calculated for two FBGs at varying wavelength locations to produce a series of simulated measured spectra. The properties $n_{\mathrm{eff}} = 1.46$, $\delta n_{\mathrm{eff}} = 3 \times 10^{-6}$, $\nu = 1$, $\delta\lambda = 0.1$ pm, $\Lambda = 531$ nm were used for the simulations. The length of FBG 1 was 10 mm and the length of FBG 2 was 12 mm.

The Bragg wavelengths of the two FBG sensors were originally separated by approximately 0.5 nm, well beyond the bandwidth of each reflected spectrum. The initial reflectivities, $r_1(\lambda)$ and $r_2(\lambda)$ were also used as the reference spectra for the cross-correlation algorithm. The Bragg wavelength of FBG 1 was held stationary, while the reflected spectrum of FBG 2 was shifted in the wavelength domain until it was equal to that of FBG 1.

Fig. 1 shows the combined reflected spectrum from the two multiplexed sensors at each simulation step, along with the predicted location of each sensor from the cross-correlation