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Improvements on the cross-correlation algorithm used for tracking fractional Bragg grating wavelength shifts in multimode fibres

Antreas Theodosiou[a,b,*], Michael Komodromos[a], Kyriacos Kalli[b]

[a] Department of Electrical Engineering, Frederick University, Nicosia, Cyprus
[b] Photonics and Optical Sensorsing Research Laboratory, Department of Electrical Engineering, Cyprus University of Technology, Limassol, Cyprus

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ABSTRACT

In this paper we report on the deployment of Finite Impulse Response (FIR) filters as an extension to the common cross-correlation algorithm (CCA), for accurate peak tracking of multimode and single mode fibre Bragg gratings when dealing with wavelength shifts below the sampling resolution of the demodulator; the well-known peak-locking effect. The performance of the common CCA under these conditions was studied using simulations for single and multiple peak grating spectra and was compared with the performance of proposed, improved CCA method. We studied the cases where fibre Bragg gratings are wavelength-shifted with triangular and sinusoidal manner and how the proposed method behaves under these conditions. We experimentally evaluated our proposed method by utilising strain measurements using a fibre Bragg grating inscribed in a multimode gradient index CYTOP polymer fibre. The method and algorithm showed significant improvement concerning the peak-locking effect, while maintaining the response speed.

1. Introduction

Over the years, fibre Bragg gratings have been applied and tested for a wide range of sensing applications. The working principle of fibre Bragg grating (FBG) sensors is based on tracking the FBG wavelength peak that undergoes shifts following exposure to external parameters, such as temperature, strain, pressure etc. applied to the grating [1–3]. The cost of fibre and sensor production is relatively low; however, the cost of the entire sensing system, such as the light sources and the interrogation devices are still quite expensive, particularly in situations where high accuracy is required in terms of optical resolution. One approach to minimise costs and at the same time maintain a highly accurate FBG interrogation system, is to combine low optical resolution spectrometers with suitable demodulation algorithms.

Using these algorithms, the new FBG spectrum is compared to the reference FBG spectrum and the wavelength correlation between them is extracted using fitting methods, Hilbert Transformation, Fourier Transform etc. [2,4–6]. In this way, the spectrum recovered with the medium optical resolution spectrum is post-processed and the wavelength shift of the Bragg grating is extracted computationally with much higher accuracy. A general schematic diagram of this procedure is represented in Fig. 1. Small changes among various algorithms may exist but the general concept follows the one represented in the corresponding diagram.

All demodulation algorithms are more or less susceptible to two main issues, the peak-locking effect and distortion of the FBG profile shape [7–9]. The peak-locking effect is related to the optical sampling resolution of the device. More specifically, if the maximum peak of the FBG is located somewhere between two sampling points, say p_1 and p_2, then the device will read that the FBG peak is located at p_1 if its real position is closer to the p_1 and at p_2 if it is closer to p_2. As a result, the interrogation system always contributes a systematic measurement error, which can be minimised using the demodulation algorithms.

The second issue relates to the profile of the FBG spectrum. If the FBG sensors are used for measurements in harsh environments then distortions on their profile may occur and as a result, demodulation algorithms that use fitting techniques are more susceptible to higher errors. Moreover, in the same manner, a distortion on the FBG profile may occur when FBG sensors contain multiple peaks [10,11]. An essential issue is the computation speed of the demodulation algorithms. This is critical for some applications where the dynamic response and real-time measurements are important [1,12–14].

Most of proposed demodulation algorithms have been tested and evaluated only with single peak FBGs, inscribed in single mode fibres, while only a few of them have been characterised with complicated FBG spectra. A classic case of complicated FBG profiles results from gratings inscribed in multimode (MM) or few-mode fibres [2,11,15]. Conventional inscription methods induce index changes across the

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[*] Corresponding author at: Department of Electrical Engineering, Frederick University, Nicosia, Cyprus.
E-mail address: theodosiou.antreas@gmail.com (A. Theodosiou).

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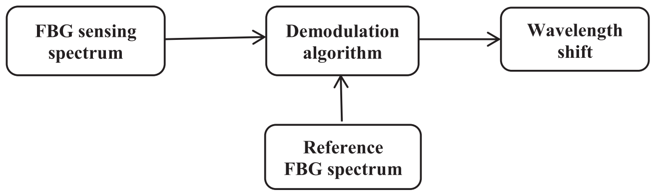

Fig. 1. General schematic diagram of the FBG tracking through post processing of the spectrum through demodulation algorithms.

whole core of the MM-fibre and thus we have the excitation of various propagation modes supported by the fibres. The excitation of higher order modes are detected as multiple peaks in the reflection and transmission spectra and this in turn can significantly complicate the interrogation process. This issue becomes more significant if one considers the increased interest demonstrated during the past few years in manufacturing optical fibres for sensing applications using alternative materials, such as with different polymer optical fibres [16,17].

Lim et al. [18] successfully used correlation signal processing to measure the strain and thermal response of FBGs inscribed in silica multimode (MM) fibres. They reported a reduction in the variation of the recovered signal amplitude and shape of the MM-FBG wavelength spectrum and a general reduction in noise. However, the main drawback of correlation processing is its inefficiency in dealing effectively with the peak-locking effect.

In this paper, we present a simple method to minimise the peak-locking effect of the cross-correlation algorithm (CCA) and enhance its capabilities when dealing with wavelength shifts below to the sampling resolution of the interrogation device. First, we investigate the case of the peak-locking effect using simulated spectra (evaluated with coupled-mode theory) for both single peak and multimode spectra. We consider the cases where the wavelength of the fibre Bragg grating with triangular and sinusoidal profiles are dynamically shifted and we evaluate how the proposed method behaves under these conditions. Finally, we experimentally measure the wavelength shift of multiple-peak FBG inscribed in a multimode gradient-index polymer CYTOP fibre when axial strain applied.

The paper is structured as follows. In section II we introduce the principles and the basic equations of the common CCA and the proposed algorithm. Section III discusses the details of the simulation details for the multiple peak and single peak FBGs, describing also the method used to shift the simulated FBGs with triangular and sinusoidal profile and the comparison of the common CCA results with the proposed method. Finally, section IV describes the experiment of using a multimode gradient index perfluorinated polymer fibre with multiple peak spectrum as a strain sensor to evaluate our proposed method.

2. Demodulation algorithms

2.1. Principles of the common CCA

The CCA is commonly used for measuring the similarity between two signals, as a function of the lag of one relative to the other. In the case of FBG sensing, the CCA measures the similarity of two spectra as a function of wavelength shift. The correlation processing was first adapted and used as a demodulation algorithm in 2007 by Huang et al. [1]. Their algorithm used an undisturbed FBG spectrum as a reference spectrum, denoted as $R(\lambda_i)$, that was recorded as an N-sample array for $i = 1, 2, \ldots (N-1)$ where,

$$N = \frac{\lambda_{max} - \lambda_{min}}{d\lambda}, \tag{1}$$

while $\lambda_{max} - \lambda_{min}$ represents the scanning range of the interrogation device and $d\lambda$ is the wavelength sampling interval. When a perturbation is detected by the FBG sensors due to an external temperature variation or a strain imposed on the grating, the spectrum is shifted and is recorded as $R'(\lambda_i)$, $for\ i = 1, 2, \ldots, (N-1)$. We can also write $R'(\lambda_i)$ as

$$R'(\lambda_i) = R(\lambda_i - \Delta\lambda), \tag{2}$$

where $\Delta\lambda$ is the wavelength shift between the reference and the perturbed spectrum. The wavelength shift between a reference spectrum and the perturbed spectrum is calculated using the cross-correlation productC_j as,

$$C_j = \sum_{i=0}^{N-1} R(\lambda_i) R'(\lambda_{i+j}), \tag{3}$$

for $j = 0, 1, 2, \ldots, (2N-1)$ and $C_j$is an output sequence containing 2 N-1 samples. By applying the equation below, the wavelength shift $\Delta\lambda_{CCA}$ of the grating is extracted [4],

$$\Delta\lambda_{\mathrm{CCA}} = (\mathrm{p} - \mathrm{N}) d\lambda, \tag{4}$$

$$\lambda_B = \lambda_R + \Delta\lambda_{\mathrm{CCA}}, \tag{5}$$

where p is the x-coordinate index of the centre peak of reference spectrum λ_R, $\Delta\lambda_{\mathrm{CCA}}$ is the wavelength variation of the FBG as calculated with the CCA and λ_B is the perturbed Bragg wavelength.

2.2. Improved CCA algorithm

Our proposed method is based on the use of an averaging finite impulse response (FIR) filter applied on the output of the common CCA. In general, a moving average filter achieves the smoothing of the data by replacing each data point with the average of a number of neighbouring data points. This process is equivalent to low-pass filtering of the data and can be implemented using the difference equation describing the FIR filter. At any given time, the last M outputs of the common CCA are used as input to the smoothing filter. The proposed FIR filter behaves as a moving average FIR smoothing filter and its difference equation can be expressed as,

$$y(n) = \frac{1}{M} \sum_{i=0}^{M-1} x(n-i), \tag{6}$$

where y(n) and $x(n-i)$ are the output and the input of the FIR system and M is the order of the moving average filter. The wavelength shift, Δλ is calculated through the common CCA and is stored in an array of length M, with n corresponding to the current value, as shown in Eq. (6). The required length of the array depends on the degree of the FIR filter M, as expressed in equations below,

$$\Delta\lambda_{CCA} = \begin{bmatrix} \Delta\lambda_{\mathrm{CCA}}(n) \\ \Delta\lambda_{\mathrm{CCA}}(n-1) \\ \cdots \\ \Delta\lambda_{\mathrm{CCA}}(n-M) \end{bmatrix} \tag{7}$$

$$\Delta\lambda_{\mathrm{FIR}} = \frac{1}{\mathrm{M}} [\Delta\lambda_{\mathrm{CCA}}(\mathrm{n}) + \cdots + \Delta\lambda_{\mathrm{CCA}}(\mathrm{n-M})] \tag{8}$$

where $\Delta\lambda_{CCA}$ is the wavelength shift value calculated by the CCA and $\Delta\lambda_{FIR}$ is the wavelength shift after it is filtered by the FIR filter. At first glance it may appear that this method will be M times slower than the common CCA. However, the moving average filtering process implies that when the first 'M' cross-correlation calculations are completed, the proposed CCA algorithm is waiting for only one value, the present value$\Delta\lambda_{CCA}(n)$ and thus, the running time is almost equal to that of the common CCA. However, a small-time delay will be introduced that depends on the length, M, of the smoothing FIR filter. Note that the improved CCA algorithm is more appropriate to use for dynamic measurements, such as measuring the vibrating response of various engineering structures [1,19,20].