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Advanced signal processing techniques for fibre-optic structural health monitoring

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Abstract— Fibre optic sensors can measure a range of physics and chemical parameters. Some of the more common fibre optic sensors are the fibre Bragg grating (FBG), the long period grating (LPG), the Fabry-Pérot Interferometer (FPI) and various distributed fibre optic sensors based on optical time-domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR). Each of these sensor types utilises different interrogator hardware and signal processing software. The goals of this research are to develop new algorithms for multi-parameter sensing and to improve the sensitivity and resolution of fibre optic sensing by developing new approaches. This is done by stepping back from current algorithms, and considering what additional information is expected to be present in and can be extracted from the signal. Recent publications have shown that advanced signal processing techniques can be used for bend sensing, for damage type classification and to improve the spatial resolution of the sensing. Structural health monitoring requires the measurement of different structural parameters to determine the health of a structure. A commonly used definition of structural health monitoring is "*SHM is the integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be recorded, analysed, localized, and predicted in a way that non-destructive testing (NDT) becomes an integral part of the structure and a material*". From this definition four levels of structural heath monitoring are defined: (1) mechanical and environmental load monitoring, (2) identification and location of damage, (3) damage quantification, and (4) prognosis of residual life. The paper will explore how advanced signal processing techniques can drive the development of multi-parameter sensing with fibre optics, and can lead to the goal of integrated fibre optic sensing system for structural health monitoring applications.

Keywords—fibre optic sensors, signal processing, structural health monitoring, aerospace

I. INTRODUCTION

Fibre optics consist of a silica core, along which the light propagates, a silica cladding of slightly lower refractive index to constrain light within the core and reduce propagation losses and usually an external coating to protect the fibre. A fibre optic sensor acts as a transducer, modifying the light propagating along or reflected from the end of the fibre in response to changes in an external parameter, such as strain, temperature, pressure or refractive index.

Fibre optic sensors generally operate according to the principles of intensity, time-of-flight, interferometry or spectroscopy. Spectral analysis can further be subdivided into spectral changes due to scattering or gratings. The most common fibre optic sensors nowadays are fibre Bragg gratings (FBGs), Fabry-Pérot (F-P) and the Raman, Brillouin and Rayleigh- Backscatter distributed sensing techniques.

The first sensing applications of fibre optics [1] were intensity based, such as loss due to bending or light interacting with external media via evanescent modes, interferometric sensing, or refractive index sensing using optical time domain reflectometry (OTDR). Fibre Bragg gratings were developed in the late 1980's [2] and rapidly developed applications in telecommunications and then sensing [3]. An early design of fibre F-P sensing was reported in 1996 [4]. Later F-P designs included monolithic fabrication of the fibre end [5]. Fibre-optic Raman scattering for thermometry developed in the 1980's [6], with fibre-optic sensing applications using Brillouin scattering developing in the mid 1990's [7,8]. Rayleigh-Backscattering developed first in the 1990's and with continuing research at Luna Technologies Inc. has developed into commercial instrumentation [9,10].

Structural health monitoring (SHM) is the integration of sensing in structures to monitor loading and the presence of damage, with the objective of improving the safety and the scheduling of maintenance [11]. SHM is divided into different levels of monitoring. The initial condition of the structure is important and SHM Level 0 is assessed by considering non-destructive testing (NDT) performed after production, transportation and assembly. SHM Level 1 is the measurement of loads applied to the structure in service, with the objective of checking and recording if the structure operates within its design load. In SHM Level 2, the objective is the detection and localisation of damage. Information from SHM Level 2 monitoring can be used to guide NDT inspectors to a location on the structure for more detailed assessment. SHM Level 3 goes a step further as it aims to quantify the size and type of damage in order to assess the severity of the damage to the structure. SHM Level 4 is based on using models to predict the remaining life of the structure, enabling cost effective maintenance scheduling, without compromising the safety of the structure.

Fibre optic sensors are a competitive technology for Structural Health Monitoring as the sensors are lightweight, can be multiplexed, have multi-functional sensing capabilities, and depending on the technology, the interrogators can be lightweight and compact. Currently FBGs are the most used fibre-optic SHM technology, with F-P being used for specialist applications. Distributed fibre optic sensing are developing for new applications currently, however the interrogators are still too large for weight sensitive applications.

This paper will focus on developing advanced signal processing techniques for FBG sensors as this technology offers the most opportunity for retrofitting to existing structural health monitoring hardware, as well as supporting new SHM installations. The theory of FBGs will be given in Section II of the paper, followed by a discussion of recent developments in signal processing in Sections III to V. Challenges will be discussed in Section VI and Conclusions are presented in Section VII.

II. Background

Fibre Bragg grating are formed by introducing a periodic refractive index modulation into the optical fibre core using ultraviolet laser irradiation and interferometric [2] or phase mask [12] methods. The reflectivity of the grating is controlled by using different laser powers and irradiation times to introduce different magnitudes of refractive index change in the core.

Theoretically, the periodic modulation in the fibre core is a perfect sine wave. The Fourier transform of a sine wave is a delta function, which corresponds with the well-known equation for the wavelength reflectivity of a Bragg grating [13]

$$\lambda_B = 2 n_{eff} \Lambda \tag{1}$$

where λ_B is the reflected Bragg wavelength, n_{eff} is the effective refractive index of the grating and Λ is the grating period.

In practice a Bragg grating does not have an infinite length or a perfectly sinusoidal grading. Hill and Metz (1997) [13] describe the wavelength dependent reflectivity of a Gaussian-apodized Bragg grating as

$$R(\lambda) = j\left[\left(4\pi / \lambda_B\right)\left(\delta n_{eff} - \left(\delta\lambda / \lambda_B\right) - \phi'\right)\right]\rho + j\kappa\left(1+\rho^2\right) \tag{2}$$

where $R(\lambda)$ is the modified reflectivity, λ is the optical wavelength, φ' is the modified phase, ρ is the reflectivity, $\kappa = (\lambda/2)\,\delta n\, g(z)\,\eta$, n is the refractive index, g(z) is an apodisation function and η is the modal overlap factor.

III. Bend Sensing with an FBG

Equation (2) shows that the spectral reflectivity of an unstrained grating depends on factors beyond the effective refactive index and period of the grating. The same is true of a mechanically-loaded grating, as will be demonstrated in this section.

Experimentally, the spectral reflectivity of an FBG is often observed to vary in bandwidth as well as in centre frequency when the specimen is loaded. This provides a challenge for algorithms that detect the peak, as the centre of the peak is less well-defined and may not be present symmetrically in the centre of the reflection bandwidth. For this reason, FBG peak detection algorithms typically use simple curve fitting to three, or more, data points, making them insensitive to changes in the spectral bandwidth. While this makes them robust in the peak detection, they then ignore the additional information present in the reflectivity signal.

Mizutani and Groves (2011) [14] investigated the change in the spectral bandwidth of an FBG adhered to a beam that was loaded to give a bending strain. Consider the measurement of bending strain in a beam by conventional strain gauges. The usual practice is to adhere one strain gauge to the upper surface of the beam, SG_U, and a second strain gauge to the lower surface, SG_L. On the application of a bending load, both the axial and bending strains change. Both SG_U and SG_L measure a combination of bending strain, $\varepsilon_{bending}$, and axial strain, ε_{axial}, according to

$$\varepsilon_{bending} = \varepsilon_{SGU} - \varepsilon_{SGL} \tag{3}$$

$$\varepsilon_{axial} = (\varepsilon_{SGU} + \varepsilon_{SGL})/2 \tag{4}$$

An FBG offers the opportunity to measure both axial strain and bending strain from a single FBG. First this was performed empirically by calibrating the FBG axial and bending strain response experimentally. The obtained results could be reproduced by considering the following theoretical approach, where the deflection of the beam is described by

$$\varepsilon(x) = (3h\delta/2L^3)x \tag{5}$$

where $\varepsilon(x)$ is the strain at position x, h is the thickness of the beam, δ is the deflection and L is the length of the beam, see Fig. 1.

The refection spectra, $F(\alpha)$, is given by

$$F(\alpha) = \exp(-4\ln 2[\alpha-\{(1-P_e)\varepsilon(x)+1\}\lambda_B]2c^{-2}]dx \tag{6}$$

where α is the optical wavelength, P_e is the photoelastic constant and c is the speed of light. The bending strain is obtained by iteratively applying equation (6) to the FBG spectral intensity distribution. It should be noted that the direction of the bending, upwards or downwards, cannot be determined. Results show the trend in comparing linear strain measurements, with scatter, from a 4-point bending test with those from a cantilever beam, see Fig. 2.

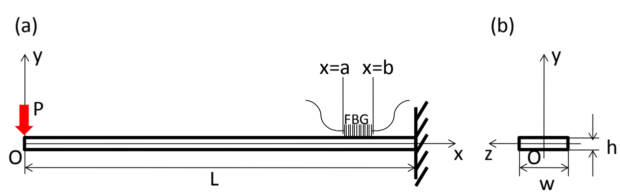


Fig. 1. The beam has length, L, width, w, and thickness, h. The FBG position on the beam is from x=a to x=b, where b-a is the gauge length of the FBG sensor [14].

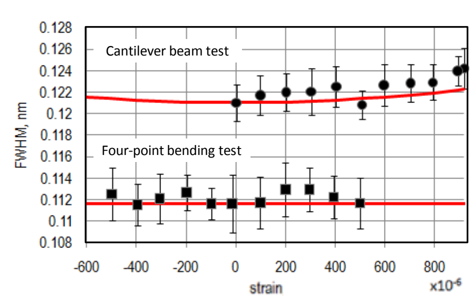


Fig. 2. Calculated FWHM by the proposed equation and measured FWHM at different strain levels. [14].

Although the technique above was successfully calibrated for measuring bending strain, it was not able to resolve the linear distribution of the strain along the grating. This topic is investigated in the next section.

IV. Distributed Strain Sensing with an FBG

In many structures, the strain experienced over the length of a Bragg grating is not expected to be constant, either due to the loading applied, or discontinuities in the material. This is particularly important when considering composite materials, which can contain distributed matrix cracking and delamination damage.

One approach is to consider the fibre Bragg grating as a series of shorter gratings each with their own spectral reflectivity, based on the local strain. Instead of iterating the FBG reflection intensity spectra to match a specific loading case, as was done in Section III, in the paper by Rajabzadeh et al. (2017) [15], the spectral intensity distribution was used as input to a transfer matrix model (TMM) which is solved iteratively to reconstruct the forward and backward propagating modes at each element. The procedure is as follows.

The forward and backward propagating modes at element i, A_i and B_i, respectively are given by

$$\begin{pmatrix} A_i \\ B_i \end{pmatrix} = F_i \begin{pmatrix} A_{i-1} \\ B_{i-1} \end{pmatrix} \tag{7}$$

where

$$F_i = \begin{pmatrix} \cosh(\gamma\Delta z) - j\dfrac{\Delta\beta}{\gamma}\sinh(\gamma\Delta z) & -j\dfrac{\kappa}{\gamma}\sinh(\gamma\Delta z) \\ j\dfrac{\kappa}{\gamma}\sinh(\gamma\Delta z) & \cosh(\gamma\Delta z) + j\dfrac{\Delta\beta}{\gamma}\sinh(\gamma\Delta z) \end{pmatrix} \tag{8}$$

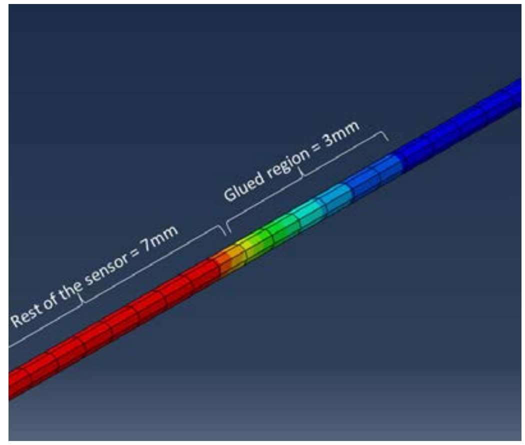
and κ is the coupling coefficient between forward and backward waves, $\Delta\beta=2\eta_{eff}(\lambda^{-1}-\lambda_B^{-1})$ is the difference between the backward and forward propagating constants in the axial direction and $\gamma=\sqrt{(\kappa^2-\Delta\beta^2)}$. To compute the forward and backward wave propagation through the FBG sensor, the elements are combined as

$$\begin{pmatrix} A_m \\ B_m \end{pmatrix} = F_M \cdot F_{M-1} \ldots F_2 \cdot F_1 \begin{pmatrix} A_0 \\ B_0 \end{pmatrix} \tag{9}$$

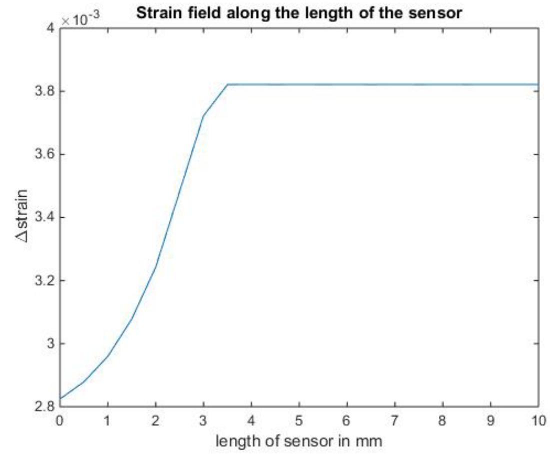
Finally the spectral reflectivity, $R(\lambda)$, can be calculated from the ratio of the squares of the amplitudes

$$R(\lambda) = \left| \frac{A_M}{B_M} \right|^2 \tag{10}$$

The strain along the FBG is shown in Fig. 3 and simulated and experimental reflection spectra are compared in Fig. 4.



(a)



(b)

Fig. 3. Finite element modelling of the optical fibre for the grating region (a) and the resulting strain distribution along its length (b) for the case of 3mm adhesive coverage [15].

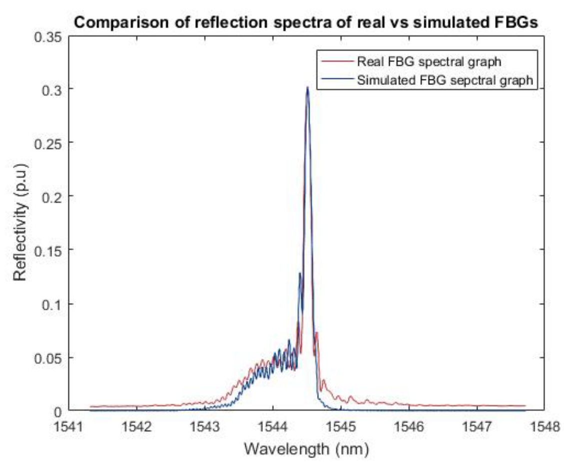


Fig. 4. Reflection spectra for the measured and simulated FBG sensors. Due to the applied stress, there is an approximate of 5 nm wavelength shift on both simulated and measured reflection spectra [15].

V. FIBRE OPTIC SENSORS FOR SHM

The objective of the development of these advanced signal processing algorithms is to support applications in structural health monitoring. As introduced in Section I, load monitoring and damage detection are of particular interest for fibre optic sensors.

Previously FBGs have been used as a direct replacement for strain gauges in load monitoring applications, based on their reduced cabling needs and their multiplexing capabilities. A common design is to have 20 to 50 sensors [16] per optical fibre and for the FBG interrogator to be able to switch between different fibre channels, allowing sequential monitoring of the complete structure. The combination of experimental strain data with finite element models using model-based updating techniques was one of the core themes of the Photomechanics conference, held in Delft in 2015 [17,18]. A related application is shape sensing using FBGs for active control of a structure [19]. The combination of optical fibre strain sensing and model-based updating will be explored in the upcoming SmartX project at TU Delft.

Damage detection using FBGs can be achieved either by real-time monitoring for acoustic emission events [20], by detecting deviations in load carrying capacity [21] or by hotspot monitoring with the fibre optic sensors close to the *potential* damage location [22]. Below the hotspot monitoring case will be considered in more detail.

In recent work by Rajabzadeh et al. (2017) [23], spectral features in the FBG reflection spectra were classified using support vector machines with a quadratic kernel. The FBGs were embedded in unidirectional (UD) glass fibre composite and subjected to mode I and mode II loading.

Support vector machines (SVM) is a classification scheme that aims to find the affine plane where the input data is maximally separated. The vectors between the classification groups are the support vectors [24]. In previous work, mean values of Euclidean or Mahalanobis distances, linear or polynomial kernel functions, and Radial Basis Functions (RBF) were investigated [25]. In [26] a quadratic kernel was used to map the feature set to a higher dimension, where it is hoped that the data is linearly separable. For data of the form

$$(x_1,y_1), (x_2,y_2), \ldots (x_n,y_n) \quad (11)$$

the following hyperplane is defined

$$f(x)=w^T x+b \quad (12)$$

where w^T is the weight vector and b is the offset vector. Applying the kernel function to the hyperplane results in

$$f(x)=w^T \Phi(x)+b \quad (13)$$

$$\text{where } \Phi=K(x,x')=(x,x'+1)^2 \quad (14)$$

Results from the classification showed that SVM with a quadratic kernel was able to correctly classify 92.7% for the fatigue load case and 93.8% for the static load case, see Fig. 5.

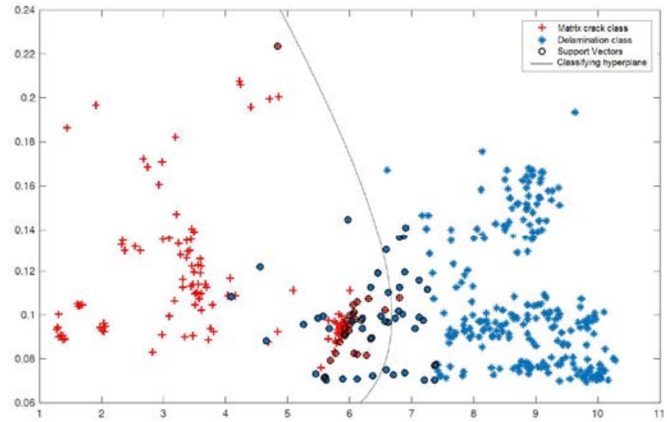


Fig. 5. Classification result of the two classes, based on two of the best features in wavelet domain [23].

VI. CHALLENGES

One of the challenges for fibre optic signal processing is to connect the sensor output, the spectral reflectivity in the case of an FBG sensor, to the actual decision making process in the maintenance, repair and operations (MRO) of structures. Two approaches are commonly used, physics based and data driven models [26]. Physics based models range from analytical models of processes to complex finite element models and there is increasingly a trend towards developing digital twins [27]. Data driven models depend on stochastic methods [28], probabilistic models such as Bayesian [29], and machine learning approaches [30], such as artificial neural networks (ANN), genetic algorithms, and classification schemes such as SVM presented in the previous section. Physics-based models are difficult to develop, sometimes requiring the effort of an academic career to develop a well-understood model. In data driven approaches, care must be taken in separating correlation and causality, however the models are much simpler to develop if sufficient data, and quality of data, are available. Between these approaches are the hybrid models [31], which use building block elements of physics-based models and combine them with data driven approaches. The challenges for this hybrid approach is in the design of the hybrid model and in developing the needed cross-disciplinary skills in mechanics and signal processing.

Fibre optic sensors have some well-known practical issues, including sensor integration, reliability, repair and maintenance of the sensor network, and overcoming certification issues in some industries, such as aviation. One of the advantages of focussing on the direction presented in this paper, the development of advanced signal processing techniques, is that this software processing can be retrofitted to existing fibre optics sensor hardware. This also allows benchmarking of the new algorithms with existing algorithms. Over time this approach should result in the generation of new knowledge about the design of sensor networks which will enable optimisations in the hardware design and the efficiency of monitoring systems.

VII. CONCLUSIONS

In conclusion this paper has shown that there are advances to be gained by focussing on the development of new signal processing algorithms for fibre optic sensors. Approaches demonstrating both physics-based models of the wave propagation in the fibre optic and data driven methods using Support Vector Machines have been demonstrated. In future it is expected that the approach shown in the paper will first lead to retrofitting of advanced signal processing techniques for existing fibre optics sensor hardware, followed by advances in the design of fibre optic sensor networks.

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