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The Study of the Directional Sensitivity of Fiber Bragg Gratings for Acoustic Emission Measurements

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Abstract

Structural health monitoring (SHM) of engineering structures plays a crucial role in ensuring their safety and integrity. Acoustic emissions (AE) can be one of the several ways to monitor the structural health. Fiber Bragg grating (FBG)-based AE measurement technique is emerging as a solution to assess cracks in structures remotely and has advantages of being less bulky and having low noise, high bandwidth and ease of implementation. This paper presents a study on the impact of AE signals on FBGs attached to a substrate, focusing on the directional sensitivity using different configurations. For ease of installation, the FBG sensors are metallically packaged similar to lead zirconium titanate (PZT) sensors in which they can withstand temperatures of up to 250 °C. The directional AE sensitivity of the packaged FBG sensor device is studied and compared with that of a surface attached FBG. Experimentally, the AE signals are generated by a metal ball drop impact on aluminum plate and are measured using an FBG AE interrogation system. A numerical simulation of the design was carried out using ANSYS explicit dynamics and the AE wave propagation in structure was analyzed and experimentally verified.

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The study of the directional sensitivity of fibre Bragg gratings for acoustic emission measurements

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Abstract—Structural health monitoring (SHM) of engineering structures plays a crucial role in ensuring their safety and integrity. Acoustic emissions (AE) can be one of the several ways to monitor the structural health. Fibre Bragg grating (FBG) based AE measurement technique is emerging as a solution to assess cracks in structures remotely and has advantages of being less bulky and having low noise, high bandwidth and ease of implementation. This paper presents a study on the impact of AE signals on FBGs attached to a substrate, focusing on the directional sensitivity using different configurations. For ease of installation, the FBG sensors are metallically packaged similar to lead zirconium titanate (PZT) sensors in which they can withstand temperatures of up to 250 °C. The directional AE sensitivity of the packaged FBG sensor device is studied and compared with that of a surface attached FBG. Experimentally, the AE signals are generated by a metal ball drop impact on aluminium plate and are measured using an FBG AE interrogation system. A numerical simulation of the design was carried out using ANSYS explicit dynamics and the AE wave propagation in structure was analysed and experimentally verified.

Index Terms— Fibre Bragg gratings; Acoustic emission; Structural health monitoring; Directional sensitivity; Packaged sensors.

I. INTRODUCTION

Structural health monitoring (SHM) is a developing research area which helps to discern and depict the damages, assess structural integrity and safety and thereby prevent catastrophic failures in various areas such as aerospace, civil infrastructures and pipeline industries [1]. Damages mainly tend to occur in structures when they are subjected to stress which makes imperfections such as cracks in the material to grow and propagate; this should be monitored. The area of SHM has grown to play a vital role in monitoring defects which remain invisible to the human eye and make the examination difficult [2]. Currently, the most efficient way to monitor is using non-destructive evaluation (NDE). One of the most popular techniques for the NDE is the

technique of Acoustic Emission (AE) which became popular due to its high sensitivity and its capability to reveal any impending failures from within the structure, and it can also be used in real-time monitoring [3–6]. Contemporary standard methods of sensing these emissions use PZT sensors/transducers. However, PZTs are prone to electromagnetic interference, are bulky, provide narrow band response owing to their inherent resonances and cannot monitor crack nucleation and propagation [7]. Optical fibre sensors (OFS) are appropriate for sensing high frequency AE as they have high sensitivity and higher bandwidth and can respond to surface displacement of strain in the sub pico-meter range, which is considered as a major challenge. Among the different types of OFSs, the fibre Bragg gratings (FBGs) are one of the most commonly used technology for structural health monitoring [8, 9].

The method of AE detection using FBGs is an NDE method in which the basic idea is to use FBG sensors as acoustic receivers. FBG is highly sensitive to AE induced strain in the longitudinal direction compared to that in the transverse direction [10]. As the AE measurement sensitivity of the FBG is direction dependent [11], in practice for most experimental conditions, the FBG sensor might be responding to only a component of the acoustic wave in the axial direction of the FBG. Other factors that affect the acoustic measurement sensitivity of FBG are the gluing material, which affects the strain transfer from the substrate to the optical fibre and also the acoustic impedance of the materials involved. Several studies have been conducted and the authors have propounded the directional sensitivity of the FBGs [12, 13]. Perez et al. demonstrated the AE measurement capability of the FBGs using metallic ball drop [12] and C. Zhang et al. showed that the directional responses of the FBG sensors make them suitable for determining principal strains and the direction of the AE source [13].

Even though the directional sensitivity of standard unpackaged FBG has been demonstrated by other authors [10-13], there are very limited studies conducted on packaged FBGs. In most of the engineering applications, FBGs are typically packaged and the packaging design will affect the propagation and dynamic strain transfer from the structure/substrate to the FBG. In this paper, we investigate the use of FBGs for directional detection of AE using packaged and unpackaged sensors, in a view towards its implementation in practical

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applications such as pipeline monitoring. Using FBGs for AE detection facilitates accurate localisation of the source of the imperfection through the directional sensitivity characteristics. Also to help in the design of suitable packaging, we have developed a numerical FE model of AE propagation in metallic packaged FBGs.

The directional response of the FBGs to AEs is studied by generating AE waves in a substrate using metal ball impact and detecting them using a commercial FBG AE interrogation system. Design and construction of the packaged sensor and the FEM modelling of the directional sensitivity of FBG are carried out using ANSYS explicit dynamics. It is anticipated that the results presented in the paper will provide further insights to engineers working in the implementation of FBG sensors in applications such as welding and pipelines for crack detection.

II. BACKGROUND AND OPERATING PRINCIPLE

An FBG comprises a short section of single-mode optical fibre in which the core refractive index is periodically and spatially modulated using an intense optical interference pattern typically at UV wavelengths [14]. This periodic index modulated structure enables the light to be coupled from the forward propagating core mode into the backward propagating core mode, generating a reflection response λ_B that is given by

$$\lambda_B = 2n_{eff}\Lambda, \quad (1)$$

where Λ is the grating period and n_{eff} is effective refractive index of the fibre.

The basic principle of operation of any FBG-based sensor system is to monitor the shift in the reflected wavelength due to changes in measurands such as strain, pressure or temperature. When an acoustic wave impinges on an optical fibre with an FBG, the refractive index of the fibre and the FBG period are modulated due to the acoustic wave-induced mechanical strain in the fibre through the elasto-optic effect [15]. The dynamic wavelength shift, corresponding to the acoustic signal-induced strain $\Delta\epsilon(z, t)$ can be written as

$$\Delta\lambda_B = \lambda_B(1 - p_\alpha)\Delta\epsilon(z, t) \quad (2)$$

where $\Delta\epsilon$ is the induced dynamic strain and p_α is the photo-elastic coefficient, z is the axial direction along which longitudinal strain propagates and t is the time.

In a simple case, a Gaussian strain field generated by the acoustic emission wave along the FBG axis can be represented as,

$$\epsilon(z, t) = \epsilon_m \cdot e^{-\frac{(t-t_0)^2}{a^2}} \sin\left(\frac{2\pi}{\lambda}z - 2\pi f t\right), \quad z \in (0, l) \quad (3)$$

where ϵ_m is the strain field displacement amplitude, t_0 is the arriving time, λ and f denote the wavelength and frequency of acoustic emission waves and l is the FBG gauge length [16].

To measure an AE induced strain wave an FBG interrogation system will typically need sub-micro wavelength resolution and high frequency measurement capability. Standard spectrum interrogation methods utilising an optical spectrum analyser (OSA) or other commercial interrogation systems with low resolution, low strain sensitivity and low data acquisition rate cannot satisfy the requirements of accurate detection of dynamic variations of FBG's central wavelength induced by AE events. Therefore, it is crucial to find an FBG interrogation method with high resolution and high data acquisition speed [17]. In this research, a commercial fibre optic acoustic emission sensor (FAESense, Rodendo Optics Ltd) system having the ability to interrogate multiple FBG sensors sensitive to acoustic events that induce nano level strains was used, having a maximum frequency measurement capability of up to 1.16 MHz and the 3-dB frequency range up to 100 kHz. This AE interrogator operation is based on adaptive two-wave mixing (TWM) interferometry [18]. The correlation between the dynamic wavelength shift and relative phase shift induced by then unbalanced interferometer within the interrogator is given by,

$$\Delta\lambda_B(z, t) = \Delta\phi(z, t)\lambda_B^2 / 2\pi nd, \quad (4)$$

where d is the optical path length difference of the TWM interferometer, λ_B is the peak reflected wavelength of the FBG, $\Delta\lambda_B$ is the dynamic wavelength shift and $\Delta\phi$ is the relative phase shift.

III. SENSOR DESIGN, FABRICATION AND FINITE ELEMENT ANALYSIS

As the unpackaged FBG sensor is quite fragile and easily damaged, it requires sufficient protection to be used for SHM applications [19, 20]. Hence, adequate packaging of the FBG is required for practical applications. In this work, a metal-packaged FBG is considered which can be used in high temperature applications such as crack monitoring in welding applications and in pipeline monitoring. In such applications, directional sensitivity of the sensor significantly impacts the identification of cracks. FBG, due of its directional property, selectively responds to different modes of propagating acoustic waves in the structure depending on their orientations. FBGs placed with different orientations are found to be sensitive to different modes of acoustic wave propagation [12]. To provide more clarification on these aspects for practical applications, the directional sensitivity of a metallic-packaged FBG and unpackaged FBG sensors are studied and quantified. The design and construction of a metallic-packaged FBG and a ball drop model to generate an AE wave on the packaged and unpackaged FBGs are presented and analysed in this section.

A. Design and construction of the packaged sensor

Considering the SHM application, the packaging for the sensor is designed with a stainless steel base and the FBG sensor is embedded in melted tin within the mould. The

stainless steel square base is machined having sides of 25 mm each and a thickness of 3 mm and a hollow region in the middle to accommodate the tin plate as shown in Fig. 1(a) and Fig. 1(b), respectively. A hole of 1 mm diameter is drilled through the side walls of the stainless steel base to insert the FBGs. The FBGs used in this work are 3 mm long with polyimide buffer coating and with peak reflected wavelengths of circa 1550 nm, peak reflectivity greater than 70% and a bandwidth of <0.5 nm. FBGs are inserted through the holes in the stainless steel base and the tin plate is placed on the top of the inserted FBG and is heated to a temperature of 270 °C which is higher than the melting point (232 °C) of tin [20]. This is to ensure that the tin has melted and been evenly distributed within the steel base. Thereafter, the entire assembly is allowed to cool down to room temperature. The final assembly after the fabrication is shown in Fig. 1(c).

Figure 1. The parts of the packaged sensor: (a) stainless steel base with FBG, (b) tin plate; (c) the packaged sensor after heating

B. Finite Element analysis model of the AE event

This section describes the modelling approach for impact-generated acoustic wave propagation in an aluminium plate with packaged and unpackaged FBG attached to it. The numerical simulation of the aluminium plate impacted by a metal ball was performed using ANSYS 16.1 explicit dynamics. Using sketching options, an aluminium plate was modelled as a square of dimensions 220 x 220 x 3mm and 2 circles of diameter 100 mm and 200 mm were drawn from its centre to mark the points of impact. A new plane was chosen at a height of 230 mm and the metal balls were modelled.

In order to detect the impact of the ball drop, unpackaged FBG sensors were modelled as a silica cylinder with length 10 mm and diameter 125 μm and was assumed bonded on to the substrate using cyanoacrylate adhesive. For the packaged FBG sensor, stainless steel and tin for encapsulating the FBG were modelled according to the dimensions described in Section

3(A), and the corresponding material properties provided in Table 1 were assigned to them. Finally, a cylinder, as mentioned above, was also modelled at the centre of the stainless steel structure to represent the silica fibre. These structures were combined into a single part to ensure that it acts as a standalone structure which was attached to the substrate. The schematics of the modelled substrate with the unpackaged and packaged FBG's are shown in Fig. 2(a) and Fig. 2(b), respectively.

TABLE I
MATERIAL PROPERTIES USED FOR FEM MODELLING

Material	Usage	Density (Kg m ⁻³)	Young's modulus (GPa)	Poisson's Ratio	Tensile yield strength (GPa)	Compressive yield strength (GPa)
Aluminium	Substrate	2770	71	0.33	0.28	0.28
Optical fibre	FBGs	2650	70	0.15	0.231	0.04
Stainless steel	Metal Ball	7750	191	0.31	0.207	0.586
Tin	Packaging	7287	45	0.33	0.220	0.015
Cyano acrylate	Adhesive	1090	1.34	0.33	0.014	0.005

Figure 2: The schematic of aluminium substrate with the metal ball which was modelled in ANSYS geometry for (a): unpackaged FBG sensors, (b) packaged FBG sensors

A metallic ball drop was selected to create an impact on the substrate and to generate the AE signal. In order to model the impact, the velocity (v) of the metallic ball determined by the principle of conservation of energy by equating the kinetic energy to the potential energy is considered as follows,

$$v = \sqrt{2gh}, \quad (5)$$

where g is the gravitational force acting on the metallic ball and h is the height from which the ball is dropped. In the experiment, the ball was dropped from a height of 230 mm; therefore, the same height was considered in the simulation as well. The velocity calculated was 2.123 m/s and this was considered as the initial velocity and was made to act along the negative z-axis towards the aluminium plate. The mesh size used for the simulation was 4 mm in the solver which provides a total of 7000 elements in the mesh. The analysis time was calculated in such a way that there was still adequate time after the impact of the ball on the substrate for it to

bounce back if required. In order to simulate AE events of different amplitude and frequency, different ball sizes (6 mm and 12 mm) were used, and to study the damping of the AE signal through the substrate, the distance of impact from the centre of the FBG was set as 50 mm and 100 mm.

C. Analysis of the AE wave through the substrate

The equivalent elastic strain induced by the acoustic waves detected by the packaged and unpackaged FBG was calculated for the 6 mm and 12 mm ball drop impacts at distances of 50 mm and 100 mm from the FBG. The profile for the propagation of the AE waves through the substrate and packaged and unpackaged sensors was determined. For the 12 mm ball's impact on substrate at a distance of 50 mm away from the unpackaged FBG and packaged FBG, the strains obtained were 39.93 $\mu\epsilon$ and 16.72 $\mu\epsilon$, respectively. The acoustic wave propagating through the aluminium plate is shown in Fig. 3 (a) and Fig. 3 (b) from which the frequencies of the impact of the balls were determined; they were 16.7 kHz for the 6 mm ball drop and 21.4 kHz for the 12 mm ball drop impacts. The simulation was repeated for various points from 0° till 180° and the plots for the dependence of the strain on the angle of the applied impact was obtained for each of the two metal balls for the unpackaged and packaged sensors at distances of 50 mm and 100 mm as shown in Fig. 4(a) and Fig. 4(b), respectively. From the plots, we can observe that the

(a)

(b)

Figure 3: The propagation of the AE wave through the substrate at (a) 60 μs , (b) 120 μs .

sensitivity was the highest for 0° and 180° and was the lowest for the force applied at 90°, thus proving the directional dependence of the FBG. From the results for the unpackaged FBG, it can be observed that the strain observed with the 12 mm ball impact at 50 mm is 17.29% higher than the impact at 100 mm distance, while for the 6 mm ball impact, the difference is 12.24%. For the same impact distance of 50 mm, the 12 mm ball impact-induced strain was 24.34% higher than that of the 6 mm ball, and similarly for 100 mm impact distance, the differences in the strains induced by the 12 mm and 6 mm balls was 25%.

(a)

(b)

Figure 4: The directional sensitivity obtained for (a) the unpackaged FBG sensor, (b) Packaged FBG sensors

With packaged sensors, the strain was 18% higher at 50 mm distance when compared to 100 mm for 12 mm ball and 44% higher for 6 mm ball at 50 mm distance. For impact distances of 50 mm and 100 mm, the change in strain induced for the 12 mm ball was observed to be 44% and 60% higher, respectively. When the ball size varies from 12 mm to 6 mm or the impact location varies from 50 mm to 100 mm, it is observed that the amplitude drops because the amplitude and the distance of the impact varies. The frequency remained the same for both the ball sizes.

IV. EXPERIMENTAL STUDY ON THE DIRECTIONAL SENSITIVITY OF PACKAGED AND UNPACKAGED SENSORS

A. Analysis of the AE wave through the substrate

The experimental setup for directional sensitivity is shown in Fig. 5. The experiments were performed on an aluminium plate of the aforementioned dimensions on which the unpackaged FBG sensor (peak reflective wavelength 1550 nm, length 3 mm) is attached using cyanoacrylate adhesive at the centre of the plate. The packaged FBG was attached to the aluminium substrate using silica gel. Metallic balls of size 6 mm and 12 mm were dropped on to the substrate from a height of 230 mm. The height and ball drop impact location on the substrate was also ensured by using a custom-made stand. Metallic balls were made to impact on to the substrate at a distance of 50 mm and 100 mm away from the centre of the FBG. Experiments were conducted for both the packaged and unpackaged FBG sensors using a metallic ball drop method with balls of diameters namely 12 mm and 6 mm at a distance of 50 mm and 100 mm away from the centre of the substrate, and the AE which were generated as a result of the ball drop was obtained using a commercial FBG AE interrogator system.

Figure 5: The experimental arrangement for the metal ball drop test using the FBG AE interrogation system

Though the maximum data acquisition capability of the FAEsense system is 1.167 MHz, in this experiment data was acquired at a sampling rate of 291.7 kHz based on the information from simulation results and also from a PZT AE transducer. Reducing the sampling rate to the required level will significantly reduce the post-processing computing time. A PZT based transducer (B225.5) along with a high-speed oscilloscope (Techtronic DP070604C digital phosphor oscilloscope) was used to measure the frequency of ball drops on the substrate. From this experiment, it was found that the maximum AE frequency of the impact was circa 20 kHz and 30 kHz respectively for the 6 mm and 12 mm balls drops. The measured AE waveform of the 12 mm ball drop using the oscilloscope is shown in Fig 6(a) and the corresponding spectrograph (Short time Fourier Transform, STFT) of the event is shown in Fig 6(b).

The predicted values of frequency calculated by the FEM method is 21.4 kHz and 16.7 kHz for 12 mm and 6 mm ball impacts, respectively. These observed frequencies from the simulation were in accordance with the frequency observed from the transducer. It is comparable with the experimental values and the difference can be attributed to the boundary conditions selected.

(a)

(b)

Figure 6: (a) the AE waves obtained from the 12 mm ball drop using oscilloscope, (b): the corresponding STFT plot

B. Experimental results and discussions

i. Temporal response of the AE wave

The amplitude (in volts) vs. time plot for the ball drop impact of the unpackaged and packaged FBGs are shown in Fig. 7 for different ball sizes and different locations and various time ranges of the amplitude v time plot are synchronised to have the AE events occurring at around similar time. Fig 7(a-d) shows the AE response of the unpackaged FBG for 6 mm and 12 mm balls at 50 mm and 100 mm distances respectively, whereas Fig. 7(e-h) is for the packaged sensor. From the figures, it is observable that the amplitude varies as the ball size is varied from 3 Vpp for the 12 mm ball and 2.8 Vpp for the 6 mm ball for the unpackaged FBG sensors at a distance of 50 mm and 1.1 Vpp for the 12 mm ball drop and 0.5 Vpp for the 6 mm ball drop for packaged sensors at a distance of 50

Figure 7: the amplitude v. time plot containing an AE from the unpackaged sensor with (a) a 6 mm ball 50 mm distance, (b) 6 mm ball 100 mm distance, (c) 12 mm ball 50 mm distance, (d) 12 mm ball at 100 mm distance; with packaged sensor at (e) 6 mm ball 50 mm distance, (f) 6 mm ball at 100 mm distance, (g) 12 mm ball at 50 mm distance, (h) 12 mm ball at 100 mm distance

mm. The interrogator system can only measure and record the data in voltage and conversion of this dynamic voltage change to equivalent strain is not possible as there is no calibration data available as the device was designed for dynamic frequency measurements. The peak for the 6 mm ball drop at a distance of 50 mm and at an angle of 0° is shown in Fig. 7 and the amplitude vs. time plot is shown in Fig 7(a) in which the maximum amplitude is 2.65 V. Selected STFT of the AE events (Fig 7(a) and (c)) are shown in Fig 8 (a and b). The STFT shows that the AE wave has a maximum frequency of 29.7 kHz for 12 mm and 16.3 kHz for 6 mm ball drop impacts. The frequency changes may be due to the increase in size of the ball.

ii. Directional Sensitivity

To understand the directional sensitivity of the packaged and unpackaged sensors, data were analysed for ball drop impacts with different ball sizes and distances at varying angles from 0° to 180° at 30° angle intervals. The results for the case of unpackaged and packaged FBGs are shown in Fig 9(a) and Fig 9(b), respectively. It is observed that the highest peak-to-peak voltage occurs at 0° and 180° at 1.5 V for the 12 mm ball drop at 50 mm and at 2.5Vpp for 6 mm ball drop at 50 mm away from the FBG. It is observed that the sensitivity is highest at 0° and 180° for both 12 mm and 6 mm balls using both sensors with a maximum amplitude of 3 Vpp and 2.5 Vpp, respectively.

Figure 8: the STFT containing an AE from the unpackaged FBG with (a) 12 mm ball 50 mm distance, (b) a 6 mm ball 50 mm distance.

Figure 9: The plot for the directional sensitivity obtained after the ball drop tests with the 12 mm and 6 mm balls (a): unpackaged FBGs, (b): Packaged sensor

It is noteworthy that the AE interrogator measures the amplitude signal in volts and in simulation, it was in micro strain. Therefore to compare the experimental and simulation results, the change in amplitude was compared. The change in voltage measurement using unpackaged FBG was approximately 13% more at 50 mm distance using different ball sizes in both cases during 6 mm and 12 mm metal ball impacts. However, for packaged sensors, the change in the voltage was found to be 25% higher at an impact distance of 50 mm for the 6 mm ball impact and 32% higher at 50 mm distance for the 12 mm ball impact. The percentage increase in voltage for 12 mm ball impact was 21% compared to the 6 mm ball impact at 50 mm impact distance, 23% at 100 mm impact distance using unpackaged FBGs and 50% and 68% higher respectively for packaged sensors. The percentage change in amplitude complies with the percentage change in strain obtained with the simulation as discussed in section 3.4. The data and the STFT spectra obtained from this directional study shows that the frequency of the AE waves obtained is very close to that of studies by other researchers where the impact signal frequency was shown to be around 20 kHz [13]. The plate geometry, edge reflections and source to receiver distances were some of the factors attributing to the change in the intensity of the AE signal

V. CONCLUSIONS

This study was done to investigate the directional sensitivity of the FBG towards AE depending on the incident angle and linear distance. Although many researchers have worked on

the directional sensitivity of FBGs towards acoustic emission, this is the first time the experiments have been conducted with metal-packaged FBG sensors and compared it with unpackaged FBG sensors. The experiments conducted here shows that for the unpackaged sensor the changes in the amplitude was approximately 13% whereas for the packaged sensor it was observed to be 25% at a distance of 50 mm from the sensor. Generation and propagation of the AE wave is demonstrated by FEM. The successful verification of this method supports the view that this metal packaged FBG sensor can be used for monitoring and locating the micro cracks in welding and pipeline monitoring using fibre optic acoustic emission methods. This is a stepping stone to future experiments in source localisation of cracks using FBG arrays. Further modification should be done to increase the measurement frequency range of the FBGs to help crack identification of engineering structures.

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