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SIMULATION OF WAVE PROPAGATION IN REMOTE BONDED FBG SENSORS USING THE SPECTRAL ELEMENT METHOD

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Abstract. *Ultrasonic guided waves (GW) due to their ability to monitor large areas with few sensors, are commonly employed for structural health monitoring (SHM) in aerospace, civil, and mechanical industries. The FBG sensors in the edge filtering setup are re-emerging as a favored technique for GW sensing. The FBG sensors offer embeddability, ability to be multiplexed, small size, and immunity to electric and magnetic fields. To enhance the sensitivity of these sensors, these sensors are deployed in the so-called remote bonding configuration where the optical fiber is bonded to the structure while the FBG sensor is free. This configuration not only enhances the sensitivity but also opens up possibility of self-referencing. In this setup the GW in the structure is coupled to the fiber and converted into fiber modes. These modes propagate along the fiber and then are sensed at the FBG. The conversion of the plate modes to fiber modes is a phenomenon which is still being studied. The effect of the adhesive layer and the material properties of the adhesive on the coupling are still not known. Furthermore the directional nature of this coupling and its marked difference from the directly bonded configuration needs to be studied in detail. For this detailed study a computationally efficient model which captures the physics of the coupling is necessary. Hence, in this research we develop a numerical model based on the spectral element method (SEM) for the modeling of the remote bonded configuration of the FBG. The model comprises four meters long optical fiber bonded to the center of the plate by the adhesive layer and the piezoelectric disc (PZT) used for wave excitation. The ability of the SEM model to capture the effect of the adhesive and the remote bonding as well as the directional nature of the coupling has been studied in this paper. The model is validated with analytical and experimental results. It has been shown that the SEM model captures the physics of the coupling and is computationally more efficient than other methods using conventional finite element software.*

1 INTRODUCTION

The structural health monitoring (SHM) techniques are used in order to track the deterioration of structure caused due to ambient loading, fatigue, corrosion or accidental damage due to impact, tool drop, etc. The SHM techniques allow us to make decisions about the need for maintenance and continued use of the structure. Several different techniques making use of different damage sensitive features have been proposed in literature [1, 2, 3]. The guided waves (GW) based technique are very popular for large plate like structures. They allow us to monitor large areas with relatively few sensors. The GW based SHM has been popular using piezo-ceramic actuators and sensors. But there is an increasing interest in the use of optical fiber sensors utilizing fiber Bragg gratings (FBG). The optical fiber sensors are small in size and weight, are electrically and magnetically immune and may be embedded in the structure as well as multiplexed, thus making them easily scalable for deployment on large structures.

The new trend is to make use of the edge filtering approach to improve the sensitivity of the FBG sensors to GW. The edge filtering approach makes use of amplitude based detection and has been explained in detail in [4, 5, 6]. In addition to using the edge filtering approach, the sensitivity of the FBG sensors for GW can be further enhanced by using them in the remote bonding configuration. The remote bonding configuration has been shown to enhance the sensitivity significantly by Wee et al [7]. The GW propagating in the structure gets coupled into the optical fiber at the location of the adhesive bond. The plate modes are converted into the longitudinal and flexural mode of the fiber and travel along the fiber. The optical fiber acts as an excellent wave guide for the traveling wave and the longitudinal wave can be easily detected at the location of the FBG.

The ability of FBG sensors to be used in remote bonding configuration opens up various opportunities for their application. The remote bonded sensors have been used in the self-referencing configuration for reference free damage detection [8]. The optical fiber may be used as an acoustic coupler and a remote FBG may be useful to measure the propagating wave at different locations using only one FBG sensors [9]. All these opportunities make it imperative that we understand the physics of the coupling of the structure modes into fiber modes. Also the different factors affecting this conversion need to be studied and understood. For this purpose having a calibrated and validated numerical model which captures the physics of the system is very useful. Unfortunately, the numerical modeling of the optical fiber and structure is a very computationally demanding task. The main problem arises due to the high spatial resolution needed for capturing the mode separation in the fiber and the small time step needed to achieve the convergence. Very few researchers have developed numerical models for such a study due to this complexity [10, 11, 12, 13, 14]. Recently, the authors developed an efficient strategy for the modeling of the wave propagation in the fiber using the spectral element method (SEM) [14]. The frequency domain SEM has shown promise due to its ability to work with very large elements (thus reducing the mesh size requirement) but the suitability of the technique for capturing the physics still needs to be investigated. The time domain SEM has been shown to capture the physics of the system for directly bonded FBG sensors. This paper takes the work forward and investigates its suitability for the remote bonding configuration. The study investigates the effect of the adhesive as well as the directionality of the coupling for remotely bonded FBG sensors.

2 The spectral element method

The time-domain SEM, uses the shape function $N = N(\xi)$ interpolated by high-order Jacobi polynomials, such as Chebyshev and Legendre polynomials. Due to the simplicity, the Legendre polynomials [15] are used in this study.

In the SEM, the nodes are distributed non-uniformly in the element, according to the Gauss-Lobatto-Legendre quadrature (GLL). The nodes are located at the roots of the equation:

$$(1-\xi^2)P'_{p-1}(\xi) = 0, \tag{1}$$

where P' is the first derivative of Legendre polynomial of degree $p-1$. The integration weights are given as:

$$w(\xi) = \frac{2}{p(p-1)(P_{p-1}(\xi))^2.} \tag{2}$$

The details of the computation of the weight functions and the roots are provided by the authors in [14]. The convergence in the SEM is already achieved for six nodes per wavelength, while at least fifteen nodes are needed in the classic FEM in which linear shape functions are used [10].

In addition to using the SEM technique, the internal force computations for the elements as parallelized to reduce the computation time. Furthermore a non-matching mesh approach was implemented to reduce the constraints on the meshing of the structure, adhesive and the optical fiber. The parallelization and the non-matching interface approach has been explained in detail in [14].

3 Numerical studies

In order to show that the SEM approach indeed captures the physics of the system and yields equivalent results to numerical studies carried out using conventional FE models, studies were carried out on two different structures.

3.1 Aluminium beam

Firstly, an aluminum beam similar to the one used by Wee et al. [10] with dimensions $70 \times 1 \times 0.1$ mm^3 was modelled along with an optical fiber 125 μm diameter and length 160 mm. The adhesive layer too was modelled and different thickness and material properties were studied. Two FBGs of 10 mm length were assumed at 60 mm and 85 mm from one of the ends. The fist grating was coincident with the beam edge and was applied the adhesive (direct bond) while the other FBG was in remote configuration.

The fiber and beam were modeled with 3D spectral elements with the number of nodes $5 \times 5 \times 8$ for the fiber and $7 \times 3 \times 8$ for the beam respectively. Five elements were used to discretize cross-section of fiber, as it is shown in Fig. 1. In the sub MHz range only the flexural (F) and longitudinal (L) waves can propagate in the fiber. While the wavelength of the F_{11} mode at frequency 1 MHz is 3 mm, the mesh satisfied at least eight nodes per wavelength. The time increment of the simulation required is less than 5e-10 s for the convergence of the equation of motion. It should be mentioned that the time step in the proposed algorithm was 1e-10 s, while the one for the paper by Wee et al. was of the order of 2.5e-8 s. Such a small value of the time step is due to the Courant-Friedrichs-Lewy convergence condition, which depends on the size of the spectral element and the velocity of the wave propagated in the structure. Run time of the simulation performed on the workstation was of the order of 3 minutes.

The waterfall plot for the z displacement along the optical fiber with time for the scenario with modeled adhesive and without the adhesive are shown in Figure 2. The wave crest maximas may be used to calculate the group and phase velocities of the longitudinal and flexural modes propagating in the fiber and are shown to be comparable to the analytical velocities. This shows that indeed the SEM based approach can capture the conversion and the propagation of the wave along the fiber comparable to the conventional FE approach.

The shear lag effect is seen in the region where the FBG is bonded to the structure. The sensor in remote bonded configuration does not experience the shear lag effect. As a result the remote bonded configuration shows a higher amplitude than the directly bonded sensor. This can be shown in Figure 3.

It can be concluded that indeed the physics of the coupling of the wave to the fiber is captured accurately by the SEM model. Also, the effect of the adhesive bond and the difference in the response shown by the FBG in remote and directly bonded configuration is reflected well in the study.

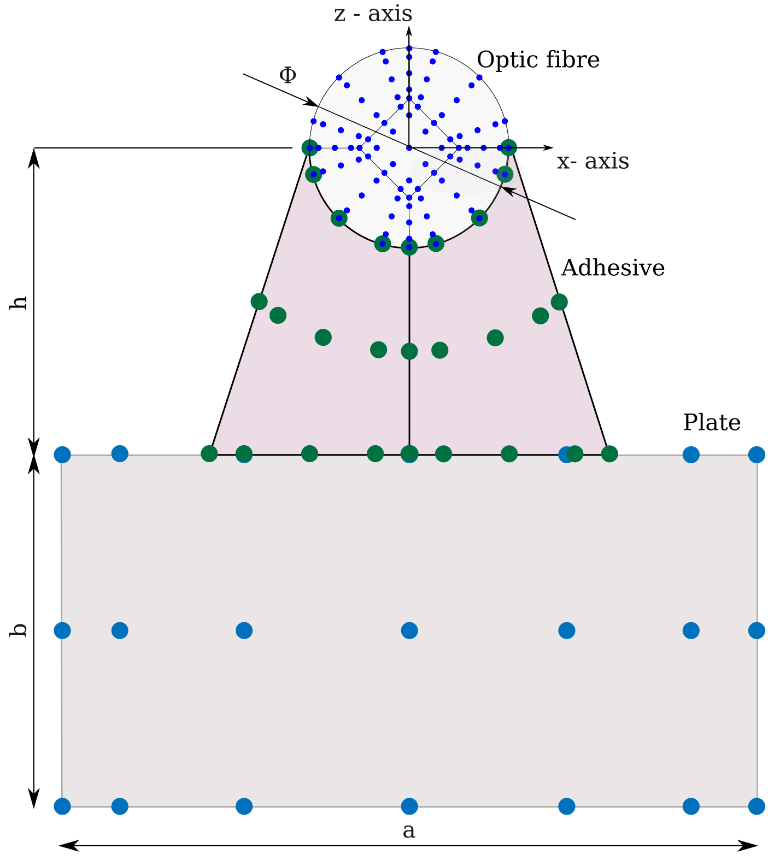

Figure 1: In-plane mesh of the optic fiber of diameter $\Phi = 125\ \mu$m and the beam of $a = 1$ mm, $b = 0.1$ mm and adhesive with $h = 250\ \mu$m

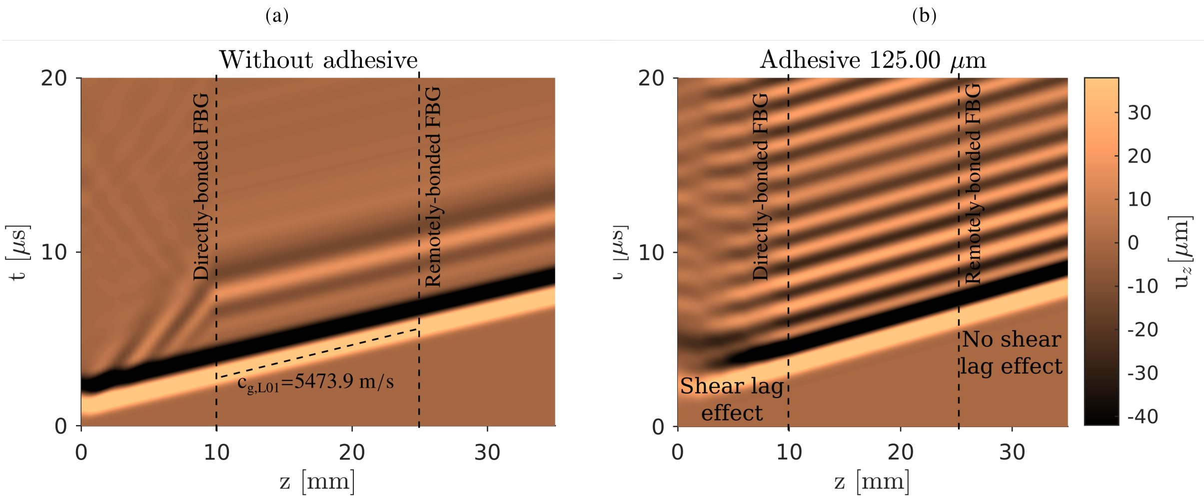

Figure 2: Displacements of particles of the optical fiber axis in z-direction with time a) with adhesive and b) without adhesive

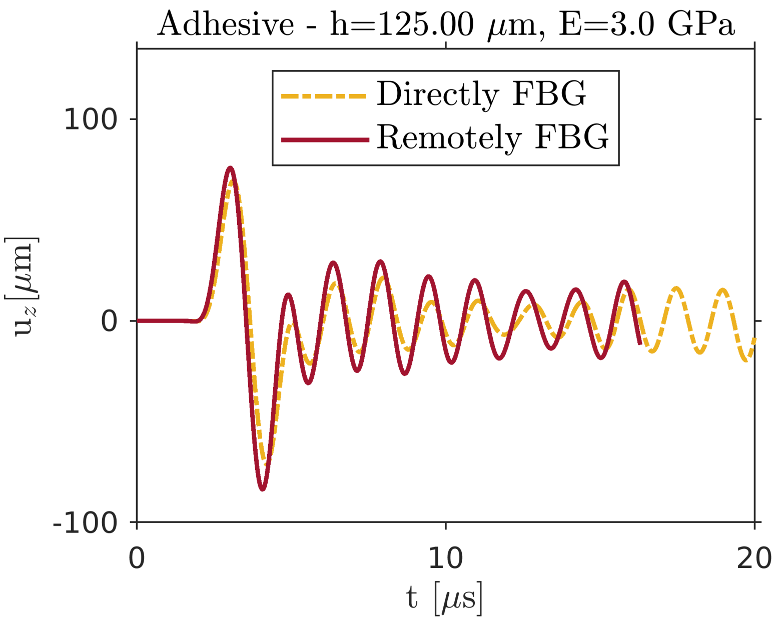

Figure 3: Comparison of amplitudes of response at the direct and remote bonded FBG

3.2 Aluminium plate

The second study was conducted to study if the SEM model captures the directional nature of the coupling of the wave from the structure to the fiber. The optical fiber was assumed to be bonded at the center with an adhesive to an aluminium plate ($500 \times 500 \times 1$ mm^3) as shown in Figure 4.

The fiber length was assumed to be 4 m so that the reflected wave from the end of the fiber would not interfere with the signal recorded at the bond. The bond length was 10 mm. These parameters were taken similar to Fiborek et al. [14] to facilitate the comparison. The key difference in the work reported by Fiborek et al. is the simulation of the adhesive bond instead of the perfect bond assumed in the previous study. The simulations were performed with various locations of the wave source defined in polar coordinates as $p = (r, \theta)$. Where radius $r = 120$ mm is a distance from the centre of the bond, and $\theta = [0°, 15° \dots 180°]$. The angle $\theta = 0°$ corresponds to the direction parallel to the fiber. An out-of-plane force as 5-cycle Hann windowed sine at 50 kHz frequency. The 50 kHz frequency is chosen to ensure easier extraction of the time of arrival. The observations remain valid for other frequencies, as well as for the S0 wave which is dominated by in-plane displacement. The magnitude of the first wave packet for the different excitation locations are shown in Figure 5.

As can be seen the numerical results fit very well with the cosine fit. This has been validated experimentally by Soman et al [16]. The numerical model has been successfully implemented for the direct bonded configuration in [14] and indeed follows a cosine-squared fit. Thus it can be seen that SEM based model is indeed able to capture the coupling of the wave and its directional nature.

4 Discussion and Conclusion

The paper outlines the framework of a time domain SEM based modelling approach for the simulation of the wave coupling in an optical fiber. The initial studies indicate that the modelling approach captures the physics of the coupling including the shear lag effect and the directionality. The code developed is

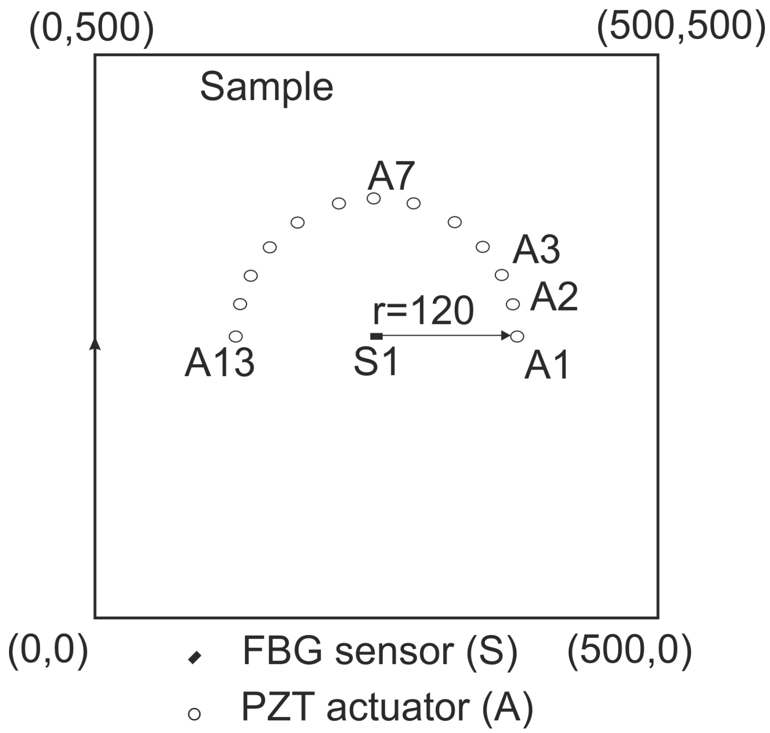

Figure 4: Aluminium plate simulated for directionality study

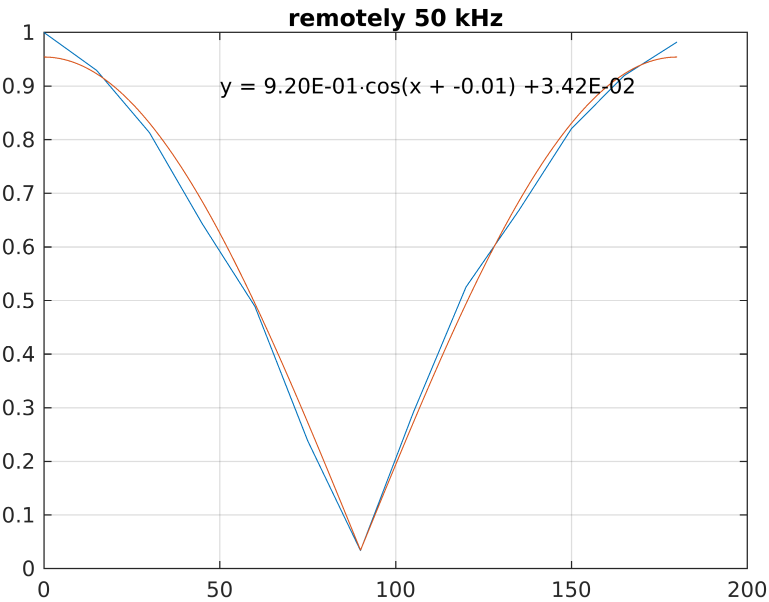

Figure 5: Normalized polot showing directionality of the wave coupling in the remote configuration (blue- SEM modelling, red- Cosine fit) x axis- angle in degrees

suitable for parallel implementation and hence is computationally efficient. The results obtained agree fairly well with numerical simulations from commercially available software as well as experimental and analytical estimates. The computation time for the simulation is an order of magnitude better than that for conventional FEM software.

The future work will investigate in detail on the mode conversion of the plate waves into the fiber modes. The study will also look to develop analytical models to estimate the effect of different adhesives on the wave coupling which will be useful to determine the optimal properties and thickness of the adhesive. The analytical models will find application where optical fibres are used as acoustic couplers.

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