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Elastic Wave Sensing Using Fiber Bragg Grating-Based Sensors and Dynamic Interrogators

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Abstract | Elastic Wave Sensing is a potent tool for Structural Health Monitoring (SHM) applications. In this paper, we review the use of fiber Bragg gratings (FBGs) as a viable alternative to conventional piezoelectric transducers. In particular, we present Fabry-Perot filters based on fiber Bragg gratings (FP-FBG) as a possible configuration for enhanced sensitivity elastic wave sensing. Finally we discuss the directional response of FBG-based sensors, and their role in the unique identification of different Lamb modes based on their dispersion characteristics.

1 Introduction

The primary goal of maintaining any capital-intensive structures such as bridges, dams, ships, aerospace vehicles, and power transformers is to prolong their lifetime through early identification of defects. Such defect identification, preferably through non-destructive evaluation techniques is addressed under the broad umbrella of Structural Health Monitoring (SHM). Structural Health Monitoring is a process of implementing a diagnostic strategy for aerospace, mechanical, civil, or electrical structures through frequent monitoring of their strength and performance.[1–3]

A wide variety of techniques is employed for Structural Health Monitoring including the measurement of mechanical impedance,[4,5] vibrations,[6] and acoustic emissions.[7–9] Impedance based methods rely on monitoring of variations in structural mechanical impedance caused due to any damage. The changes in mechanical impedance are coupled to electrical variations using suitable piezoelectric materials.[4,5] In vibration based approach, the vibration characteristics of a given structure—in time or frequency—are examined for abnormalities to determine defects in the structure.[6] Another interesting measurand in SHM systems is acoustic emissions that are generally released due to damage in structures, such as those from the growth of cracks or disbonds.[3]

Of the above techniques, acoustic emission sensing is a powerful tool for the above applications as it is minimally invasive, and provides a rich variety of information.[8] Acoustic emission sensing may be classified as (i) passive sensing and (ii) active sensing. In the former, acoustic waves may be generated as a result of an event, e.g. a tool drop in a machine or incipient discharge inside a power transformer, and the same is captured using an appropriate sensor (Fig. 1). In such a technique, the sensor coupled with a suitable interrogator has to be vigilant at all times. For example, consider the case of incipient discharge monitoring in power transformers. The random electrical discharges generated as a result of partial discharge (PD) activity creates acoustic emissions in the transformer oil.[10–13] Conventionally, these acoustic waves are sensed by piezo-electric transducers (PZTs), which are mounted externally on the transformer. Recent trends involve the use of fiber optic based sensors for capturing such signals.[14–16]

Even though passive sensing is effective for capturing the transients, one of the major disadvantages is the fact that passive sensing does not give any indication of the actual damage corresponding to the event.[17] A passive sensor system may miss the event due to insufficient sampling rate or the inability of the interrogator to maintain vigilance

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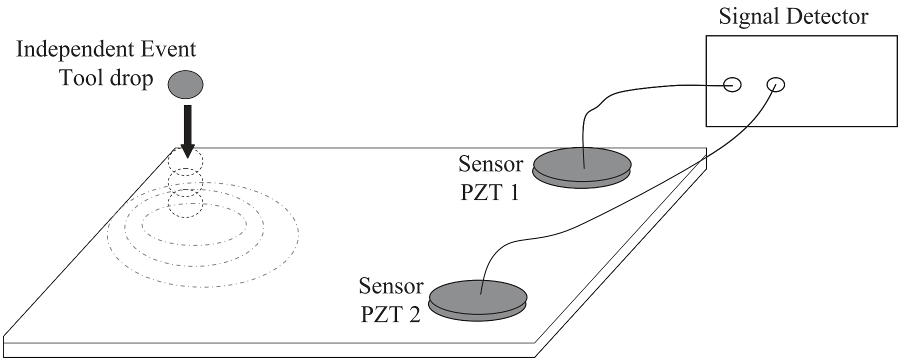

Figure 1: Schematic diagram of a passive acoustic emission monitoring system. The sensor system is vigilant and is triggered by an event that produces acoustic emissions.

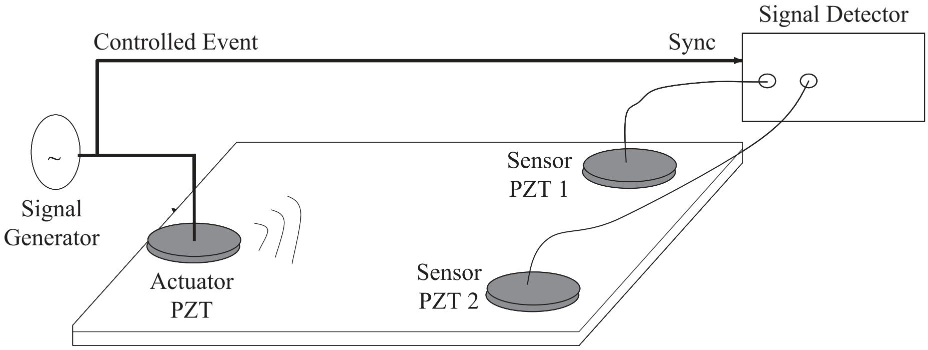

Figure 2: Schematic diagram of an active acoustic emission monitoring system. The measurement is periodically triggered by the actuator that produces acoustic emissions, which are picked up by sensors placed at strategic locations.

at all times. Even if the event is captured, there is no guarantee that the event caused any significant defects in the structure.

On the other hand, active sensing consists of periodically exciting acoustic modes in a metallic substrate, typically using a piezo-electric transducer and monitoring them at different locations on the substrate as illustrated in Fig. 2.[17,18] In such a technique, also popularly known as elastic wave sensing, any defect that develops in the path of the elastic waves will alter the modes captured by the receivers. By analyzing such received modes, the size and location of the defect may be identified.

Among the active schemes, guided-wave testing and specifically the use of Lamb waves has emerged as a very promising option to examine relatively large sections of a structure for damage.[19] Lamb waves exist in thin plates with parallel free boundaries and are found to travel over a long distance (in the order of meters), even in materials with high attenuation. Different modes of Lamb waves can be excited and their propagation characteristics vary with entry angle, excitation and surface geometry. The location, severity and extent of the damage can be easily predicted using this scheme. A sensor-actuator network built on the structure can detect the faults in a relatively short span of time. This is particularly advantageous over the passive sensing scheme, which requires a large number of sensors distributed over the structure under test.[19]

Sensors conventionally used for sensing acoustic waves are based on piezoelectric effect. This effect is characterized by the generation of an electric voltage in a material in response to stress or strain. An attractive feature of these sensors is that the mechanical measurand can be converted directly into an output electrical signal.[18] However, these sensors are characterized by a resonant frequency response. Also, deployment of large number of sensors for simultaneous measurements make the PZT sensor system bulky and prone to electro-magnetic interference.[20]

Fiber optic sensors offer plenty of advantages over the conventional PZT sensors. The prime feature being that they are immune to Electromagnetic Interference (EMI) due to their dielectric construction. Also, they are small, light-weight, respond over a wide temperature range and are easily integrated into complex structures.[21–23] Besides, fiber sensors offer access to areas with harsh environment and capability of easy multiplexing.[3] As such they are excellent candidates for sensing in SHM platforms.[24] Specifically, Fiber Bragg Gratings (FBGs) are attractive in this scenario as they respond to the linear strain generated by Lamb waves in the material.[25] In this paper, we review the use of FBGs for elastic wave sensing, which is of relevance to SHM applications as discussed above.

2 Background on Fiber Bragg Grating-Based Acoustic Emission Sensors

As mentioned above, a mature class of fiber optic sensors that has emerged in the last couple of decades is the fiber Bragg grating (FBG) technology. A fiber Bragg grating (FBG) is a periodic perturbation of the refractive index of the core of the fiber extending over a limited length. The grating is characterized by its period, relative refractive index change and length. The FBG acts like a narrowband optical filter, which reflects a narrow band of wavelengths around a center wavelength from the incident broadband signal.[26]

One of the excellent features of FBG is that it encodes the sensing information in wavelength. A multitude of sensor configurations using FBG have been reported in literature.[3,21,24,25,27–30] A schematic diagram for using FBG as a sensor is shown in Fig. 3. A broadband light is used to illuminate the FBG sensor connected to the port 2 of the circulator. A conventional FBG interrogation system uses a spectrometer connected to port 3 of the circulator to track the wavelength of the light reflected back from the FBG. When the FBG is subjected to an external perturbation like strain or temperature, Bragg wavelength changes. The shift in Bragg wavelength is typically 1.3 pm/$\mu\varepsilon$ and 12 pm/°C for strain and temperature respectively, in germano-silicate optical fibers.[26] The spectrometer tracks the wavelength shift, which may be correlated to the amount of strain or temperature experienced by the FBG. By calibrating the change in the wavelength to the change in temperature or strain, the FBG can be used as a sensor. In this scheme, the resolution of the sensor is dependent on the spectrometer used for tracking the wavelength.

A key challenge in using FBG based sensors for sensing acoustic waves of frequency greater than 10 kHz is the interrogation of the wavelength encoded signals to efficiently extract the sensing information. The conventional CCD-based spectrometers are not capable of sensing these high frequency signals. Earlier work on interrogation of FBGs include the use of tunable narrow band laser,[31,32] arrayed waveguide grating[33,34] or interferometric methods based on Mach-Zehnder,[35,36] Michelson,[37] Sagnac[38] and Fabry Perot interferometers.[39] Among these techniques, the edge filter is more attractive because of its simple structure, rapid response, cost-effectiveness and ease of usage. Edge filters provide a wavelength dependent loss as the FBG reflection spectrum scans over the slope of the filter offering a linear relationship between the wavelength shifts and the output intensity changes of the filter.[40,41]

One of the simplest and cost-effective techniques for the dynamic interrogation using edge

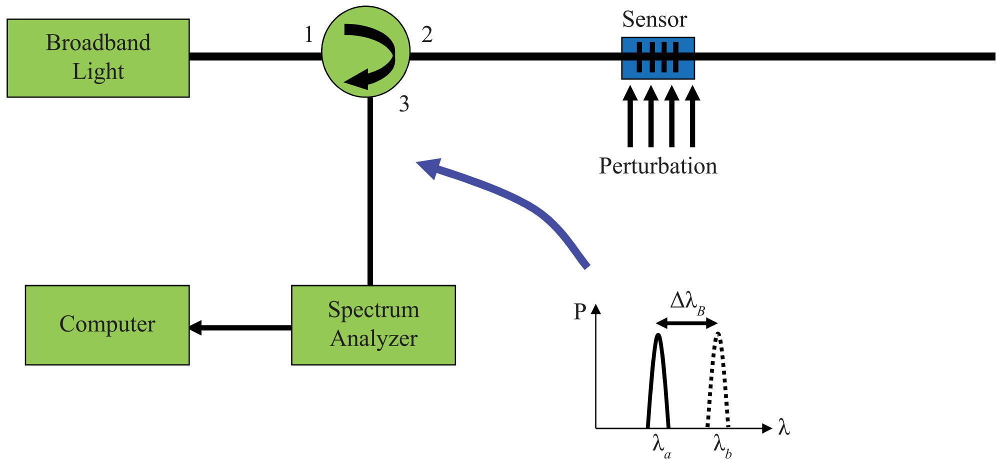

Figure 3: Schematic diagram of a typical FBG-based sensor system.

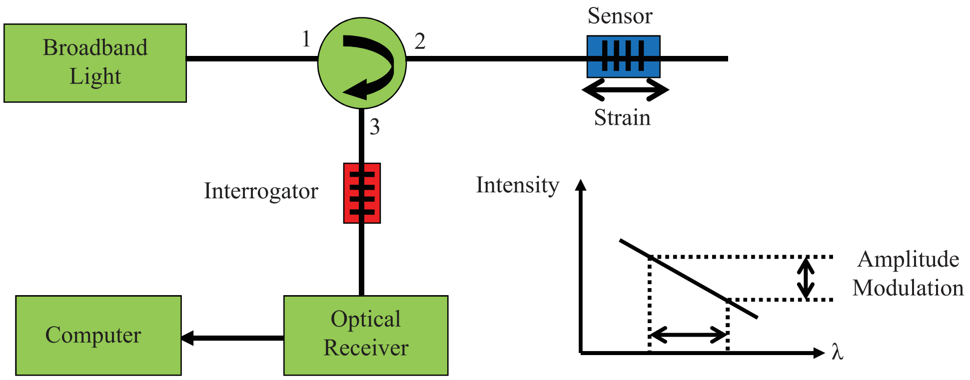

Figure 4: Schematic diagram illustrating the matched filter sensing technique.

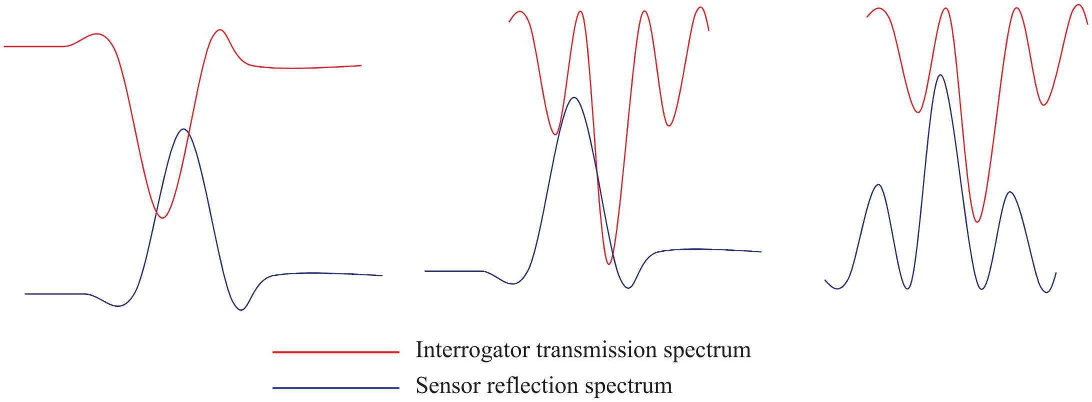

Figure 5: Different sensor-interrogator configurations for elastic wave sensing using FBGs and FP filters viz. a) FBG-FBG, b) FBG-FP, and c) FP-FP.

filter method is to employ matched FBGs as both a sensor and an interrogator[40] as shown in Fig. 4. As mentioned earlier, the key advantage of the FBG sensor is that the sensing information is normally wavelength encoded, and hence is quite impervious to noise. To exploit such an advantage, one can use a broadband light source to illuminate the FBG and use another matched FBG at the receiver to convert wavelength modulation (due to vibrations) into amplitude modulation, which can be captured by a high speed photodetector and associated receiver circuitry. However, to achieve high sensitivity one has to use FBGs with extremely sharp roll-off characteristics as the interrogator. Such characteristics may be achieved using Fabry-Perot filters based on fiber Bragg gratings.[42] As shown in Fig. 5b, the Fabry-Perot resonances are much sharper compared to the slope of a typical FBG resonance (Fig. 5a).

An alternative approach has been devised wherein the Fabry-Perot filters based on FBGs (FP) are used not only as the sensor element, but also the interrogating element as illustrated in Fig. 5c. Such a configuration is attractive, since it is a transmission-type interrogator[42] and is capable of providing much higher sensitivity compared to the conventional matched FBG sensor/interrogator system.

3 Elastic Wave Sensing Using FBG-Based Dynamic Interrogator

A complete sensor/interrogator system consisting of the above FBG-based configurations is presented in Fig. 6. The acoustic emissions which are generated in the aluminum plate are picked up by the sensor pasted on the plate. The interrogator is provided with a DC bias to fine tune its Bragg wavelength to that of the sensor, while compensating for any temperature change.

In order to compare performance of the different configurations, one FBG and FP sensor was pasted at equal distance from the point of excitation and the response to an elastic wave was captured using a matched interrogator and optical receiver. The experimental comparison between

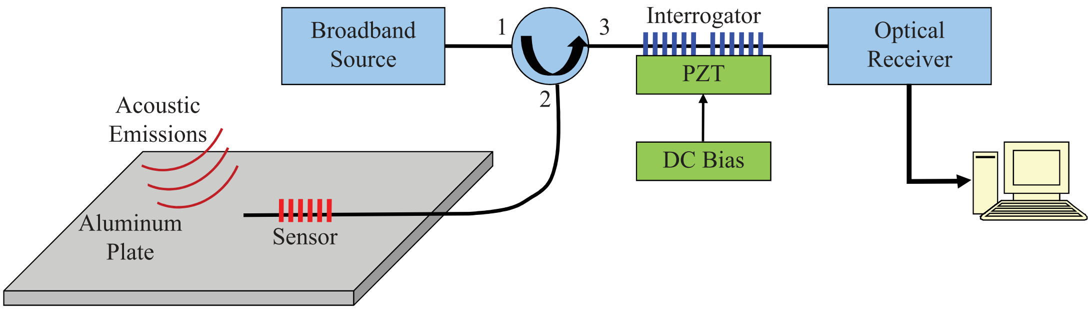

Figure 6: Detailed schematic of the FBG based dynamic interrogator.

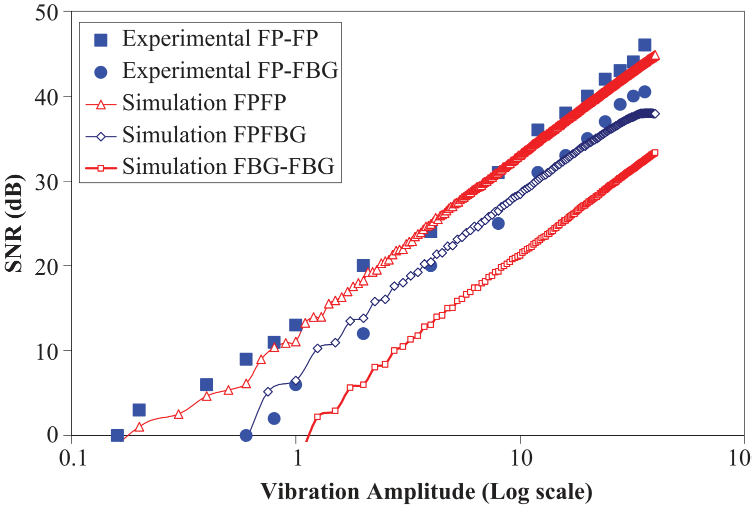

Figure 7: Comparison of the experimental data and simulation results obtained for different sensor-interrogator configurations as a function of vibration amplitude in με.[42]

them is made by plotting the SNR at an excitation of 133 kHz for various elastic wave amplitudes. As shown in the Fig. 7, the experimentally measured values are consistent with simulation results and they both clearly show that the FP-FP configuration provides 10 dB more sensitive detection compared to the conventional FBG-FBG configuration.

Further improvements in SNR are made possible by incorporating suitable signal processing techniques.[43,44] One such technique is the Adaptive Line Enhancement (ALE) technique, which has been widely adopted in several applications.[45] The principle of ALE is based on processing the delayed input signal with a transversal filter and then subtracting it from the input signal to produce a prediction error. The weights of the transversal filter are adaptively adjusted to minimize the prediction error, as shown in Fig. 8. When a sinusoid passes through the filter, the time delay Δ forces its delayed version to become uncorrelated with the noise in the input, while introducing a simple phase difference. The adaptive filter responds firstly by compensating for the phase shift so that the sinusoidal components cancel each other at the output, and secondly by removing as much noise as possible to minimize the output error. The output error is then recursively fed back to adjust the filter weights according to the principle of a stochastic gradient search.

One of the key requirements for any signal processing algorithm is to ensure that it does not corrupt the acoustic signals. In order to verify this, we compared the frequency content of the acoustic signals before and after applying ALE. Figure 8 illustrates the time domain and the corresponding frequency domain data respectively, for a 2 mm drop ball test before and after passing the data through ALE. It can be seen clearly that the frequency content of the two plots are similar, indicating that the ALE does not significantly alter the frequency components of the original signal while discriminating against noise.

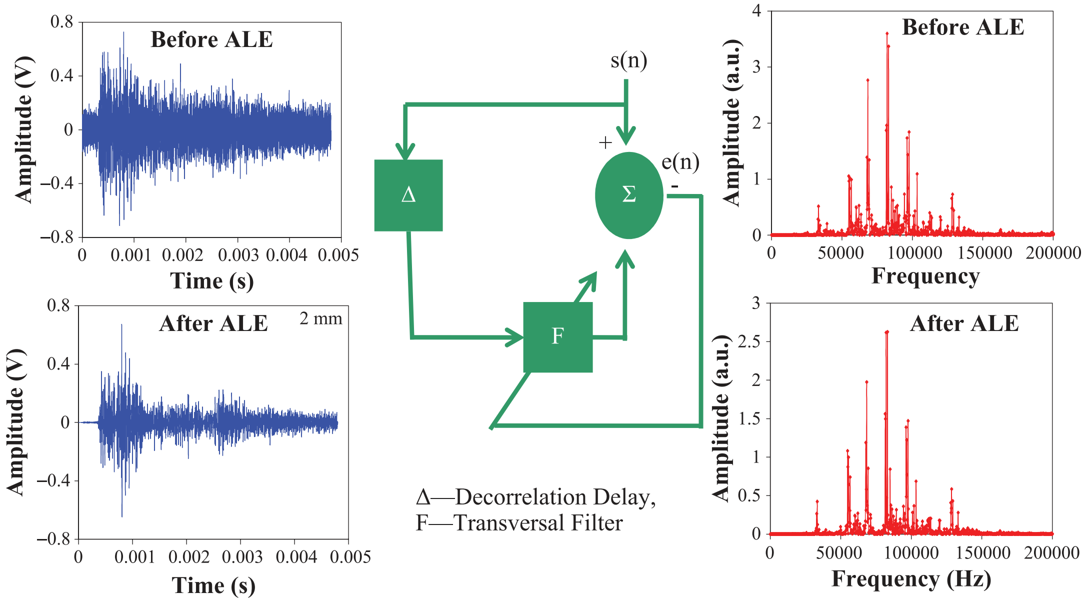

Figure 8: Time and frequency domain plots of the 2 mm drop ball tests showing the frequency content of the signal captured before and after ALE.[46]

4 Directional Response of FBG to Elastic Waves

As discussed in the previous section, a FBG based sensor/interrogator system provides a viable alternative to conventional piezo-based sensors. A desirable property in elastic wave sensing is the ability to detect the direction of the waves. FBGs provide such an opportunity since the optical fiber possesses a cylindrical geometry of high aspect ratio. Moreover the FBG is highly sensitive to strain in the longitudinal direction compared to the transverse direction. Exploiting such a property, the elastic waves can be captured using the FBGs and the direction of the wave picked can be deduced.[47] Figure 9 illustrates the directional response of the conventional PZT sensors and FBG sensors. Even though the conventional PZT sensors are able to pick up in-plane elastic waves with high sensitivity, they are independent of the direction of the acoustic wave. In this case, locating the defects becomes difficult and alternative expensive methods are required.

Lamb waves like surface waves propagate parallel to the surface in solid plates.[48,49] They are elastic waves whose particle motion lies in the plane that contains the direction of wave propagation and the plate normal (the direction perpendicular to the plate surface). They are produced in plates where the thickness of the plate is comparable to the wavelength of excitation. The FBGs can detect the Lamb waves in the plate and can be captured using appropriate electronics.[50–52] Furthermore, it is observed that FBG due to its directional property selectively responds to different modes of propagating Lamb waves in the structure depending on their orientations.

A test bed consisting of FBG sensors in radial and transverse direction to the source is shown in the Fig. 10. The elastic waves are induced in the plate using an elastic wave generator (buzzer), which will prominently produce out-of-plane vibrations in the plate. Such vibrations are picked up by the FBGs pasted on the plate as in-plane strain due to the Poisson effect.

Figure 11 shows the plots of time domain response of the radial and transverse FBGs for 100 kHz and 300 kHz. The transverse FBG exhibits lower and delayed response compared to the radial FBG. The elastic waves which are captured by the FBGs following different paths as the delay in time for the radial and transverse FBG is different. Such directional detection of the elastic wave is very desirable, since it is useful for efficient detection of the defects in the structures for monitoring their health.

5 Elastic Mode Identification Using Dispersion Measurement

In the previous section, we discussed the possibility of identifying the direction of an elastic wave using appropriate orientation of the FBG. A more useful feature would be to identify the specific Lamb mode itself. In aluminum plates whose thickness is comparable to the wavelength of the elastic waves, several modes are excited. Prominent among these modes are the fundamental

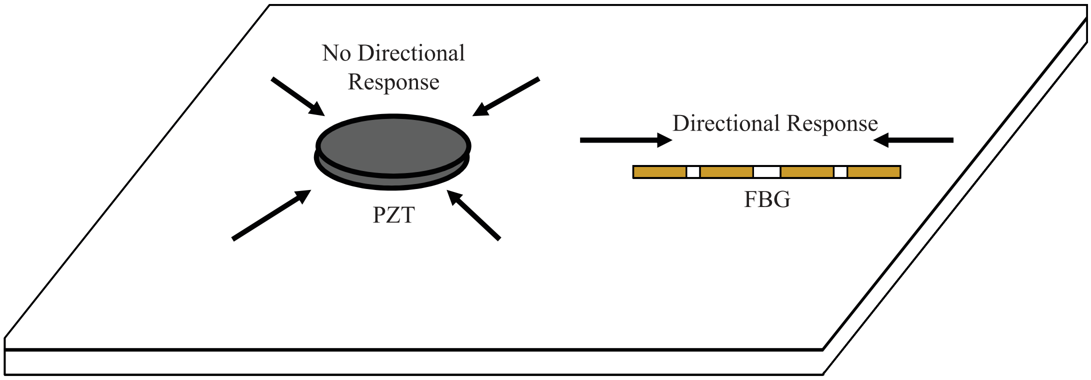

Figure 9: A schematic illustration of the directional response of FBG compared to conventional PZT.

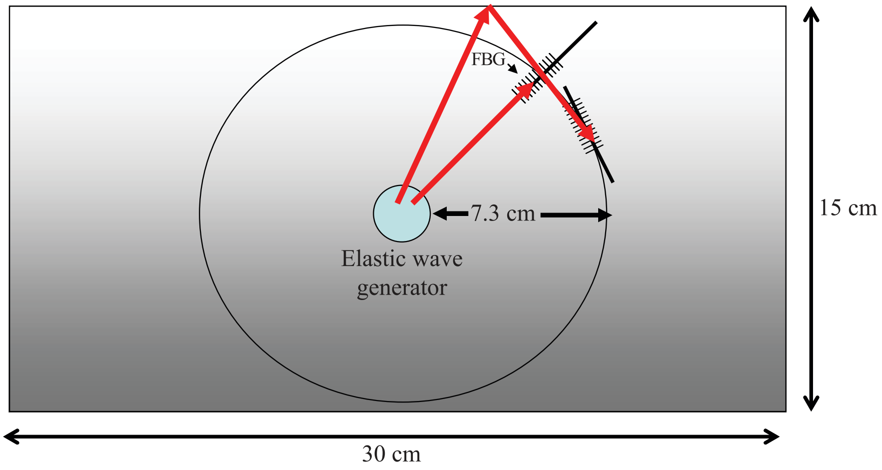

Figure 10: Schematic diagram of a test bed in which FBG is pasted in different orientations.

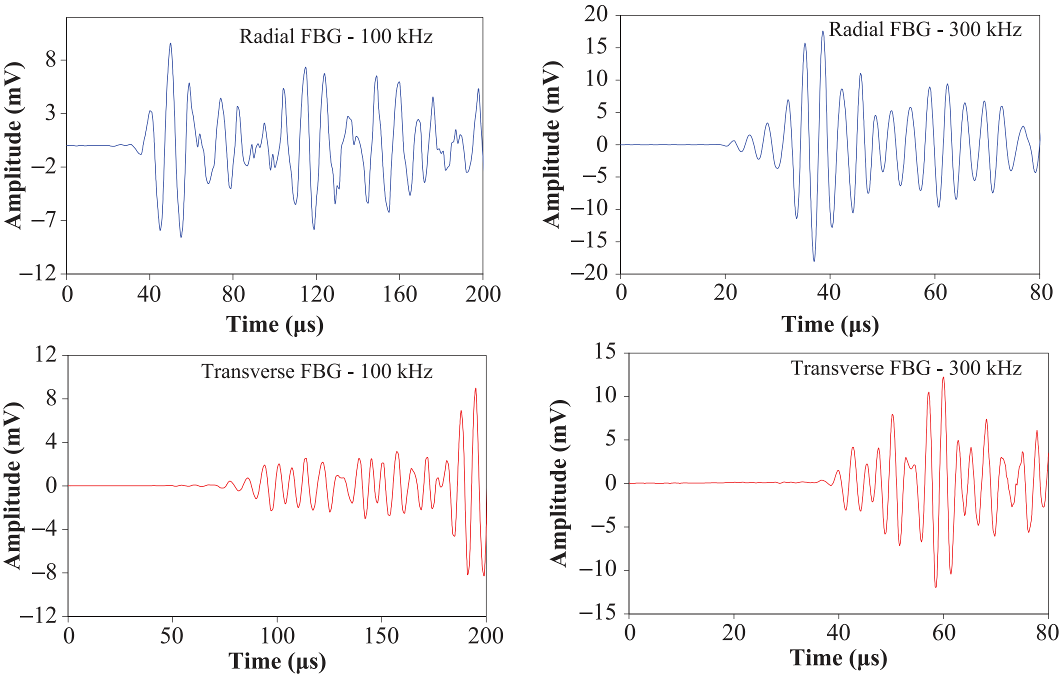

Figure 11: Lamb waves captured from the radial and transverse FBG at 100 kHz and 300 kHz.[53]

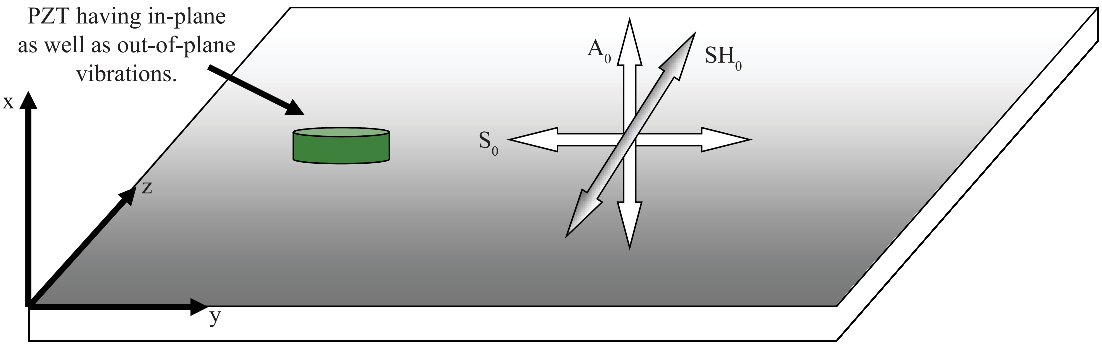

Figure 12: Fundamental Lamb wave modes excited in an aluminum plate.

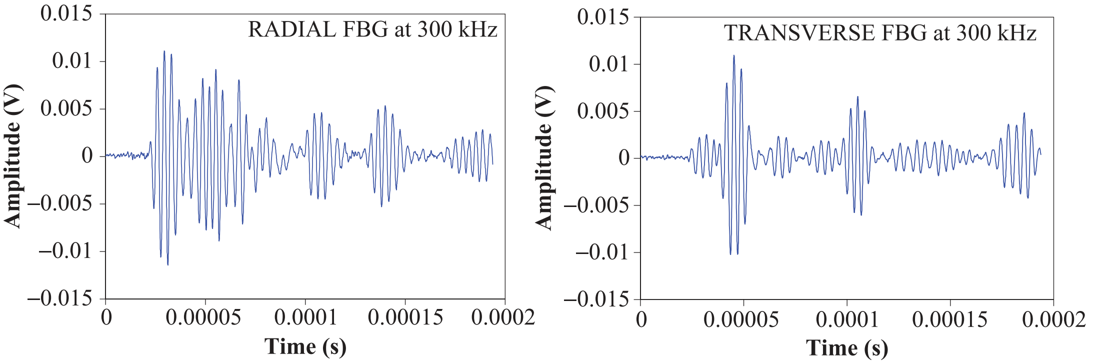

Figure 13: Plot of the acoustic signals picked up by the radially placed FBG (left) and the FBG placed along the transverse direction (right) on a 1 mm thick aluminum plate.

asymmetric (A_0) mode and the fundamental symmetric (S_0) mode. Exciting the A_0 and S_0 modes require a PZT which induces both in-plane and out-of-plane displacements in the plate (Fig. 12). There is also another mode which can be excited in such a plate called the Shear Horizontal (SH_0) mode. Normally, in conventional PZT sensors, it is not possible for us to distinguish between the different modes of propagation.

A significant opportunity to identify the elastic Lamb mode would be to observe the dispersion experienced by the different modes through a time-frequency analysis.[54] We have implemented this technique using our above FBG-based configuration. We simulated the dispersion characteristics of the A_0, S_0, and SH_0 modes using the commercial software—Disperse. This was then compared with the dispersion measured experimentally by observing the arrival time of different wave packets picked up using radial as well as transverse oriented FBGs.

The dispersion measurement is carried out as follows: a PZT element is excited using different frequencies ranging from 50 kHz to 500 kHz, and the response of the above two FBGs were recorded as a function of time. Based on the arrival time of different wave packets with respect to the time of excitation, the group velocity experienced by each wave packet may be deduced. For example, Fig. 13 shows the plots detected by the radial and transverse FBGs for a PZT excitation frequency of 300 kHz. It may be clearly seen that two different wave packets are received by the radial FBG at 30 µs and 55 µs respectively, which is quite different from the wave packet detected at 45 µs by the transverse FBG. This alludes to the possibility that these wave packets correspond to different Lamb modes. By plotting the dispersion curves for the packets observed, the modes can be easily identified since each mode has its own unique dispersion characteristics as deduced through simulations. In this case, we have identified the two wave packets picked up the radial FBG as the S_0 and A_0 modes and the wave packet picked by the transverse FBG as the SH_0 mode.[55]

The detection of the SH_0 mode quite clearly by the transverse oriented FBG is very exciting from the NDE perspective, as it holds much promise for detection and dimensioning of planar defects and cracks in butt weldments.[56] Such modes are not picked up easily using conventional PZT sensors. As such, there is a lot of scope for pushing the envelope of NDE and specifically SHM, using FBG-based sensors and interrogators described above.

6 Summary

In this paper, we have attempted to highlight elastic wave sensing using fiber Bragg gratings as a promising technique for Structural Health Monitoring (SHM) applications. We have demonstrated enhancement in the elastic wave detection sensitivity using Fabry Perot filters based on fiber Bragg gratings (FP-FBGs) as sensors as well as interrogators. Such results have been facilitated by the development of a compact interrogator incorporating Adaptive Line Enhancement (ALE) technique to improve the SNR. Finally, we discuss some unique characteristics of FBG sensors including directional response and elastic mode identification, which hold much promise for precise defect identification and possible replacement of conventional PZT sensors for certain niche applications.

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