

The use of fibre Bragg gratings for ultrasonic Lamb wave detection and source location

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Abstract. There is an increasing interest in the use of ultrasonic Lamb waves for materials characterisation and the detection of structural defects. Fibre Bragg gratings offer some significant advantages over more traditional transducers such as piezoelectrics for ultrasound detection and are also dual purpose, since the same sensors can also be used for strain mapping.. We describe the use of fibre Bragg gratings to detect ultrasound signals and thereafter to determine both their direction of propagation and source location. The main aspects that will be concentrated upon will be – optimising FBG interrogation techniques; maximising the efficiency of strain transfer from the sample to the FBG sensors; describing the directional response of FBGs; how this allows them to be configured into rosettes to determine the direction of the received ultrasound signal and, finally, how an array of 2 or more rosettes can be used to determine the source of the ultrasound.

1. Introduction

The use of ultrasound Lamb waves for material characterisation and structural health monitoring is a technique that has experienced increasing interest in recent years. Since Lamb waves propagate in a direction parallel to the surface of a plate they can, in principle, be used to interrogate a large area without the need for scanning that is a feature of the more well established c-scanning method. Lamb waves are guided acoustic waves that exhibit modal properties; these modes being classified as either symmetric (S) or antisymmetric (A) according to the symmetry of particle motion about the neutral axis. The number of modes excited in a particular sample will be dependent on the product of the thickness of the sample and the frequency at which the source transducer is driven. The properties of a Lamb wave (eg amplitude, phase, frequency spectrum etc) measured at any point on a plate will be dependent on the properties of the material between the source and receiving transducers. The presence of defects such as holes, cracks and delaminations will similarly affect the signal.

2. The use of fibre Bragg gratings for Lamb wave detection

Lamb waves can readily be detected through the use of PZTs identical to those used as source transducers; however FBGs can be shown to have several important advantages over them. The most important of these are:

- (i) FBGs are smaller and lighter than PZTs, making them easier to incorporate into structures, especially composite materials.
- (ii) Since many FBGs of differing wavelengths can be written into a single fibre, multiplexing is readily achievable
- (iii) No electrical wiring is required
- (iv) FBGs exhibit well defined directional characteristics which, as described below, enable them to be used to determine not only the amplitude, but also the direction, of an incident wave.

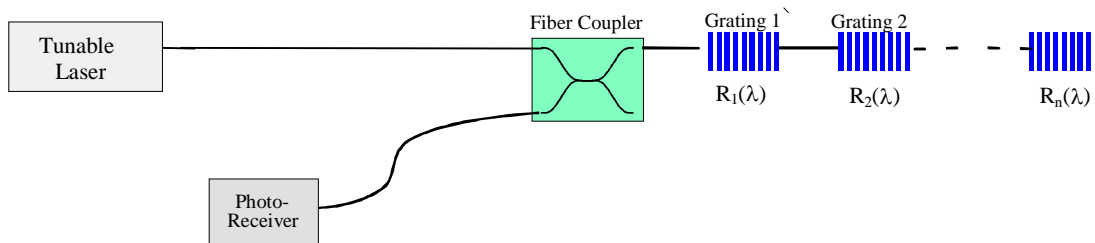


Figure 1. Interrogation of fibre Bragg gratings

The interrogation technique (figure 1) is based on the use of a tunable laser that is set to a wavelength that is on midpoint of the linear part of the FBG spectrum (figure 2). Ultrasound waves produce in-plane strains that modulate the peak wavelength of the spectrum and hence produce a varying reflective power whose value can be monitored using a low noise photodiode and amplifier [1]. For optimum sensitivity it is clearly desirable that the FBG spectrum should have a narrow linewidth. The length of the grating that is an important factor in determining linewidth is, however, limited by the wavelength of the ultrasound in the sample. As the length of the grating increases relative to the ultrasound wavelength, the modulation depth of the output signal is reduced (figure3).

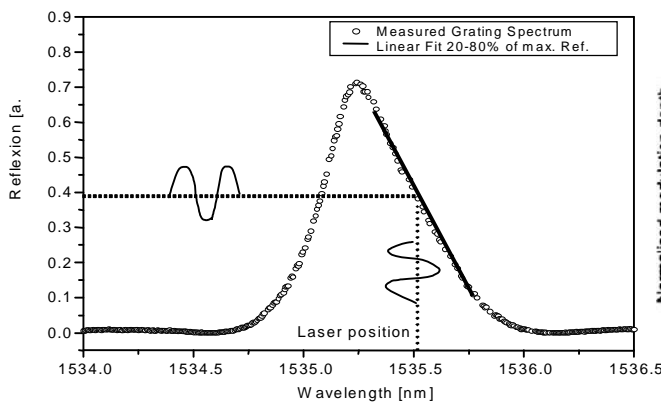


Figure 2. Position of laser on FBG spectrum

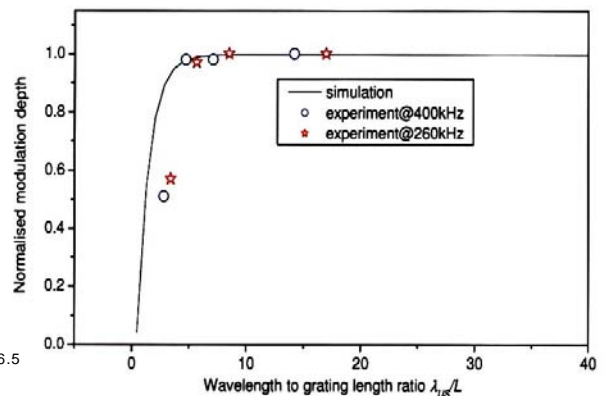


Figure 3. Effect of grating length to wavelength ratio on modulation depth

In our experiments, the Lamb waves have been excited using PZT transducers bonded to the sample. These are driven using an input signal of suitable frequency with a toneburst (typically of 4.5 cycles) with a Hamming window added to limit frequency sidebands. A tone burst is used rather than a cw wave for two reasons. Firstly, since the S_0 wave travels faster than the A_0 , the use of a toneburst allows these two modes to be temporally separated, provided that the propagation distance is sufficient. Secondly, signals emanating from areas of interest in the sample can be separated from reflections from the edges.

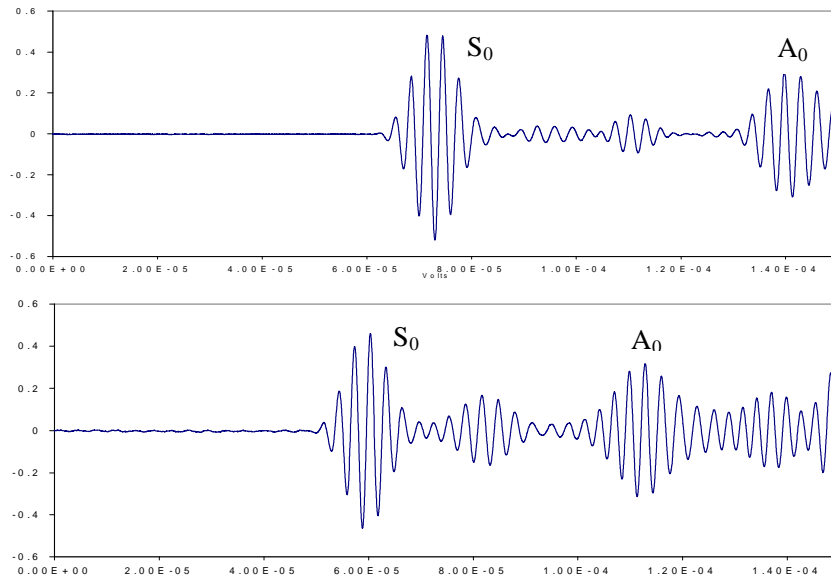


Figure 4. Lamb wave signal obtained from (top) PZT (bottom) FBG.

A comparison between signals obtained using a PZT and an FBG is shown in figure 4. The symmetric mode S_0 and the antisymmetric mode A_0 are indicated. On the sample plate the FBG was slightly closer to the source, resulting in earlier times of arrival than for the corresponding parts of the PZT signal. The quality of the signals will depend on many factors including the stability of the laser wavelength, the noise characteristics of the photodiode/amplifier and the bond between the FBG and the sample. For ultrasound frequencies, the mechanical characteristics of the bond layer are crucial. The FBGs used in these experiments were recoated with an ormocer layer that has a much higher modulus than that of the more commonly used polymers (FBGS Technologies, Jena) and the adhesive used was a low viscosity methacrylate designed for strain gauge bonding applications.

3. Utilisation of the directional characteristics of FBGs

FBGs exhibit maximum sensitivity to static strain when the direction of maximum strain is parallel to the fibre axis, and minimum when it is normal to the axis. It would be expected that the signal amplitude obtained from the interaction of an FBG with an ultrasound wave would show a similar trend. This behaviour has been confirmed experimentally by mounting PZT source transducers on an aluminum plate in a semicircular array with an FBG at the centre. The amplitude of the signal detected by the FBG was then measured as each PZT was excited in turn. Curve fitting shows a cosinudoidal relation ship between the signal amplitude and the angle between the wave propagation direction and the FBG axis (figure 6).

This well defined relationship enables a rosette grating (figure 7) to be configured from 3 FBGs and used to determine not only the amplitude, but also the direction, of an incident wave. If the FBGs are interrogated in turn using the tunable laser, the amplitudes of the detected signals can be inserted into an appropriate algorithm in order to obtain the required information. This process is directly analogous to the use of electrical strain gauge rosettes to determine principle strain magnitudes and directions. A fourth FBG can be added to the rosette in order

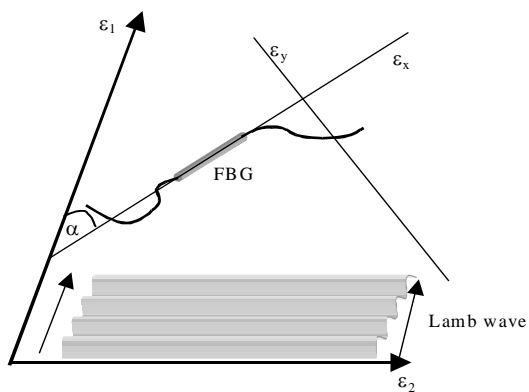


Figure 5. Relationship between FBG and Lamb wave direction

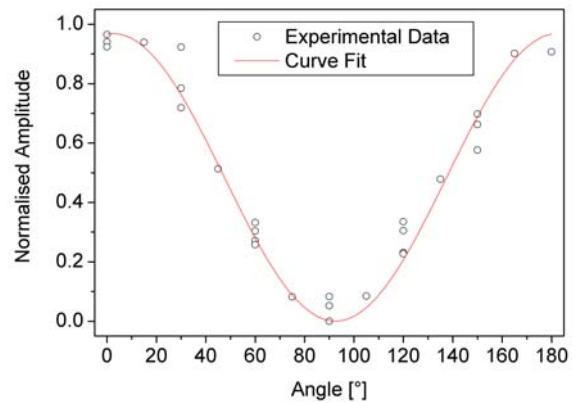


Figure 6. Experimental and curve fit for directional sensitivity of FBG

to provide temperature compensation [2]. If 2 or more rosettes are used, the location of the source of the ultrasound may be obtained by calculating the intersection point of the 2 wave directions [3,4] (figure 8).

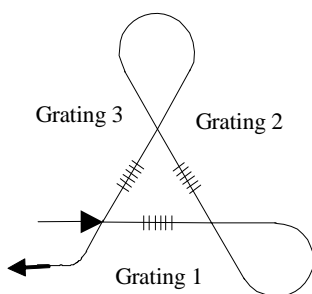


Figure 7. Grating rosette

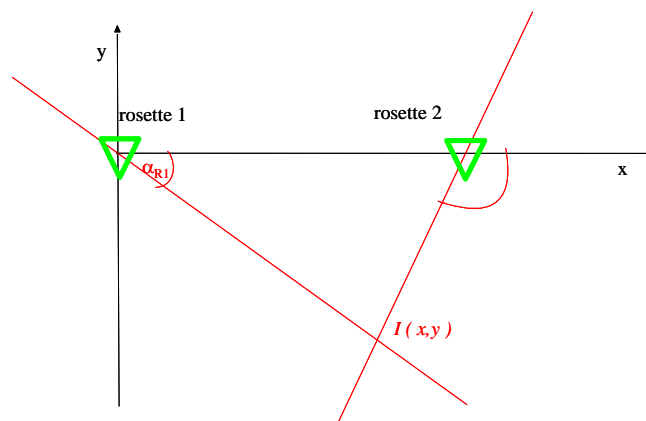


Figure 8. Source location through the intersection of 2 directions

This source may be an active source, such as a PZT transducer, but it may also be a passive source such as a hole. In order to establish the location of a hole it is necessary to separate

out that part of the signal that emanates from the hole from the remainder. In order to do this signals must be obtained from all of the PZTs for the plate in a without hole and with hole conditions. The differences between the two sets of signals will be the signals produced by the hole.

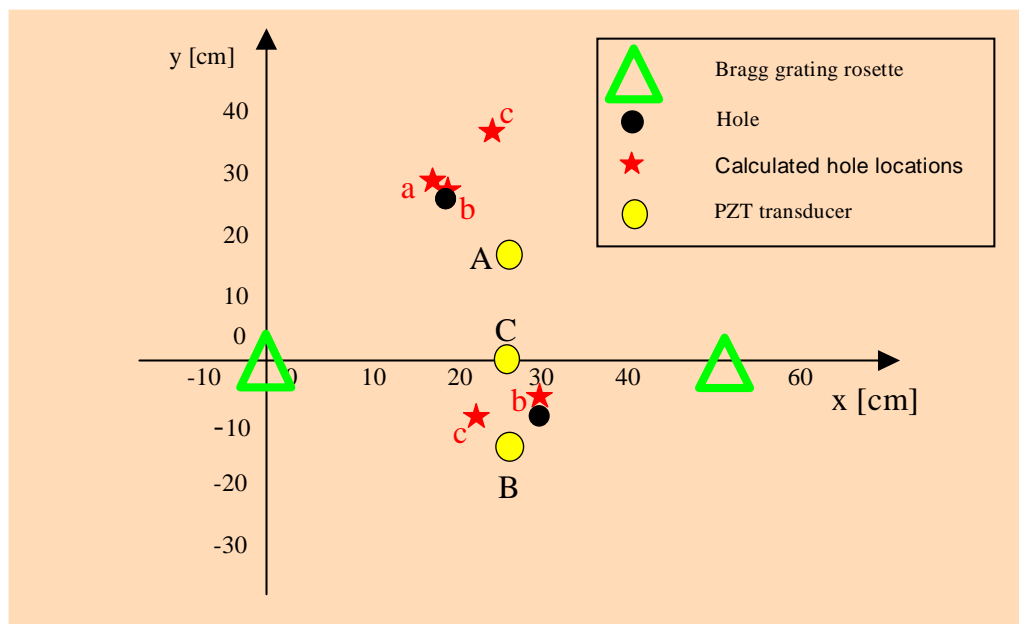


Figure 9. Experiment to determine the position of holes using reflection of Lamb waves

This concept has been proven experimentally in the following experiment. Two rosettes and 3 PZTs were bonded onto an aluminium plate as shown. Signal amplitudes were measured from each of the FBGs in both rosettes whilst one of the PZTs was excited. A hole was then made in the plate and the signal measurements repeated. From the difference between the set of measurements taken before and after the hole was made, the position of the hole was calculated. The experiment was then repeated for each of the other PZTs in turn. The results are shown in figure 9. PZTs *a* and *b* gave excellent results but *c* less so. This was probably due to one FBG in each rosette being directly along the direction of propagation of ultrasound from PZT *c*, producing a large background signal from which it was difficult to separate from the much smaller signal coming from the hole.

3. Conclusions

We have shown that FBGs are effective detectors of ultrasound Lamb waves that may be used for material characterization and structural health monitoring. Their small size, ease of multiplexing and well defined directional properties give them significant advantages over the more conventional PZT transducers. Their directional properties enable them to be configured into rosettes that may be used to determine not only the amplitude, but also the direction of an incident wave. The use of two of these rosettes to accurately locate the position of a hole in a plate has been demonstrated

References

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