A Comparison of 3 Optical Systems for the Detection of Broadband Ultrasound

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ABSTRACT

There are many applications of ultrasound in the field of material properties' evaluation and structural health monitoring. Here we will consider the detection of broadband laser generated ultrasound taking as an example acoustic emission as simulated by the pencil break test. In this paper three optical methods of detecting these ultrasound signals are compared; these are polarimetry, fibre Bragg gratings and vibrometery. Of these, the first two involve the bonding of a fibre sensor to the sample, whilst the vibrometer is a non-contact instrument that measures out-of-plane displacements. FBGs respond to the in-plane strains associated with an ultrasound wave whilst the polarimeter detects birefringence produced by pressure waves acting normal to the fibre. The sensitivities of the systems are compared and their relative merits are discussed. It will also be shown that the polarimetric responses of symmetric and antisymmetric Lamb waves differ, which opens up the possibility of learning more about the nature of an acoustic signal using this technique than can be determined simply from the measurement of in-plane or out-of plane displacements alone.

Key Words: Optical fibre sensors, polarimetry, FBGs, Acoustic Emission, Lamb waves

1. INTRODUCTION

Guided wave ultrasound, in particular Lamb waves, have many applications in materials testing from providing data from which the mechanical properties of a sample material can be obtained, to detecting damage or flaws within a structure. There are many ways of detecting ultrasound and in this paper we will compare the responses of 3 different optical sensors, each of which responds to different properties of the ultrasound wave. The 3 sensors are-

(i) A commercially available vibrometer manufactured by Polytec. A HeNe laser beam, which is directed normal to the surface of the sample, is focussed onto it and the reflected beam detected. Out-of plane motion of a sample excited by ultrasound causes changes in the phase of the recovered light and this can be processed in two ways to obtain either displacement or velocity. In all of the experiments described here, the instrument was used in the displacement mode. Further details of the instrument can be obtained from the Polytec website[1].

(ii) A fibre Bragg grating bonded onto the sample surface is primarily sensitive to changes in in-plane strain. Details of its interrogation are given in section 2

(iii) A fibre bonded to, or embedded in the sample is subject to a pressure wave which induces changing birefringence in the fibre. This changing birefringence is the source of the signal and the technique for recovering it is described in section 3

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Lamb waves are guided acoustic waves that propagate along sheets of material. There are two types of wave, symmetric and antisymmetric, where the symmetry referred to is of the particle motion in the sheet relative to the neutral axis. This is shown in figures 1[2], from which it is clear that the modes contain both longitudinal and shear strain. Although not apparent from the diagrams below, it is important to note that the relative magnitudes of in-plane and out-of-plane motion are quite different for the 2 modes; the precise difference depending on the mechanical properties of the sample and the frequency of excitation. Clearly, the relative sensitivities of the vibrometer and the FBG will therefore be different for the 2 modes, but the expectation of the polarimeter response is much less obvious.

The first series of experiments to be described uses a PZT actuator to launch narrowband ultrasound at frequencies where just the 2 fundamental modes propagate. Following on from this, tests were carried out where pencil lead break tests were used to simulate the signal obtained from acoustic emission. Comparisons were then made on the differing sensor responses to the two types of acoustic wave

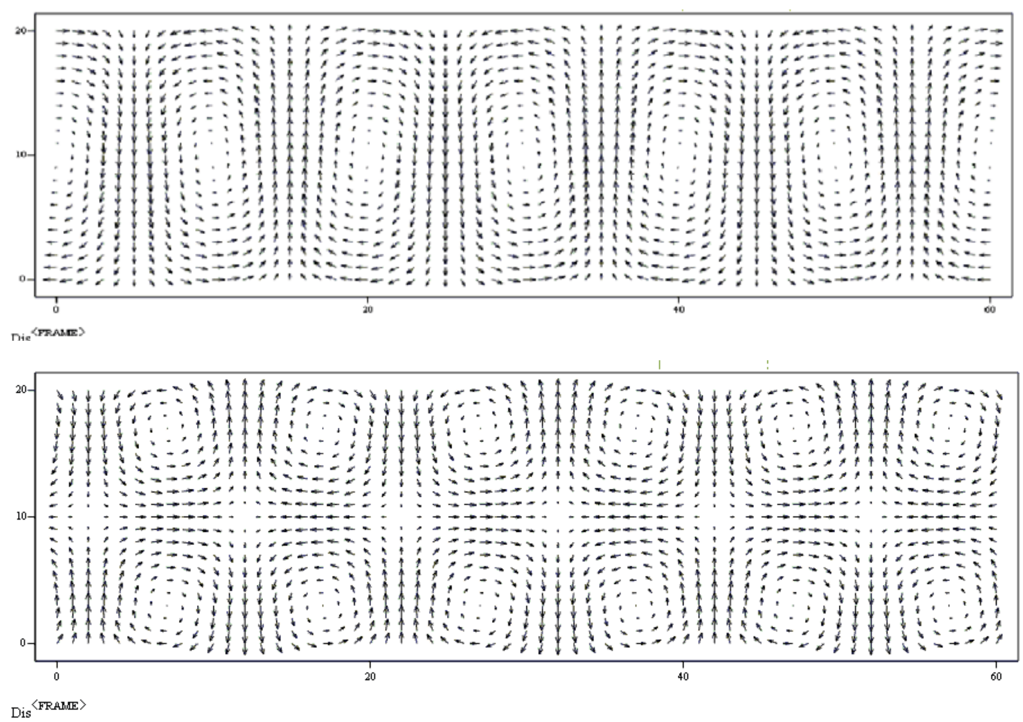

Figure 1. Particle Motion in an Antisymmetric Lamb Wave (top) and in a Symmetric Lamb Wave (bottom)

2. ULTRASOUND DETECTION USING FIBRE BRAGG GRATING SENSORS.

Bragg gratings can be used to detect ultrasound, since Lamb waves produce changing linear strain in the material through which they are travelling. It should also be noted that Lamb waves also produce out of plane displacements in addition to linear strain, but that Bragg gratings are relatively insensitive to these if they are bonded directly on to the sample surface. If the wavelength of the laser is set to a certain part of the grating spectrum, any shift of the spectrum will as a consequence modulate the reflected optical power at the photo-receiver. The interrogation method used here concentrated on the part of the spectrum where the grating response can be assumed to be linear and the slope is at a maximum. A DFB laser diode was thermally tuned to the appropriate point on the FBG response curve (shown by a dotted line in fig 4) and the changing reflected power was recorded using a high sensitivity ac coupled detector together with an oscilloscope. If more than 1 FBG is to be addressed on the same length of fibre, a tunable laser can be employed to interrogate each one in turn, but the signal to noise ratio has been found to be significantly worse

An important consideration in choosing an FBG for ultrasound detection is the gauge length of the device, which should be no more than a fifth of the ultrasound wavelength. This is because if the FBG is long compared to the ultrasound wavelength, the strain along the grating is significantly non-uniform and can even result in one part of the grating being in tension whilst another part is in compression[3]. This results in broadening of the response curve and in consequence very low responsivity. During these experiments we neglected any shift in the grating spectra might be caused by slow varying temperature or static strain. For real applications the interrogation system would require a feed-back loop that ensures the laser always matches the wavelength at FWHM.

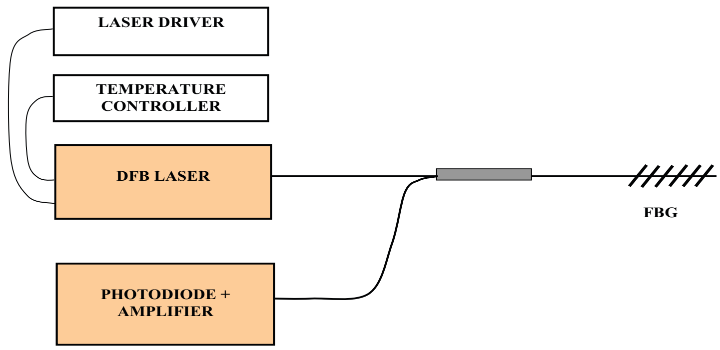

Figure 3. Interrogation of fibre Bragg gratings for ultrasound detection grating

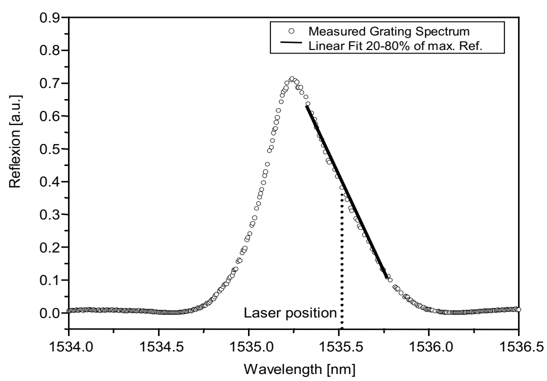

Figure 4. Wavelength response of a fibre Bragg grating

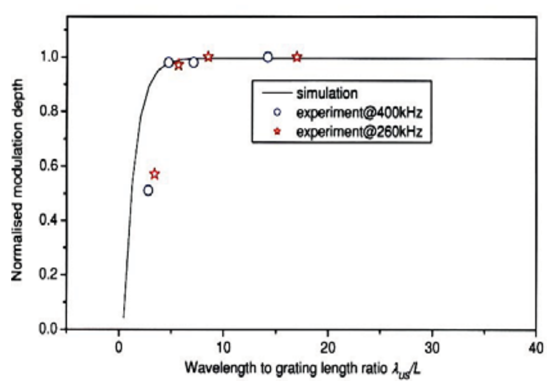

Figure 5. Responsivity related to FBG/ultrasound wavelength ratio

3. POLARIMETRIC DETECTION OF LAMB WAVES

The following experiments describe an initial investigation into the possibilities of detecting Lamb waves using polarimetry and the nature of the information that could be obtained from this technique[4]. A linearly polarised laser source was connected via a polarisation controller to the sensor fibre, which was cast into a polymer resin mould of dimensions 100x 6x2.5mm which was then bonded to the sample plate. The output of the sensor fibre was terminated with a GRIN lens, so that the light could be directed through a rotatable polariser and on to a photodiode. Care was taken to ensure the output fibre was kept as short and as straight as possible so that the polarisation state changed as little as possible between the end of the bonded length and the polariser. The length of the bonded section of the fibre was chosen such that the acoustic wave was never more than λ/4 out of phase along it. Lamb waves were generated by a piezoelectric transducer glued to the plate and excited by a 5-cycle tone burst at the resonant frequency of the transducer/plate combination

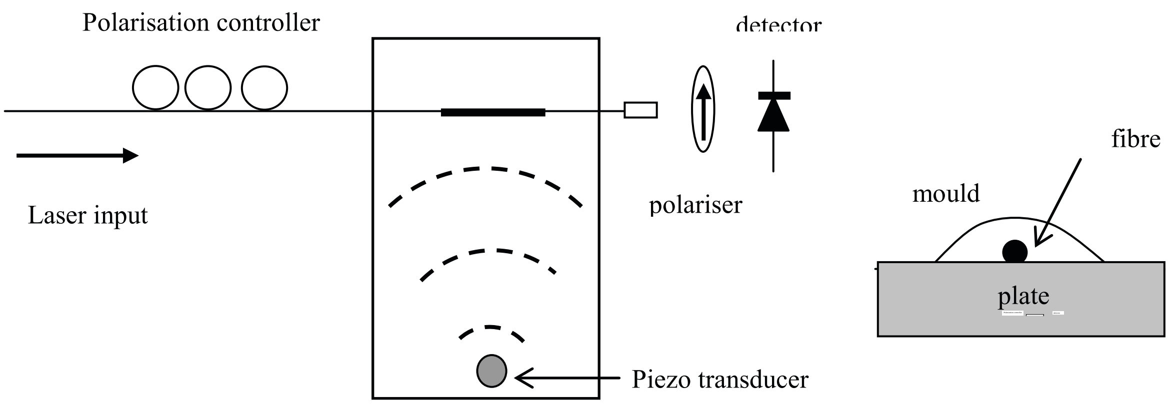

Figure 6: Polarimetric detection of Lamb waves and cross section of fibre sensor moulding

It was found that fringes were produced by this set-up whose amplitudes were dependent both on the input state of polarisation and the orientation of the polariser. Accordingly, the following experiments were carried out: -

(ii) A combination of the input polarisation state and the polariser orientation that gave the maximum fringe amplitude was established. The polariser was then rotated whilst maintaining the same input polarisation and the resulting changes in fringe amplitude were measured, together with the DC value of the detected light. Measuring the minimum and maximum values of the DC light level allowed the ellipticity and of the orientation of the major axis of the polarisation state that gave the maximum fringe amplitudes to be determined.

(ii) Linear output states of polarisation were set at various orientations by using the polarisation controller to establish a null DC level in the orientation orthogonal to that to be studied. Fringes were obtained by rotating the polariser by 45° and their amplitudes measured.

The results of these experiments for a 3mm thick Perspex sample plate excited at 150kHz with a 5 cycle tone burst showed that the optimum output polarisation state for maximum fringe amplitude was an elliptical polarisation state with a transmitted power aspect ratio of 2.64 (⇒ E-field 1.62) at an orientation

of 58° with respect to the plane of the plate. The amplitude of the signal was 5% of DC under optimum conditions, suggesting that the effects observed are sufficiently large to allow the technique to be used as a detection mechanism. Experiments conducted with linear output polarisation showed little variation in signal amplitude with changing orientation of the polarisation. The maximum signal obtained by using linear birefringence was less than 10% of that obtained using the optimum polarisation state.
It was observed that the relative sensitivities of the S_0 and A_0 were to a considerable extent dependent on the orientation of the polariser for a given output SOP (figures 7 and 8a, b) and that other polarisation states

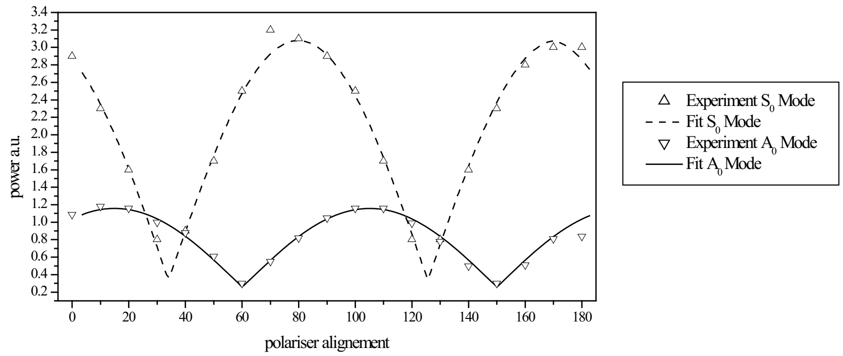

Figure 7. Variation of S_0 and A_0 amplitudes with polariser orientation

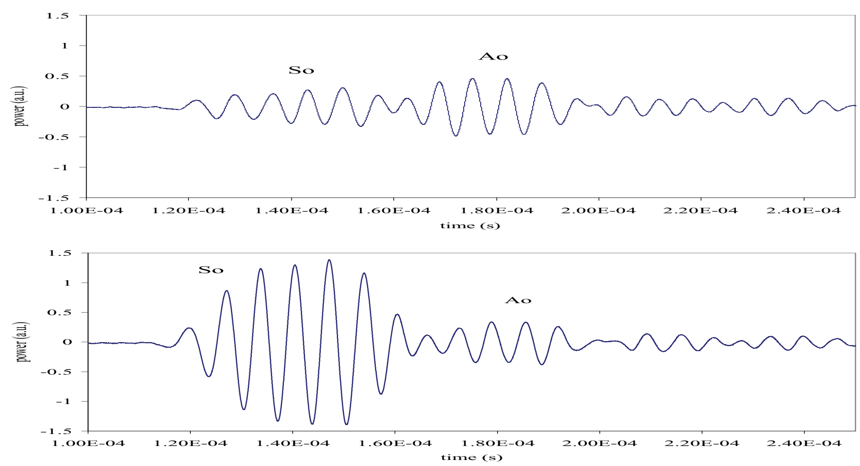

Figure 8. Lamb wave signals obtained by the polarimetric method for different polariser orientations: top - 10° to the plane of the plate, bottom - 60 °orientation

could be found for which the A_0 signal was much larger than that for the S_0. Presumably this is also due to the differences in particle motion for the two modes. This suggested that, if the polarimetric fibre sensor was interrogated using either different input polarisation states or different analyser orientation, more information could be obtained concerning the properties of the modes from polarimetric studies than from interferometry or vibrometry alone. One area of application might be to determine whether damage to a plate would cause detectable changes in the polarimetric properties of the signals due, for example to mode conversion.

4. VARIATION IN THE RESPONSE OF DIFFERENT SENSORS TO PZT GENERATED LAMB WAVES

In this experiment Lamb waves were generated in the aluminium plate using a PZT excited by a waveform generator that was programmed to produce 4.5 cycle Hanning windowed tonebursts at a variety of frequencies. The frequencies were chosen in a range where only 2 modes could be excited, the S_0 and the A_0. Two frequencies were studied 270KHz and 122KHz, these being the ones empirically determined to excite most strongly the S_0 and A_0 respectively. Detection of the acoustic waves was carried out using the vibrometer, the FBG and the polarimeter. Since an aluminium plate was to be used, it did not seem appropriate to cast the polarimetric sensing fibre in a resin mould since there would be a poor acoustic match between the mould and the sample. In addition it was intended to investigate higher frequency ultrasound which was likely to be attenuated by the polymer. It was also decided to shorten the bonded length of the fibre to 3cm to minimise the variation of acoustic phase along the sensor length and to bond it directly on to the plate using nail varnish. Polyimide coated fibre was used since the jacketing on this fibre is thinner and tougher than the more normal polyacrylate and would therefore provide better acoustic coupling. The waveplates of the polarisation controller and the orientation of the analyser were both adjusted to produce the maximum polarimetric signal amplitude. The top 3 traces shown in figure 10 were simultaneously recorded on an oscilloscope with the excitation set at 270KHz. It was then found that by

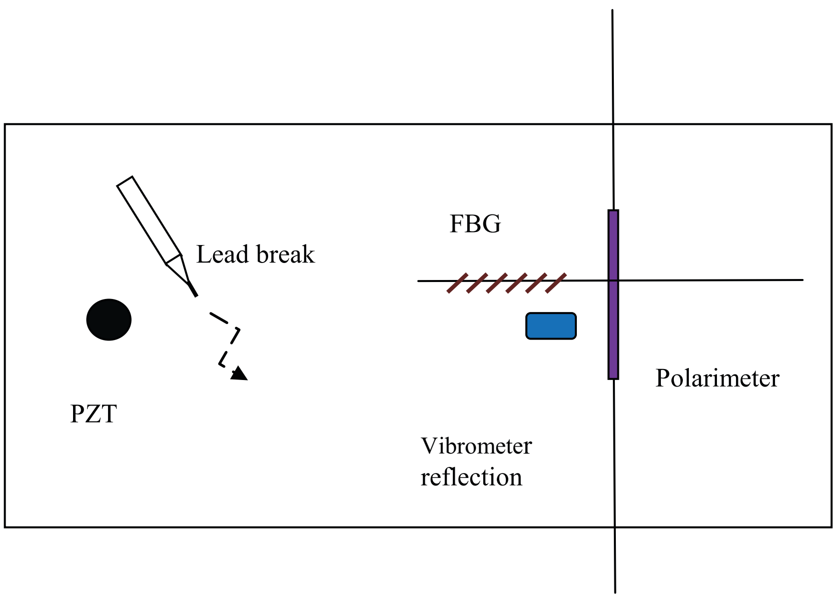

Figure 9. Plate layout for sensor comparison experiments

rotating the analyser whilst keeping the input polarisation state constant the A_0 response cold be made the disappear whilst the S_0 signal was only slightly reduced in amplitude. The trace obtained is shown in figure 10b. One of the most striking features of these traces is the large difference in relative sensitivity of the two fibre sensors and the vibrometer to the S_0 and A_0 modes. The 2 fibre sensors have the greatest sensitivity to S_0 modes which have relatively small out-of-plane motions compared to in-plane motions whilst the

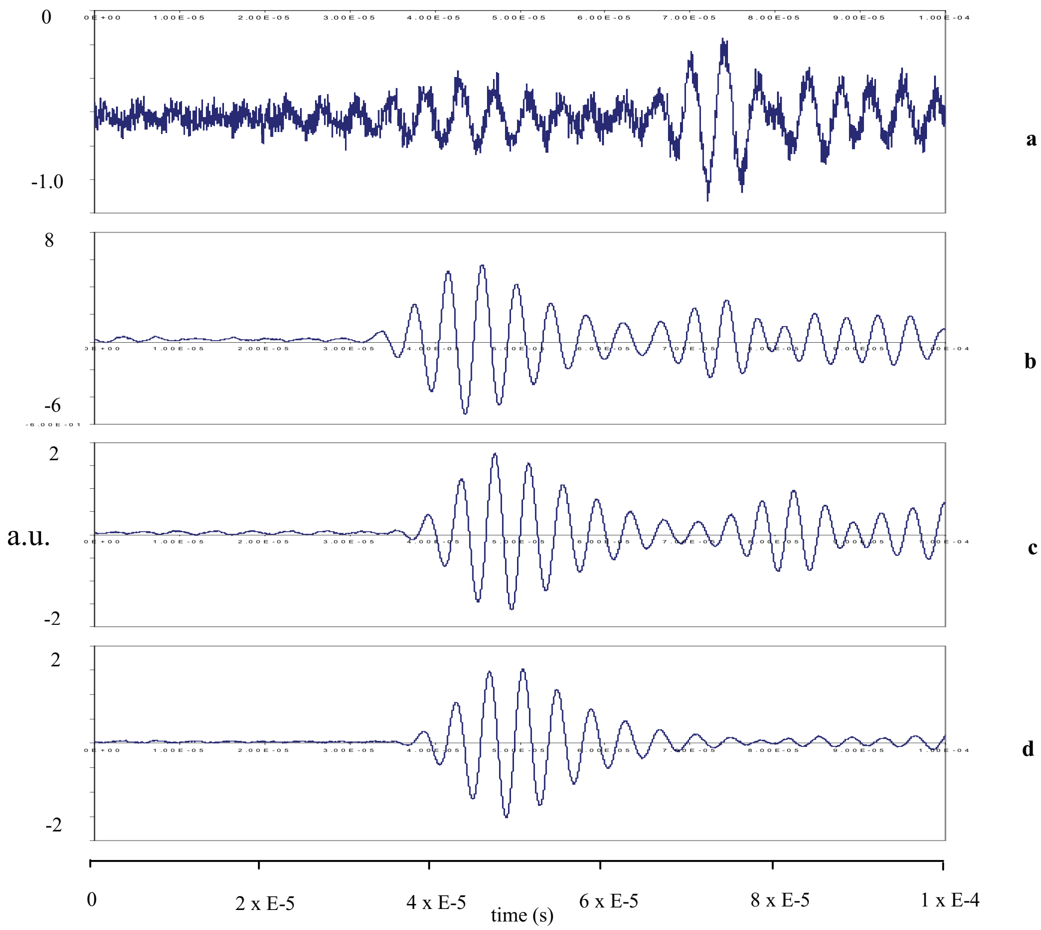

Figure 10. Comparison of sensor response to 4.5 cycle toneburst at 270KHz. (a) vibrometer (b) FBG (c) polarimeter with A_0 set to maximum (d) polarimeter with A_0 minimum

vibrometer is much more sensitive to the A_0 mode which has a larger out-of-plane component. With the polarimeter optimised as described above, the signal obtained is very similar in shape to that obtained from the FBG, though this not the case when the analyser is rotated to eliminate sensitivity to the A_0 mode. The amplitudes of the S_0 and A_0 signals were then plotted as a function of analyser orientation. In this case the polarmetric state was set to be circular at the fibre output, rather than optimising them for S_0 and A_0. The general trends exhibited are similar to those for the perspex plate experiment, but with the difference that the S_0 mode does not have its amplitude altered by rotation of the analyser to the same degree. Why this should be so has yet to be determined, though a possible explanation may be found in the difference in bonding method of the fibre sensor to the sample plate with the consequent change in interaction between the acoustic wave and the fibre.

These results demonstrate the different relative sensitivities of the sensors to the S_0 and A_0 modes and also shows that the polarimetric sensor shows different responses to the 2 modes depending on how it is interrogated. If the polarimetric sensor could be used to determine the difference between symmetric and antisymmetric modes, then it might be possible to detect mode conversion within a structure that could be caused by damage to it.

6. LEAD BREAK EXPERIMENTS

The objective of this experiment was to compare the responses of the Polytec vibrometer, an FBG grating and a polarimetric sensor to acoustic emissions as simulated by pencil lead breaks on a sample surface. A

1mm thick aluminium plate was set up as shown below. The FBG and the polarimeter were located as close together as was practical and an area polished close by to provide a reflective area for the vibrometer to interrogate. The 1mm gauge length FBG was attached using a polyacrylate strain gauge adhesive whilst the polarimetric sensor consisted of a 3 cm length of polyimide coated single mode fibre bonded to the plate using nail varnish. The 2 fibre sensors were mounted orthogonally since the FBG is most sensitive to strain in the direction of propagation whilst the polarimeter responds to pressure waves along its length.
Before carrying out the lead break experiments the polarimeter had to be set up and characterised using acoustic signals whose properties could readily be controlled. In order to do this a PZT transducer was bonded to the surface of the plate and the acoustic wave produced by exciting it with a waveform generator. For the first set of experiments the polarimeter was set up as follows. A 4.5 cycle toneburst produced by a waveform generator was used to excite to the PZT disc bonded to the surface of the plate. A frequency of 180 KHz was used in order to generate both S_0 and A_0 modes. The position of the polarisation controller and the orientation of the output analyser were adjusted such that the signals from the two modes were approximately equal. A series of lead break tests were carried out and the sensor responses compared. Although obviously lead breaks are not entirely repeatable, several significant differences could be consistently be seen between the responses of the vibrometer and the FBG and Polarimeter. Both the FBG and, to an even greater extent in the polarimeter, showed a stronger initial high frequency component of the signal. The lower frequency components of the signal which appeared later increased with time in the vibrometer signal, but reached a peak and then declined in the polarimeter response (figure 12). This suggested that these waves had a higher relative out-of plane to in-plane displacement with decreasing frequency.

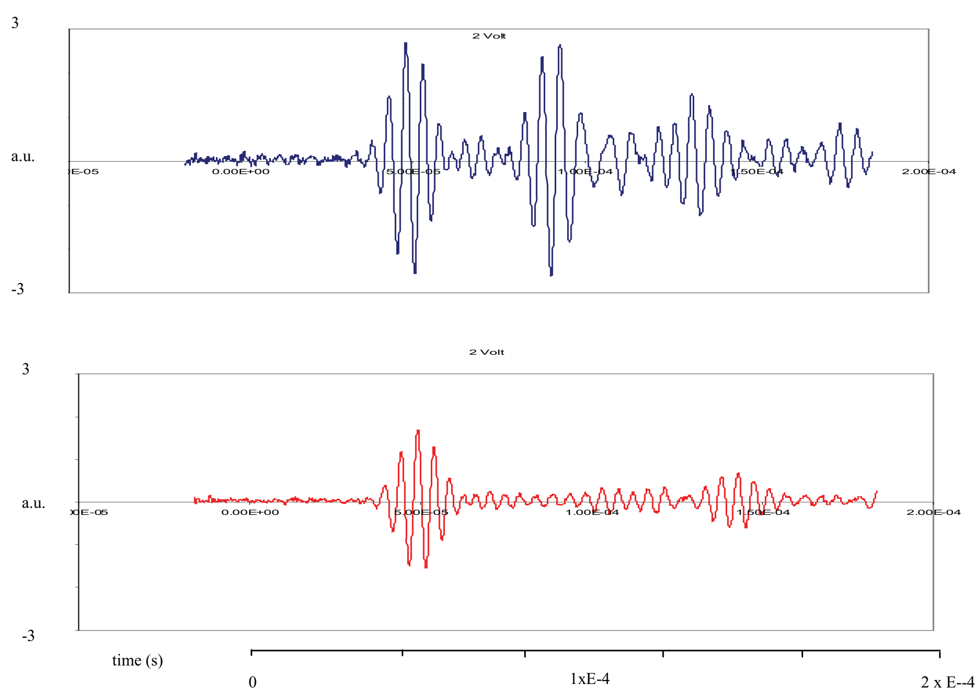

Figure 11. Polarimeter set to detect S_0 and A_0 equally (top) A_0 minimised (lower)

The polariser was then reset using the PZT generated source signal. This time the analyser was rotated until the A_0 signal disappeared whilst the amplitude of the S_0 was much less affected. A new series of lead break experiments was carried out, (figure 13) but this time the polarimeter recorder virtually no signal whilst the signals from the other sensors remained similar to before. This suggested that the wave generated by the lead break had A_0 like properties; an impression reinforced by the dispersive nature of the wave.

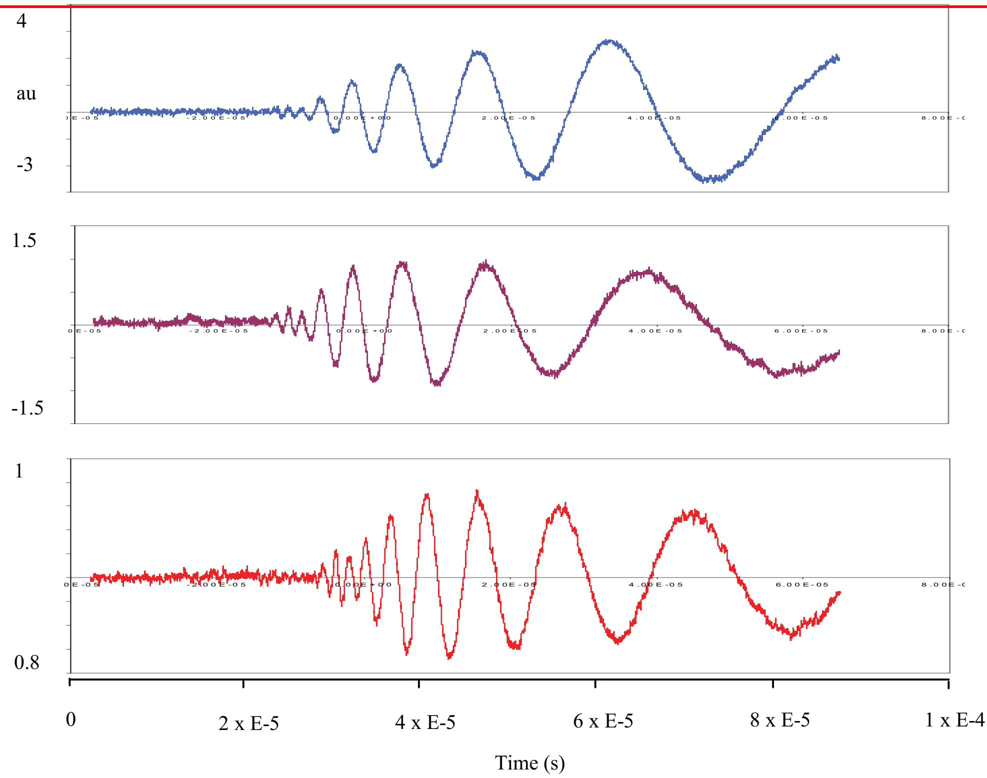

Figure 12. Typical pencil lead break signals with Polarimeter set for equal S_0:A_0

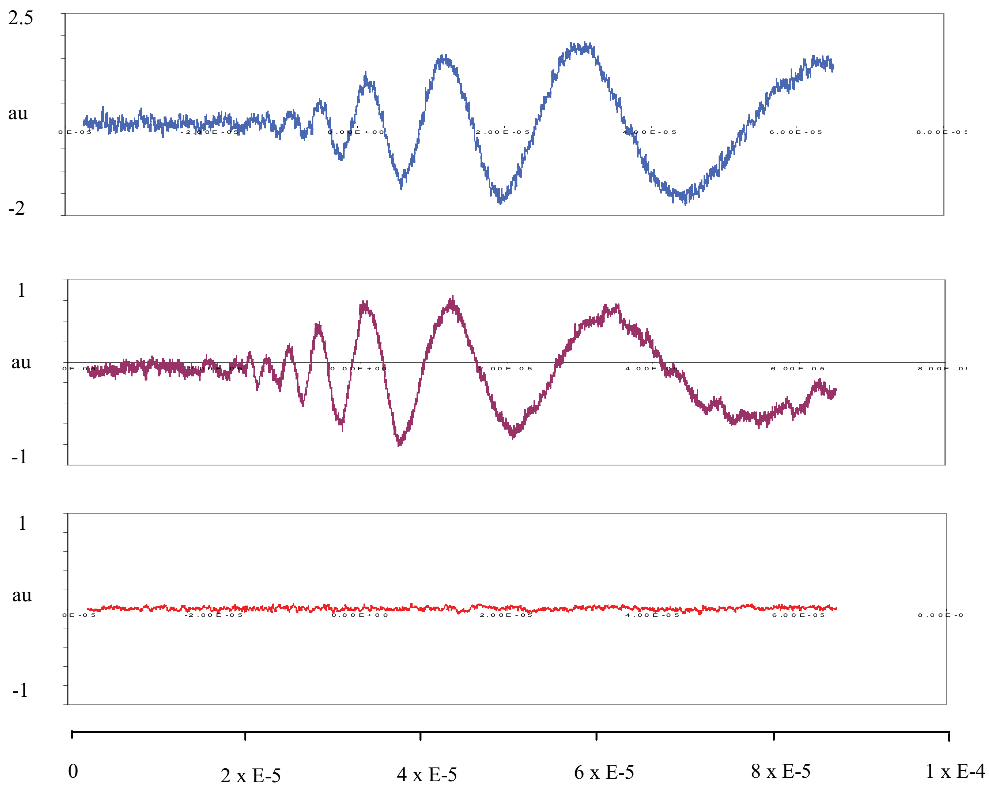

Figure 13. Typical pencil lead break signals with polariser set for minimum A_0

CONCLUSIONS

The differences between the responses of three optical sensors to both narrowband and broadband sensors has been demonstrated. In particular the difference in relative in-plane and out-of-plane motions for symmetric and antisymmetric modes has been shown to give greater sensitivity to FBGs and the vibrometer respectively. The response of the polarimeter has been shown to be heavily dependent on the polarisation state launched into the sensing fibre and the orientation of the analyser. This changing response is probably due to the difference in the orientation of the birefringence axes produced by the symmetric and antisymmetric modes. It has been seen that the pencil lead break test signal disappears when the polarimeter analyser is oriented to give a minimum A_0 response, suggesting that it is this mode that is primarily generated by this test. A comparison between the FBG and vibrometer signals also demonstrates that the relative in-plane motion decreases relative to the out-of-plane motion as the acoustic wavelength increases. Future planned work includes the extension of broadband signals to include the detection of laser generated ultrasound and theoretical modelling to understand the interaction between the acoustic signal and the optical fibre. To this end it is intended to embed both FBGs and polarimetric sensors at different locations within a carbon composite plate.

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