Validation of an Optical Fibre Based Plate-Wave Mode Conversion Technique for Damage Detection in Plates

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Abstract

This paper describes an experimental study into the use of an optical fibre sensor containing a dense array of short fibre Bragg gratings (FBG) to detect Lamb wave mode conversion caused by structural defects in plates. Laser Vibrometry (LV) is first used to demonstrate mode conversion of higher-order Lamb wave modes due to a notch. An FBG sensor array is then applied to the same problem. The array is shown to provide a reliable means of detecting mode conversion from the notch.

Keywords: Lamb waves, Piezoelectric Transducers, Laser Vibrometry, Fibre Optics, Distributed Sensing, Acousto-Ultrasonics, Nondestructive Testing, Structural Health Monitoring.

Introduction

Acousto-Ultrasonics (AU) provides an efficient method for large area scanning of plate-like structures, particularly when applied using Lamb waves for in-situ structural health monitoring (SHM). The method allows for relatively large area coverage using a sparse sensor network. The conventional AU approach is to use structurally integrated piezoelectric transducer pairs to generate and acquire Lamb waves in a pitch-catch arrangement [1]. However, the existence of at least two potentially dispersive modes at any given frequency makes an analysis of the wave signatures difficult. In an attempt to simplify the analysis, AU approaches have focused on using the fundamental symmetric (S_0) and antisymmetric (A_0) Lamb wave modes in a non-dispersive regime to detect damage, a regime where wave packets are generally temporally separated and coherent [1-6]. These modes, however, are not necessarily the most informative for the detection and characterisation of structural damage.

Higher-order modes offer the potential for greater sensitivity to damage. Moreover, the use of a multi-modal signal affords the opportunity to use wave-mode conversion as a diagnostic tool; the richer the modal content, the higher the likelihood of mode conversion in the presence of defects. Mode conversion in a complex multi-modal signal, conventionally acquired in the time domain using a single sensor, is not easily distinguishable. However, by acquiring spatially separated measurements, the propagating modes can be separated using a two-dimensional Fourier transform [3]. In plate wave research, experimental data is most commonly acquired using a laser Doppler vibrometer (LDV). However, the large size and delicate construction of these instruments limits their use to a controlled laboratory environment. In the case of in-situ SHM, measurements are normally derived from surface bonded piezoelectric wafers [1-2], and whilst these can also sample a wave-field across a dense grid their use in that capacity is cumbersome and the resolution achieved is vastly inferior to what can be achieved by an LDV scan.

Optical fibres provide an alternative means of in situ Lamb wave sensing [8-14]. The fibres are relatively non-intrusive, are immune to Radio frequency (RF) interference, have good mechanical and environmental durability [7] and permit relatively dense sensor multiplexing. The latter point relates to the fact that a single fibre can host a large number of sensors. Writing sensors in a fibre at separations sufficiently small to permit the resolution of high frequency Lamb waves does pose significant challenges, but can be done, as reported previously by the authors [12]. That previous study described the development of a sensor comprising 14 Fibre Bragg Gratings (FBG) and its successful decomposition of a Lamb wave field consisting of the fundamental Lamb modes only. A stiffness inhomogeneity introduced into the panel under investigation caused mode conversion from S_0 to A_0 which was successfully detected by the sensor. This paper extends the frequency range of that work beyond the first cut-off frequency to investigate the potential for obtaining diagnostic information from higher order modes in a complex multi-modal environment.

The work details the evaluation and validation of an FBG sensor array, called the Acoustic Mode Assessment Photonic (AMAP) sensor. Firstly, the modal content above the first cut-off frequency for a metallic plate is characterised using laser vibrometry (LV). Mode conversion due to a manufactured notch is then demonstrated. The data is then undersampled to represent the resolution achievable by an optical fibre sensor and re-analysed to determine the FBG separation and gauge length required to reliably isolate the target high-order mode conversion process in-situ. Using this information an optical fibre sensor array is manufactured and then applied to the same detection problem on a similar plate.

Experimental Method

The test bed for the experimental study was a 600 mm square plate specimen, made from a 5 mm thick Al5005 sheet. The experimental set-up is shown in Fig. 1. The actuator is a semi-circular piezoelectric element mechanically cut from a 1 mm thick and 10 mm diameter commercially sourced Pz27 disc. The element was bonded with the straight edge aligned along the edge of the plate using a conductive epoxy. The plate was scanned in its pristine condition using a LDV along a line parallel to and 10 mm from the edge of the plate, as shown in Fig. 1. The beam was aligned normal to the plate so as to measure the out-of-plane component of the velocity. A nominal notch location was chosen along the edge of the plate. LDV line scans were then measured upstream and downstream of that location. Both LDV line scans were 185.5 mm long and comprised 961 points resulting in a wavenumber Nyquist frequency of 6510 rad/m. The acoustic drive frequencies ranged from 500 kHz to 1 MHz in 50 kHz increments. The drive signal was a fixed duration (20 microseconds), Hanning-modulated toneburst. A notch was then milled with varying depth and length in the plate using the milling machine shown in Fig. 1 with a 1 mm diameter tungsten carbide miller.

In the first part of the study, a notch length sensitivity study was performed to ascertain whether the acoustic signal was sensitive to a relatively shallow notch growing in length perpendicularly to the acoustic wave front. The notch was progressed from a starting length of 2 mm, as measured from the edge of the plate, and a depth of 1 mm, and extended lengthwise in 2 mm increments. LDV line scans were performed after each increment. This process was repeated until a noticeable change in the acoustic response was observed. In the second part of the study, the notch depth was increased over the full length by 0.5 mm and 1 mm, respectively, and LDV line scans performed upstream and downstream of the notch after each depth change as per the notch length sensitivity experiment described previously.

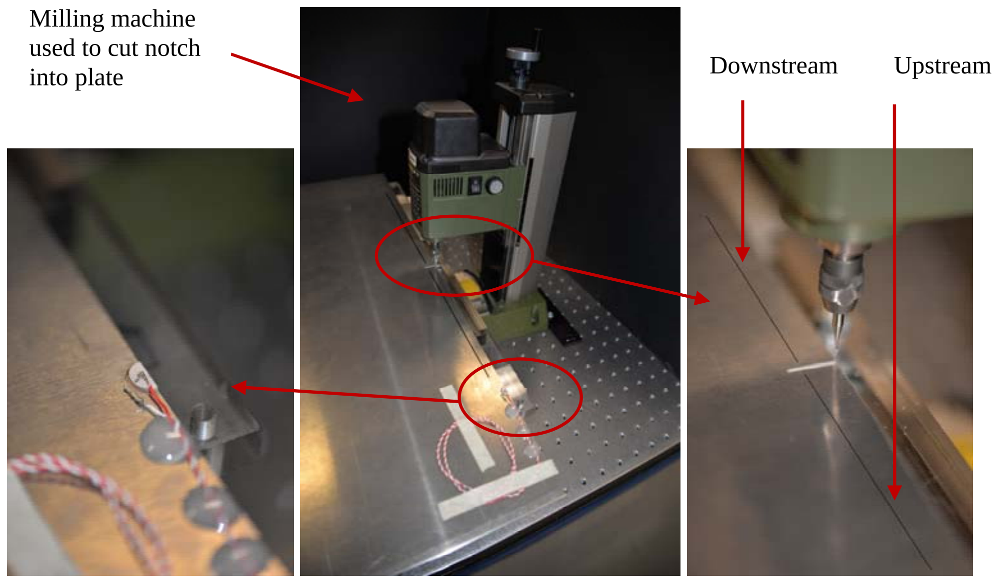


Fig. 1: Experimental set-up showing the semi-circular piezoelectric source element (left); the milling machine to create the notch (middle); and the tungsten carbide miller (right).

Results

The wave field from the LDV line scans were arranged in an array and time gated to exclude boundary reflections from the ends of the plate. The data was then zero padded, stripped of the DC component and finally spectrally decomposed into the constituent modes by applying a two-dimensional Fast Fourier Transform (FFT) [3]. Fig. 2 shows the modal content of the pristine plate from 500 kHz to 1 MHz, with four modes identified, namely the A_0, S_0, A_1 and S_2. The results were validated against the theoretical wavenumber spectrum for the plate, obtained using the commercial DISPERSE package [15]. The only significant difference between the two graphs is the absence of the S_2 mode in the downstream plot at the higher frequencies. This simply reflects a weakening of the wave with geometric spread.

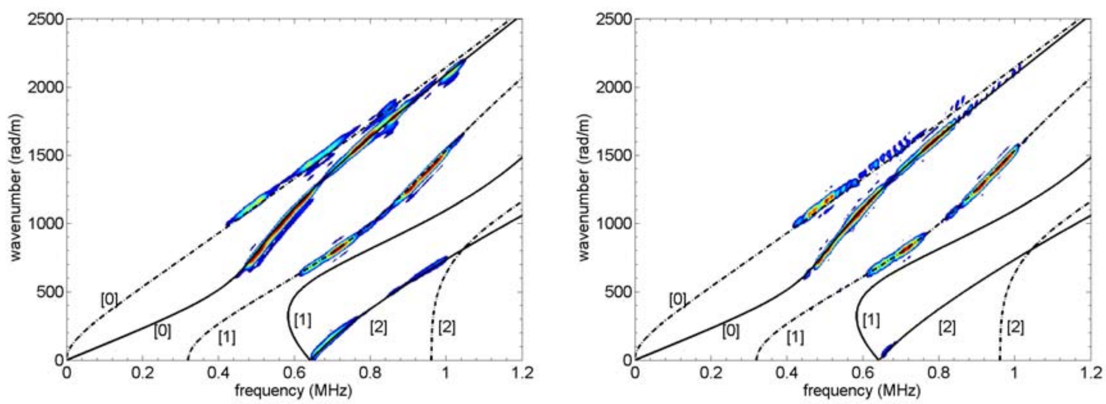


Fig. 2: Upstream (left) and downstream (right) spectral decomposition for pristine plate. Dotted lines denote dispersions lines for antisymmetric modes and solid lines for symmetric modes. The modal order is given in parentheses.

Notch Length Sensitivity

The results for each drive frequency were then assessed for mode conversion from the notch. An acoustic drive frequency of 950 kHz was found to be particularly informative. The downstream scans for the pristine plate (Fig. 3) show that the A_1 mode is dominant with some energy in the S_0 mode. As the notch is progressed lengthwise at a fixed depth, the amplitude of the S_0 mode is seen to grow as a result of conversion from the A_1 mode. Some energy also leaks into the S_2 and A_0 modes for notch lengths of 4 mm and beyond. However, most of the energy is converted into the S_0 mode. Fig. 4 shows line plots taken through each spectral decomposition centred on the frequency at which the energy in the converted S_0 mode is a maximum. These confirm a relatively constant S_0 strength upstream and a growth in strength downstream, supporting mode conversion as the source.

These observations suggest that for this panel, a robust diagnostic regime for a notch might be achieved by selectively exciting a first order antisymmetric mode and selectively detecting a fundamental symmetric mode. In principle, such a scheme should be more tolerant to extraneous effects than conventional AU approaches [13].

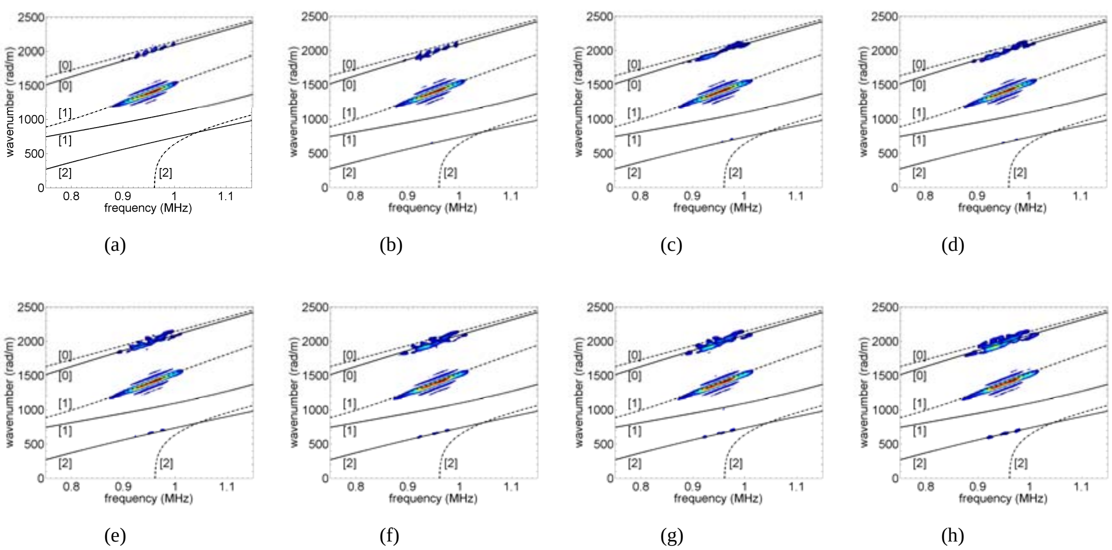


Fig. 3: Downstream spectral decomposition for (a) no notch; (b) 2 mm; (c) 4 mm; (d) 6 mm; (e) 8 mm; (f) 10 mm;(g) 12 mm; (h) 14 mm long notch.

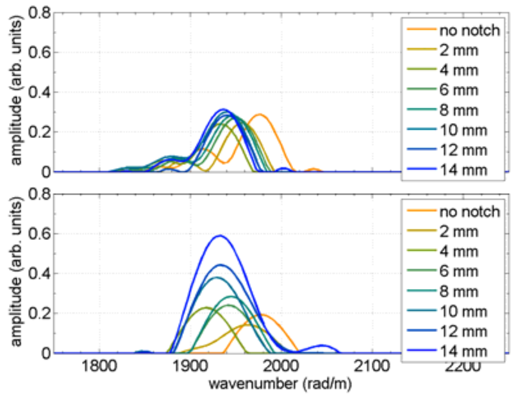
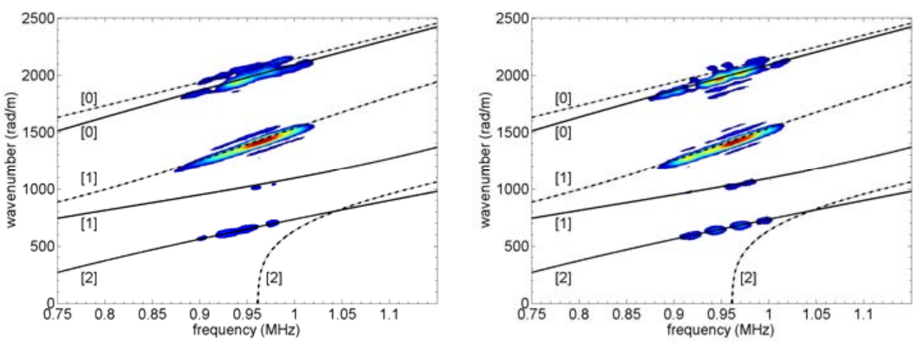


Fig. 4: Wavenumber profile at peak energy of the mode converted S_0 mode downstream of the notch (bottom) as its length is increased. The wavenumber profile upstream of the notch is shown (top) for reference.

Notch Depth Sensitivity

Following the notch length sensitivity study, the depth of the notch was increased to 1.5 mm and finally to 2.5 mm. Fig. 5(a) and (b) show the modal content of the response signal at 950 kHz, downstream of the notch. The strength of the mode-converted S_0 increases with notch depth, however, a line plot at the frequency of peak strength (Fig. 6) indicates a wider spread with respect to wavenumber, with a small proportion of the energy overlapping the A_0 mode. Interestingly, the results in Fig. 5 suggest that conversion from A_1 to S_1 is sensitive to a change in notch depth with the strength of the converted S_1 mode marginally increasing with depth.



(a) (b)

Fig. 5: Downstream spectral decomposition for (a) 1.5 mm; (b) 2.5 mm deep notch.

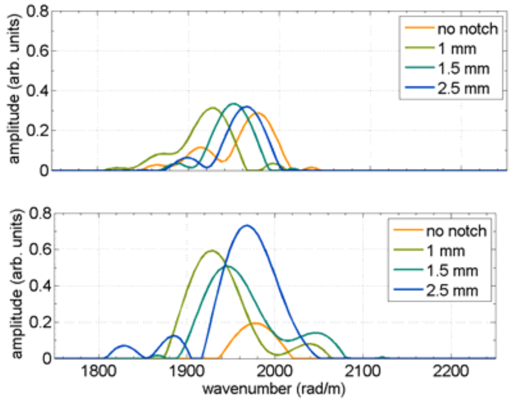
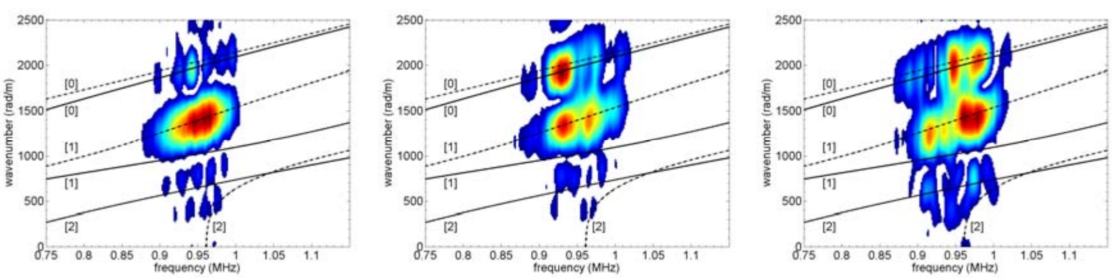


Fig. 6: Wavenumber profile at peak energy of the mode converted S_0 mode downstream of the notch (bottom) as the depth is increased. The wavenumber profile upstream of the notch is shown (top) for reference.

Optical Fibre Based Sensing

The results from the LV measurements show that mode conversion can provide a useful basis for detecting defects in a plate. However, as mentioned previously, an LDV is not a viable sensing instrument for in-situ SHM. An optical fibre sensor by contrast is. The question is whether an optical fibre sensor can resolve the identified higher-order mode conversion process. The LDV data described in the previous section is instructive. By undersampling this data to match the FBG separation length as well as the total length of the array, one can estimate the response of the array. The estimate is of course approximate as the LDV measures out-of-plane velocity whilst an FBG measures in-plane strain. A candidate optical fibre sensor array was designed consisting of 16 FBGs at a separation of 1 mm. The LDV data set was sampled accordingly, i.e. at a sampling interval of 1 mm. The resulting wave field was spectrally decomposed and the results for three test cases are shown in Fig. 7. The A_1 to S_0 mode conversion can still be observed. Satisfied that the proposed array design had the potential to resolve the conversion process, its manufacture proceeded.



(a) (b) (c)

Fig. 7: Spectral decomposition based on a low spatial resolution of the wave field at 950 kHz for (a) pristine plate; (b) a 14 mm long, 1 mm deep notch and (c) a 14 mm long, 2.5 mm deep notch.

FBG Measurements

Using the FBG writing facility described previously [14], an array was written into a photosensitive optical fibre (GF1) comprising 16 FBGs, each 1 mm in length with no separation between them. Each FBG was produced by aperturing the Ultraviolet (UV) laser beam to 0.2 mm and scanning across a 0.8 mm length of uncoated fibre through a phase mask. Multiple phase masks and fibre strains were used to achieve different grating pitches and thereby Bragg wavelengths. The index profile was apodised using an air-bearing stage according to a Blackman-Harris window to reduce lobes in the grating reflection spectrum.

The FBG sensor array was then applied to a second panel with similar dimensions as that described previously, again using a semi-circular piezoelectric source element. The fibre was bonded onto the plate using cyanoacrylate, parallel to and 10 mm from the edge at a location equivalent to the LDV line scan performed downstream of the notch. The drive signal was again a fixed duration (20 microseconds), Hanning-modulated toneburst. However, the acoustic drive frequency range was expanded to 100 kHz to 1.25 MHz to test the limits of the sensor array. The plate was scanned in its pristine condition. A notch was subsequently milled in the plate upstream of the FBG sensor array to a length of 14 mm and depth of 2.5 mm and the plate scanned again. Fig. 8 shows the modal content of the plate for an excitation frequency of 950 kHz and 1.25 MHz based on a wave field acquired using the FBG sensor array. Comparing the results from the LV measurements at the same frequency, it can be observed that the modal content extracted from the FBG sensor array are different. At 950 kHz, there is a noticeable decline in A_1 strength but little evidence that conversion to the S_0 mode has occurred. Although inconsistent with the LV analysis the selective suppression of the A_1 mode is potentially also a useful diagnostic metric. The FBG data yielded another potentially informative frequency regime. At 1.25 MHz, mode conversion was observed from A_1 to A_0 or S_0 and to S_1 and A_2. The difference between the LDV and FBG observations are most likely due to the two sensors measuring different field quantities. Nevertheless, the results suggest that detection of high-order mode conversion is possible using an in situ FBG sensor array.

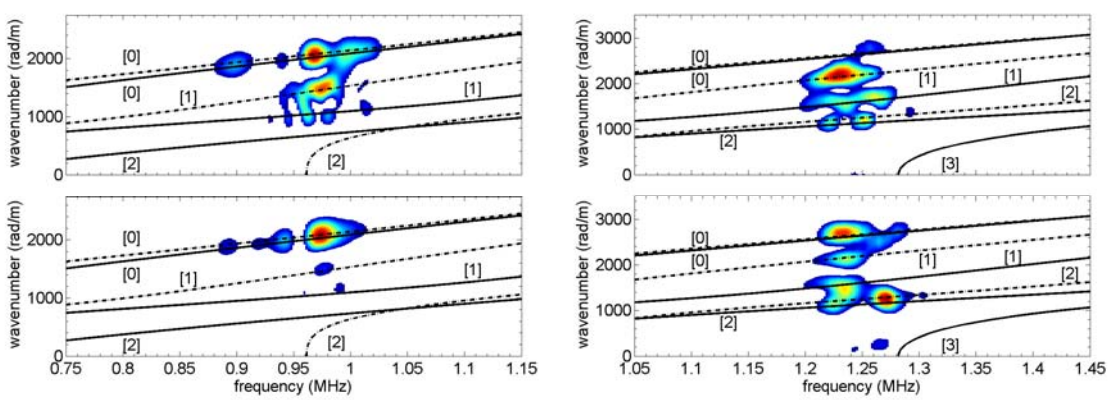


Fig. 8: Spectral decomposition of wave field acquired using FBG sensor array at 950 kHz (left) and 1.25 MHz (right). The top figures show the results for the plate in pristine condition and the bottom figures for the plate with a notch.

Discussion and Conclusion

The validation of an optical fibre based plate-wave mode conversion technique for damage detection in plates has been presented. Lamb wave mode conversion due to a notch in a metallic plate was demonstrated for higher-order modes at 950 kHz using LV with the A_1 to S_0 mode conversion particularly sensitive to length changes in the notch and A_1 to S_1 mode conversion apparently sensitive to changes in notch depth. The FBG sensor array was able to detect higher-order modes, despite having a much lower spatial sampling density than the LDV system. Suppression of the A_1 mode was observed at 950 kHz and conversion from A_1 to the fundamental modes (A_0 or S_0) as well as to S_1 and A_2 was observed at 1.25 MHz. The fundamental modes were not able to be distinguished because of a lack of sensor spatial resolution; however in the context of the proposed diagnostic approach where modes are selectively excited this may be of little consequence. The differences between the LDV and FBG observations are possibly due to the fact that different field quantities are involved. This suggests that although convenient and powerful, an LDV cannot be used to directly validate the response of an FBG or any other strain-coupled sensor. This shortcoming can be addressed by converting out-of-plane velocity measurements to in-plane strains, as shown in [16]; however this step was not applied in the present study. Ultimately, the aim is to replace empirical studies employing an LDV with Finite Element (FE) modelling for the design of a mode-conversion based SHM system. FE modelling is far more efficient and flexible and permits access to the field quantities of direct interest. The ability to selectively excite a particular mode is an important element in this diagnostic approach. Monolithic piezoelectric elements offer some scope for modal tuning [17] via the selection of disc diameter and bondline thickness, however where this approach is not selective enough interdigitated transducers might offer a better solution.

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