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Acoustic Source Localisation using Distributed Sensing

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Abstract

The actuation of Lamb waves in thin plate-like structures and subsequent interpretation of the scattered wave field offers a capability for broad area damage detection and location. In practice, interpretation of a scattered field can be difficult when there are several overlapping wave modes propagating which is a realistic scenario for many applications. This paper reports on the use of spatially distributed in situ measurements to decompose a wave-field into its constituent modes. A pass-band filter is applied to the complex spectrum of the wave-field and an inverse transform then applied to affect a complete time-domain separation of the constituent modes. Knowledge of the group velocity and time-of-flight for each mode allows the distance of the sensor from the source to be accurately determined while the pass-band filtered spectrum enables a determination of the relative orientation between the source and the sensor via the application of a corrective angle. The method is validated numerically and experimentally.

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1. Introduction

In-situ structural health monitoring (SHM) has garnered great interest over recent years, especially in the aviation industry due to the high ongoing costs involved in the maintenance and repair of ageing aircraft. Of the many techniques available, Acousto-Ultrasonics (AU) using Lamb waves (LW) is one of the most promising as it allows for large area scanning using a relatively sparse sensor network. The method is normally implemented using

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structurally integrated piezoelectric wafer active sensor (PWAS) pairs to generate and acquire Lamb waves in a pitch-catch arrangement [1]. The technique has been successfully applied to detect damage in plate-like structures [1-6].

The presence of multiple modes and dispersive wave propagation generally makes the interpretation of a scattered wave field difficult. As a result, AU-LW approaches have tended to use only the fundamental symmetric (S_0) and antisymmetric (A_0) modes which are normally excited in a non-dispersive frequency regime [1-6]. In this regime, the wave packets are temporally coherent and, given sufficient distance from the source, easily separated. Although this generally simplifies diagnostic analyses, these modes 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, and multiple modes provide increased capacity to use wave-mode conversion processes for structural diagnosis. Mode conversion in a complex multi-modal signal, conventionally acquired using a single PWAS, is not easily distinguishable. However, a spatially resolved measurement obtained using a laser Doppler vibrometer (LDV) enables the propagating modes to be easily separated using a two-dimensional fast Fourier transform (2D-FFT) [3]. The ability to make a similar type of measurement in situ would be of enormous value in SHM; however an LDV is not a viable in situ SHM technology and conventional PWAS elements are generally impractical for this type of measurement.

Optical fibres provide an alternative means of in situ Lamb wave sensing [7-15] and offer several advantages over PWAS sensing. They are relatively non-intrusive, are immune to radio frequency (RF) interference, have good mechanical and environmental durability [15] and permit relatively dense sensor multiplexing. This latter characteristic was exploited in experimental studies [7-9] to demonstrate the use of an in-situ fibre Bragg grating (FBG) array for spatially distributed contact sensing to measure multi-modal Lamb waves. In a recent extension to this work, pass-band filtering of the complex spectrum of the wave field was applied to affect a complete time-domain separation of the constituent modes [13]. Pass-band filtering of the complex spectrum provides the opportunity to isolate specific modes of interest and exclude extraneous effects such as interference from overlapping modes, boundary reflections and noise. This in turn allows for a robust diagnostic analysis of an AU-LW signal. For example, it was shown in [13] that based on the knowledge of the group velocity and the time-of-flight of each mode, the distance to an acoustic source was able to be accurately determined. In that particular study, the sensor array was aligned with the source to avoid an oblique sampling of the wave field.

The current study considers the situation where an acoustic source is at an unknown orientation relative to the sensor array. It is shown that if the thickness and material composition of the plate is known, the orientation of the source can be determined from the wavenumber shift in the measured spectrum. In combination with a determination of distance made using the approach in [13], this results in a robust estimate for the location of the source. The concept is proven both numerically, using a finite element model, and experimentally using measurements from an LDV. The numerical study is outlined first.

2. Numerical Study

A three-dimensional finite element model of a 3 mm thick aluminium square plate, with nominal side dimensions of 300 mm, was created in the commercial COMSOL multiphysics package. To reduce the size of the computational problem, only a quarter of the plate was modelled and is shown in planar view in figure 1. The excitation signal was applied at the origin of the quarter model (corresponding to the centre of the plate) and the propagating waves were extracted along the lines, hereafter referred to as scan lines, at angles of 0°, 22.5°, 30°, 45° and 60° relative to the position vector of the reference point, as shown in figure 1. These orientations were chosen arbitrarily. The drive signal was a fixed duration (20 μs), Hanning-modulated tone-burst with a centre frequency of 900 kHz, which is above the first cut-off frequency for the plate. The model was discretised such that the nodal separation was 0.5 mm along the length, width and depth. The transient analysis of the model was advanced at 0.067 μs intervals. The spatial and temporal discretisation was sufficient to resolve the shortest wavelength, being the A_0 mode at 3 mm and fastest wave, being the A_1 mode at 3708 m/s, as shown in figure 2 which traces the theoretical wavelength and group velocity spectra for the first five modes in the plate. These values were obtained using the commercial DISPERSE package [16]. The latter relies on the material properties and thickness of the plate to predict the aforementioned