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A modified time reversal method for Lamb wave based diagnostics of composite structures

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ABSTRACT

This experimental study presents Lamb wave based diagnostics of damage in a composite plate using time reversal of signals for baseline-free damage detection. A modified time reversal method (MTRM) is developed which requires only one transducer to actuate signals and the other transducer acts as a sensor for any signal path. An 8-layer symmetric cross-ply carbon-epoxy composite plate is fabricated and four PZT actuators/sensors are surface bonded at the corners of the plate. A 20 kHz, 9.5 cycle tone burst signal is used to generate fundamental asymmetric Lamb waves with high signal-to-noise ratio and low dispersion. Theoretical analysis and experimental measurements show that conventional time reversal method (TRM) and the MTRM yield identical signals at the end of time reversal. The composite plate is impacted incrementally with a steel ball to cause three levels of damage and MTRM is applied for prediction of damage severity. Results show that magnitudes of the two damage indices used are directly correlated to the severity of damage along any signal path. The development of MTRM paves the way for implementing time reversal of signals using a single actuator and multiple sensors, including non-contact sensor such as a laser vibrometer.

1. Introduction

The use of composites for engineering structures (aerospace, wind energy, civil infrastructure, etc.) is increasing rapidly due to several advantages, such as higher specific strength and modulus, fewer joints, improved fatigue life, and higher resistance to corrosion. However, composite structures have complex damage mechanisms such as delamination between plies, fiber–matrix debonding, fiber breakage, and matrix cracking. These damages often occur below the surface due to foreign object impact, fatigue, etc., and may not be visible. The existing practice for ensuring structural safety (that is, scheduled-based maintenance) leads to expensive inspections, unnecessary downtime and retirement, and sometimes catastrophic failures without any warning. Therefore, a structural health monitoring (SHM) system capable of detecting damage presence, location, and severity in composite structures is urgently needed. A reliable SHM system would provide tremendous benefits in terms of life-cycle costs by detecting damages early and allowing a much more efficient maintenance schedule (condition-based maintenance).

Lamb wave based SHM of composite structures has shown significant promise. Lamb waves are particularly suitable due to the similarity between their wavelength and the thickness of composite structures generally used and their ability to travel far distances. These two features allow for detection of not only superficial, but internal flaws also, and the ability

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to examine large areas. However, it is difficult to analyze measured responses due to the multimodal and dispersive characteristics of Lamb wave propagation. Therefore, a tone burst signal, with carefully selected center frequency and cycle number, is generally used for actuating Lamb waves. Signal processing and dispersion curves are typically used to help the damage detection process and understand complex Lamb waves. The books by Giurgiutiu [1] and Su and Ye [2] and the review article by Raghavan and Cesnik [3] contain the fundamentals of Lamb wave based structural diagnostics and extensive lists of related publications. Interested readers may also refer to [4–10] for some of the more recent articles on the use of Lamb waves for SHM of plate-like structures.

Lamb wave based damage detection is generally performed using "baseline" data from a healthy (pristine) structure. The baseline data are compared with the new measurements (obtained from a possibly damaged structure) and any significant difference beyond a threshold value indicates damage. However, obtaining reliable baseline data is very challenging in practice because of the effects of varying operational, environmental, and manufacturing conditions. Therefore, "baseline-free" damage detection methodology is highly desirable for the practical use of SHM. The concepts of "instantaneous baselines" [11] and "relative baseline" [12] have been proposed to overcome the need for pre-stored baseline data.

The "time reversal" method (TRM) is a novel approach to mitigate Lamb wave dispersion effects and perform SHM without the need for baseline data. Initial applications for TRM were aimed at increasing Lamb wave resolution by using time reversal mirrors. In this process, a Lamb wave pulse is emitted at a target and the reflected signal is recorded by an array of transducers, or time reversal mirrors. The reflected section of the received signal is reversed in time and reemitted toward the target. By repeating this procedure, dispersion and unknown material deformation is compensated for by focusing the signal. Applications using this pulse-echo technique were able to detect flaws in inspected areas [13]. Applications of time reversal using the pitch-catch method for damage detection in metallic and composite plates have received some attention [14–19] in the last decade. In this process, a tone burst signal is actuated from one transducer and received by another. The received signal is then reversed in time and re-emitted to the original transducer where the signal is received and reversed in time ("final signal"). Based on the assumption of linear reciprocity within a healthy structure, the final signal and the original signal compare exactly (both signals are normalized using their peak amplitudes). When nonlinearities are introduced into the system by damages, linear reciprocity breaks down and the differences between the two signals indicate the presence of damage.

Wang et al. [14] presented experimental and theoretical investigation of the time-reversal concept to dispersive and multi-modal guided waves in plates. They showed that both spatial and temporal focusing can be achieved through the time reversal process with a distributed network of circular patch transducers for broad area monitoring. Park et al. [15] used a narrowband excitation waveform to address the frequency dependence of the time reversal operator and developed a wavelet-based signal processing technique to enhance the time reversibility of Lamb waves in thin composite plates. Sohn et al. [16] applied the TRM to determine presence and location of delamination damage in composite plates using a rigorous statistical classifier based on extreme value statistics. Giurgiutiu [1] simulated time reversal with two-mode Lamb waves (fundamental symmetric and asymmetric modes) and showed that the reconstructed wave has two extra packets, placed symmetrically about the main wave packet. Park et al. [17] investigated various effects on TRM such as frequency dependency, within-mode dispersion, multi-modal behavior, and boundary reflections. Gangadharan et al. [18] showed that time reversal can be used to achieve temporal recompression of Lamb waves under both narrowband and broadband signal excitations. Poddar et al. [19] investigated different parameters such as frequency, band width, transducer size and the effects of tuning these parameters on the quality of the reconstructed signal after time reversal.

This paper presents a modified time reversal method (MTRM) which can reduce the hardware (PZT power amplifier, wiring, etc.) requirements significantly by using a single actuator and multiple sensors for structural diagnostics. For any signal path, MTRM requires only one transducer to actuate signals and the other transducer to sense signals. This is in contrast with conventional TRM where both transducers need to work as actuators and sensors. Furthermore, the developed MTRM has the potential to use non-contact sensors such as a laser vibrometer. The MTRM is validated through theoretical analysis of Lamb waves actuated by PZT transducers. It is shown that TRM and MTRM have the same signal at the end of the time reversal process, which is further verified through experimental measurements. Knowledge of damage severity is crucial in SHM, but it has not been investigated using TRM. The developed MTRM is used for diagnosis of damage severity in an 8-layer cross-ply composite plate impacted incrementally to cause three levels of damage. Section 2 of this paper presents the derivation of dispersion curves for Lamb waves and its experimental verification. Section 3 discusses time reversal and modified time reversal methods along with its theoretical analysis in Fourier space. Section 4 contains details of the experimental setup and shows similarity between TRM and MTRM signals. The detection of damage severity in a composite plate using two damage indices is given in Section 5. Finally, Section 6 presents the concluding remarks.

2. Lamb wave dispersion curves

Discovered by Sir Horace Lamb in 1917 and first implemented as a means for damage detection by Worlton in 1960, Lamb waves result from the superposition of guided longitudinal and transverse (shear) waves. Lamb waves travel in thin plates with unconstrained boundaries and have the capability of traveling long distances with little attenuation. Due to their propagation characteristics, Lamb waves can be used as a means to detect both superficial and internal flaws in a structure. Local stiffness degradation, cracks or delaminations (in composite laminates) cause reflections, dispersion, attenuation and mode shape changes in propagating Lamb waves. These changes in wave characteristics can be used to diagnose structural defects.