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Effects of adhesive, host plate, transducer and excitation parameters on time reversibility of ultrasonic Lamb waves

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ABSTRACT

To develop an effective baseline-free damage detection strategy using the time-reversal process (TRP) of Lamb waves in thin walled structures, it is essential to develop a good understanding of the parameters that affect the amplitude dispersion and consequently the time reversibility of the Lamb wave signal. In this paper, the effects of adhesive layer between the transducers and the host plate, the tone burst count of the excitation signal, the plate thickness, and the piezoelectric transducer thickness on the time reversibility of Lamb waves in metallic plates are studied using experiments and finite element simulations. The effect of adhesive layer on the forward propagation response and frequency tuning has been also studied. The results show that contrary to the general expectation, the quality of the reconstruction of the input signal after the TRP may increase with the increase in the adhesive layer thickness at certain frequency ranges. Similarly, an increase in the tone burst count resulting in a narrowband signal does not necessarily enhance the time reversibility at all frequencies, contrary to what has been reported earlier. For a given plate thickness, a thinner transducer yields a better reconstruction, but for a given transducer thickness, the similarity of the reconstructed signal may not be always higher for a thicker plate. It is important to study these effects to achieve the best quality of reconstruction in undamaged plates, for effective damage detection.

1. Introduction

Most structural failures are the result of the growth of an initially unsuspecting structural damage or progressive accumulation of material defects, reaching a critical level. In some cases, e.g. in transportation vehicles and pressurized equipment, such failures may lead to irretrievable and sometimes catastrophic consequences. For example, between 1990 and 2007, there were 1502 passenger aircraft crashes in the U.S. of which 386 (26%) were fatal, resulting in 1104 deaths [1], many of which happened due to material failure. This happened in spite of the fact that the aircraft industry follows the most advanced design principles, and a very elaborate maintenance and inspection regime, through nondestructive evaluations (NDE). The world's most serious high-speed train disaster, the German Eschede train crash in 1998, was caused by fatigue cracks in the wheel rims under repetitive load (500,000 cycle per day). Its detection in time could have prevented the catastrophe. Such failures bring to evidence a serious gap in today's science and technology capabilities. This underlined the need for real time detection of damage, which has recently led to the concept structural health monitoring (SHM), essentially by combining the NDE with built-in sensors and actuators [2,3]. By replacing a schedule-driven maintenance with a condition-based as-needed maintenance regime, SHM would not only prevent catastrophic failures, but also lead to a significant reduction in the cost of maintenance and repairs, enhancement of reliability and increase in the operating time and life of the structures. Among various methodologies proposed for SHM, the ultrasonic guided wave (e.g. Lamb waves in plates) based techniques using thin piezoelectric wafer patches for actuating and sensing have gained extensive interest for their ability to detect damage of small size (up to half its wavelength) with low energy consumption [4–9].

Generally, the damage location and size are determined by comparing the scattered signal from a possible damage with a reference or baseline signal of the ultrasonic Lamb wave, which corresponds to the undamaged state of the structure [6,10]. However, since the measured changes in the signal can be caused by many factors other than the damage, such as fluctuations in the temperature and stress levels in the structure [11], this technique

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cannot be implemented unless robust compensation methods for the baseline data are developed, which is an extremely challenging task. Some researchers have attempted compensation for varying environmental conditions, specially temperature changes, by storing several baseline measurements over a range of temperature [12,13]. Such compensation methods are not suitable for practical SHM systems, as it is not possible to subject a real structure to all possible environmental conditions that it is likely to encounter, for acquisition of a database of baseline measurements. Moreover, the storage and management of such a large database of baseline measurements can also cause several complications. Hence, the idea of developing baseline-free methods for damage detection is being explored in recent years.

Originally studied for acoustic waves under various names, matched filter [14], matched signal technique [15] and time-reversal process (TRP) [16], the concept of TRP of elastic waves is being currently studied as a promising candidate for baseline-free damage detection in thin-walled structures like beams, plates and shells. According to this concept, in an undamaged structure, an input signal can be reconstructed at the source transducer, if the output signal at the sensor is reversed in time and emitted back to the original source transducer. But, this property of linear spatial reciprocity breaks down in presence of damage, due to the nonlinear interactions of the transmitted wave with the damage, and the resulting dissimilarity between the original input and time reversed signals indicates the presence of damage. Fig. 1 shows the concept schematically. However, unlike body waves encountered in acoustics for which the TRP has been successfully applied, the time reversibility of Lamb waves are complicated due to two characteristics: dispersiveness and multi modality. Due to its dispersive nature, different frequency components of Lamb waves travel at different speeds (velocity dispersion) and attenuate at different rates (amplitude dispersion). While the velocity dispersion can be compensated by the TRP, the amplitude dispersion renders it nearly impossible to achieve a perfect reconstruction of the original waveform, particularly when a broadband excitation (e.g. Gaussian pulse) is used, as was observed by Wang et al. [17].

Park et al. [18] demonstrated both theoretically and experimentally in a composite plate that it is possible to minimize the amplitude dispersion effect and successfully reconstruct the original input waveform by using a narrow-band excitation signal. The frequency was selected so as to excite only the fundamental antisymmetric A_0 mode. Xu and Giurgiutiu [19,20] and Santoni et al. [21] also studied single-mode tuning effects on Lamb wave time-reversal in thin metallic plates with surface-bonded PZT patch transducers, and concluded that single-mode Lamb waves are rigorously time reversible under narrow-band excitation, and hence are recommended for time-reversal based damage detection. The time-reversal of a mixed mode ($S_0 + A_0$) Lamb wave creates two extra wave packets symmetrically placed around the main wave packet. Their experimental results conducted on an aluminum plate using surface mounted PZT transducers, however, showed that a two-mode ($S_0 + A_0$) Lamb wave yielded a better reconstruction by the TRP than either of the single modes (S_0 or A_0).

The use of the TRP of Lamb waves for damage detection was illustrated by Sohn et al. [22], examining the deviation of the reconstructed signal from the known input signal in a composite plate containing delamination damage. Poddar et al. [23] used the time-reversal method for experimentally detecting notch, block mass and surface corrosion type defects in metallic plates. At the same time, it has also been reported by several researchers that the similarity index of the reconstructed signal with the original input signal does not show appreciable difference between the undamaged and damaged states for notch and surface damages in metallic plates [24,25]. This aspect was recently examined by the authors [26] through finite element (FE) simulations verified by some experimental data. Using frequency sweeping with narrow-band modulated tone burst excitations, they showed that (i) the single-mode tuning does not lead to the best reconstruction of the original input signal in the undamaged plate, and (ii) the damage index computed using the conventional main wave packet of the reconstructed signal does not indeed show any appreciable change in presence of notch-type damage. To overcome this drawback, the authors introduced the concept of the *best reconstruction frequency* at which the similarity index in the undamaged plate is maximum over a given range of excitation frequency. It can be determined for a given structure-transducer-adhesive system in undamaged state by frequency sweeping over a desired frequency range depending on the size of defects to be detected. At this frequency, the wave contains both S_0 and A_0 modes in general. A refined method of computing the damage index was proposed using an extended wave packet ranging between the two side bands accompanying the main wave packet, which showed excellent sensitivity to damage when used at the best reconstruction frequency. The FE model employed in the aforementioned study, however, assumed a perfect bonding between the transducers and the plate. Apart from the excitation frequency, several parameters such as the bonding between piezoelectric wafer transducers and the host plate, the transducer size, the plate thickness as well as the tone burst count in the excitation signal affect the amplitude

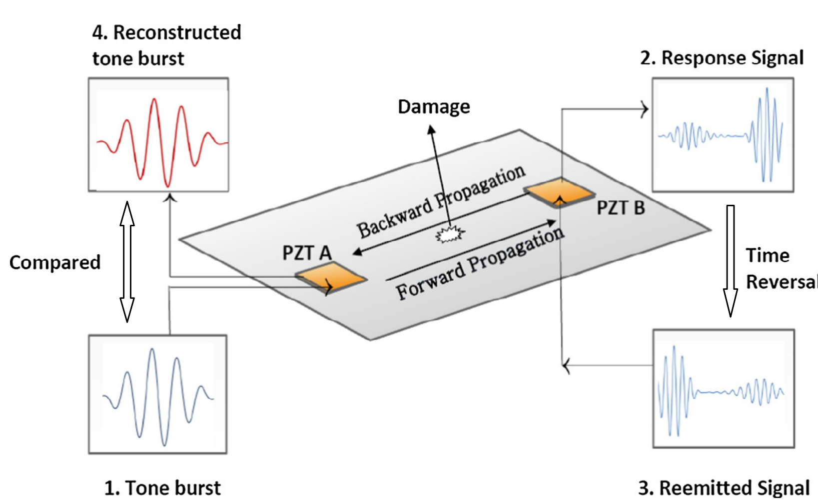

Fig. 1. Schematic concept of damage identification in a isotropic plate through time-reversal process.