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Lamb wave mode decomposition for structural health monitoring

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HIGHLIGHTS

- A Lamb wave mode decomposition method is proposed based on two rules.
- The first rule is the group velocity ratio rule.
- The second rule is the mode amplitude ratio rule.
- The proposed method is validated through the experiment.

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ABSTRACT

Lamb waves propagate over large distances in plate-like thin structures and they have received great attention in the structural health monitoring (SHM) field as an efficient means to inspect a large area of a structure by using only a small number of sensors. The times-of-flight of the Lamb wave modes are useful for detecting damage generated in a structure. However, due to the dispersive and multi-mode nature of Lamb waves, it is very challenging to decompose Lamb wave modes into symmetric and anti-symmetric modes for potential applications to structural health monitoring. Thus, we propose an efficient Lamb wave mode decomposition method based on two fundamental rules: the group velocity ratio rule and the mode amplitude ratio rule. The group velocity ratio rule means that the ratio of the group velocities of A_0 and S_0 modes must be constant. The mode amplitude ratio rule means that the ratio of the magnitudes of A_0 and S_0 modes in a measured response signal must be always greater than one once the center frequency of the input signal is determined, such that the magnitude of the A_0 mode in the excited signal is larger than that of the S_0 mode, and *vice versa*. The proposed method is verified through experiments conducted for a plate specimen.

1. Introduction

Once a damage is generated in a structure, it may grow to result in a serious disaster due to structural failure. Thus, during the last decade, structural health monitoring (SHM) techniques have received considerable attention for monitoring and detection of early-stage damage in structural systems in the military and civil engineering fields.

Lamb waves are elastic waves that propagate in plate-like thin-walled waveguides. They propagate over relatively long distances with little attenuation, and are considered to be a promising way to inspect a large area of a structure quickly and efficiently by using only a small number of sensors. Thus, many researchers have applied Lamb waves to various SHM techniques [1]. In 1967, Viktorov [2] reported that Lamb waves have dispersive and multi-modal properties. Lamb waves

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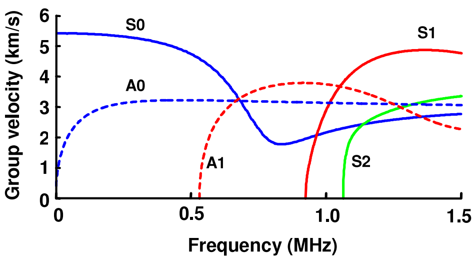
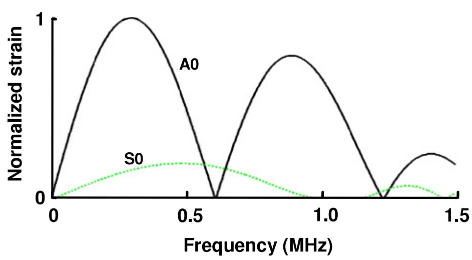


(a) Dispersion curves.



(b) Amplitudes of S_0 and A_0 modes.

Fig. 1. Dispersion curves and the amplitudes of fundamental Lamb wave modes in a plate.

consist of two types of wave modes: symmetric modes (represented by S_n) and anti-symmetric modes (represented by A_n). The number of Lamb wave modes generated in a structure and their dispersive characteristics strongly depend on the excitation frequency.

Ing and Fink [3] were the first to apply the time-reversal of Lamb waves to structural damage diagnosis. Wang [4] proposed an imaging method wherein the damage signals extracted from the time-reversal of Lamb waves are used to represent damage generated in a plate structure as a digital image. In these studies [3,4], baseline data, which are measured at the intact state of a structure, are required for structural damage diagnosis. In order to avoid using the baseline data, which are by their nature very sensitive to a change in the environment, baseline-free SHM techniques have been proposed recently. Park et al. [5] proposed a baseline-free SHM technique wherein the pattern comparison method is used by assuming that perfect time-reversal of Lamb waves will break down once damage is generated in a structure. Recently, Jun and Lee [6] have proposed an imaging method-based baseline-free SHM technique wherein damage signals extracted from a hybrid time-reversal process for Lamb waves are used. In the hybrid time-reversal process for Lamb waves, a measurement-based backward process in the standard time-reversal process is replaced by a computation-based approach.

For the imaging method-based SHM techniques in which the times-of-flight (TOFs) of all Lamb wave modes are required, all Lamb wave mode types must be identified in advance. However it is very challenging to identify all Lamb wave modes in practice. This is why most previous Lamb wave-based SHM techniques have been limited to (1) utilizing only a single fundamental Lamb wave mode (the S_0 mode or A_0 mode) which can be selected only by using a very delicate Lamb wave modes tuning technique; and (2) ignoring boundary conditions from which various types of Lamb wave modes can be reflected via the wave mode conversion phenomenon. Among very few studies devoted to the decomposition of Lamb wave modes, Luangvilai et al. [7] proposed a method to decompose fundamental Lamb wave modes from the response signals measured at two different locations based on the assumption that the dispersion characteristics of Lamb waves are known in advance. Xu et al. [8] proposed a Lamb wave mode decomposition method that uses a matching pursuit method. Recently, Yeum et al. [9] have proposed a new technique using concentric ring and circular piezoelectric transducers specially designed for application to the decomposition of Lamb wave modes.

The goals of this study were to (1) propose an efficient Lamb wave mode decomposition method by which fundamental Lamb wave modes (A_0 and S_0 modes) can be identified, and (2) to validate the proposed method through experiments. The new method was developed based on the group velocity ratio rule and the mode amplitude ratio rule. The new method was found to be very simple and efficient in practice, compared to existing methods [7–9], while providing very reliable results.

2. Boundary signals in measured Lamb waves

The dispersive and multi-modal nature of Lamb waves can be readily observed from the measured or predicted dispersion curves as shown in Fig. 1(a) [2,6]. Fig. 1(a) illustrates that the number of Lamb wave modes to be excited in a thin plate depends on the excitation frequency. Furthermore, the group velocities of Lamb wave modes vary with frequency. As previously mentioned, Lamb wave modes can be classified into symmetric modes S_n ($n = 0, 1, 2, \ldots$) and anti-symmetric modes A_n ($n = 0, 1, 2, \ldots$). The presence of multiple Lamb wave modes makes the signal processing needed for structural damage diagnosis extremely complicated. Thus, it is essential to choose an excitation frequency such that only two fundamental Lamb wave modes (the A_0 and S_0 modes) are excited. For instance, Fig. 1(a) illustrates that only two fundamental Lamb wave modes can be excited if the excitation frequency is lower than 500 kHz, while more than three modes can be excited if the excitation frequency is higher than 500 kHz. As illustrated in Fig. 1(b), one of the fundamental Lamb wave modes can be either suppressed or enhanced by tuning the excitation frequency [10].

Fig. 2 shows a tone-burst input signal with a 200 kHz center frequency that is applied at a point on a plate by using a PZT actuator (named, PZT A), together with the response signal measured at another point of the plate by using a PZT sensor (named, PZT B). The thin plate considered in this study is an aluminum plate (AL6061-T6) with the thickness of 2 mm. The response signal shows that the S_0 and A_0 modes, which travel the linear path connecting PZT A and PZT B, arrive at sensor PZT B first, in order. The damage signal reflected from the damage arrives next, but earlier than the time denoted by t_b as shown in Fig. 2. The signals, which arrive later than time t_b, are the boundary signals that are reflected from boundary edges