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Spatial resolution improvement for Lamb wave-based damage detection using frequency dependency compensation

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A B S T R A C T

In Lamb wave inspection systems, the transfer functions of the transmitter and receiver, and the attenuation as Lamb wave propagates through the structure, result in frequency dependency in the amplitude of Lamb modes. This frequency dependency in amplitude also influences the testing resolution and complicates the damage evaluation. With the goal of spatial resolution improving, a frequency dependency compensation method is proposed. In this method, an accurate estimation of the frequency-dependent amplitude is firstly obtained, then a refined inverse filter is designed and applied to the raw Lamb mode signals to compensate the frequency dependency. An experimental example is introduced to illustrate the process of the proposed method. Besides, its sensitivity to the propagation distance and Taylor expansion order is thoroughly investigated. Finally, the proposed method is employed for damage detection. Its effectiveness in testing resolution improvement and damage identification could be obviously demonstrated by the imaging result of the damage.

1. Introduction

With the advantages of high sensitivity and low attenuation, Lamb waves have attracted considerable attention for industrial nondestructive evaluation (NDE) [1]. High resolution and accurate location are the crucial goals associated with the application of Lamb waves for inspection purposes. However, the frequency dependency of Lamb waves causes the received Lamb modes usually overlap in time, which highly restricts the testing resolution and complicates the damage evaluation.

Lamb modes are generally dispersive, that is to say, their phase and group velocities are frequency dependent. The dispersion characteristic of Lamb waves has been intensively investigated in the previous work [2]. Especially, various methods have been proposed to compensate the dispersion effects for the goal of testing resolution enhancement. Wilcox [3] developed a signal processing algorithm which maps signals from time domain to distance domain by utilizing the prior knowledge of dispersion to compensate the dispersion effects. Liu and Yuan [4] applied the first-order Taylor series expansion to the wave number of Lamb waves, and the dispersion effects could be removed by this linear expansion. Marchi et al. [5,6] employed the warped frequency transform (WFT) for dispersion compensation of Lamb waves. Zeng et al. [7,8]

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performed dispersion pre-compensation on the excitation signals to reduce the effects of dispersion and compress the time duration of the received wave-packets. Xu et al. [9] synthesized the dispersion reversal excitations by the two-dimensional finite-difference time-domain method and proposed a wideband dispersion reversal technique to realize the time re-compression of the Lamb waves. Cai et al. [10] took the signal waveform correction into consideration and proposed a time-distance domain transform method to remove the dispersion effects.

Similar to the velocities, the amplitude of Lamb modes is also frequency dependent, which is related to the characteristics of the transducer and the fundamental properties of the plate (e.g., density, flexural stiffness and thickness). Giurgiutiu [11] presented an analytical model of the Lamb wave tuning mechanism with piezoelectric wafer active sensors (PWAS) transducers, and found that the displacement response varies with frequency. Park and Sohn [12] applied transformation techniques in the spatial and time domains to the wave equations, and obtained the frequency response function of Lamb modes. Kamal et al. [13] presented an analytical model for power and energy transfer between excited PWAS and host structure, and found that the active power varies with frequency remarkably. Schubert and Herrmann [14] investigated the frequency dependent material damping for guided wave propagating in viscoelastic composites. Lin et al. [15] presented an experimental method to measure the attenuation of Lamb waves due to material damping, as a function of the frequency. These studies already reveal the factors which arise frequency dependency in the amplitude of Lamb modes. However, the influences of this frequency dependency to the testing resolution of Lamb waves have not been systematically analyzed.

This paper investigates the influences of the frequency-dependent amplitude to the testing resolution of Lamb waves, and proposes a frequency dependency compensation method to mitigate these effects. Benefitting from that, the time duration of the wave-packets could be compressed and the testing resolution of Lamb wave methods could be enhanced. The rest of paper is organized as follows. In Section 2, the frequency dependency of Lamb waves is analyzed. Then the effects of the frequency dependency to the testing resolution of Lamb waves are analyzed and a frequency dependency compensation method is established in Section 3. In Section 4, an experimental example is introduced to illustrate the effectiveness of the proposed method. Besides, its sensitivities to the propagation distance and the Taylor polynomial order are also investigated in this section. The frequency dependency compensation method is then applied for damage detection in Section 5, and the conclusions are drawn in Section 6.

2. Frequency dependency of Lamb wave

A typical Lamb wave inspection system consists of the instrumentation, transmitter, receiver, and structure. It is assumed that all the instrumentations are ideal, and keep linear over the whole operation frequency range. The system transfer function $H(x,\omega)$ may include the transfer functions of the transmitter and receiver, and the function(s) describing wave propagation between transmitter and receiver. Generally, the system transfer function can be expressed as,

$$H(x,\omega) = G(x,\omega)e^{i\cdot\phi(x,\omega)} \tag{1}$$

where $G(x,\omega) = |H(x,\omega)|$ and $\phi(x,\omega)$ are the amplitude and phase of the system transfer function, respectively. For instance, if the piezoelectric (PZT) transducers are employed as the transmitter and receiver, the frequency dependency in the amplitude $G(x,\omega)$ and phase $\phi(x,\omega)$ could be illustrated as follows.

2.1. Frequency dependency of phase

It is assumed that the bonding layer between the PZT and the structure is ideal (i.e., thin and stiff), so that the PZT experiences the same strain as the structure. The phase shifts due to Lamb wave activating (by the transmitter) and receiving (by the receiver) may be neglected [16,17]. Thus the phase of the system transfer function is dominated by the phase shift of each frequency as Lamb wave propagates between the transmitter and the receiver, *i.e.*, $\phi(x,\omega) \approx k(\omega)x$ [11,17]. For Lamb wave modes propagate in a plate with thickness of 2 h, the wave number k of the symmetrical and anti-symmetrical modes could be obtained from the Rayleigh-Lamb equations as [18],

$$\text{Symmetrical modes:}\quad \frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2qp}{(k^2-q^2)^2} \tag{2-a}$$

$$\text{Anti-symmetrical modes:}\quad \frac{\tan(qh)}{\tan(ph)} = -\frac{(k^2-q^2)^2}{4k^2qp} \tag{2-b}$$

where

$$p^2 = (\omega/c_L)^2 - k^2, \quad q^2 = (\omega/c_T)^2 - k^2 \tag{3}$$

here, ω is the angular frequency, c_L and c_T are the velocities of longitudinal and transverse wave modes, respectively.

It can be observed that the (angular) wave number $k(\omega)$ of each Lamb mode is a function of the (angular) frequency ω, and so does the phase of the system transfer function.