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Analytical and experimental investigation of the interaction of Lamb waves in a stiffened aluminum plate with a horizontal crack at the root of the stiffener

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ABSTRACT

This paper addresses an analytical and experimental analysis based on the physics of the Lamb wave propagation and interaction with the discontinuity. An analytical method called “complex modes expansion with vector projection (CMEP)” is used to calculate the scattering coefficients (amplitude of the out-of-plane velocity) of Lamb wave modes from geometric discontinuities. Two cases are considered in this research: (a) a plate with a pristine stiffener and (b) a plate with a cracked stiffener. Complex-valued scattering co-efficients are calculated from 50 kHz to 350 kHz for A0 incident waves. Scatter coefficients are compared for both cases to identify a suitable frequency range to excite Lamb waves using a piezoelectric wafer active sensor (PWAS) to detect the crack. The frequency-dependent complex-valued scatter coefficients are then inserted into the global analytical model. The global analytical solution predicts time domain scattered signal from the discontinuity. The crack can be detected by comparing the waveforms for pristine stiffener and cracked stiffener. An experiment was conducted for both pristine stiffener and cracked stiffener to compare with the analytical results. A long PWAS was placed parallel to the waveform to create straight crested Lamb wave modes in the plate. Antisymmetric Lamb wave modes were selectively excited by using two PWAS transducers placed on opposite sides of the plate and energized by out-of-phase signals. A single-point laser Doppler vibrometer (LDV) was used to measure the out-of-plane velocity of scattered Lamb waves on the plate. The obtained experimental results agree well with the analytical predictions.

1. Introduction

Lamb waves propagating over long distances and carrying damage-related information facilitate the inspection of a wide variety of structures. The basic principle of using guided Lamb waves for damage detection in structural health monitoring (SHM) applications of a structure are based on the investigation of the incident, reflection, transmitted waves, and mode conversion of Lamb wave modes as they interact with damage. The interaction of Lamb waves with damage is a complex phenomenon. Existing discontinuity in the structure (e.g., a stiffener, a notch or delamination) makes the physics of wave

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propagation more complicated [1–4]. Lamb wave scattering and mode conversion provide useful information for the detection of a crack. The structural discontinuity interacts with Lamb waves and acts as a damage source. In practice, it may be difficult to distinguish the scattered wave field from the overall Lamb wave fields. In this paper, an improved and accurate analytical global-local method has been introduced to detect crack from a complex structure. The first step towards the goal is to predict scattered wave fields from the complex structure of the (a) plate with pristine stiffener and (b) plate with cracked stiffener. Next, comparing the predicted results from pristine stiffener plate and cracked stiffener plate, the effect of crack can be detected. Analytical prediction is very helpful in designing the experimental implementation of the SHM principle.

In general, damage detection can be divided into two main groups: active detection and passive detection. In active detection, energy is imparted to the structure using transducers to create elastic waves [5]. These incident waves travel in the structure, and they are scattered when they encounter damage or sudden change in the geometry or material properties. Guided wave based non-destructive evaluation (NDE) techniques have been used widely for identifying local damage and detecting incipient failures in critical structures [6,7]. Guided waves, such as Lamb waves, interact with the damage during long-range monitoring or inspection to determine the state of the thin-wall isotropic or composite structures [8–10]. The key parameter is to identify the scattered wave field due to local damage and flaws. The prediction of the scattering of Lamb waves from damage has been a major focus for researchers in NDE and SHM. Damage characterization is an inverse problem that requires fast and accurate prediction of scattered waves [11]. However, the solution of the scattering problem is highly challenging because of the existence of multiple dispersive Lamb wave modes, which undergo scatter and mode conversion at the damage location for various frequencies.

Finite element method (FEM), boundary element method (BEM) or other numerical techniques have been widely used for the study of elastic waves propagation due to structural flaws and damage [12–15]. However, FEM and BEM require extensive computational effort to attain computational accuracy for simulating elastic wave propagation in a large structure. Therefore, many researchers have adopted semi-analytical finite element (SAFE) method [16,17]. In SAFE approach, in-plane displacements were accommodated using an analytical double integral Fourier transform, while, the transverse displacement approximated by using finite elements. Doyle published his work on the formulation of the spectral element method (SEM) for the wave propagation in structures [18]. The frequency domain spectral element method uses shape functions build upon an analytic solution. Many researchers have adopted an efficient combined global analytical-local FEM analysis [19–22]. The early applications of this approach consisted of the simultaneous use of the local finite element method and the global classical variational technique [23]. This method shows a higher computation efficiency as compared to an entire FEM analysis of the model. The global analytical-local FEM analysis approach couples the global analytical wave expression with the local FEM analysis around the damage incorporating the wave damage interaction coefficients [19]. However, the FEM analysis over local damage maybe sometimes time-consuming depending on the size and type of damage. Hence, it is worth investigating a complete analytical approach in both global and local damage models.

Alleyne et al. [24] studied the interaction of straight crested Lamb with different types of notches using FEM analysis and results were compared with experiments. The FEM analysis was done by considering straight crested waves. However, for experimental validation, a circular crested wavefront was used, and at a distance from the source, the circular crested wave was assumed as a straight crested wave. Lowe et al. [25] also performed a similar type of study by assuming straight crested Lamb wave. Benmeddour et al. [26] reported the mode conversion phenomenon of symmetric and antisymmetric modes at notches in a plate. Santhanam et al. [27] have studied the reflection of obliquely incident symmetric and anti-symmetric Lamb wave modes at the edge of a plate.

In this article, we proposed a complete analytical analysis in both global and local damage region to predict the scattering of Lamb waves. The overview of the global-local analytical analysis is illustrated in Fig. 1. We demonstrated this approach on a realistic problem: to detect a horizontal crack in a stiffener on the plate. Two cases are considered: (a) a plate with a pristine stiffener and (b) a plate with a cracked stiffener. We adopted a local analysis based on complex modes expansion with vector projection (CMEP) method for determining the scattering coefficients instead of local FEM analysis. CMEP method makes the current analysis more computationally efficient than the previous global-local FEM analysis [19,20]. The experiments are conducted to compare the results of the present approach.

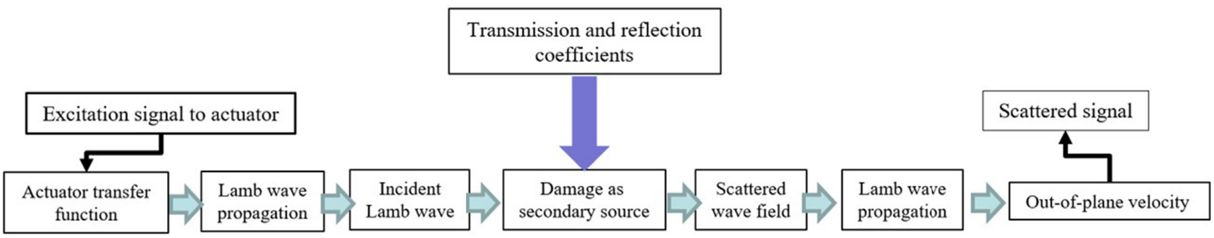

Fig. 1. Overview of global-local analytical approach.