Lamb Wave Actuation Techniques for SHM System- A review

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ABSTRACT

Lamb waves-based structural health monitoring (SHM) system has gained significant consideration due to its excellent performance in both precision and versatile accessibility. This paper specifically reviews the active actuation techniques of Lamb waves in the SHM system for diagnostic analysis. It is axiomatic that appropriate signal actuation is of vital necessity and important for a reliable SHM system. Multimodal and dispersive characteristics of the Lamb waves are the main factors for the variety of applied actuation techniques. Multiple Lamb modes synchronously exist, and their dispersive properties are not identical which lead to complex superimposed signals. Various techniques for single mode generation have been proposed to reduce the complexity of the measured signals. Generally, the applied techniques can be clustered to frequency tuning and actuator configuration. The findings showed that the applied techniques were proven to be effective in producing pure mode for further analysis. All these studies have revealed the evolution of Lamb waves-based SHM system for controlling and monitoring the condition of the structure.

Keywords: Structural health monitoring; Lamb waves; actuation techniques.

INTRODUCTION

Among the SHM based techniques, Lamb Waves (LW) method is proven to be a promising and widely employed techniques in many areas. LW were used as a means for the internal and surface damage detection due to their special characteristics that are able to propagate throughout the entire thickness of the plate [1]. Thus, the valuable information related with structural integrity can be extracted from the detected waves. Its ability to perform inspection for a large structure from limited access helps this technique to grow rapidly [2].

The active LW technique for SHM involves the utilisation of wave actuator and the sensor. The actuator generates the LW on the monitored structures and the sensor receives the generated LW. Before any meaningful analysis is performed, an appropriate actuation technique is necessary for a reliable signal acquisition by the sensor. Considering the complexity of the dispersive and multimode LW, it is desirable to generate a single or pure LW mode to simplify the signal analysis.

To achieve this objective, some factors need to be considered during the LW actuation such as the type of actuator used, the configuration of the actuator during the testing and the input actuation parameter. In the literatures, various different actuation methods for single mode generation have been suggested. This article summaries the actuation method available in literatures up to the authors knowledge. This information is important, prior to designing a proper LW-based SHM system set up.

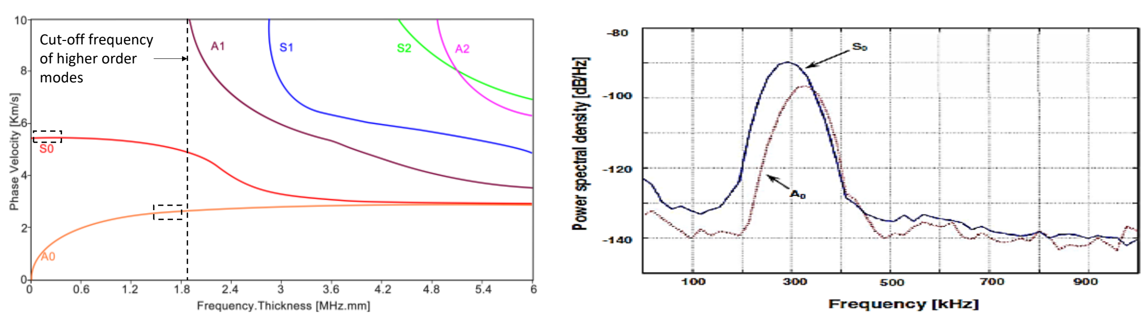
Dispersive and multimode of the Lamb Waves

Information of dispersive and multimode characteristics can be extracted from dispersion curve as shown in Fig. 1 (a). This curve can be generated by Equation 1 and 2, describes about the motion of LW propagation which can be in symmetrical (S) or anti-symmetrical (A) mode, respectively.

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2 qp}{\left(k^2 - q^2\right)^2} \qquad (1)$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{\left(k^2 - q^2\right)^2}{4k^2 qp} \qquad (2)$$

where $p^2=(\omega^2/c_L^2)-k^2$, $q^2=(\omega^2/c_T^2)-k^2$, $k=\omega/c_p$. k, h, c_L, c_T, c_p and ω are the wavenumber, plate thickness, velocities of longitudinal and transverse modes, phase velocity and wave circular frequency, respectively. This dispersion phenomena leads to the spreading of wave-packet in space and time as it transverses through a monitored structure. This property affects the spatial and temporal resolutions, thus can potentially compromise the receiver detectability.



(a) (b)

Fig 1. (a) The dispersion curve; (b) Frequency domain features of the fundamental symmetric and anti-symmetric at original excitation frequency of 300 kHz [3].

Consider a plate structure,actuated at a center frequency of 300 kHz. The result of frequency domain analysis using the measured LW signal displayed the peak occurring at 293kHz for symmetric and 332kHz for an anti-symmetric mode as presented in Fig. 1(b). This indicates the dispersion phenomenon since the measured center frequency is not identical to the original center frequency.

Meanwile, the multimode property refers to the existence of at least two modes that coexist at any given frequency. At low frequency, minimum two modes (fundamental symmetric and anti-symmetrical mode) can propagate. As the frequency increases, more modes are possible and the interpretation of signals tends to become more complicated [4]. This characteristic leads to the complexity of the response signals which are difficult to be analysed and interpreted. By considering these problems, many studies were focused on devising their experimental set up to generate single Lamb mode to ease the post-processing analysis. Different researchers performed different methods based on the applicability and suitability of their applications. The next section provides the comprehensive description about the approaches that have been reported by the researchers in SHM system using LW approach.

GENERATION OF SINGLE LAMB MODE

Frequency Tuning

In frequency tuning approach, the frequency of the input wave contributes most to the actuation of the desired modes. Most of the researchers called this procedure the mode tuning method which aims to identify the frequency points where single-mode LW can be tuned into. In a simple way, researchers referred to the theoretical dispersion curve to determine the appropriate frequency point for single-mode generation. In other words, knowledge of the dispersion curve is required before performing the mode tuning. The selected frequency is based on minimum number of modes that exist at the given excitation frequency; and, in the less dispersive frequency region, as highlighted by the dotted rectangular in Fig. 1 (a). The higher steepness slope of the curve indicates higher dispersion. Thus, multimode and dispersive problems can be avoided by choosing the suitable actuating frequency which is in a less-dispersive region at low frequency range, which is lower than cut-off higher frequency value.

In the meantime, several studies had derived the LW mode tuning curves analytically. For instance [5] derived the curve indicates the frequencies that exist when the A_0 mode or the S_0 mode can be either suppressed or enhanced. Verification of these tuning curves was extensively performed using experimental tests, and the results exhibited an agreement with each other. The findings was implemented for monitoring of a large area using Piezoelectric Wafer Active Sensors (PWAS).

Meanwhile, different types of actuators applied different strategies for frequency tuning techniques. The excitation of pure mode using electromagnetic acoustic transducers

(EMATs) is determined by the meander-line coil spacing interval *L*, the exciting-current frequency *f*, and the thickness of specimen *d* for single mode generation. G. Zhai et al. [6] have established the excitation equation for choosing a reasonable operating point to generate a single mode of LW using EMATs. Z. Guo et al. [7] had selected the *L* size to be twice the interested mode wavelength λ. The authors were successfully generated the pure A_0 mode to study its interaction with the crack-like notch. Successful single-mode generation using EMAT also can be found in [8] and [9]. Some innovations to the existing EMAT have also been invented for single-mode generation.

For flexible interdigital polyvinylidene fluoride (PVDF) transducers, an individual modes can be excited by adjusting the electrode finger spacing. The basic principle is based on the wavelength of mode of interest is equal to the PVDF comb transducer's finger spacing [10]. Meanwhile, interdigital transducers (IDT) were designed with apodisation to enhance A_0 mode and attenuate S_0 mode dedicated for the CFRP laminates [11]. Modification of the frequency function response was used to determine the frequency range that generated the lowest order of symmetric and anti-symmetric modes. T. Liu et al. [12] developed a numerical simulation tool to investigate the acoustic wave field excited by IDT in composite plates. The developed tool could perform the mode isolation based on certain factors such as the apodisation, number of array elements, thickness, and width of the elements. The thickness and materials of possible backings should also be considered. For this purpose, frequency tuning was applied by choosing half wavelength of the targeted mode as the spatial distance between two adjacent elements at the centre frequency of the excitation pulse.

J. Li and J. L. Rose [13] built a multi-channel time-delay system to conduct the mode tuning procedure to solve the problems related with the conventional transducer array for the generation of individual wave modes . In principle, the wavelength of the modes of interest should be identical to the element spacing and all elements should work in-phase in order to perform frequency tuning. Automatic time delay algorithm was an added value for the real practice implementations.

Actuator Configuration: Double side excitation

Other than frequency tuning, many research works have manipulated the actuator configuration for the single mode generation. Utilisation of the double side actuation has shown its outstanding ability for pure modes generation. Pure symmetric and anti-symmetric modes were excited by in-phase and out-of-phase voltages application. Two actuators were utilised to implement this phase cancellation method. X. Lin and F. G. Yuan [14] and H.-Y. Zhang and J.-B. Yu [15] have explained this principle in detail in their reports. A pair of the PZT actuators was symmetrically attached on the upper and lower surfaces (double side actuation) of a structure as shown in Figure 2(a). Some researchers applied this method using EMAT [16] and macrofibre composite (MFC) actuators and it showed that the technique is capable to generate a single wave mode.

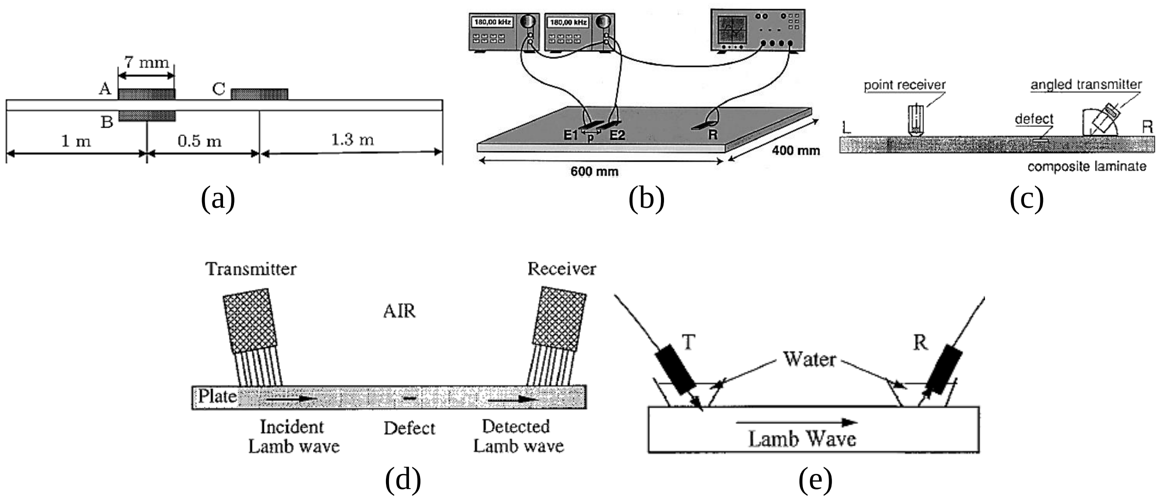


Fig. 2. (a) Double side actuation [15]; (b) opposite side actuation [17]; (c) angled actuator [18]; (d) angled air-coupled transducer [19]; (e) angled fluid-coupled transducer [20]

Actuator Configuration: Opposite side excitation

On the other hand, N. Mori et al. [21]and Y.-H. Kim et al. [22] performed the excitation strategies using a pair of transducers which were surface-bonded opposite to each other (opposite side actuation) to generate a single-LW mode. The method is known as dual-element transducer setup as shown in Figure 2(b). In this method, two actuators were placed opposite of each other at an optimised distance and were excited in-phase to dominantly generate the desired modes. The distance between two PZT elements is the main contributory aspect for the excitation of modes of interest. Despite the promising result from the method in the single mode generation, the requirements for such an experimental system should be taken into consideration. The system demands double transducer numbers and higher hardware requirement if compared with the single side excitation method.

Angled actuator

Another common method in generation of pure Lamb mode is by the angle adjustment of the actuator. The principle used in this technique is based on Snell's law. Depending on the elasticity and acoustic properties of the medium, the desired phase velocity of the excited Lamb mode at a specific frequency can be controlled by adjusting the incident angle. [23], [18] adjusted the angle probe to excite the selected mode for the delamination detection on the carbon/epoxy prepreg laminates. General experimental setup for this approach can be illustrated by Figure 2(c). This method can be performed in air [19] and fluid [20] as shown in Figure 2(d) and (e). However, air- or fluid-coupled transducers suffers from a low efficiency due to the large differences in mechanical impedances between the air or fluid and the objects under detection. This method also leads to the flexibility problems for the real practice especially when accessing in-service systems even though showing effectiveness in single mode generation.

Actuator embedment

Actuator embedment strategies are other approach that was introduced for the single mode excitation. [24] have demonstrated the use of embedded microstructured optical fibre (MOFBG) based sensors to selectively generate two fundamental LW modes. The excitation of the interested modes was based on the sensor orientation. Its selective sensitivity behaviour to axial and transverse strains allows the generation of preferential modes. The experimental arrangement for this technique can be referred to Figure 2(f). B. Hailu et al. [25] using embedded IDT for the single mode excitation. The position of the transducer embedment in the plate thickness defined the generated modes. Symmetric mode was excited if the transducer is embedded exactly at the centre of a plate. However, when the transducer position deviates from the centre, symmetric and antisymmetric will simultaneously generated.

Other method

Zi li et. Al [26] proposed a new way of a selective generation of Lamb waves using laser scanning method. The essential procedure of this method is to vary the scanning speed of the beam to match the phase velocity of a specified mode.

Table 1. The summarised information about the excitation approaches for the pure mode generation

<table>
<tr><th>Method</th><th>The procedure</th><th>Limitations</th></tr>
<tr><td>Frequency tuning</td><td>The frequency is tuned accordingly for the single mode generation.</td><td>1. Time consuming and a tuning frequency may not be available for real practice.</td></tr>
<tr><td>Double side actuation</td><td>A pair of actuators was surface mounted or embedded on the top and bottom of the structure.</td><td rowspan="2">1. Demanding double transducer numbers, which is increases the hardware requirement
2. High consistency in the location of transducer pair is required.</td></tr>
<tr><td>Opposite side actuation</td><td>A pair of the actuator was attached in the opposite position to each other on the structure surface.</td></tr>
<tr><td>Angle of incidence:

1. Direct
2. Air-coupled
3. Fluid-coupled</td><td>The generation of the selected modes can be obtained by adjusting the angle of incidence of the actuator.</td><td>1. Time consuming and technically challenging for in-service assessment

2.Suffering from a low efficiency due to the large differences in mechanical impedances between the air or fluid and the objects under detection</td></tr>
</table>

Actuator embedment	The actuator was embedded at certain thickness of the structure for the separation of the different modes.	Symmetric and antisymmetric will simultaneously generated when the transducer position deviates from its original position.

CONCLUSIONS

LW method have shown a great potential as a SHM tool due to their advantages. Offering cost-effective evaluation, covering relatively long distances, being highly susceptible to even barely visible internal damage, have made them widely used for structural health monitoring. However, the acquired LW signal is a complex product of its its dispersive and multimodal characteristics. This can affect the accuracy of the signal interpretation. Hence, various different approaches were introduced by researchers to improve the LW signal interpretation. One of the approaches is by controlling the Lamb waves excitation. This strategy was applied in order to overcome the effect of multimodal and dispersive problem of the Lamb wave. Some flexible and practical excitation strategies were implemented with the purpose to generate selective pure modes. The mode of interest was decided based on the sensitivity and suitability of the application. Such selection is proven to ease the following post-processing analysis and provide reliable information during the inspection.

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