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Guided wave phased array beamforming and imaging in composite plates

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ABSTRACT

This paper describes phased array beamforming using guided waves in anisotropic composite plates. A generic phased array algorithm is presented, in which direction dependent guided wave parameters and the energy skew effect are considered. This beamforming at an angular direction is achieved based on the classic delay-and-sum principle by applying phase delays to signals received at array elements and adding up the delayed signals. The phase delays are determined with the goal to maximize the array output at the desired direction and minimize it otherwise. For array characterization, the beam pattern of rectangular grid arrays in composite plates is derived. In addition to the beam pattern, the beamforming factor in terms of wavenumber distribution is defined to provide intrinsic explanations for phased array beamforming. The beamforming and damage detection in a composite plate are demonstrated using rectangular grid arrays made by a non-contact scanning laser Doppler vibrometer. Detection images of the composite plate with multiple surface defects at various directions are obtained. The results show that the guided wave phased array method is a potential effective method for rapid inspection of large composite structures.

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1. Introduction

Rapid inspection of large areas with nondestructive evaluation (NDE) methods is critical for ensuring operation ability and safety in aerospace industry, especially where safety related structural components are used [1,2]. Advanced composite materials have been increasingly used in aerospace industry. The Boeing 787 Dreamliner has an airframe comprising nearly 50% carbon fiber reinforced plastic and other composites [3]. Though various NDE methods have been developed for metallic structures and proven effective, reliable and efficient evaluations for large composite structures are not yet well established [1,4]. Complexity of the advanced composite material manufacturing and in-service maintenance present challenges in evaluation tools and methods [4].

Ultrasonic NDE is the technique to provide an invasive means to inspect the condition of a component. Among various NDE methodologies, ultrasonic method is directly sensitive to mechanical changes and can be used to directly assess the mechanical condition and integrity of the composite structure [4]. However it is commonly considered that NDE using bulk waves is time-consuming since it requires point-by-point measurement over the inspected area and therefore is not efficient for large area inspection. To address this deficiency, the guided waves (GW) based ultrasonic techniques have been studied, developed, and demonstrated great potentials on metallic structures [5–8]. Compared to bulk waves, GW can travel long distances within the waveguides with low energy loss [9,10]. However, GW NDE is facing major challenges when being applied on composite structures [4]. The GW complexity caused by anisotropic and inhomogeneous properties in composite materials makes the traditional metal-based NDE methods inappropriate and sometimes even misleading [11–13].

When generating inspection results, an image of the structure being inspected often gives an efficient solution that quickly identifies and locates defects. Various imaging methods based on GW NDE have been explored including tomography [6,14–16], sparse array [7,17–24], synthetic aperture focusing technique [25–27], reconstruction algorithm for probabilistic inspection of damage (RAPID) [5,28–30], and phased array [8,31–64]. Among them, the phased array imaging is attractive since it uses sensors that are placed closed to each other in a compact format, steers the outputs of all sensors in a desired direction, and inspects the entire structure like a radar [31]. It hence allows for rapid inspection of large area with limited access. The additional advantages include reinforced wave energy in the steered direction, efficient and flexible

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control of the direction, improved signal-to-noise-ratio, and promising damage detection results [31].

Intensive study has been conducted on the GW phased array beamforming and damage detection on metallic plate like structures [8,31–58]. A general beamforming algorithm for isotropic materials has been developed [31,32] with investigation of beamforming optimization [33–36]. 1-D linear [37,38] arrays and 2-D planar arrays [8,31,39] in various configurations have been designed and used for damage detection of hole or cracks with the arrays made of piezoelectric wafer sensors [31], piezoelectric paint sensors [39], or electromagnetic acoustic transducer (EMAT) [8].

Some researchers have started investigating the phased arrays for anisotropic composite materials [59–64]. Yan and Rose studied beamsteering of linear arrays in composite plates [59]. They found the traditional beamsteering technique for isotropic materials might fail in composite materials due to the anisotropic behaviors of the composite plates. Hence, they chose a quasi-isotropic wave mode for beamsteering, which can suppress the influence of the anisotropic behavior. Rajagopalan et al. adopted an array of a single transmitter and multiple receivers (STMR) to locate a defect (hole) in a composite plate [60]. In their array imaging method, they used a weakly anisotropic wave mode and assumed that the phase and group velocity directions coincide locally. Later, Vishnuvardhan et al. used the STMR array to detect impact induced delamination damage in a quasi-isotropic composite plate [61]. Leleux et al. used ultrasonic phased array probes for long range detection of defects in composite plates [62]. Their method was limited to wave modes having phase and group velocities oriented in the same direction, where the skew angle was zero. Purekar and Pines investigated the capability of 1-D linear phased arrays in detecting delamination damage in a cross-ply composite plate [63]. They showed the array can detect damage at 0° direction, where the phase and group velocities had the same orientation. Osterc et al. investigated the beamsteering of 1-D linear arrays in composite laminates [64]. In their study, the exact phase velocity curve was used to develop a beamforming algorithm that accounted for non-omnidirectional guided wave propagation in anisotropic materials. It has found that compared to the array beamforming in isotropic plates, the array beamforming in anisotropic composite plates are more challenging. In anisotropic composite plates, guided wave parameters such as wavenumbers, phase velocities and group velocities are direction dependent due to the direction dependent physical properties of composite materials [11–13]. Moreover, the GW have energy skewness that the direction of group velocity is not always aligned to that of the phase velocity. Last but not least, the wave fronts of GW are no longer circular in composites. The traditional beamforming technique for isotropic materials may fail in composite materials due to the complexity involved with GW propagation.

In this paper, we investigate GW beamforming in anisotropic laminated composite plates. Based on the classic delay-and-sum principle, a generic formula of phased array beamforming in anisotropic composite plates is developed, in which the direction dependent guided wave properties are adopted. The beamforming is demonstrated by implementation of 2-D rectangular grid arrays. Beamforming with various array configurations of rectangular grid arrays are investigated. For the proof of concept, laboratory tests are performed using rectangular grid arrays made of scanning points of a non-contact scanning laser Doppler vibrometer (SLDV) for detecting surface defects. The results show that multiple defects at various directions can be successfully detected and the phased array method can be useful for rapid inspection of large composite structures. The remainder of this paper is organized as follows: Section 2 presents the formulation of phased array beamforming in anisotropic composite plates; Section 3 presents beamforming characterization of 2-D rectangular grid arrays; Section 4 presents the implementation and detection of multiple defects in a composite plate using arrays made of scanning points of a non-contact SLDV. Section 5 concludes the paper with novelties, discussions and planned future work.

2. GW beamforming in composite laminates

In this section, we formulate general GW phased array beamforming in anisotropic composite laminates based on the classic delay-and-sum principle.

2.1. GW in composite laminates

When a guided wave with frequency ω and wavenumber $\mathbf{k}$ is generated from a source at the coordinate origin O in a composite plate, the wave arriving at the location $\mathbf{x}$ that is far away from the source (Fig. 1a) can be expressed as [9,10,13],

$$u(t,\mathbf{x}) = Ae^{j(\omega t-\mathbf{k}\cdot\mathbf{x})} \tag{1}$$

where A is the amplitude, assuming independent of wave frequency. With the geometric relation illustrated in Fig. 1a, we have,

$$\mathbf{k}\cdot\mathbf{x} = |\mathbf{k}|\,|\mathbf{x}|\cos\beta = k(\gamma)|\mathbf{x}|\cos\beta \tag{2}$$

with β being the angle between the wave propagation and wavenumber $\mathbf{k}$. Hence,

$$u(t,\mathbf{x}) = Ae^{j[\omega t-k(\gamma)|\mathbf{x}|\cos\beta]} \tag{3}$$

Using Eq. (1), for a source located at location $\mathbf{p}_m$, the wave resulted at the location $\mathbf{x}$ is,

$$u_m(t,\mathbf{x}) = Ae^{j[\omega t-\mathbf{k}\cdot(\mathbf{x}-\mathbf{p}_m)]} \tag{4}$$

In anisotropic composite laminates, GW parameters such as wavenumbers, phase velocities and group velocities are direction dependent, due to the direction dependent physical properties of composite materials [11–13]. Fig. 1b plots the wavenumber curve $k(\gamma)$ and slowness curve $k(\gamma)/\omega$. As illustrated in Fig. 1b, the wavenumber vector $\mathbf{k}$ is perpendicular to the wave front and the group velocity vector $\mathbf{c}_g$ is orthogonal to the wavenumber curve $k(\gamma)$ [11–13]. The angle γ of the wavenumber vector $\mathbf{k}$ is referred to as wavenumber angle. The angle θ of the group velocity vector $\mathbf{c}_g$ is referred to as group velocity angle (or energy propagation angle). The angle β between wavenumber angle γ and energy propagation angle θ is referred to as skew angle, with the relation $\beta = \gamma - \theta$. It can be seen when $\mathbf{c}_g$ is not parallel to $\mathbf{k}$, the skew angle β is not zero and hence the wave energy propagation direction is not perpendicular to the wave front.

2.2. Delay-and-sum beamforming

Consider an array with M identical elements located at $\{\mathbf{p}_m\}$ ($m = 0,1,2,\ldots,M-1$) which are geometrically close to each other. The phase center is defined as the origin O of the Cartesian coordinate system, i.e., $1/M\sum_{m=0}^{M-1}\mathbf{p}_m = \mathbf{0}$. Each element serves as a wave source. When all elements generate waves with frequency ω and wavenumber vector $\mathbf{k}$ simultaneously, using Eq. (4) the total output (synthesized wave) of the array at location $\mathbf{x}$ can be derived as,

$$z(t,\mathbf{x}) = \sum_{m=0}^{M-1} Ae^{j[\omega t-\mathbf{k}\cdot(\mathbf{x}-\mathbf{p}_m)]} = u(t,\mathbf{x})\sum_{m=0}^{M-1} e^{j\mathbf{k}\cdot\mathbf{p}_m} \tag{5}$$

It is seen from Eq. (5) that the synthesized wave $z(t,\mathbf{x})$ is an amplification of the wave $u(t,\mathbf{x})$ emitted from the Origin. The amplification is controlled by the exponential component $\sum_{m=0}^{M-1}e^{j\mathbf{k}\cdot\mathbf{p}_m}$ in Eq. (5). Therefore, by adjusting the component $\sum_{m=0}^{M-1}e^{j\mathbf{k}\cdot\mathbf{p}_m}$, we can control the amplification. One way to adjust

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