Delamination detection in composites through guided wave field image processing


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Abstract
This study explores the feasibility of using a non-contact guided wave imaging system to detect hidden delamination in multi-layer composites. The study is conducted in two phases. In the first phase, Lamb waves are excited by a lead (Pb) Zirconate Titanate transducer (PZT) mounted on the surface of a composite plate, and the out-of-plane velocity field is measured using a one-dimensional (1D) scanning laser Doppler vibrometer (LDV). From the scanned time signals, wavefield images are constructed and processed to study the interaction of Lamb waves with delamination. The paper presents additional signal and image processing techniques used to highlight the defect in the scanned area. The techniques are demonstrated using experimental data collected from a 1.8 mm thick multi-layer composite. In the second phase, a completely non-contact system is described to excite and measure guided waves. A modulated continuous wave (CW) laser source in conjunction with a photodiode is used to wirelessly excite an attached PZT and the resulting waves are again sensed using the vibrometer. The non-contact system is used to excite and measure elastic waves in a composite channel test article. The elastic wave propagation image sequences are created from the non-contact excitation system.

Keywords: Ultrasenics, Non-destructive testing, Delamination, Scanning laser doppler vibrometer

1. Introduction

In recent years, there has been an increasing demand for a structural health monitoring (SHM) that apprises users of the integrity and safety of the structure being monitored [1]. SHM often infers the current condition of the structure based on a stream of data collected from installed sensors. Guided ultrasonic waves have emerged as one of the most prominent tools for SHM due to their well-established theories, ability to detect small damages within relatively large inspection areas, and recent advancements in transducer technologies used for guided wave sensing and excitation.

Guided waves are specific types of elastic waves confined by the boundaries of a structure. For instance, when a plate structure is excited at a high frequency, the top and bottom surfaces of the plate "guide" the elastic waves along its axis, producing a specific type of guided waves called Lamb waves [2–4]. Various types of transducers can be used to excite and sense guided waves. The most commonly used transducers include angled piezoelectric wedge transducers, comb transducers and electromagnetic acoustic transducers and surface-bonded piezoelectric wafer transducers [5–9]. Some transducers are mainly used for sensing applications such as polyvinylidene fluoride (PVDF) and fiber optic sensors [10,11]. Although each transducer mentioned above has its own set of strengths and weaknesses, all of them are primarily used for discrete point measurements. Therefore, a dense array of transducers is required to achieve a good spatial resolution and cover a large inspection area. Moreover, the embedding of sensors and the associated instrumentation can be a source of additional mass and may possibly disturb elastic waves.

A potential solution to this problem uses non-contact scanning laser techniques for creating wavefield images with a high spatial resolution [12]. One such technique is to excite a fixed point using a conventional PZT and scan the guided wave response across the surface of the structure using an LDV [13–15]. Previous works in this field include detecting fatigue cracks from the variation of ultrasonic amplitude profile [13,14] and using frequency-wave-number domain filtering to locate scatters in the ultrasonic medium, some of which could be defects [15]. Another technique is to use a pulsed laser source to generate guided waves at arbitrary locations, then corresponding responses are measured at a single point using a conventional ultrasonic transducer; the wavefield images are then constructed using the principle of dynamic reciprocity [16–18]. Note that the wavefield imaging discussed above is different from the traditional phased array ultrasonic imaging technique in which time-of-flight or wave attenuation information is used to image all reflectors in the ultrasonic medium [19,20].
This study is conducted in two phases. In the first phase (Section 2), we excite a fixed point using a surface-bonded piezoelectric wafer transducer and scan the guided wave response using an LDV. In this case, only the sensing part is wireless while the excitation is achieved through wired connections. The groundwork of delamination detection in composites is laid in this section by introducing signal and image processing techniques used to extract delamination sensitive features. In the second phase (Section 3), an intensity modulated continuous wave (CW) laser source in conjunction with a photodiode is used to wirelessly excite the attached piezoelectric wafer transducer and then the guided wave response is scanned using an LDV. Thus, the entire interrogation system (i.e. both excitation and sensing) in Section 3 is non-contact.

The uniqueness of the present paper is threefold. First, we observe and explain a phenomenon of standing wave formation when ultrasonic waves interact with delamination. Second, we propose novel signal and image processing techniques to highlight the interactions of standing and traveling ultrasonic waves with delamination. Third, we demonstrate a fully non-contact excitation and sensing system for imaging ultrasonic wave propagation in composites.

2. Wavefield image processing for delamination detection in a multi-layer composite plate

In this section we present experimentally obtained wavefield images from a composite plate with an internal delamination using an LDV. We describe how standing waves are formed when ultrasonic waves interact with the delamination, and propose signal and image processing techniques to highlight such interactions.

The composite plate tested in this study is shown in Fig. 1. This 27.5 cm x 27.5 cm x 1.8 mm plate is composed of IM7 graphite fibers with 977-3 resin material, and consists of 12 plies with a lay-up of [0/±45/0/±45]. The test article was subjected to impact, and the formation of an internal delamination near the center of the plate was confirmed from nondestructive thermographic imaging (Fig. 2). The 3 cm long damage area could be seen on the back side of the plate (Fig. 1), but on the front (impacted) side there was only a small dent, barely visible to the naked eye.

A Kapton coated piezoelectric wafer transducer (6.35 mm diameter by 0.254 mm thick, PZT-5A material powered by an AWG and a signal amplifier was used to generate guided waves in the test article. In Fig. 1, the PZT transducer used for actuation is marked with an arrow. The other transducers visible in Fig. 1 were used for other studies and are not relevant to this paper. The guided wave responses at points within a specified area were sensed by a LDV, and the data was collected by a built-in data acquisition system. The data was then exported to the MATLAB\textsuperscript{\textregistered} software program and processed on a personal computer.

A 5.5 cycle tone burst signal with 100 kHz center frequency was used as the input waveform. The output voltage from the AWG was ±10 V and was amplified to ±50 V using a power amplifier before being applied to the actuator.

The guided waves were measured by a Polytec PSV-400-M4 LDV. The 1D LDV used in this study measures the out-of-plane velocity of a target point using the principle of Doppler frequency-shift effect on light waves [21]. For the 100 kHz excitation signal used in this study, the out-of-plane component of the velocity field corresponding to the fundamental antisymmetric mode is more strongly excited than the in-plane component corresponding to the fundamental symmetric component. Therefore, the LDV is providing appropriate measurements of the antisymmetric mode [22]. The wavelength corresponding to the fundamental antisymmetric Lamb mode was found to be about 1.2 cm.

The LDV was placed about 0.9 m away from the test article, and the sensitivity of the velocity measurement was set to 10 mm/s/V. The spatial grid density was 9 points per centimeter and the temporal sampling rate was 2.56 MHz. The time response at each measurement point was averaged 20 times to improve the signal-to-noise ratio, and a 75–125 kHz band pass filter was applied to reduce noise outside the driving frequency band. It took about 40 min to scan a circular area with 5 cm radius containing about 6400 scan points (Fig. 1).

The data are stored in a universal file format and exported to the MATLAB\textsuperscript{\textregistered} software program. The raw data contains time signals from each of the scanned points. Using MATLAB\textsuperscript{\textregistered} graphic tools, a wave propagation video is created where each frame in the video represents the out-of-plane velocity field across the scanned surface of the target specimen at a particular instant in time. The snapshots at three representative time instants are shown in Fig. 3. All images are plotted in RGB scale where low to high values are mapped from blue to red with green indicating middle range values. In Fig. 3a, the incident waves can be clearly seen, and the...
interaction with the delaminated area is apparent in Fig. 3b. Ultrasonic oscillations at the delamination location can be observed long after the incident waves had passed the delaminated area (Fig. 3c). Similar phenomenon was observed by Krohn et al. [23] and Willemann et al. [24] and a possible explanation for this phenomenon is given below.

Fig. 4 shows a schematic through-the-thickness side view of a delamination. The incident waves enter the delamination zone, split, and then propagate independently through the upper and lower lamina. A significant portion of these waves is reflected back from the exit. The reflected waves travel through the laminates and undergo reflection again at the original entrance. Numerical simulations by Hayashi and Kawashima using the strip element method have confirmed such multiple reflections taking place inside the delaminated zone [25,26]. As a consequence of multiple reflections at the entrance and the exit, a considerable amount of ultrasonic energy is trapped inside the individual lamina.

Now, the ultrasonic waves reflected from opposite ends of the delamination travel in opposite directions and interfere to produce standing waves according to the following equation:

$$A \cos(\omega t - kx) + B \cos(\omega t + kx + \phi)$$

$$= 2B \cos(\phi/2) \cos(\omega t + \phi/2) + (A - B) \cos(\omega t - kx + \phi/2)$$

(1)

In Eq. (1), $A$ and $B$ are the amplitudes of the waves propagating in opposite directions ($B + A$ without loss of generality); $\omega$ and $k$ are the frequency and wavenumber of the propagating waves; $\phi$ is an arbitrary phase; $t$ and $x$ represent time and space coordinates respectively; $x$ is the zero-shifted coordinate given by $x = x + \frac{\phi}{2\omega}$. The first term in the right-hand side of the equation represents the standing waves at delamination while the second one represents the part of the wave that propagates. The standing waves remain trapped inside the delamination site long after the incident waves have passed. With time, however, the standing waves subside as the ultrasonic energy leaks out through the boundaries of the delamination and attenuates. Eq. (1) describes the propagation and interference of pure longitudinal waves or pure shear waves. Although the equations describing Lamb waves would be more complex, Eq. (1) captures the essence of standing wave formation.

The production of standing waves was verified through numerical simulation using commercial finite element software [27]. A two-dimensional plane strain model of a 3 mm thick graphite plate was excited using a piezoelectric wafer transducer. Technically speaking, a two dimensional plane strain model cannot yield a realistic result for wave propagation in the composite plate as there is no direction of symmetry for wave propagation in a composite plate. However, the model is good enough to capture the essence of standing wave formation at a delamination type defect. A 5-cycle tone-burst voltage signal centered at 100 kHz was used as input. This excited the fundamental antisymmetric Lamb wave mode in the laminate with a 0.8 cm wavelength along with other Lamb wave modes. A 3.5 cm wide delamination was modeled by a viscoelastic layer between the delaminated surfaces [28]. This model assumes linear distributed contact at the delamination zone comprising of chopped fibers and granular matrix phase. The model also eliminates the possibility of interpenetration which is encountered in a zero-volume delamination model. The delaminated region is assumed to be one element thick. For the sake of consistency with experimental results, only the out-of-plane velocity field is reproduced in this article. Fig. 5 shows the snapshots of the out-of-plane velocity field at three different time instants. Standing wave at the delamination site (marked with a line) can be observed in addition to the transmitted and reflected waves.

Next, we propose a “standing wave filter” which is essentially a signal processing technique to isolate only the standing waves from a given wavefield. The first step is to convert the velocity field $v(x,y,t)$ from space–time domain to wavenumber-frequency domain $k_x,k_y,\omega$ using a three-dimensional Fourier transform (3D FT) [15]:
Here, $V(k_x, k_y, \omega)$ corresponds to the wavefront traveling in the vector direction $-k_x \hat{x} - k_y \hat{y}$, where $\hat{x}$ and $\hat{y}$ are the unit vectors along the $x$ and $y$ axes, respectively. A standing wave can be envisioned as a superposition of two waves of equal amplitude propagating in opposite directions over the same spatial region at the same time instant. If the two waves traveling in opposite directions have different amplitudes, then the amplitude corresponding to the weaker wave will also be the amplitude of the standing wave, as described in Eq. (1). Therefore, standing waves can be obtained from $V(k_x, k_y, \cdot)$ as following:

$$V_{sw}(k_x, k_y, x) = \min \left[ |V(k_x, k_y, \omega)|, |V(-k_x, -k_y, \omega)| \right] \quad \forall \omega$$

(3)

where the suffix $sw$ stands for standing waves. The processing steps described in this section are all implemented in MATLAB in discrete-time paradigm. The range of $\omega$ in Eq. (3) is below the Nyquist frequency. The portion of $V_{sw}$ above the Nyquist frequency is modified to force the conjugate symmetry condition. Upon filtering, the residual signal can be transformed back to space–time domain using an inverse 3D FT:

$$v_{sw}(x, y, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V_{sw}(k_x, k_y, x) e^{i(k_x x + k_y y + \omega t)} dk_x dk_y d\omega$$

(4)

This filtered wavefield $v_{sw}(x,y,t)$ simply contains any standing wave that is present in the originally scanned wavefield. For example, if the process described above is applied to the wavefield in Eq. (1), the resulting field will only contain the standing wave component: $2B \cos(k_x x) \cos(\omega t + \frac{\pi}{2})$. Fig. 6 shows the time sequenced wavefields when the originally measured wavefield images in Fig. 3 are passed through the standing wave filter. In Fig. 6b, standing waves can be observed at the delamination location. Although mitigated, standing waves are found to be present long after the incident waves have passed (Fig. 6c). Notice that the incident waves are filtered out in Fig. 6.
To visualize the total amount of standing wave energy experienced at location \((x,y)\) at time \(t\), a mass-normalized value of the cumulative kinetic energy \(E_{sw}\) is computed as follows:

\[
E_{sw}(x,y,t) = \int_{t=0}^{t} \frac{1}{2} v^2 sw(x,y,t) dt
\]  

The cumulative energy field when plotted at the end of the scanning duration (180 μs) helps locate and visualize the delamination (Fig. 7).

Another way to highlight the interaction of ultrasonic waves with delamination is by simply considering the total amount of ultrasonic energy that has passed through a certain point. As standing waves are formed, ultrasonic energy remains trapped inside the delamination region for a longer time as opposed to other locations where the incident or reflected waves are present only for a short time. Therefore, by computing the accumulated mass-normalized kinetic energy \(E_c\):

\[
E_c(x,y,t) = \int_{t=0}^{t} \frac{1}{2} v^2 (x,y,t) dt
\]  

it is possible to accentuate the delamination location in the entire scanned area (Fig. 8) [24]. The visual indication of the delamination can be enhanced even further by image processing. A well-known blob detection algorithm called Laplacian image filtering [29] is applied to the image in Fig. 8c to produce Fig. 9. The Laplacian mask \(L\) used in the filter is given by:

\[
L = \begin{bmatrix}
-1 & -1 & -1 \\
-1 & 8 & -1 \\
-1 & -1 & -1 \\
\end{bmatrix}
\]  

The signal processing steps described above highlight the defect area with respect to the background. These steps might prove cru-
cial while developing automated damage detection algorithms in the future.

3. Non-contact guided wave excitation and sensing

This section demonstrates the simultaneous use of a laser excitation source and LDV measurements to construct wavefield images in a composite specimen. The uniqueness of the laser based excitation used in this study is that, unlike conventional pulse laser sources, the proposed technique can excite arbitrary waveforms at selective frequency ranges. Moreover, there is little risk of ablation damage to the monitored structure since the laser source remains focused on the photodiode. Using this setup, we can also excite hidden locations by running a wire from the photodiode to the PZT affixed at an interior region of the inspection article where a laser beam could not illuminate directly. However, it is observed that the amplitude of the ultrasonic waves excited by the 60 mW CW laser is quite low and wavefield imaging is possible only after using expensive reflective tapes.

Fig. 10 shows the laser excitation setup. The actuator node consists of a PZT wafer, a photodiode and a transformer padded with rubber sheets. The actuator is remotely excited using a laser light source. The output power of the laser used in this experiment is 10 mW and controlled by the laser driver. The source light is modulated by the electro-optic modulator (EOM) to produce user defined waveforms. In our experiments, a 5.5 cycle tone burst signal at 100 kHz driving frequency is used. The strength of the optical signal is then enhanced using an optical amplifier up to 80 mW before it is focused on the photodiode. A commercial photodiode (FDG1010, Thorlab Inc.) converts the input optical power into electric voltage and this voltage is applied to the PZT through a transformer. The PZT when thus electrically excited generates ultrasonic waves in the structure. The excitation amplitude achieved in this study amounts to ±800 mV. More detailed explanation about wireless laser excitation can be found in [30].

Fig. 11 shows the experimental specimen. The 71.8 cm long composite channel has a 13 cm wide base and 3.7 cm high walls on either side. The specimen is 7 mm thick. Details of the material used to fabricate this structure were not provided to the authors. The sensing region was about 25 cm away from the actuator node. Reflective tape (3 M Scotchlite™) was used to improve the quality of the signals from the LDV.

Before creating the ultrasonic wavefield image of the scanned area, a comparison between non-contact laser excitation and conventional wired excitation was made. A 5.5 cycle tone burst signal centered at 100 kHz and ±800 mV peak amplitude was used in each case. The resulting out-of-plane velocities measured at PZT B in Fig. 11 using the LDV are shown in Fig. 12. The AWG and the laser source have different processing times and produce slight difference in phase in the measured signals. The phase difference has been corrected through cross-correlation measurement in Fig. 12.

Once the laser excitation setup is validated through point measurements (Fig. 12), the ultrasonic velocity field images are obtained using the LDV. A tone burst signal at 30 kHz was used for excitation. A sampling frequency of 1.28 MHz and a band pass filter with cutoff frequencies of 15 kHz and 65 kHz were used for data acquisition using LDV. The other vibrometer settings remained identical to those used in preceding sections. The scanned area is a square with 5 cm long sides containing 9000 scan points. Fig. 13 shows the wavefield images obtained using the wireless data interrogation system. Because of the multiple reflections from the junction between the base and the walls, the wave fronts in Fig. 13 are not as distinct as in the previous experiments.

4. Conclusions

This paper studied the applicability of non-contact wavefield imaging techniques to detect delamination in composite structures. A PZT was used to excite guided ultrasonic waves in the target structure and an LDV was used to image the resulting ultrasonic velocity field. The wavefield images thus obtained were further processed to highlight the defect location in the entire scan area. In particular, two novel processing techniques are proposed in this paper: a standing wave filter and another Laplacian image filter. Both were found effective for detecting delamination. Furthermore, a fully non-contact interrogation system consisting of a laser source and an LDV was used to construct ultrasonic field images in a composite specimen. The system described in this study can generate arbitrary user defined waveforms at selective frequencies without having to use a complicated and expensive array of optical lenses. However, the amplitude of the ultrasonic waves produced was low and reflective tape had to be used to obtain useful results from the LDV. The experimental results successfully demonstrate a fully non-contact interrogation system. Further work is needed to provide a practical fully non-contact interrogation system.

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