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Accelerated noncontact laser ultrasonic scanning for damage detection using combined binary search and compressed sensing

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ABSTRACT

Laser ultrasonic scanning is attractive for damage detection due to its noncontact nature, sensitivity to local damage, and high spatial resolution. However, its practicality is limited because scanning at a high spatial resolution demands a prohibitively long scanning time. Inspired by binary search and compressed sensing, an accelerated laser scanning technique is developed to localize and visualize damage with reduced scanning points and scanning time. First, the approximate damage location is identified by examining the interactions between the ultrasonic waves and damage at the sparse scanning points that are selected by the binary search algorithm. Here, a time-domain laser ultrasonic response is transformed into a spatial ultrasonic domain using a basis pursuit approach so that the interactions between the ultrasonic waves and damage, such as reflections and transmissions, can be better identified in the spatial ultrasonic domain. Second, wavefield images around the damage are reconstructed from the previously selected scanning points using compressed sensing. The performance of the proposed accelerated laser scanning technique is validated using a numerical simulation performed on an aluminum plate with a notch and experiments performed on an aluminum plate with a crack and a carbon fiber-reinforced plastic plate with delamination. The number of scanning points that is necessary for damage localization and visualization is dramatically reduced from $N \cdot M$ to $2\log_2 N \cdot \log_2 M$. N and M represent the number of equally spaced scanning points in the x and y directions, respectively, which are required to obtain full-field wave propagation images of the target inspection region. For example, the number of scanning points in the composite plate experiment is reduced by 97.1% (from 2601 points to 75 points).

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1. Introduction

Laser ultrasonic techniques are emerging as an attractive noncontact testing technique in the field of nondestructive testing (NDT) [1–8]. Ultrasonic waves can be generated and measured in a noncontact manner using a pulse laser and a laser Doppler vibrometer, respectively. Their generation and measurement locations are also freely controllable to the desired target points using mirrors. These techniques are very attractive for damage detection and localization due to their noncontact nature, long working distance and sensitivity to local damage.

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Among various laser ultrasonic techniques, laser ultrasonic wave propagation imaging techniques visualize damage by constructing continuous images of full-field ultrasonic wave propagation in the target inspection region [9–14] with respect to time. Wave reflections, scattering, waveform and wave speed changes resulted from damage can be visually identified in the constructed wavefield images. This damage detection process can also be automated by extracting standing wave energy [12], wavenumber changes [13], or sudden changes in the ultrasonic wavefield images [14]. However, certain limitations of these techniques exist. First, the quality of the measured ultrasonic signals is highly dependent on the surface condition of the target specimen and the incident angle of the sensing laser beam [15]. A special surface treatment is often necessary to minimize measurement noise and improve the signal-to-noise ratio. Second, a high-power pulse laser used for ultrasonic excitation may induce impairments, which are referred to as ablation, on the specimen surface and impose a safety concern, particularly for human eyes [16]. Therefore, the parameters associated with laser excitation should be carefully tailored, and users should wear special eye protection goggles. Third, laser scanning requires a prohibitively long scanning time to achieve a high spatial resolution and a good signal-to-noise ratio required for damage detection. For example, 40 min was required to scan a 5 cm × 5 cm square area from an aluminum plate with a spatial resolution of 1 mm, averaging 100 times and a pulse laser with a repetition rate of 100 Hz.

In this study, an accelerated laser scanning technique is developed so that damage can be located and quantified by using a reduced number of scanning points addressing the afore mentioned scanning time issue. First, sparse scanning points are adaptively selected using a binary search algorithm [17], and the approximate damage location is identified by examining the interactions between the ultrasonic waves and the damage at the selected scanning points. Here, a time-domain ultrasonic response from each selected scanning point is transformed into a spatial domain ultrasonic response using a basis pursuit approach so that the interactions between the ultrasonic waves and the damage can be better identified in the spatial ultrasonic domain. Second, the wavefield images around the damage are reconstructed from the selected scanning points using compressed sensing [18]. The number of scanning points that are needed for damage detection can be theoretically reduced from $N \cdot M$ to $2\log_2 N \cdot \log_2 M$. N and M represent the number of equally spaced scanning points in the x and y directions, respectively, which are required to obtain full-field wave propagation images of the target inspection region.

This paper is organized as follows. Section 2 provides a brief overview of the laser ultrasonic scanning system and a number of scanning strategies. In Section 3, an accelerated laser scanning technique is proposed using combined binary search and compressed sensing. The effectiveness of the proposed technique is validated using the numerical simulation described in Section 4 and experimental tests performed on an aluminum plate specimen with a crack in Section 5 and a carbon fiber-reinforced plastic (CFRP) plate with an impact-induced delamination in Section 6. This paper concludes with a brief summary and discussions in Section 7.

2. Laser ultrasonic scanning system and scanning strategies

Fig. 1 shows a schematic of the laser ultrasonic scanning system used in this study. This system is composed of an excitation unit, a sensing unit and a control unit. In the excitation unit, a pulse laser is used for noncontact ultrasonic generation. When a pulse laser beam radiates to an infinitesimal area of a target specimen, a localized heating of the surface causes thermoelastic expansion of the material and generates ultrasonic waves [19]. An excessive temperature increase due to a high-power pulse laser beam may cause surface damage, which is referred to as ablation [20]. Parameters for the laser ultrasonic generation, such as the peak power, beam size and pulse duration, should be carefully designed to prevent ablation. In the sensing unit, the ultrasonic response is measured by a laser Doppler vibrometer (LDV). When a laser beam is reflected from a vibrating surface, the reflected laser beam experiences a frequency shift. A LDV measures this frequency shift and relates it to the out-of-plane velocity of the target surface based on the Doppler effect [21]. The performance of the LDV highly depends on the intensity of the returned laser beam, which can be affected by the incident angle of the sensing laser beam and the light reflectivity of the target specimen [15]. A special surface treatment is often necessary to improve the reflectivity of the surface [22], and the incident angle is typically limited to ±20°. The position of the laser beam on the target specimen is controlled by adjusting the angles of the two mirrors inside a galvanometer. The measured responses are collected and analyzed in the control unit. All units are synchronized and controlled by a personal computer in the control unit.

For fully noncontact scanning, two different scanning strategies are represented in Fig. 2. The first strategy generates ultrasonic waves at a fixed point and measures the corresponding responses at predetermined points in the inspection region. This strategy is named the fixed excitation and scanning sensing (FE/SS) strategy. The second strategy works in reciprocal to the FE/SS strategy. Ultrasonic waves are sequentially generated at predetermined points and the corresponding responses are measured at a fixed sensing point. This strategy is named the fixed sensing and scanning excitation (FS/SE) strategy. Theoretically, FE/SS and FS/SE provide identical results based on the linear reciprocity of the ultrasonic waves [23]. However, the FS/SE strategy is preferred in practice because the intensity of the returned laser beam in the LDV, and consequently the quality of the LDV measurement, can be substantially affected by the incident angle of the laser beam [16]. For example, when the FE/SS strategy is used to scan a large surface, particularly a curved one, maintaining the intensity of the returned laser beam for consistency is challenging. On the other hand, because the thermoelastic expansion of the material produced by the excitation laser beam is not substantially affected by the incident angle, the FS/SE strategy can easily scan a curved surface.

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