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Fatigue crack detection using dual laser induced nonlinear ultrasonic modulation

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ABSTRACT

In this study, a nonlinear ultrasonic modulation technique based on dual laser excitation is proposed for fatigue crack detection. Two pulse lasers are shot on the target specimen for ultrasonic generation. The corresponding ultrasonic responses are measured by a laser Doppler vibrometer (LDV) and analyzed to extract the crack induced nonlinear ultrasonic modulation. First, the effect of the pulse laser beam size on the frequency content of the generated ultrasonic waves is numerically and experimentally investigated. Then, this finding of the laser beam size effect is utilized to generate wideband (WB) and narrowband (NB) ultrasonic waves by adjusting the laser beam sizes of the two pulsed excitation lasers. Nonlinear ultrasonic modulation results from the interaction of WB and NB ultrasonic waves when a fatigue crack exists in the target specimen. The fatigue crack is then detected by comparing the spectral responses obtained under a single WB input and both WB and NB inputs. In the end, a fully noncontact dual laser ultrasonic system is developed and used to detect micro fatigue cracks in aluminum and steel plate specimens.

1. Introduction

Significant efforts have been devoted to the detection, location and even sizing of fatigue crack because early detection of fatigue crack is an important concern to plan maintenance and guarantee the safety of a variety of metallic structures [1]. Under cyclic loading, fatigue damage can grow to critical degrees at an alarming rate without sufficient warning, causing catastrophic consequences [2]. Among various techniques for fatigue crack detection, the ultrasonic technique is one of the most promising approaches and has proven its effectiveness in achieving a reasonable compromise between resolution, sensing range and sensitivity. Conventional linear ultrasonic techniques measure variations of the amplitude, phase, and mode conversion of ultrasonic waves either transmitted or reflected from a crack [3–5]. However, these linear techniques focus on detecting crack towards the middle and end of a specimen's fatigue life, and could be insensitive to the early stage of fatigue crack [6]. Recent studies have shown that alternating opening and closing of fatigue crack occurs under vibration or wave propagation, producing nonlinear ultrasonic responses. Then, crack can be detected by investigating resulting harmonics, modulations between different frequencies, or changing resonance frequencies as the amplitude of the driving input changes. These nonlinear ultrasonic techniques have shown a much higher sensitivity to early stage fatigue crack than the conventional linear techniques [7–10].

More specifically, for a nonlinear ultrasonic modulation technique, a low-frequency input and a high-frequency input are simultaneously applied to a damaged specimen to create modulation [7]. For example, a fatigue crack in an aluminum plate was detected by using a piezoelectric stack actuator for a low-frequency input generation and a surface-mounted piezoelectric transducer for creation of a high-frequency input [8]. Low and high frequency ultrasonic waves were generated in an aluminum alloy by two oblique incident shear transducers, and the corresponding nonlinear modulation response induced by a fatigue crack was investigated under cyclic loading [9]. Nonlinear ultrasonic modulation has also been used for detecting micro cracking and deterioration in concretes with an impact hammer for the generation of a low-frequency input and a piezoelectric transducer for high-frequency excitation [10].

Recent advances have made it possible to conduct the nonlinear ultrasonic modulation technique in a noncontact manner, facilitating testing of structures or components that are continuously rolled on a production line, in harsh environments, or just difficult to physically access. For fatigue crack detection, a pair of air-coupled transducers (ACTs) was used to generate and receive longitudinal or flexural ultrasonic waves in plate-like specimens [11]. Signals were scanned with a laser Doppler vibrometer (LDV) under two distinct frequency inputs generated by ACTs [12]. Two excitation laser beams were intensity modulated to generate ultrasonic waves at two distinct frequencies [13]. Also, nonlinear features were extracted from the responses induced by a wideband pulse laser input [14,15].

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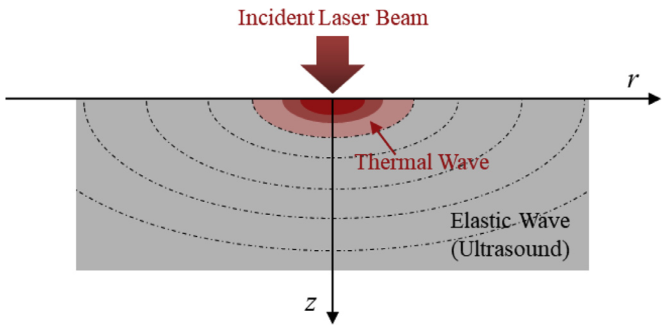

Fig. 1. Illumination of laser ultrasonic generation.

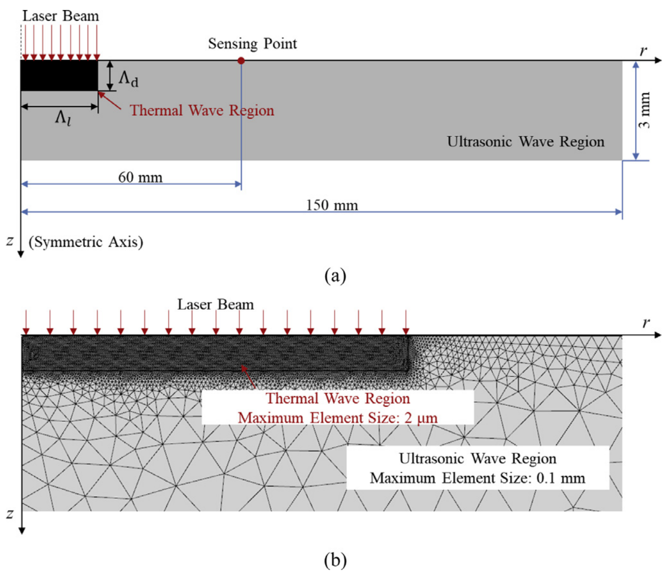

Fig. 2. Schematic of the 2D-axisymmetric FEM model. (a) Geometry of the plate model, (b) finite element meshes for thermal and ultrasonic wave regions.

This paper investigates the effect of the laser beam size on the frequency content of the generated ultrasonic waves, and develops a dual laser ultrasonic system to identify nonlinear ultrasonic modulation induced by fatigue crack. The uniqueness and advantages of the proposed technique include the followings: (1) the effect of the laser beam size on ultrasonic wave generation is numerically and experimentally investigated; (2) a noncontact dual laser ultrasonic system is developed to identify crack induced nonlinear ultrasonic modulation; (3) the broadband nature of the pulse laser input increases the likelihood of nonlinear ultrasonic modulation generation at the existence of fatigue crack; and (4) using dual laser excitation, a damage feature is defined without relying on any baseline data obtained from the pristine condition of a target specimen.

This paper is organized as follows. Section 2 presents the numerical and experimental investigations of laser induced ultrasonic waves with different laser beam sizes. Section 3 describes the developed dual laser induced nonlinear ultrasonic modulation technique for fatigue crack detection. In Section 4, the test setup and the test results from aluminum plate specimens with fatigue cracks are presented. Section 5 further demonstrates the effectiveness of the developed technique on detection fatigue cracks in steel plate specimens. Finally, a conclusion is provided in Section 6.

2. Laser ultrasonic generation with varying laser beam size

2.1. Working principle of laser ultrasonic generation

Fig. 1 shows thermal waves and subsequent elastic waves created by a pulse laser shot on the top surface of an isotropic specimen in a cylindrical coordinate system. The illuminated area absorbs the electromagnetic radiation from the laser, and the resulting thermal conduction can be expressed as follows [16]:

$$\rho C_p \frac{\partial T(r,z,t)}{\partial t} = \nabla (k \nabla T(r,z,t)) + Q \quad (1)$$

where $T(r, z, t)$ represents the time-dependent temperature variation along the radial direction r and the depth direction z. ρ, C_p and k are

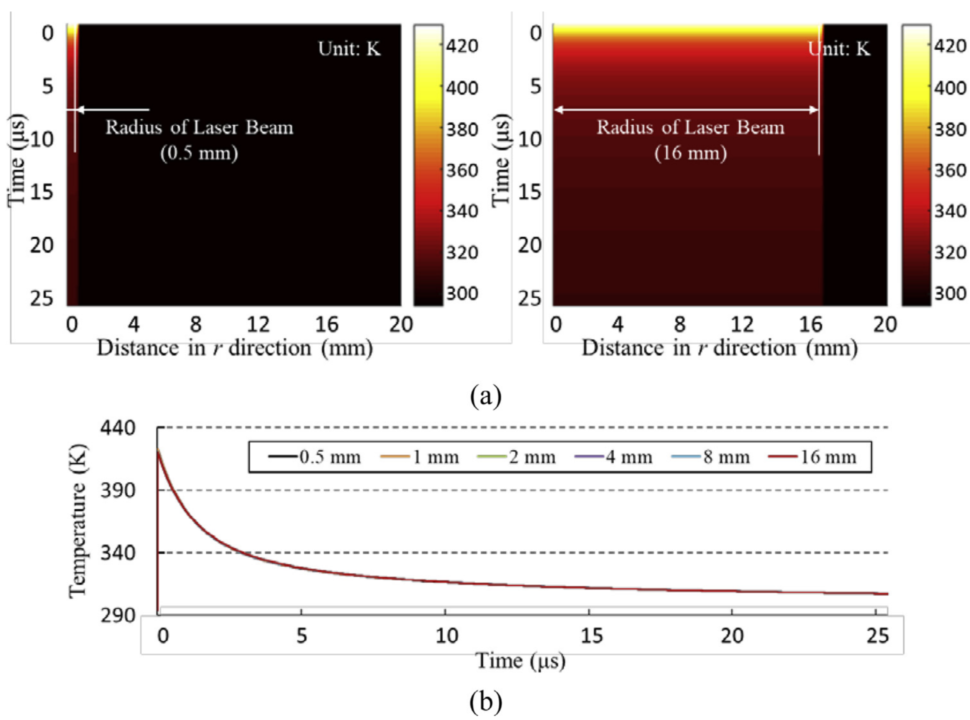

Fig. 3. Temperature responses irradiated by a pulse laser with different beam sizes. (a) Temporal and spatial profile of temperature response at $z = 0$ and with $r_{laser} = 0.5$ and 16 mm, (b) time responses of temperature at $r = z = 0$ with $r_{laser} = 0.5$, 1, 2, 4, 8 and 16 mm.