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Numerical simulation of damage detection using laser-generated ultrasound

Peipei Liu, Ab Wahab Nazirah, Hoon Sohn [*]

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-338, Republic of Korea

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ABSTRACT

Laser ultrasonic techniques have been widely investigated due to its high spatial resolution and capacity for remote and noncontact measurement. In this study, the laser induced ultrasonic wave on an aluminum plate is simulated, and a nonlinear feature is used to detect a micro crack introduced in the plate model. A multi-physics simulation is conducted and optimized considering the effect of thermal diffusion. A nonlinear feature, called Bhattacharyya Distance (BD), is calculated to show the crack-induced geometric difference among the state space attractors obtained from closely spaced measurement points near the crack. First, a 3D model is built, and its simulation result is compared with an experiment performed using a noncontact laser ultrasonic measurement system. Then, by creating a micro crack in the model, BD is extracted and the crack is successfully detected and visualized. Finally, the effects of BD parameters, such as embedding dimension and frequency band, on damage visualization are investigated.

1. Introduction

Among various non-destructive evaluation (NDE) and structural health monitoring (SHM) techniques, ultrasonic based NDE/SHM techniques have been widely studied and have proven their effectiveness in achieving a reasonable compromise among resolution, sensing range and detectability [1]. For generating and sensing of ultrasonic waves, various types of contact transducers are available, such as piezoelectric stack actuators, surface-bonded piezoelectric wafer transducers, fiber optic sensors and mechanical shakers. One common issue with all the contract transducers is that a dense array of transducers are often required to achieve good spatial resolution and cover a large inspection area for damage localization or visualization. Moreover, the installation of contact transducers under harsh environments such as high temperature and radioactive conditions is a daunting task. On the other hand, noncontact techniques can be used to take measurements in hostile environments, from geometrically complex and moving specimens, and at a remote distance from the test structure. Currently, noncontact ultrasonic techniques are feasible using laser generation, optical interferometers, electromagnetic acoustic transducers (EMATs), air (gas)-coupled transducers and hybrid combinations of the above [2].

For laser-generated ultrasound, solid state Q-Switched Nd:YAG and gas lasers (CO_2 or Excimers) are commonly used. A number of different physical processes may take place when a metal surface is illuminated by a laser beam. At a low power level of the laser beam, these processes include heating and the generation of thermal and elastic waves (ultrasound). At a high power level, the surface of the specimen may be ablated and a plasma formed, causing melting and plastic deformation of the specimen and even the formation of cracks [3]. In this paper, the discussion of the laser power is restricted to a low power level so that ultrasound can be generated and used for SHM/NDT applications without harming target specimens. The behaviors of laser-generated ultrasonic waves depend not only on the characteristics of the specimen such as optical penetration, thermal diffusion, elasticity, and geometry, but also on the parameters of the laser such as the shape, spot size, and pulse width of the laser beam [4]. Numerical models have been developed for simulating laser-generated ultrasound [4–7], but some of the models consider the laser source as an effective elastic source, neglecting its thermoelastic nature. As for laser ultrasonic sensing, two-beam homodyne, two-beam heterodyne, time-delay, Fabry-Perot, dynamic holographic, multi-beam, fiber interferometry, optical beam deflection, and knife edge detection are available [8]. Among these, laser interferometry using the Doppler effect, which is one type of the two-beam heterodyne methods, is the most widely used because of its high sensitivity and stability compared to the other intensity modulation interferometers.

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* Corresponding author.
E-mail address: hoonsohn@kaist.ac.kr (H. Sohn).

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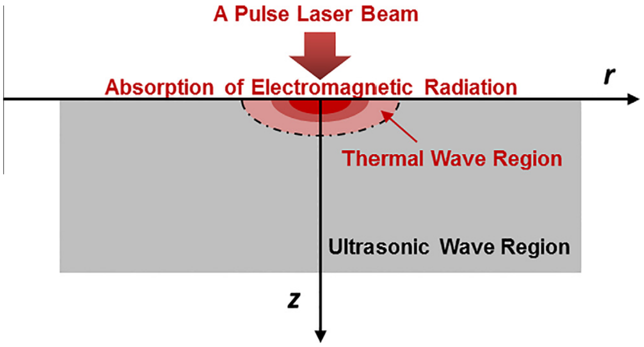

Fig. 1. Illustration of the ultrasonic wave generated by a pulse laser beam.

When the excitation and sensing lasers are incorporated with scanning mirrors, ultrasonic wavefield images with high spatial resolution can be constructed, making subsequent damage diagnosis more intuitive and easier [9]. Previous examples include the detection of fatigue crack based on the variation of the ultrasonic amplitude profile [10] and the visualization of delamination in composites using a standing wave filter [11]. However, with only a few exceptions [12–15], there have been few laser ultrasonic scanning techniques yet which visualize damage using nonlinear features. Lim et al. visualized different stages of fatigue crack formation in aluminum plates based on nonlinear ultrasonic wave modulation [13]. Two distinctive frequency input signals were created by two air-coupled transducers, and the corresponding ultrasonic responses were scanned by a 3D Doppler vibrometer. Liu et al. developed a laser nonlinear wave modulation spectroscopy (LNWMS) technique, where a broadband ultrasonic wave was generated by a Nd:YAG pulse laser and the corresponding responses were measured by a laser Doppler vibrometer [14,15]. Two different nonlinear features were extracted, named as maximum sideband peak count difference (MSPCD) and Bhattacharyya Distance (BD), respectively. For MSPCD, the damage is detected by counting the number of spectral peaks above a moving threshold based on the premise that a spectral signal obtained from a nonlinear system would have more spectral peaks compared to a linear system [14]. BD is computed to quantify the degree of damage-induced nonlinearity from the state space attractors, which are reconstructed from the ultrasonic responses measured by LNWMS [15].

This study develops a 3D simulation model for laser-generated ultrasound, and the simulation results are verified with experiment tests using a noncontact laser ultrasonic measurement system. In addition, a simulated crack in the 3D model is detected using the nonlinear feature BD. The uniqueness of this paper are as follows: (1) Sub-region division guideline for the multi-physics simulation of laser excitation is proposed by theoretically investigating the effect of thermal diffusion caused by laser excitation; (2) The proposed simulation technique for laser-generated ultrasound is experimentally verified using an noncontact laser measurement system; (3) Simulated micro crack is successfully detected and visualized using the nonlinear feature BD; and (4) the effects of BD parameters, such as embedding dimension and frequency band, on damage detection are investigated.

This paper is organized as follows. In Section 2, the working principle of ultrasound generation by a pulse laser is briefly reviewed, and the nonlinear damage feature, BD, is defined. Sections 3 and 4 describe the 3D simulation model and the corresponding verification experiment. The results from the simulation and the experiment are shown and compared in Section 5. Section 6 presents the crack detection results based on the nonlinear feature BD and investigates the effects of BD parameters. This paper concludes with a brief summary and discussions in Section 7.

2. Theoretical backgrounds

2.1. Ultrasound generation by a pulse laser

When the surface of an isotropic specimen is illuminated by a pulse laser, the surface region absorbs the electromagnetic radiation from the laser, causing heating. The resulting thermal conduction can be expressed in a cylindrical coordinate system (Fig. 1) as follows [4]:

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

where $T(r, z, t)$ represents the temperature distribution at time t, r is along the radial direction, z is along the depth direction. ρ, C_p and k are the density, specific heat capacity at a constant pressure, and thermal conductivity, respectively. Q is the power density of a heat source. Because pulse laser is often treated as a heat flux rather than a heat source ($Q = 0$), Eq. (1) can be simplified as:

$$\rho C_p \frac{\partial T(r,z,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T(r,z,t)}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T(r,z,t)}{\partial z}\right) \tag{2}$$

The normal boundary conditions are listed as follows:

$$-k\frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=0} = If(r)g(t), \quad \frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=h} = 0 \tag{3}$$

where I is the power intensity of the absorbed laser beam, and $f(r)$ and $g(t)$ are the spatial and temporal distributions of the pulse laser beam, respectively. $z = 0$ is at the top surface and $z = h$ is at the bottom surface (Fig. 1). h is the thickness of the specimen.

Then, the thermal energy acquired from the pulse laser propagates into the specimen as thermal waves. Also, the thermal wave region is accompanied by thermal expansion, which in turn generates stresses and strains within the specimen. The sudden change in stress within a region of the specimen will act as a source of elastic waves (ultrasound) which then redistribute the stress throughout the specimen and produce a transient displacement field (ultrasonic wave region), as illustrated in Fig. 1. In an isotropic specimen, the displacement satisfies [4]:

$$\begin{aligned}(\lambda + 2\mu)\nabla(\nabla\cdot\mathbf{U}(r,z,t)) - \mu\nabla\times\nabla\times\mathbf{U}(r,z,t)\\ - \alpha_t(3\lambda+2\mu)\nabla T(r,z,t) = \rho\frac{\partial^2\mathbf{U}(r,z,t)}{\partial^2 t}\end{aligned} \tag{4}$$

where $\mathbf{U}(r, z, t)$ is the time-dependent displacement, λ and μ are the Lamé constants, and α_t is the thermoelastic expansion coefficient of the isotropic specimen.

2.2. Bhattacharyya Distance (BD) extraction from state space attractors

A nonlinear mechanism generated by damage evolution can distort ultrasonic waves, create accompanying harmonics and modulations at various frequencies, and/or change resonance frequencies as the amplitude of the driving input changes [16]. In Liu et al., a broadband pulse laser excitation is used in their developed laser nonlinear wave modulation spectroscopy (LNWMS) technique [14,15]. When a broadband pulse signal is used as the input signal, nonlinear wave modulations among various frequency components of the input signal can occur at the presence of damage. By extracting nonlinear damage features from the broadband responses, the damage can be detected. In this study, a nonlinear feature named as Bhattacharyya Distance (BD) is used to detect a simulated crack. Also, in conjunction with laser scanning, BD is used for damage visualization.

Assume a dynamical system described by a first order differential equation:

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