Laser Induced Narrowband Ultrasound for Fatigue Crack Detection

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Abstract

Laser ultrasonic technique is often adopted in non-destructive evaluation (NDE) and structural health monitoring (SHM) for broadband generation of ultrasonic waves. However, in some cases, it is advantageous to manipulate the laser input for the ultrasonic generation with a concentrated frequency of interest. In this study, a spatial mask is used to shape the input pulse laser shot on the target structure, and to excite a narrowband ultrasonic wave with specified central frequencies. Numerical simulations and experimental tests are performed, and the obtained ultrasonic waves are compared with various spatial masks. Then, a dual laser excitation approach is developed to simultaneously introduce two distinct narrowband frequency inputs into the target structure. Nonlinear ultrasonic modulation will occur between the two inputs when the structure is damaged. Finally, the feasibility of the proposed technique is validated by detecting fatigue crack on aluminum plates.

Keywords: Nonlinear ultrasonic modulation, laser ultrasonic, spatial mask, dual laser excitation, fatigue crack detection

1. Introduction

When a structure is illuminated by a pulse laser, the surface of the structure absorbs the electromagnetic radiation from the laser, causing heat. The heated region undergoes thermal expansion, and the thermalelastic stresses generate elastic waves (ultrasound) which can propagate within the structure [1]. The laser ultrasonic technique has fascinated the non-destructive evaluation (NDE) and structural health monitoring (SHM) communities in a noncontact manner, facilitating testing of structures or components that are continuously rolled on a production line, in extremely harsh environments, or just difficult to access. For example, a pulse laser was excited and scanned over a target surface for damage detection in metallic and composite structures [2-4].

Multiply signal processing methods have also been developed to indicate the wave interaction with damage, such as frequency-wavenumber filtering or standing wave extraction [5, 6]. Meanwhile, to detect damage at its very early stage, two independent lasers were intensity modulated to generate ultrasonic waves at two distinct frequencies and extract the crack induced nonlinear modulation [7]. Nonlinear damage features were also extracted from the response signals induced by a single pulse laser input [8, 9].
This paper studies the laser generated narrowband ultrasonic waves using a spatial mask, and develop a dual laser excitation approach for fatigue crack detection based on nonlinear ultrasonic modulation. The uniqueness and advantages of the proposed technique include the followings: (1) A narrowband ultrasonic signal is generated by shaping the input pulse laser shot on the target structure with a spatial mask; (2) The narrowband ultrasonic components generated using spatial masks are numerically and experimentally studied; (3) A full noncontact dual laser excitation system is developed to investigate the crack induced nonlinear ultrasonic modulation; (4) Fatigue crack can be detected by comparing the ultrasonic responses obtained under a single laser excitation and dual laser excitation.

This paper is organized as follows. Section 2 presents the numerical and experimental investigations of laser induced narrowband ultrasonic waves with different spatial masks. Section 3 describes a developed dual laser excitation system and a fatigue crack detection approach based on nonlinear ultrasonic modulation. An experimental validation on aluminum plates with real fatigue cracks are also presented in Section 3. In the end, a conclusion is provided in Section 4.

2. Laser Induced Narrowband Ultrasound with a Spatial Mask

2.1 Laser simulation

A 2D model of a 3 mm thick aluminum plate was built using the commercial finite element software COMSOL Multiphysics. As shown in Figure 1, the x-axis is aligned with the length direction of plate whereas the y-axis is aligned to the plate thickness direction. The material properties of the aluminum used for simulation are listed in Table 1. A pulse laser, treated as heat flux, was applied onto the top surface of the plate at x = 0. The laser illumination area has a shape of 10 parallel lines with a gap of λ (Figure 1). Here, λ dominates the wavelength of the generated ultrasonic waves in the aluminum plate. To enhance the computation efficiency, a multi-scale element strategy.
was used for two sub-regions, i.e. thermal and ultrasonic wave regions (Figure 1). Within the thermal wave region, one thermal degree of freedom and two mechanical degrees of freedom are solved for each node of the elements. Within the ultrasonic wave region, each node has only two mechanical degrees of freedom. Detailed explanation about the multi-scale element strategy can be found in [10].

Table 1. Material properties of the aluminum used for numerical simulation.

<table>
<thead>
<tr>
<th>Density ( \rho ) (kg/m(^3))</th>
<th>Young’s modulus ( E ) (GPa)</th>
<th>Poisson’s ratio ( \nu )</th>
<th>Coefficient of thermal expansion ( \alpha_r ) (K(^{-1}))</th>
<th>Thermal conductivity ( K ) (W/(m·K))</th>
<th>Heat capacity at constant pressure ( C_p ) (J/(kg·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2700</td>
<td>68.9</td>
<td>0.33</td>
<td>2.34×10^{-5}</td>
<td>170</td>
<td>900</td>
</tr>
</tbody>
</table>

In the simulation, the gap \( \lambda \) of the parallel line array was set as 3 and 4 mm. It is assumed that the heat flux within the laser illumination area is Gaussian distributed and has a peak power intensity of 2.5 \( \times \) 10\(^5\) MW/m\(^2\) for 12 ns. The initial temperature and displacement field values at \( t = 0 \) were set to \( T = 293.15 \) K and \( U = (0,0) \) in \( x \) and \( y \) directions. The time duration for each simulation was 150 \( \mu \)s. 1 ns time step was used for the first 12 ns, and then the time step was increased to 200 ns.

Figure 2 shows the out-of-plane (along the \( y \) direction) velocity signals measured from a sensing point positioned at \( x = 100 \) mm (Figure 1). When \( \lambda = 3 \) mm and 4 mm, two dominant wave packages with different central frequencies can be clearly identified from Figures 2(a) and 2(b), respectively. As mentioned above, the \( \lambda \) value decides the wavelength of the generated ultrasonic waves in the aluminum plate. Also, considering about the multi-mode and dispersion in thin plates, \( \lambda \) will correspond to different wave modes with the same wavelength of \( \lambda \) but different central frequencies.

Take \( \lambda = 4 \) mm as an example, the dispersion curves plotted in Figure 3 give a frequency of 0.677 MHz for A0 mode and 0.900 MHz for S0 mode, respectively, which are consistent with the simulation results (0.682 MHz for A0 mode and 0.894 MHz for S0 mode) shown in Figure 2(b). Note that the group velocities shown in Figure 3 also match with the arrival time for different wave packages obtained from simulation. Table 2 lists the frequency values obtained from both dispersion curves and simulations when
\( \lambda = 3 \text{ mm and } 4 \text{ mm.} \) Based on this observation, though the pulse laser with a parallel line array cannot generate ultrasonic waves at a single central frequency, it is still able to effectively compress the broadband response induced by a simple pulse laser. Moreover, it has been proved that, with a parallel line array for excitation, the signal-to-noise ratio for laser induced ultrasonic waves can be improved [11].

![Dispersion curves](image)

Figure 3. Dispersion curves of group velocity and wavelength in a 3 mm thick aluminum.

<table>
<thead>
<tr>
<th>( \lambda ) (mm)</th>
<th>Frequency components (MHz)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A0</td>
<td>S0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Numerical dispersive curves</td>
<td>0.930</td>
<td>1.077</td>
</tr>
<tr>
<td></td>
<td>FEM models</td>
<td>0.920</td>
<td>1.064</td>
</tr>
<tr>
<td></td>
<td>Experiments</td>
<td>0.936</td>
<td>1.061</td>
</tr>
<tr>
<td>4</td>
<td>Numerical dispersive curves</td>
<td>0.677</td>
<td>0.900</td>
</tr>
<tr>
<td></td>
<td>FEM models</td>
<td>0.682</td>
<td>0.894</td>
</tr>
<tr>
<td></td>
<td>Experiments</td>
<td>0.712</td>
<td>0.901</td>
</tr>
</tbody>
</table>

### 2.2 Experimental validation on an aluminum plate

To experimentally investigate the effect of the parallel line array on ultrasonic wave generation, a 3 mm thick circular aluminum plate with a radius of 150 mm was prepared. Figure 4 shows the experimental setup for this test. A diode pumped Q-switched Nd:YAG pulse laser (Quantel Centurion+) was used for excitation. The Nd:YAG pulse laser has a wavelength of 532 nm, a pulse duration of 12 ns and a maximum pulse energy of 25 mJ. An optical lens, together with a spatial mask, in front of the pulse laser can shoot the laser at a desired excitation position with a shape of parallel line array. Following the same cases in simulation, 10 parallel lines with \( \lambda = 3 \text{ mm and } 4 \text{ mm} \) were used for excitation in this experiment (Figure 4). Note, besides using a spatial mask [11, 12], the parallel line array can also be generated by adopting multiple laser sources [13] or diffractive optical elements (DOEs) [14]. The out-of-plane ultrasonic responses were measured by a commercial laser Doppler vibrometer LDV (Polytec MSA-100) with a sampling frequency of 3.125 MHz for 150 \( \mu \text{s} \). The excitation
was applied at the center of the aluminum plate, and the sensing point was located 100 mm away from it.

![Figure 4. Experimental setup for narrowband ultrasonic generation with a spatial mask.](image)

Figures 5(a) and 5(b) show the time domain and frequency domain velocity signals obtained from the circular aluminum plate under a parallel line array laser excitation with \( \lambda = 3 \) mm and 4 mm, respectively. The central frequency values for A0 and S0 modes are summarized in Table 2 as well. Comparison of the simulation and experimental results from Figures 2 and 5 consistently shows that, using a spatial mask, the broadband response of a pulse laser can be effectively compressed and the central frequencies can be manipulated by adjusting \( \lambda \). Note that the difference between the time domain signals in Figures 2 and 5 is mainly attributed to the fact the length of the parallel lines is infinite in simulation.

![Figure 5. Experimental results obtained using a spatial mask with \( \lambda = 3 \) mm and the corresponding spectra: (a) \( \lambda = 3 \) mm, and (b) \( \lambda = 4 \) mm.](image)

### 3. Fatigue Crack Detection with a Dual Laser Excitation Approach

#### 3.1 Nonlinear ultrasonic modulation using a dual laser excitation system

When two inputs with different frequencies are applied to an intact (linear) structure, the structural response contains the frequency components corresponding only to the input frequencies. However, if the structure behaves nonlinearly (e.g., due to fatigue crack
existence), the structural response will contain not only the input frequencies but also their harmonics (multiples of input frequencies) and modulations (combinations of input frequencies) [15]. This phenomenon is called nonlinear ultrasonic modulation and it has been considered as an effective signature of the presence of fatigue crack at its very early stage.

By taking advantage of the laser induced narrowband ultrasound with a spatial mask, this study develops a nonlinear ultrasonic modulation technique using a dual laser excitation system. As shown in Figure 6, a diode pumped Q-switched Nd:YAG pulse laser (Quantel Centurion+) and a Q-switched Nd:YAG pulse laser (Quantel Ultra) are used for dual laser excitation. For the Quantel Centurion+ (Excitation I), a spatial mask is installed in front of its optical lens to generate pulse lasers in the form of a parallel line array. For another Q-switched Nd:YAG pulse laser (Excitation II), the Quantel Ultra laser has a wavelength of 532 nm, a pulse duration of 8 ns, and a maximum pulse energy of 30 mJ. The optical lens in front of the pulse laser can shoot the laser beam at a desired location with a relatively big laser beam size. It has been proven that the spectral response can be shifted to a low frequency range (< 200 kHz) once the radius of the laser beam increases over 10 mm [16]. The two pulse lasers are synchronized in the dual laser excitation system and can be simultaneously emitted up to 20 times per second. The above-mentioned LDV (Polytec MSA-100) is also adopted to measure the out-of-plane ultrasonic responses in the developed dual laser excitation system.

Figure 6. Schematic of a dual laser excitation system.

Fatigue crack in a target structure can be detected with the following two steps:

**Step 1:** A single laser excitation (Excitation I with a parallel line array) is applied to the target structure. The spectrum of the acquired ultrasonic response is treated as reference. Here, the λ value of the parallel line array is chosen to ensure that the generated central frequencies are higher and distinguishable from the spectral response induced by Excitation II.

**Step 2:** A dual laser excitation (Excitation I with a parallel line array, and Excitation II with a big beam size) is applied simultaneously to the target structure. The spectrum of the corresponding response is collected and compared with the reference spectrum.

For an intact (linear) structure, the Excitation II doesn’t have much effect on the response in the higher frequency band induced by Excitation I. Once fatigue crack
exists, coupling between responses induced by Excitation I and II occurs and the Excitation II affects the response in the higher frequency band induced by Excitation I. As illustrated in Figure 7, based on nonlinear ultrasonic modulation, the Excitation II will introduce modulation components next to the spectral response of Excitation I in the frequency domain. Alternatively, it may also broaden the distribution of the spectral response induced by Excitation I (Figure 7). Therefore, by comparison of the spectral responses induced by a single laser excitation and a dual laser excitation, fatigue crack can be identified. Moreover, this approach doesn’t require any baseline data obtained from the pristine condition of the target structure.

![Figure 7. Illustration of fatigue crack induced nonlinear ultrasonic modulation using a dual laser excitation system.](image)

### 3.2 Fatigue crack detection in aluminum plates

Three 3 mm thick aluminum plates (6061-T6 aluminum alloy) were prepared to evaluate the proposed technique. All geometrical information of the specimens can be found in Figure 8. Cyclic loading tests were carried out using a universal testing machine (INSTRON 8801) with a 10 Hz cycle rate, maximum load of 25 kN, and stress ratio of 0.1, to initiate fatigue crack from a notch in two specimens, named D1 and D2, respectively. The introduced fatigue crack is approximately 15 mm long, and the overall width of the crack is less than 50 µm and less than 15 µm near the crack tip. The intact specimen is labelled as I1.

![Figure 8. Geometrical dimensions of aluminum plate and laser excitation and sensing arrangement.](image)

The developed dual laser excitation system was adopted in this test. As shown in Figure 8, Excitation I was used to generate a parallel line array with $\lambda = 3$ mm and a pulse energy of 25 mJ. Excitation II is used to shoot a pulse laser with a big beam size (radius = 12 mm) and a pulse energy around 20 mJ. The LDV measured the out-of-plane velocity responses with a sampling frequency of 3.125 MHz for 200 µs. The sensing laser was located near the crack or the notch for each specimen.
From each specimen, two responses were measured by applying (1) single excitation (Excitation I), and (2) dual excitation (Excitation I & II). To improve the signal to noise ratio, all the responses were measured 200 times and averaged in the time domain.

Figure 9 gives the representative time domain signals acquired from the intact specimen I1 under both single and dual laser excitation. Here, the low frequency components introduced by Excitation II in dual excitation response can be clearly seen in the time domain. Figure 10 plots the spectral responses of Excitation I under both single and dual laser excitation from all the three specimens. Two spectral peaks can be clearly identified according to A0 and S0 modes with a wavelength of 3 mm. Also, comparing with the intact case (I1), the damage cases (D1 and D2) exhibit more differences between the spectral responses under single and dual laser excitation. As explained above, this is due to the fatigue crack induced nonlinear ultrasonic modulation.

![Figure 9](image)

**Figure 9.** Time domain signals obtained from an intact aluminum specimen I1.

![Figure 10](image)

**Figure 10.** Test results in the frequency domain obtained from: (a) intact I1, (b) damage D1, and (c) damage D2.

However, because the amplitude of the crack induced nonlinear modulation is at least one or two orders of magnitude smaller than that of the linear components, the
difference between the intact and damage specimens is not very eminent. Additional feature extraction techniques (e.g., sideband peak count technique [17] and spectral correlation technique [18]) need to be included for further signal processing.

4. Conclusions

This paper numerically and experimentally investigated the effect of using a spatial mask to generate a narrowband ultrasonic response in a target structure. Based on this observation, a dual laser excitation system was developed to investigate the crack induced nonlinear ultrasonic modulation in a fully noncontact manner. Fatigue crack can be detected by comparing the ultrasonic responses obtained under a single laser excitation and a dual laser excitation. And it does not rely on any baseline data obtained from the pristine condition of the target structure.

The performance of the proposed technique was validated by detecting fatigue cracks from three aluminum plate specimens. The average length of these fatigue cracks is approximately 15 mm and their width is less than 50 µm.

A future study is warranted to develop damage features that can exaggerate the spectral difference shown at the existence of fatigue crack, and locate and quantify fatigue crack by introducing laser scanning technique.

Acknowledgements

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References