# Nonlinear Laser-generated Surface Wave Technique for Evaluation of surface damage

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**Abstract**

This study presents the nonlinear narrowband laser-generated surface wave technique as a non-contact method to evaluate the surface micro-damage of aluminum alloy specimens subjected to tensile deformation. The basis of narrowband surface wave generation principles by line-arrayed laser beam and second harmonic generation by acoustic nonlinearity were analyzed theoretically. For the experimental generation of the narrowband surface wave, the system consisted of pulsed laser, beam expander and slit mask was used. The acoustic nonlinearity of surface wave is evaluated by measuring the magnitude of second harmonic in the received wave signal. This process is applied to several specimens with different level of surface micro damage. Experimental results showed good correlation between the acoustic nonlinear parameter of a laser-generated surface wave and tensile deformation.

**Keyword :** Laser, Surface wave, Narrowband, Acoustic Nonlinearity

## 1. Introduction

In recent, experimental results and analytical models have shown that the second-order harmonic amplitude is directly related to the microstructural evolution [1-3]. Cantrell [3] used bulk waves to measure the acoustic nonlinearity in a longitudinal wave and demonstrated a correlation between acoustic nonlinearity and dislocation substructures. Blackshire et al. [4] used surface Rayleigh waves to effectively evaluate fatigue damage. However, these methods employed the conventional ultrasonic technique, which involves the use of contact-type transducers that must be in contact with the surface of the material. Such a technique requires not only flat or simply curved material surfaces, but also couplants. These requirements can be principal causes of experimental errors. To overcome this problem, laser-ultrasonic techniques have been studied for the generation of ultrasonic waves. [5]

In general, a narrow bandwidth wave signal is preferred for acoustic nonlinearity tests where amplitudes at the fundamental frequency and its double frequency are measured. In order to obtain a narrowband laser-generated surface wave, the use of a shadow mask in the form of line-arrayed slits to mask an expanded laser beam is an effective and easy technique. [6] Jhang [7] used this method to evaluate the acoustic nonlinearity of a generated narrowband surface wave.

In this study, the acoustic nonlinearity of a narrowband laser-generated surface wave was used to evaluate deformation in aluminum 6061-T6 specimens. The specimens were deformed with a strokecontrolled tensile tester so as to make specimens with various degrees of damage. A surface wave generation system was constructed using a Nd-YAG pulsed laser and a line-arrayed slit mask. A narrowband signal was generated by designing the slit mask according to an analytical model. The received signal was detected by a resonance-type narrowband transducer (i.e., a resonance-type piezoelectric transducer) with twice the fundamental frequency so as to effectively receive the second-order harmonic component of the surface wave. Experimental results were obtained in terms of the relative nonlinear parameter (β') for each deformed specimen.

## 2. Theory

### 2.1 Acoustic Nonlinearity of Ultrasonic Waves

The acoustic nonlinearity parameter may be obtained from measurements of the amplitudes of the fundamental and second harmonic waves, $A_1$ and $A_2$. The second-order nonlinear parameter of a material, β , is determined as follows[8] :

$$\beta = \frac{8A_2}{k^2 x A_1^2}, \tag{1}$$

where $A_1$ is the amplitude of a fundamental wave, $A_2$ is the amplitude of a second-order harmonic wave, $k$ is the wave number, $x$ is the propagation distance and $\omega$ is the angular frequency.

The nonlinear parameter $\beta$ depends on the amplitude of the fundamental and second harmonic waves, the wave number, and the propagation distance. By experimentally fixing the propagation distance ~~$x$~~ and the wave number for each target, the relative nonlinear parameter $\beta'$ of the surface waves can be simply defined and calculated by measuring the amplitudes of both the fundamental wave $A_1$ and the second-order harmonic wave $A_2$ which is proportional to the absolute $\beta$ as follows:

$$\beta' = \frac{A_2}{A_1^2}. \tag{2}$$

### 2.2 The Narrowband Laser-generated Surface Wave Generation for Nonlinear Ultrasonics

The mechanism of a laser-generated surface wave is demonstrated by the thermoelastic effect between the laser beam and a material. Duffer [5] conducted theoretical and experimental studies frequency response of a laser-produced surface wave using the optical fiber method. Jhang [7] employed the shadow mask method and analyzed frequency response of laser-generated surface wave. For a line-arrayed laser beam, the frequency spectrum of the generated surface wave, *G*(*f*), can be expressed as follows [5]:

$$G(f) = NH(f)S(f), \tag{3}$$

where *N* is the number of slit openings, *H*(*f*) is the frequency spectrum of the surface wave generated by a single laser beam, and $S(f)$ is the array function, which is dependent on *N* and the time interval of the slit.

The frequency spectrum of a surface wave generated with a rectangular pulse array beam is shown in Figure 1. From these investigations, a value of *w* that eliminates the intrinsic $A_2$ can be selected.

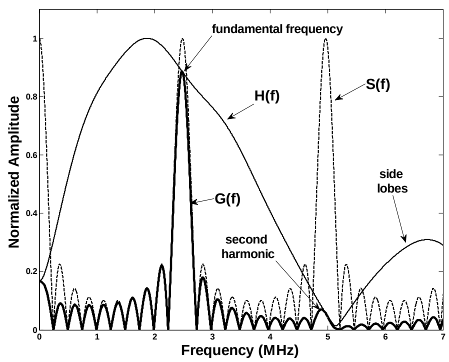


Fig. 1 Theoretical frequency spectra of narrowband surface waves generated by single and multiple line-arrayed rectangular pulse laser beams, *H*(*f*), *S*(*f*), *G*(*f*).

## 3. Experimental Procedure

In order to fabricate a damaged specimen, aluminum 6061-T6 was machined to a 330 mm length, 25 mm width, 10 mm thickness, and 220 mm gage length for ASTM plate standards. Tensile tests were carried out with a stroke control and were interrupted so as to obtain different degrees of plastic deformation.

A schematic diagram of the experimental setup for measuring the acoustic nonlinearity of a laser-generated surface wave with a slit mask is shown in Figure 2. A Nd:YAG pulsed laser was used to excite the surface wave. A slit mask was attached to the specimen surface so as to negate beam diffraction. As calculated from theory, a narrowband surface wave with a center frequency of 2.5 MHz was generated using a slit mask with a 1.168 mm slit interval. In this study, the opening width of a slit was selected as 0.6 mm so as to minimize the intrinsic $A_2$. A 5 MHz resonance-type transducer was employed to receive the laser-generated surface wave. Such a transducer served to enhance the receiving sensitivity of the second-order harmonic frequency. The propagation distance was fixed at 150 mm for all specimens. The received signal was processed by FFT so as to obtain the amplitude of the fundamental and second-harmonic waves, $A_1$ and $A_2$. The relative nonlinear parameter ($\beta'$) was calculated by Eq. (2)

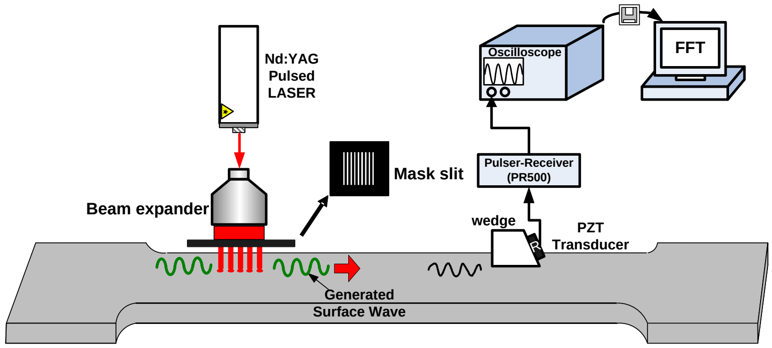


Fig. 2. Schematic diagram of the experimental setup for the measurement of the acoustic nonlinearity of a laser-generated surface wave.

## 4. Results and Disscussion

The typical time-domain signal and FFT results for a received laser-generated surface wave in an as-solutionized specimen are shown in Figure 3. As expected from the theoretical analysis, a narrowband surface wave was effectively generated with the laser. Both the 2.5 MHz fundamental wave and the 5 MHz second-order harmonic wave were present. Shown in Figure 4 are the results obtained for the calculated relative nonlinear parameter $\beta'$ of the received signals from each specimen; $\beta'/\beta'_0$ denotes the ratio of the relative nonlinearity parameter to that of an as-solutionized specimen, $\beta'_0$. The relative acoustic nonlinear parameter increased as a function of the tensile strain. The obtained findings show that the acoustic nonlinearity of surface waves may have a good correlation to the tensile strain. The overall results for the aluminum alloy indicate that the acoustic nonlinearity of laser-generated surface waves may be used to evaluate the tensile deformation.

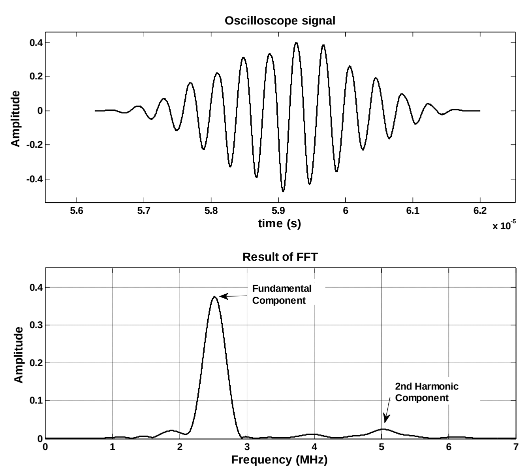


Fig. 3. Typical time-domain signals and frequency spectrum of a surface wave received from an as-solutionized aluminum alloy specimen.

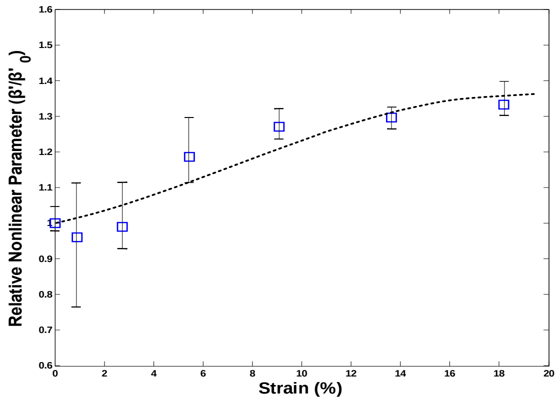


Fig. 4 Relative acoustic nonlinear parameter as a function of the tensile strain.

## ACKNOWLEDGEMENTS

This work was supported by the Innovations in Nuclear Power Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20101620100080).

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