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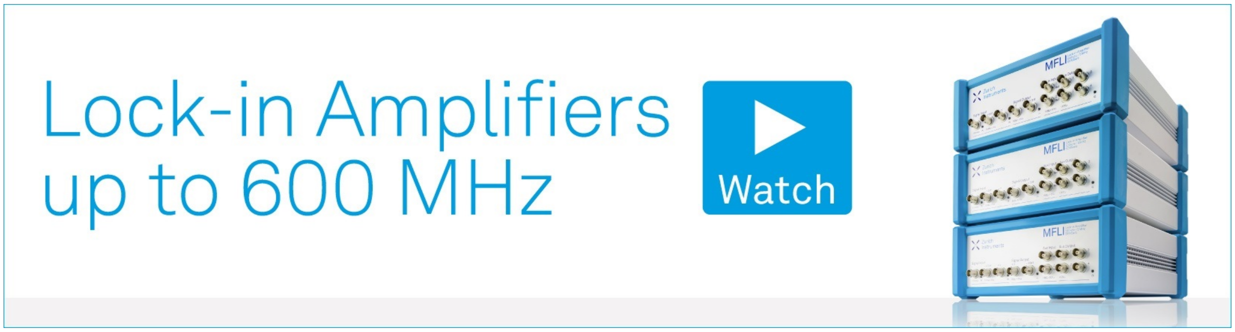

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Nonlinear Mixing of Laser Generated Narrowband Rayleigh Surface Waves

Chaitanya Bakre[a], Prabhu Rajagopal[b], and Krishnan Balasubramaniam[c]

Centre for Non-Destructive Evaluation & Department of Mechanical Engineering,
Indian Institute of Technology Madras, Chennai, India. 600036.

[a]Corresponding author: chitbak@gmail.com
[b]prajagopal@iitm.ac.in
[c]balas@iitm.ac.in

Abstract. This research presents the nonlinear mixing technique of two co-directionally travelling Rayleigh surface waves generated and detected using laser ultrasonics. The optical generation of Rayleigh waves on the specimen is obtained by shadow mask method. In conventional nonlinear measurements, the inherently small higher harmonics are greatly influenced by the nonlinearities caused by coupling variabilities and surface roughness between the transducer and specimen interface. The proposed technique is completely contactless and it should be possible to eliminate this problem. Moreover, the nonlinear mixing phenomenon yields not only the second harmonics, but also the sum and difference frequency components, which can be used to measure the acoustic nonlinearity of the specimen. In this paper, we will be addressing the experimental configurations for this technique. The proposed technique is validated experimentally on Aluminum 7075 alloy specimen.

INTRODUCTION

In recent years, nonlinear ultrasonics has been an area of interest for researchers mainly because of its ability to detect damage at the microstructural level as opposed to linear ultrasonics, which is limited to detection of large scale damages like macro cracks [1]. In the early state of damage, the dislocation density is affected, resulting in an increase in the material nonlinearity, which has negligible influence on the basic elastic properties of the material but there are significant changes in the third order elastic properties. In nonlinear acoustic measurements, higher harmonics are generated because of the inherently present material nonlinearity as well as the dislocations and precipitates present at the microstructural level which cause spectral energy transfer due to the deformation of the waveform [2]. The generation of higher harmonics can be related to the microstructural evolution [3].

Although, nonlinear ultrasonics presents a great potential in detecting the damages at an early stage, it suffers from many challenges due to its high sensitivity. A typical method for the generation and detection of an ultrasonic wave is by the use of piezoelectric transducers. Electrical components such as amplifiers, cables etc. incorporate nonlinearity in addition to the material nonlinearity. Moreover, additional nonlinearity is also incorporated in the measurements due to the variability in the coupling and the surface roughness between transducer-wedge and wedge-specimen interfaces. These factors influence the accurate measurements of the inherently small higher harmonic amplitudes, jeopardizing the repeatability of the experimental output [4] [5]. The background nonlinearities because of electrical components can be reasonably filtered out by signal processing techniques as they remain constant with the input power setting, but the coupling nonlinearities are variable in nature. Thus more reliable techniques need to be developed in order to prudently deal with the background nonlinearities. Non-contact methods presents potential to deal with such problems.

In the last two decades, noncontact ultrasonic methods such a Laser ultrasonics, EMAT's, air-coupled ultrasonics have found growing applications in NDE. Noncontact generation and detection methods demonstrate potential to

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disregard these influences and provide advantages in the applicability for in-situ testing and online monitoring in hazardous and hostile environments [6]. Perhaps, until now their application in nonlinear acoustic measurements is not explored to a great extent. Laser generation and detection of ultrasonic waves demonstrate many advantages over EMAT's which are limited to conducting specimens; and air coupled transducers which requires to be placed in the proximity to the surface of the specimen and their frequencies are limited up to 4 MHz. Moreover, Lasers do not require a plane or a curved surface unlike wedge-transducers. Thus irregular contours can also be investigated by lasers.

A more sophisticated method, known as nonlinear wave-mixing technique prevails in which two initially monochromatic waves of significant amplitude interact with each other resulting in generation of not only the second harmonics but also the sum and the difference component frequency waves [7]. Contactless broadband receivers such as Laser Vibrometer are a good choice in this case of wide frequency range. This mixing phenomenon occurs on the account of the material nonlinearity and the wide range of the generated frequencies can provide more physical information as compared to a single frequency to determine the state of the material. In this paper, we demonstrate a new technique for nonlinear mixing of Rayleigh waves and the paper is organized in the following manner. First, a 3D elastodynamic FE model is implemented to study the physics of nonlinear wave mixing of Rayleigh waves. Secondly, an experimental methodology for the generation of two co-directional Rayleigh waves using the slit-mask method is proposed and implemented on an Aluminum alloy 7075 specimen. In the next section, the experimental results are discussed. This is followed by the concluding remarks and the potential application of this technique for online monitoring is discussed.

FINITE ELEMENT SIMULATIONS

A numerical analysis is conducted to affirm the physics of generation of nonlinear mixed Rayleigh waves owing to the material nonlinearity. For this purpose, a 3D elastodynamic model is developed using COMSOL^{TM} Multiphysics 5.2. To reduce the computation time, the model dimensions are reduced to 10(mm) x 40(mm) x 20(mm). Hyperelastic material module is chosen and the literature values of Murunaghan's third order elastic constants for AA 7075 are used to incorporate material nonlinearity in the model, refer Table 1. Two Hanning windowed inputs of 2 MHz and 3 MHz frequencies, 200 µm apart, are used for the point excitation of Rayleigh waves at its critical angle. PARADISO solver is used to obtain the solution. A 3D visualization of the surface displacement field in the out-of-plane direction is shown in Figure 1 (a). Out of plane displacements are recorded on the surface at 3 mm distance from the source. The time domain signal is shown in Figure 1 (b), frequency domain analysis of which shows generation of mixed nonlinear Rayleigh waves, 1 MHz (Difference), 2 MHz (Fundamental #1), 3 MHz (Fundamental #2), 4 MHz (Second harmonic #1), 5 MHz (Sum) and 6 MHz (Second harmonic #2).

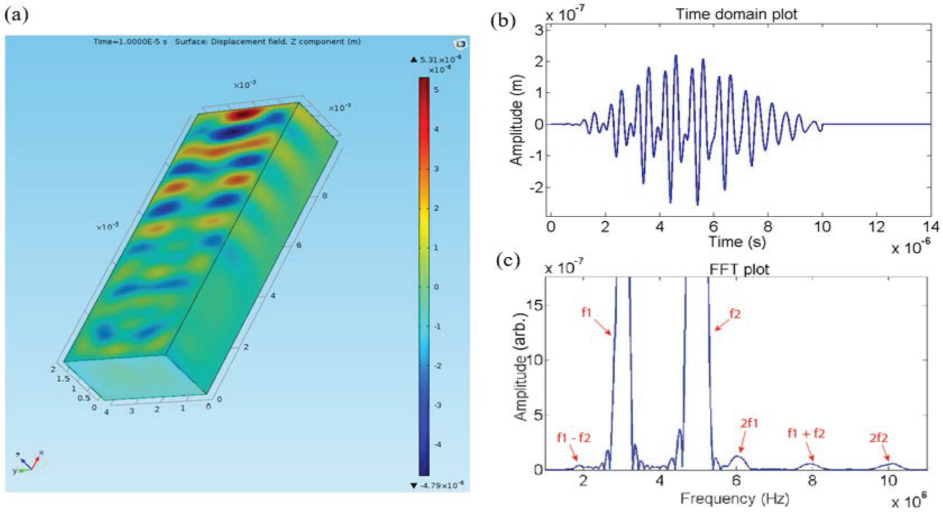

FIGURE 1. (a) A 3D visualization of elastodynamic model of out of plane displacement components of mixed nonlinear Rayleigh waves. (b) A time domain plot in the far field region representing out of plane displacements of the mixed waves on the surface. (c) A frequency domain plot of the received time domain signal (simulation) showing fundamental, second harmonics, sum and difference wave components.

TABLE 1. Elastic Parameters of Aluminum 7075.

	Values	Description
E	$7.08729.\ 10^{10}\ \frac{N}{m^2}$	Young’s modulus
σ	0.337224	Poisson’s ratio
ρ	$2700\ \frac{kg}{m^3}$	mass density
A	$-3.512\ .\ 10^{11}\ \frac{N}{m^2}$	Landau’s constant
B	$-1.494\ .\ 10^{11}\ \frac{N}{m^2}$	Landau’s constant
C	$-1.028\ .\ 10^{11}\ \frac{N}{m^2}$	Landau’s constant

EXPERIMENTAL METHODOLOGY

A schematic of the experimental setup for nonlinear mixing of Rayleigh waves by laser ultrasonic method is shown in Figure 2. A 1064 nm Nd-YAG Litron laser with maximum energy 600 mJ and 6 mm beam diameter was used for generation. A special combinational dual frequency slit-mask, made from a 0.5 mm thin copper sheet, was designed to co-generate narrowband Rayleigh waves of 3 MHz and 5 MHz frequencies that travels along the surface of the specimen in the same direction. The two co-directionally traveling Rayleigh waves interact with each other owing to the material nonlinearity and the generated mixed waves are picked up by a Polytec OFV 505 broadband Laser Vibrometer. The time domain signal is obtained on an Oscilloscope (Keysight Technologies, maximum sampling rate 5 GHz) and recorded for further signal processing in MATLAB®. The experiments are performed on an undamaged Aluminum 7075 alloy rectangular block of dimensions 300 mm × 150 mm × 20 mm.

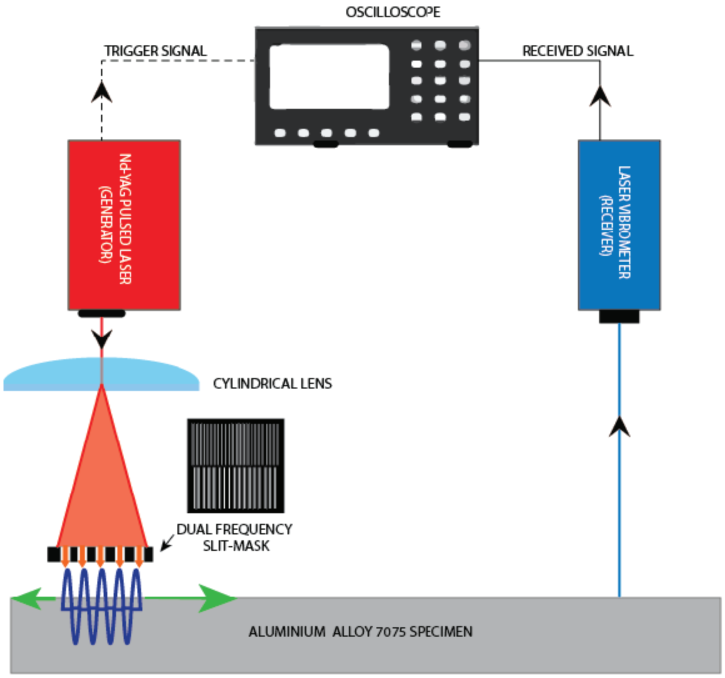

FIGURE 2. Schematic of the experimental setup.

The pulse width of the generated signal depends on the slit width and the laser spot size. In order to excite a narrowband wave in the frequency domain a long signal with higher number of cycles is desired. For this purpose, the laser beam is expanded using a cylindrical lens from Edmund Optics Inc., Part #NT48-360 to obtain the desired spatial size at the cost of energy amplitude. The expanded laser beam is allowed to impinge on the combinational slit mask creating line-arrayed sources for the 3 MHz and 5 MHz frequencies on the surface of the specimen, spatially separated by 200 μm.

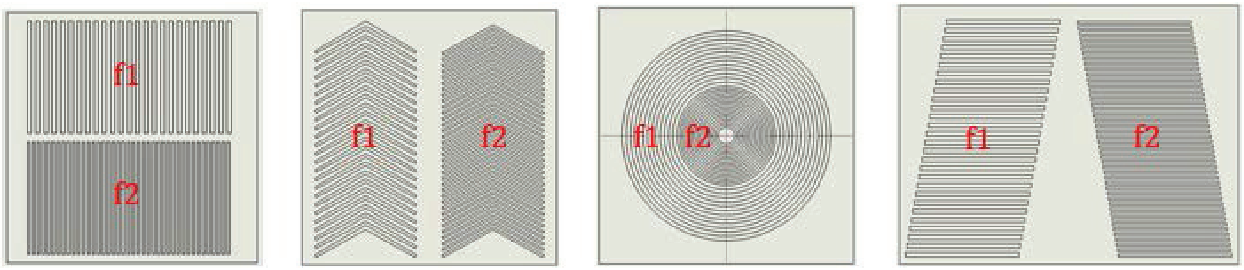

FIGURE 3. Examples of various possible sit-mask designs.

The proposed technique of nonlinear mixing of waves using lasers can be further extended to employ the nonlinear mixing phenomenon to Lamb waves, Guided waves etc. by modifying the slit-mask designs. Figure 3 shows various examples of slit-mask designs. Depending on the material under inspection and its geometry, the orientation of the slit patterns can be modified to achieve nonlinear mixing of the choice of ultrasonic waves. In this paper, we have demonstrated the primitive (first) slit-mask design which allows co-generation of dual frequency Rayleigh waves travelling in the same direction.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The time domain signal, captured along the center line of generation at a distance of 116 mm from the source is shown in Figure 4. The signal averaged by 256 times is zero padded. In the frequency domain, we can clearly see the two fundamentals at f_1 (3 MHz) and f_2 (5 MHz), their respective second harmonics $2f_1$ at 6 MHz and $2f_2$ at 10 MHz, the sum $f_1 + f_2$ at 8 MHz and the difference $f_1 - f_2$ at 2 MHz. This results establishes the use of the proposed experimental methodology to achieve nonlinear mixing of Rayleigh surface waves using lasers.

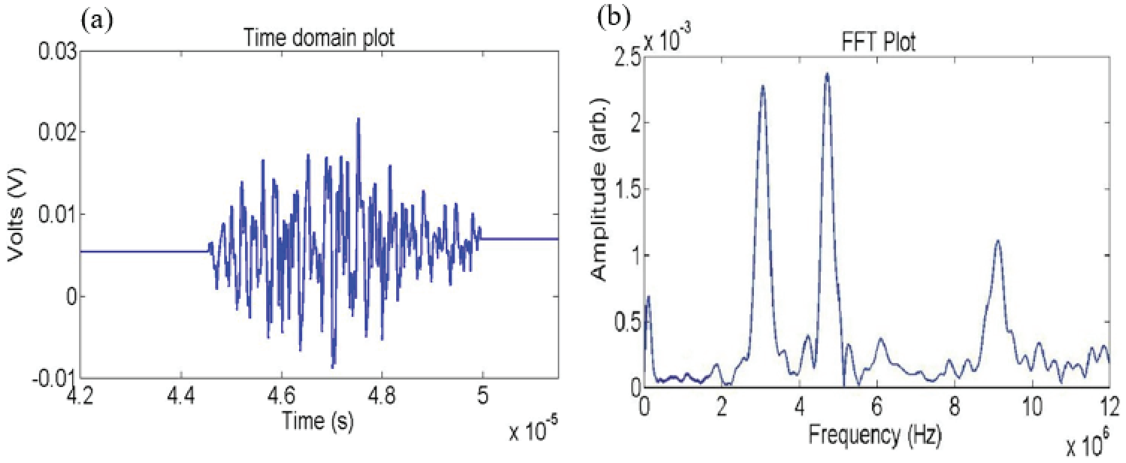

FIGURE 4. (a) Time domain plot of the received signal (experimental) at 116 mm from the source (b) Frequency domain plot showing fundamentals, second harmonics, sum and difference frequency components at 3 MHz and 5 MHz, 6 MHz and 10 MHz, 8 MHz and 2 MHz respectively.

The slit mask characteristics can be varied to achieve various frequency combinations for the mixed waves. The different frequency components behave distinctly as the depth of penetration and attenuation varies depending on the frequencies. Depending on the material to be inspected this technique can be implemented so as to excite a suitable combination of frequencies in order to obtain higher sensitivity as well as increase the range of inspection respectively, to study the variation of amplitudes for all the received frequencies.

CONCLUSIONS

This work demonstrates a noncontact laser based technique for nonlinear mixing of Rayleigh waves. The technique presents the following advantages;

- Noncontact technique; enabling inspection of irregular contours.
- Ability of Rayleigh waves to retain finite displacement amplitudes over long propagation distances.
- Nonlinear wave mixing; generation of higher harmonics which can detect microstructural damage at early stages, unlike conventional ultrasonic testing.

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