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Simulation of multi-cracks in solids using nonlinear elastic wave spectroscopy with a time-reversal process

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HIGHLIGHTS

- Harmonics and modulated wave filtering were used to show the retrofocal quality.
- We testify the feasibility of the NEWS–TR method for microdamage imaging of defects.
- The influence of frequency on the prediction of the defects was discussed.

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ABSTRACT

In non-classical nonlinear media, much characteristic information is contained in their dynamic elastic responses. A method combining nonlinear elastic wave spectroscopy (NEWS) with a time-reversal (TR) process is used in this numerical study, in which the presence of one defect and two defects acting with non-classical nonlinearity in an attenuating medium is simulated. Nonlinear defect behavior is introduced using a modified Preisach–Mayergoyz (PM) model. Two methods are used to determine retrofocal quality: harmonic filtering and modulated wave filtering. In the simulation, the nonlinear signal is filtered from the received continuous wave, then reversed and re-sent; a crack image can be obtained from the nonlinear signal in a lossy solid. By comparison with the actual defect, the image can reflect the distribution of one or two flaws, which show the feasibility and value of the NEWS–TR methodology for microdamage imaging of two defects. These results also show that images obtained with different harmonic and modulated frequencies can reflect the presence of defects. With increasing frequency, the crack positions obtained from the image change due to the influence of solid loss and interaction with sound waves.

1. Introduction

Strongly inhomogeneous media with strongly nonlinear behaviors are called non-classical nonlinear media [1,2]; they exhibit non-classical nonlinear phenomena because of the high local nonlinearity of micro- and macro-scale defects. It is now generally agreed that non-classical nonlinear acoustic phenomena are due to the microscopic properties of solid materials such as cracks. The effect of cracks on mechanical properties at the macro-scale is manifested as hysteresis, which can be used in non-destructive evaluation of materials. Nonlinear elastic wave spectroscopy (NEWS) serves to measure and analyze macroscopic signatures such as harmonic and modulated frequency components and amplitude-dependent resonance frequencies, which are due to a reversible nonlinear dependence of stress on strain at the micro scale and at the macroscopic one. Several NEWS techniques have been developed to explore nonlinearity induced by damage, such as delaminations, microcracks, weak adhesive bonds, and similar phenomena. As research in the field of non-classical

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nonlinearity developed, the formalism developed by Preisach–Mayergoyz for description of magnetic hysteresis [3,4] was first adopted by McCall and Guyer to describe the reversible nonlinear dependence of stress on strain [5,6]. This approach, called the "PM Model", was later used by other researchers to study nonlinear elastic behaviors and has been shown to be an effective method for use in non-classical nonlinear media. However, it is still difficult to determinate the position of defects in a solid using this method. Previous studies have shown that with the help of the time-reversal (TR) process [7], it is possible to overcome the disadvantages of time-delay techniques and to obtain good results for the position of a defect. Developed in the early 1990s, the TR technique was first applied in a linear medium. Later, the TR technique was used to determine the localization of defects which exhibit non-classical nonlinearity. Overall, the TR method can be divided into three steps [8]: first, launch an acoustic signal into a medium; the acoustic signal encounters the target, and the scattered signal is produced by the target and received by the receiving array. Then the received signal is time-reversed and transmitted back to the medium; the final signal will be refocused on the target. Compared with traditional delay technology, time reversal does not require a heterogeneous medium in the vicinity of the sending and receiving array. This means, without assuming that an inhomogeneous medium provides only a simple delay effect, that time reversal has incomparable advantages compared with traditional delay technology. Although the TR concept requires a non-attenuating linear medium, the technique can also be valid when the attenuation is weak and the nonlinearity is highly localized [9]. Two methods (NEWS–TR and TR–NEWS) have been derived from the nonlinearity-based TR concept, which depends on nonlinear signal processing performed before or after the TR process [8]. Several studies have focused on nonlinear elastic-wave spectroscopy using a TR technique. Zumpano and Meo et al. developed a nonlinear elastic TR acoustic method to locate the scattering zone. Although the traditional TR acoustic method was not able to localize the damage clearly, the technique as developed identified the faulted zone in an unambiguous manner [10]. The numerical simulation of the backward propagation, in that specific work performed by the pseudo-spectral time domain method, showed that the method could locate the region within the sample bearing the nonlinear elastic contribution to the overall sample response [8]. The experimental results showed that TR–NEWS could locate and interrogate a nonlinear scatterer in a linear elastic medium [11]. Comparing standard and reciprocal TR, Ulrich et al. found that each technique had its advantages and disadvantages [12]. The TR–NEWS method, which involves locally increasing the stress field using the properties of linear TR and then applying nonlinear analysis, has been experimentally demonstrated by Sutin et al. [13]. NEWS–TR was used to retrofocus on the defect position when only the nonlinear components of the received signal were time-reversed [14]. Barbieri and Meo analyzed the eigenproblem for different linear and nonlinear scatterers [15,16]. Van Den Abeele implemented numerical elastodynamic finite-integration programs in lossy media and revealed the influence of amplitude-dependent resonance behavior on cracking [17]. Van Den Abeele also used multi-mode nonlinear resonance ultrasound spectroscopy theory to obtain critical information about damage in attenuated media [18]. Ulrich et al. demonstrated through experiments and numerical calculations that with the Time Reversal Process it is possible to reconstruct a vector displacement source [19]. Previous experimental studies [11,12, 14,20] naturally included attenuation, and therefore the effect of attenuation on wave propagation must be considered in the simulations. A technique based on a combination of reciprocal time-reversal acoustics and phase-symmetry analysis was used to obtain optimal refocusing on nonlinear scatterers induced by cracks and delamination [21]. With chirp-coded excitation, TR–NEWS has been used for ultrasonic imaging of human teeth [22]. Time-reversal experiments were carried out on an aluminum plate to show the quality of the partial reconstruction of a finite-sized source [23]. In this paper, based on the technique of elastodynamic finite integration [24], a numerical technique for performing time-reversal imaging is proposed to show the influence of incident frequency on the quality of images obtained using a continuous tone-burst wave with one or two cracks. This work also validates the NEWS–TR method as a potential technique for the location of one and two defects in lossy media, especially because it is the first use of different nonlinear frequencies to reveal different portions of the crack.

2. Numerical study of NEWS–TR

2.1. Theoretical model

In the 2D numerical stimulation, the motion and constitutive equations can be written as follows [24]:

$$\dot{v}_x = \frac{1}{\rho}\left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y}\right) + F_x \tag{1}$$

$$\dot{v}_y = \frac{1}{\rho}\left(\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y}\right) + F_y \tag{2}$$

$$\dot{\sigma}_{xx} = K_1\dot{\varepsilon}_{xx} + K_2\dot{\varepsilon}_{yy} = K_1\frac{\partial v_x}{\partial x} + K_2\frac{\partial v_y}{\partial y} \tag{3}$$

$$\dot{\sigma}_{yy} = K_1\dot{\varepsilon}_{yy} + K_2\dot{\varepsilon}_{xx} = K_1\frac{\partial v_y}{\partial y} + K_2\frac{\partial v_x}{\partial x} \tag{4}$$

$$\dot{\sigma}_{xy} = \mu(\dot{\varepsilon}_{xy} + \dot{\varepsilon}_{yx}) = \mu\left(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}\right) \tag{5}$$