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Solitary waves for Non-Destructive Testing applications: Delayed nonlinear time reversal signal processing optimization

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HIGHLIGHTS

- Delayed TR-NEWS signal is proposed for NDT of complex materials.
- FEM simulation and experiments of CFRP are matched to study wave propagation.
- Wave focusing in complex medium is improved by decreasing the signal side lobes.
- The received wave at the focusing can be modified to have an arbitrary envelope.
- Method could be used in the future to study nonlinear wave interaction.

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ABSTRACT

An original signal processing method called delayed Time Reversal-Nonlinear Elastic Wave Spectroscopy is introduced in the present paper. The method could be used to amplify signal in certain regions of the material under Non Destructive Testing. It allows to optimize and change the shape of the received focused wave in the material, either by making the focusing sharper by decreasing the side lobes or making it wider by modifying the actual focusing peak. It is also possible to use the focused signal as a delta-basis to construct a signal with arbitrary envelope or reduce the side lobes of the focused signal. These concepts are shown to work well in the simulations and the physical experiments. This signal processing method is particularly promising for nonlinear and solitary wave analysis, since it allows to create an interaction of sharp and solitary wave peaks just underneath the receiving transducer. Due to simple and accurate linear prediction of the received interaction signal, any differences of measurements and predictions could indicate the presence of nonlinearities.

1. Introduction

The objective of the paper is to present the concept of delayed Time Reversal-Nonlinear Elastic Wave Spectroscopy (delayed TR-NEWS) [1]. It is an original method based on TR-NEWS method, used to obtain and modify focusing or convergence of ultrasonic waves in complex media.

Original TR-NEWS signal processing procedure can be used to focus the wave energy under the receiving transducer or vibrometer of an ultrasonic Non-Destructive Testing (NDT) setup. TR-NEWS is a promising method for evaluation of complex,

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dispersive and nonlinear media because it relies on the internal reflections as virtual transducers [1] to focus the wave energy into a specific spot in a certain time, therefore taking advantage of the complex internal structure of the material [2]. Such focused wave has an improved signal-to-noise ratio, making it suitable for investigating dispersive, chaotic or highly attenuating media [3,4].

During the last ten years there has been an increase of interest in using symmetry and similarity properties in the signal processing of nonlinear acoustics [5–7]. New signal processing methods have been developed and validated for NDT and harmonic imaging. Pulse Inversion (PI) techniques [8,9], have been extended and generalized using Symmetry Analysis [10]. Coded excitations (for example a chirp signal) and signal processing are now considered as efficient ways for imaging the complexity in bio-materials. These methods improve the determination of nonlinear properties by using optimized excitations [11].

Recently there has been a considerable development of TR based NEWS methods using invariance with respect to TR and reciprocity, both in numerical and experimental aspects. These methods have been experimentally elaborated as the well-known TR-NEWS methods [12–16]. TR-NEWS fundamental experimental demonstrations [17] have been conducted with applications in the improvement of nonlinear scatterers identification using symbiosis of symmetry analysis (TR, reciprocity, chirp-coded PI, etc.) and NEWS methods. TR-NEWS based imaging continues to be developed, with new systems being designed to obtain better focusing and optimal images. New excitations are now under study in order to give to TR-NEWS methods the practicability needed for both the NDT and the medical imaging community [18].

A new direction in NDT is the use of solitary waves, as their important properties differ from linear waves and they are overall well-studied phenomenon [19]. Nonlinear effects depend mostly on the signal power and wave shape. This shape could then be analysed and compared to linear cases to detect the presence of nonlinearities.

In this paper the delayed TR-NEWS is numerically and experimentally validated for allowing to manipulate the focused wave shape of the ordinary TR-NEWS. It is a promising method for studying the nonlinear properties of materials in nonlinear acoustics and NDT of complex materials and composites. The paper will demonstrate the signal optimization potential of the delayed TR-NEWS method for NDT purposes using experiments in bi-layered aluminium and Carbon Fibre Reinforced Polymer (CFRP) and simulations in CFRP. It will be shown that the wave focused under the receiving transducer can be manipulated to have a different shape. The method will be shown to be useful for changing the extent of the material affected by focused ultrasonic wave, side lobe reduction and introduction of low-frequency signal into the medium by amplitude modulation. It is also possible to introduce a low-frequency wave by high frequency input by using delayed TR-NEWS as amplitude modulation of the low frequency signal. Additionally, it will be shown that the method is highly predictable in linear materials, and could be used to analyse nonlinear effects as deviations from the linear prediction.

Physical experiments were carried out on a bi-layered aluminium and a CFRP sample. The findings were studied further using Finite Element Method (FEM) simulations on a linearly elastic laminate model of CFRP block with stochastic layer thicknesses to examine the signal propagation and focusing inside a complex material. It is well known that layered periodical materials can be dispersive and therefore solitary waves can emerge in the presence of nonlinearities in such materials [20,21].

The goal of this paper is to show that the delayed TR-NEWS procedure gives good results in numerical and physical experiments for examining complex materials. In Section 2 the test object and the experimental setup are described and the computational model is introduced. In Section 3 the signal processing steps of TR-NEWS and delayed TR-NEWS methods are explained. In Section 4 the results of numerical and physical experiments are presented. In Section 5 the conclusions and the possible practical uses of delayed TR-NEWS procedure are given.

2. Materials and methods

The delayed TR-NEWS signal processing method was initially validated in a bi-layered aluminium sample [22]. In the present paper the method was used to optimize the signal in a complex CFRP sample and the wave motion inside the CFRP was further studied using a FEM model. Having an agreement between the FEM model and physical experiments, it is possible to study the wave motion in more detail. While physical experiments give the actual measured values on the surface of the test object, the simulations allow to investigate the internal wave field in the object.

The simulations and experiments must agree qualitatively. The quantitative agreement is less important because: (i) We are studying how waves behave at the focusing; (ii) Simulations are in 2D due to computational constraints while the real world is in 3D and this always produces differences in quantitative results; (iii) The developed signal optimization must be robust enough to account for some variations in signal power; (iv) In this work the simulation and experimental material is considered linearly elastic, rendering amplitude analysis unnecessary.

2.1. Experiment configuration

The tests were conducted with TR-NEWS ultrasonic testing equipment which focuses the wave energy near the surface of the material under the receiving transducer. The initial validation was conducted on a bi-layered aluminium sample [22]. Thereafter the tests were performed on a CFRP block (composed of 144 layers of carbon fibre fabric). It was excited from its side with 70° shear wave transducer. The signal was received with a plane wave transducer on the top of the block (Fig. 1).