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Numerical modeling of ultrasonic coda wave interferometry in a multiple scattering medium with a localized nonlinear defect

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HIGHLIGHTS

- Modeling of nonlinear coda wave interferometry (NCWI) with spectral element method.
- NCWI observables and intrinsic properties of material are linked.
- Numerical parametric analysis of NCWI in homogeneous and heterogeneous media.

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ABSTRACT

In this paper, the spectral element method is used to perform a parametric sensitivity study of the nonlinear coda wave interferometry (NCWI) method in a homogeneous or heterogeneous sample with localized damage. The influence of a strong pump wave on localized nonlinear damage is modeled as modifications to the elastic properties of an effective damage zone (EDZ), depending on the pump wave amplitude. These modifications are quantified with coda wave interferometry through an overall wave velocity variation probed by a reverberated or multiple scattered coda wave. Results demonstrate that the NCWI observables are independent of the source/receiver positions. Also, relations between the EDZ parameters and method observables are established, e.g. the relative velocity variation is found to be proportional to the product of the change in elastic modulus and the EDZ area. The numerical results reported constitute another step towards quantification and forecasting of the nonlinear acoustic response of a cracked material, which proves to be necessary for a quantitative non-destructive evaluation. Furthermore, it is shown numerically that NCWI sensitivity and applicability are similar for the cases of reverberated waves in a cavity and multiply scattered waves in a heterogeneous medium.

1. Introduction

Over the last several years, a number of monitoring methods utilizing elastic coda waves have been proposed, for instance in seismic monitoring and ultrasonic non-destructive testing [1–6]. Coda waves produce signals of a complex

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nature, reaching a detector from the interference of many different and long wave paths, whether due to multiple scattering or reverberation [7]. These waves however have been shown to be reproducible [8] and capable of conveying precise and usable information on the propagation medium [1–4]. This information can be extracted by a method such as Coda Wave Interferometry (CWI) [9,10], which consists of comparing with high precision the signals traveling through slightly different states of the propagation medium, i.e. an initial or reference state and a disturbed state. The monitoring of local or global modifications of a complex medium is recognized to be efficiently and precisely achieved by CWI in many applications [11–13]. Effective wave velocity differences as low as 0.001% between states are now routinely detected [14]. Moreover, various processing methods that make use of signals from several sources and receivers enable spatially locating the changes between compared states, with applications to, for example, recent damage localization in a sample [13,15,16] and fault localization in seismic zones [17,18].

Nonlinear acoustic and ultrasonic testing methods have displayed high sensitivity to the physical properties of complex materials and great efficiency in detecting microcracks or early damage [19–23]. Most of the various nonlinear methods reported in the last decades, including harmonic generation [24,25], nonlinear resonance methods (also called nonlinear elastic wave spectroscopy (NEWS)) and nonlinear resonance ultrasound spectroscopy (NRUS) [26–28], nonlinear modulation, acousto-elasticity and dynamic acousto-elasticity (DAET) [29–32], provide a means for detecting a small amount of micro-damage in the material or, more generally, a change in the nonlinear elastic parameters while the linear elastic parameters are observed to remain unchanged. Interestingly, when these methods analyze the effects stemming from non-classical nonlinearities, as defined in contrast with classical potential atomic nonlinearities (usually quadratic and cubic nonlinearities in the smooth part of the stress–strain relationship), they are highly sensitive to features like microcracks and micro-contacts [33]. The background classical nonlinearity of the medium can be neglected, and only the effects stemming from defects are analyzed, which is an appealing procedure for non-destructive applications. Non-classical nonlinearities include clapping and tapping [34–37], hysteresis [38–41], nonlinear dissipation and slow dynamic effects [20,27,42,43].

By combining the advantages of CWI with non-classical nonlinear ultrasonic methods, a recent method, called nonlinear coda wave interferometry (NCWI), has been proposed in Zhang et al. [44]. NCWI is based on detecting the nonlinear influence of a strong pump wave on the effective parameters of a medium, through inspection by means of a probing ultrasonic coda wave. The classical CWI observables are analyzed as a function of the pump wave excitation amplitude and yield new NCWI observables that depend on the non-classical nonlinearity of the sample. This method has been successfully applied to several experimental configurations, in both cracked glass samples [12,44] and cracked mortar samples [6,45]. NCWI has been shown to be an efficient tool for performing a global evaluation of damage levels in differently damaged samples and for monitoring the crack healing process. However, the need now exists for a more quantitative characterization of these rather qualitative (or relative) experimental observations. Such is the motivation behind the present numerical study, which aims to bridge the gap between promising experimental observations and use of the method for a reliable quantitative evaluation of real structures.

To achieve this aim, deeper insight is needed into the most important parameters playing a role in the NCWI method, into how they are quantitatively affected and what is required. This article provides, through a numerical simulation of wave propagation in different configurations, a number of results that contribute to this deeper understanding of NCWI sensitivity. Most of the numerical models chosen lie close to available experimental results and configurations [44], in order to verify observed trends and take a step further towards a more quantitative evaluation of the damage in cracked samples. We begin in Section 2 by recalling the useful theoretical background necessary for interpreting the results and justifying the assumptions adopted. Section 3 then summarizes the experimental results and configurations we intend herein to reproduce and numerically extend, along with the numerical configurations and method. The results are presented in Section 4, in drawing a comparison with previous experiments in Section 5, and then extended to heterogeneous samples in Section 6 before a concluding section.

2. Theoretical background

2.1. Coda Wave Interferometry (CWI)

Several methods are available to evaluate the variations in wave propagation velocity from a received ultrasonic signal. Among the most widely implemented on coda signals are the *stretching* and *doublet* methods. The main advantage of *stretching* compared to *doublet* is its ability to obtain more robust results in the presence of noise [46]. This advantage offers the possibility to increase the sensitivity to small perturbations in a complex propagation medium, which is the main reason we decided to use it here. *Stretching* evaluates the correlation coefficient between a perturbed signal $u_p(t)$ and a reference signal $u_r(t)$, at an expansion rate θ_k ($k = 1, 2, \ldots, n$ for different levels of expansion) that simulates a global increase/decrease in propagation velocity within the medium [9].

$$CC(\theta_k) = \frac{\int_{t_c-T}^{t_c+T} u_r(t(1+\theta_k))u_p(t)\mathrm{d}t}{\sqrt{\int_{t_c-T}^{t_c+T} u_r^2(t(1+\theta_k))\mathrm{d}t \int_{t_c-T}^{t_c+T} u_p^2(t)\mathrm{d}t}}. \quad (1)$$

The value of the correlation coefficient $CC(\theta_k)$ in Eq. (1) represents, quantitatively, the similarity of the two signals recorded before and after perturbation of the medium within a selected time window $[t_c - T, t_c + T]$, where t_c is the central time of