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Flipped Accumulative Non-Linear Single Impact Resonance Acoustic Spectroscopy (FANSIRAS): A novel feature extraction algorithm for global damage assessment

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High amplitude non-linear acoustic methods have shown great potential for the identification of micro-damage in inhomogeneous materials such as concrete. Usually, these methods evaluate non-linearity parameters related to the hysteretic behaviour from the dependence of the shifts in both frequency and damping on the amplitude of the strain. A deep understanding of the reverberation phenomena has been obtained in order to introduce a novel signal processing approach called FANSIRAS (Flipped Accumulative Non-linear Single Impact Resonance Acoustic Spectroscopy). Traditional acoustic spectroscopy techniques, NIRAS (Non-linear Impact Resonance Acoustic Spectroscopy) and NSIRAS (Non-linear Single Impact Acoustic Spectroscopy), have been analyzed and compared with the brand new approach when providing quantitative information related to the degree of micro-cracking in thermal damaged concrete based materials. The new resonance-based algorithm demonstrates that the non-linear non-classical parameters can be determined through a single resonance frequency measurement, obtaining the expected sensitivity to internal damage. Its simplicity and robustness may be important in industrial applications.

1. Introduction

The study of the vibration of engineered materials is obtaining high levels of interest from scientific communities due to the accuracy and facility of damage assessment [1,2]. Concrete is an inhomogeneous material with a mesoscopic structure, multi-scaled, from nano- to millimetric sizes, where Hertzian contact between particles predominates. In this material, there appears an anomalous resonance frequency shift (a change in the elastic constants) when it is excited by an external source. This vibration is attenuated and finally stops, returning to its primary state, as the driving amplitude decreases and low strain values are reached [3]. This dynamic phenomenon is closely related to the hysteretic and non-linear behaviour of mesoscopic materials, whose deformations due to an external stress cannot be described by Hooke's law, making it imperative to add more complex terms to the traditional elastic equations. The first studies in mesoscopic materials focusing on its dynamic behaviour were carried out for rocks and granular solids like sandstone and limestone, reporting non-linear and hysterectic

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responses, while trying to model this phenomenon with complex equations [4,5]. Van Den Abeele et al. [6] presented a one-dimensional constitutive relation between the stress and strain in this new class of materials (Eq. (1)):

$$K\left(\varepsilon,\dot{\varepsilon}\right)=K_0\cdot\left[1-\beta\varepsilon-\delta\varepsilon^2-\alpha\left[\Delta\varepsilon+\varepsilon\cdot\mathrm{sign}\left(\dot{\varepsilon}\right)\right]\right] \tag{1}$$

where K is the non-linear hysteretic modulus with K_0 denoting the linear modulus, β and δ the classical quadratic and cubic non-linear parameters, respectively, ε the strain, $\Delta\varepsilon$ the strain amplitude in a cycle, $\dot{\varepsilon}$ the strain rate, and the parameter α is a measure proportional to the hysteresis of the material. Due to the proportionality between the resonance frequency of an element and its elastic constants, this equation describes the principal resonance frequency mode at a given strain amplitude.

Because of its granular and inhomogeneous structure, concrete can be considered a synthetic rock, with static and dynamic behaviour similar to other materials studied in geophysics and soil engineering. This material is the most important component in building and civil structures, its safety and control over its life time being critical. The continuous development and enhancement of new non-destructive techniques that allow controlling the quality and health of the concrete has become essential. Recently, several studies have focused on monitoring damage to concrete using non-linear elastic wave spectroscopy (NEWS) methods, a powerful new tool that takes advantage of the properties of mesoscopic materials in that they are more sensitive to cracks, flaws, and distributed defects. Due to the non-linearity of the material, a wave can become distorted, generating new frequency components (subharmonics and higher harmonics) during the propagation of a monochromatic wave [7], mixing waves of different frequencies [6]. Also, under resonance conditions, changes in the resonance frequency occur as a function of the driving amplitude [8]. These phenomena are very weak in undamaged materials, but remarkably larger in damaged materials [9].

In the last decade, several authors have successfully characterized the damage of materials by means of NEWS methods [10]. These experiments are based on the same phenomenological model and they can be categorized by the source of excitation (acoustic, ultrasonic or impact) and the number of signals injected into the system (one or several). The apparatus used in the different studies varies substantially, but the essence of the determination of the non-linear properties remains the same in all cases. Some authors have used an acoustical source (electroacoustic transducer, mainly) in order to induce the element under examination into a steady state of reverberation. Some investigations have evaluated this behaviour by using several signals, involving the use of frequency sweeps around the principal mode of vibration of the element, at different input amplitudes (SIngle MOde Nonlinear Resonance Acoustic Spectroscopy, SIMONRAS [4,8]; Nonlinear Wave Modulation Spectroscopy, NWMS [6]), and others have used one single signal and computed the attenuation of the material when the source of motion stops (Nonlinear Resonance Spectroscopy, NRS [11]). The signals were recorded by accelerometers or laser vibrometers. In ultrasonic excitation, there has been used a piezoelectric transducer for signal transmission and another transducer or laser vibrometer as the receiver. In this case, frequency sweeps at different input voltages have been employed to induce the element into a steady state of vibration (SIngle MOde Nonlinear Resonance Ultrasonic Spectroscopy, SIMONRUS [6]; Nonlinear Resonance Ultrasonic Spectroscopy, NRUS [12–15]). New research is focused in impact spectroscopy because of its low cost and the easy excitation of the elements under study. An impact hammer has been used to induce the vibration of the element and record the acceleration experienced by the specimen, by means of an accelerometer attached to its surface (Nonlinear Impact Resonance Acoustic Spectroscopy, NIRAS [16–18]; Nonlinear Single Impact Resonance Acoustic Spectroscopy, NSIRAS [19]; and Impact Nonlinear Reverberation Spectroscopy, INRS [20]).

A summary of NEWS methods is shown in Table 1.

As can be observed in the literature, the recent scientific research in NEWS techniques is focused on impact spectroscopy with one single signal, because of the obvious advantage in the testing time and probe conditioning. In the present study, a brand-new technique is developed, following the original methodology seen in NIRAS and inspired by a different signal processing procedure proposed by Eiras et al. [19] and Dahlen et al. [20]. The aim of this paper is to obtain a valid technique completely equivalent to NIRAS but developed with one single impact, by means of the analysis of the signal processing procedure. This technique has been tested on the thermal damage assessment of specimens of Portland cement mortar. This paper is organized as follows: In Section 1, the state of the art of NEWS techniques and the scope of the present paper are described. The mathematical background and signal processing issues of the different techniques are described in Section 2. The materials, specimens, and test layout used to obtain the results of the present study are described in Section 3. The results obtained from the new technique and a comparison of the data obtained from the different impact resonance acoustic spectroscopic methods are found in Section 4. In Section 5 the conclusions of this study are presented.

Table 1
Summary of non-linear elastic wave spectroscopy methods according to the type of excitation source and the number of signals.

Number of signals	Excitation source		
	Acoustic wave	Ultrasonic wave	Impact
>1	SIMONRAS [4,8], NWMS [6]	NWMS [6], SIMONRUS [3], NRUS [12–15]	NIRAS [16–18]
1	NRS [11]	–	NSIRAS [19], INRS [20]