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Damage identification in concrete using impact non-linear reverberation spectroscopy

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ABSTRACT

High amplitude non-linear acoustic methods have shown potential for the identification of micro damage in brittle materials such as concrete. Commonly, these methods evaluate a non-linearity parameter from the relative change in frequency and attenuation with strain amplitude. Here, a novel attenuation model is introduced to describe the free reverberation from a standard impact resonance frequency test, together with an algorithm for estimating the unknown model coefficients. The non-linear variation can hereby by analyzed over a wider dynamic range as compared to conventional methods. The experimental measurement is simple and fully compatible with the standardized free-free linear impact frequency test.

1. Introduction

The development of non-destructive testing techniques to detect early micro-cracks or imperfections in construction materials is important for efficient maintenance and management of existing infrastructure. During recent years, non-linear non-destructive methods have attracted notable interest, and have been proved to be more sensitive to the detection of damage in, for example, concrete, as compared to traditional linear acoustic methods [1]. When quasi-brittle materials such as concrete are damaged (micro-cracked), enhanced non-linear effects arise in the acoustic wave propagation characteristics [2]. Some typical non-linear manifestations in resonance frequency testing are the downward shift of the frequency and the increase in attenuation with increasing amplitudes (fast dynamics) [3–5]. The logarithmic recovery of this frequency shift with time after a stress or temperature disturbance may also be studied (slow dynamics) [6–8]. Furthermore, non-linear characteristics can be revealed by studying the behavior of higher harmonics and interference (modulation) between different frequencies [9,10]. Although many different methods have been proposed (see, e.g., [11]), there is still a need for practical and simple methods similar to the standardized linear resonance frequency testing techniques widely used today [12,13]. Non-linear ultrasound spectroscopy (NRUS) techniques are based on the measurement of resonance frequencies at different amplitudes and have shown promising results for the detection of distributed damage in concrete [14,15,3,16]. These methods can sense a large volume of a micro-cracked sample and are not too sensitive to the position of the sensors [17]. In the single-mode resonance spectroscopy (SIMONRAS) technique, the output vibration amplitude is measured while sweeping over an interval comprising a resonance frequency. The relative frequency and attenuation shift as a function of the excitation amplitude is studied and therefore several frequency sweeps with different input forces are acquired in order to evaluate the relative non-linearity parameter. Additionally, the frequency is swept very slowly to guarantee steady state response [18], making these methods both time consuming and practically cumbersome.

A faster variant of the NRUS method is the non-linear impact resonance spectroscopy (NIRAS) method, which was demonstrated on concrete by Chen et al. [19,20], Lesnicki et al. [14,21], Bouchaala et al. [22], and Eiras et al. [23]. The NIRAS technique relies on an impulse excitation of the specimen which is repeated with different impact strengths. This measurement set-up is easily performed and similar to the standardized free–free resonance test for concrete [13]. The relative frequency shift is then studied in the frequency domain by analyzing the peak amplitude and resonance frequency of one mode from multiple impacts with different strength. A practical advantage with impact resonance methods is that a wide frequency range including multiple resonance modes can be covered in a simple test [12,24,25] (in conventional NRUS, based on frequency sweep measurements, the source and experimental set-up needs to be tuned to the frequency of interest). However, a current limitation with the NIRAS method is that the extracted amplitude from each impact is not exactly related to the true physical amplitude in the sample. In

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order to move towards quantitative non-linear measurements, it is important to use the physical amplitude in the sample [26]. In the NIRAS method, the extracted peak amplitude is formed as a weighted average of the frequency- and amplitude-content in the complete (naturally damped) signal. This analysis procedure, based on the Fourier transform of each signal, results in a relatively limited dynamic range over which the frequency shift may be evaluated. The measurable dynamic range from the smallest to the largest amplitude peak is typically only about a factor 8 in the frequency domain, although each time domain signal may have a dynamic range of at least a factor 100 [19,14,22,5]. Furthermore, it should be noted that in a non-linear reverberation signal, wherein both the frequency and the attenuation change as a function of time and amplitude, both these factors will influence the width and the amplitude of the resulting resonant spectral peak [1]. The true physical amplitude and amplitude range in the sample is thus partially masked when the complete length of the signal is analyzed with a Fourier transform [27].

The non-linear reverberation spectroscopy (NRS) method introduced by Van Den Abeele et al. [1,28] instead exploits the natural reverberation of a non-linear signal in the time domain. This is done by exciting a resonance frequency of a sample with a loudspeaker source, and then utilizing the natural decay in the reverberation of the response after the loudspeaker is turned off. The non-linear parameter is evaluated by analyzing the change in the frequency and the attenuation as the signal is naturally decaying. The reverberation signal is divided into multiple small time windows, of about 20 cycles, and an exponentially decaying sine function with a constant damping and frequency parameter is fitted to each time window [28], i.e., the kth window of the (noiseless) signal, x_t, may be modeled as

$$x_k(t) = A_k e^{-\alpha_k t} \sin(2\pi f_k t + \phi_k) \tag{1}$$

where A_k, α_k, f_k, and ϕ_k denote the amplitude, attenuation, frequency, and the phase, respectively. As the sample is excited using only a single resonance frequency, the simple signal model in (1) may be used to represent the measured signal within each time window. As for the NIRAS method, the extracted amplitude is here a weighted average of the amplitude within each time window, and thus, it does not correspond to the true physical instantaneous amplitude at any specific time. For larger and heavier concrete type of samples, the continuous excitation of large vibration amplitudes with a loudspeaker or shaker can be difficult to achieve, and, as a result, limiting the measured dynamic range [1].

A simple impact hammer is usually preferred in resonance frequency testing of concrete samples [13,25]. In contrast to the single frequency source, an impact source generates a wide range of frequencies, and as a result the measured response usually contains multiple modes of vibration, making the single mode NRS analysis more difficult to apply directly to larger concrete samples. An impact-based version of the NRS technique was recently introduced by Eiras et al. [5]. In this work, the reverberation from a standard impact resonance frequency test (see, e.g. [13]) was analyzed using a short time Fourier transform (spectrogram), and the non-linear frequency shift as a function of amplitude was successfully extracted over a dynamic range of a factor 6 (in the frequency domain). The method is practical and fast, but suffers from the same smearing of the true physical instantaneous amplitude in the sample as the NIRAS and NRS methods.

In this study, we investigate a novel method of characterizing the extent of damage in a concrete specimen. The proposed technique, called “Impact Non-linear reverberation spectroscopy” (INRS), is based on a combination of the existing NIRAS and NRS techniques, but as for the spectrogram-based technique recently introduced in [5], the proposed method only requires a single impact excitation to allow for a reliable estimate of the non-linearity, although our approach allows for an estimate over a notably wider dynamic range. This is achieved by a combination of the use of a detailed *parametric* signal model as well as a robust iterative parameter estimation technique that estimates the parameters detailing each of the signal modes separately. This allows the continuous instantaneous true amplitude, frequency, and damping of each mode to be characterized as a function of time, allowing for detailed information of the non-linear parameters. By stochastic modeling of the reverberation signal after a single impulse excitation of the specimen, we aim to find parameters of the non-linearity, which may be associated with the degree of damage in the material. This method has the potential of allowing for fast and accurate operational measurements over a wide amplitude range, as well as enabling the phase and amplitude part of the signal to be studied separately. The proposed parametric model and estimation algorithm is described in detail along with an evaluation of the model using experimental data at three different levels of damage. Results indicate that the non-linear effect on both the frequency and the attenuation may be extracted over a relatively wider amplitude range as compared to the traditional NIRAS and NRS techniques, and this from the response of only a single impact. In this study, the results are restricted to the strongest measured resonance mode, although multiple modes may be studied simultaneously in a similar manner, potentially offering further information of the non-linearities of the material. Similar to the method by Eiras et al. [5], the non-linear parameters may in our setup be obtained in addition to the linear elastic constants using the same simple and standardized free–free resonant test normally conducted on concrete, stabilized soil, or other construction materials [13,24,25].

The remainder of the paper is organized as follows: in the following section, we briefly review the theoretical background of the non-linear measurements. Then, in Section 3, we discuss the experimental setup and the resulting data sets. In Section 4, we introduce the suggested signal model and the proposed parametric estimation algorithm. In Section 5, we evaluate the proposed model and the estimation algorithm using measured impact responses from concrete, showing both that the model well describes the data and that the algorithm is able to accurately estimate the unknown parameters. Finally, in Section 7, we conclude on the work.

2. Theoretical background

When concrete and other heterogeneous mesoscopic elastic materials are damaged, naturally occurring non-linear *hysteretic* effects increase [2,9]. The classical theory of non-linear atomic elasticity does not apply for mesoscopic hysteretic materials, such as concrete. In addition to the classical non-linearity stress–strain relation, one then also has to take account for hysteresis and discrete memory. The phenomenological model presented in [9] expresses the relation between the stress, σ, and the strain, ϵ, in one dimension as

$$\sigma = \int E(\epsilon, \dot{\epsilon})\, d\epsilon \tag{2}$$

where E is the non-linear hysteretic modulus

$$E = E_0[1 + \beta\epsilon + \delta\epsilon^2 + \alpha(\Delta\epsilon + \epsilon\, \mathrm{sgn}(\dot{\epsilon}))] \tag{3}$$

with E_0 denoting the linear modulus, β and δ the classical quadratic and cubic non-linear parameters, respectively, ϵ the