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Dynamic acousto-elastic test using continuous probe wave and transient vibration to investigate material nonlinearity

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ABSTRACT

This study demonstrates the feasibility of the dynamic acousto-elastic effect of a continuous high frequency wave for investigating the material nonlinearity upon transient vibration. The approach is demonstrated on a concrete sample measuring 15 × 15 × 60 cm^3. Two ultrasonic transducers (emitter and receiver) are placed at its middle span. A continuous high frequency wave of 500 kHz propagates through the material and is modulated with a hammer blow. The position of the hammer blow on the sample is configured to promote the first bending mode of vibration. The use of a continuous wave allows discrete time extraction of the nonlinear behavior by a short-time Fourier transform approach, through the simultaneous comparison of a reference non-modulated signal and an impact-modulated signal. The hammer blow results in phase shifts and variations of signal amplitude between reference and perturbed signals, which are driven by the resonant frequency of the sample. Finally, a comprehensive analysis of the relaxation mechanisms (modulus and attenuation recovery) is conducted to untangle the coupled fast and slow hysteretic effects.

1. Introduction

Investigation of the nonlinear dynamic properties of materials and structures is attracting keen interest among several scientific communities such as geosciences [1], medicine [2], and materials science [3], thanks to their improved detection of microstructural features within materials [4]. The link between the concerned materials among the different research areas is the presence of defects in a wide range of scales (from nano- to macro-scale), which enhances the nonlinear acoustic phenomena [5–7]. The internal friction between rough interfaces in their imperfect microstructures causes a hysteretic behavior in terms of their quasi-static stress–strain relationships. The resulting nonlinear modulus (M) including mechanical hysteresis can be written as [5]

$$M = M_o[1 + \beta\varepsilon + \delta\varepsilon^2 + \ldots + U(\varepsilon, \dot{\varepsilon})], \tag{1}$$

where the linear elastic modulus (M_o) is extended to include classical elastic higher order terms of strain, β and δ, and a function that takes account of mechanical hysteresis; usually written as [8]

$$U(\varepsilon, \dot{\varepsilon}) = \alpha \cdot (\Delta\varepsilon + \varepsilon \cdot sign(\dot{\varepsilon})), \tag{2}$$

where α is a parameter that controls the magnitude of the hysteretic behavior, $\Delta\varepsilon$ is the strain amplitude, ε is strain, and $\dot{\varepsilon}$ is strain rate. Under moderate dynamic strain amplitudes, $\sim 10^{-7}$ and above [9], the hysteretic behavior is manifested as an apparent softening of the material, so-called non-classical behavior. The velocity of propagation and attenuation of the material depend on the strain amplitude (fast dynamic effect), which in turn is accompanied by a long period of relaxation after dynamic excitation (slow dynamic effect). The two mechanisms are thought to coexist during dynamic excitation (material conditioning) [10], and dominate the nonlinear behavior of highly heterogeneous media such as those in concrete-like materials [11]. The equation of state as presented in Eq. (1) falls short of describing the slow dynamic effect, and only the fast dynamic effect can be considered therein [11]. The fast dynamic effect has been broadly investigated through nonlinear resonant techniques. They consist in the investigation of the downward resonant frequency shift observed in consecutive acquisitions by increasing the excitation amplitude [8]. The normalized downward resonant frequency shift is in most materials proportional to the strain amplitude [10] and is related to the parameter α because of the fast dynamic effect as [8]

$$\frac{\Delta f}{f_o} = \alpha \cdot \Delta\varepsilon, \tag{3}$$

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where f_o is the resonant frequency obtained in the linear strain regime. Therefore, the investigation of the material nonlinearity through nonlinear resonant spectroscopy-based techniques relies on the fast dynamic effect (Eq. (3)), and the unavoidable effect of slow dynamics contributes to the error in the estimation of the parameter α [10,11]. Such an effect is normally minimized by increasing the time lapse between successive resonant frequency acquisitions.

Recent research on the application of nonlinear acoustics for the characterization of biological tissues allowed investigation of the whole range of nonlinear phenomena with the technique termed dynamic acousto-elastic test (DAET) [12]. The DAET consists in monitoring the variations of the speed of sound through the material, normally through variations in the time of flight of ultrasonic pulses (probe wave), while a low frequency burst that matches a fundamental resonant mode perturbs the media (pump wave). Assuming that Poisson's ratio, and density variations are negligible during pump wave excitation, the resulted variations of modulus are related to the speed of sound (c) as

$$\frac{M - M_o}{M_o} \approx \frac{c^2 - c_o^2}{c_o^2}. \tag{4}$$

Considering that the variations of the speed of sound (Δc) with respect to the speed of sound in the linear elastic regime (c_o) are so small that $c \approx c_o$—and hence, $c^2 - c_o^2 \approx 2 \cdot (c - c_o)$—the corresponding relative variations of time of flight ($\Delta t/t_o$) are approximately related to the material nonlinearity as [12–14]

$$\frac{M - M_o}{M_o} \approx -2 \cdot \frac{\Delta t}{t_o} \approx C_E(\Delta\varepsilon) + \beta\varepsilon + \delta\varepsilon^2 + \ldots + U(\varepsilon, \dot{\varepsilon}), \tag{5}$$

where additional to the quadratic and cubic nonlinear classical parameters (β and δ) and strain rate-dependent hysteresis $U(\varepsilon, \dot{\varepsilon})$, the function $C_E(\Delta\varepsilon)$ takes into account the material conditioning effect: the apparent mix of slow and fast dynamics [10] which offsets the relation between strain and the relative variation of modulus. In addition, the variations of material attenuation produced during low frequency burst excitation, are also derived from the amplitude of the ultrasonic pulses [12–14].

Two conditions must be accomplished in DAET experiments. First, the time of flight (t_o) of the ultrasonic probe wave must be less than 1/10 times the value of the low frequency excitation [13]. In this way, the instantaneous variations of time of flight can be precisely related to the strain amplitude of the pump wave excitation. Second, the repetition rate of the ultrasonic pulse generator has to be set so that the ultrasonic wave is completely attenuated between pulses. Therefore, the succeeding ultrasonic pulses are not affected by the coda wave of the preceding ones [12–14]. In consequence of the last, the variations of time of flight and amplitude are obtained for few values of strain in several cycles of the low frequency burst (constant strain amplitude excitation). Therefore, the test has to be repeated after changing the phase of the ultrasonic pulse generator to obtain more experimental data, and describe properly the variations of time of flight and amplitude over the whole strain range excitation [12–14]. These conditions make unpractical to leverage the potential of DAET in on-site assessment of structures or in structural health monitoring applications wherein the use of ambient vibrations and transient events (variable strain amplitude excitation) are required to monitor passively the dynamic properties of structures [15–17].

In this study, a DAET is conducted by modulating a continuous monochromatic high frequency probe that propagates through the material. The approach is demonstrated on a prismatic concrete sample. The modulation of the continuous wave signal is achieved by a hammer blow configured to promote its first bending mode of vibration. The signal analysis is conducted with a short-time Fourier transform based approach. It is based on extracting the phase and amplitude variations by the simultaneous comparison between a reference (non-modulated) and an impact-modulated signal. Thus, the changes in velocity in the medium produced upon transient vibration rely on the phase changes of the continuous probe. Unlike previous DAET configurations [13,14,18–20], the approach presented herein has two main advantages. It overcomes the inconvenience of changing the phase of the high frequency probe (in case of ultrasonic pulses) in consecutive experiments for discretizing the variations of wave velocity over the whole range of strain excitation, and it allows investigation of the discrete time variation of material nonlinearity over only one cycle of low frequency excitation. Therefore, the variations of modulus can be investigated during the ring down of the mechanical energy introduced by a hammer blow. Otherwise, when a hammer blow is used as low frequency source and ultrasonic pulses as probe wave [21,22], the only measurable parameter is the maximum offset of the normalized time shift ($\Delta t/t_o$), since the strain amplitude is variable over time. Conversely, the parameters extracted herein show similarity with the nonlinear acoustic behavior derived from Eq. (5), and previously observed in compressional mode DAET experiments [13,14,18–20]. These are: (1) an offset of the material modulus upon low frequency excitation, (2) a phase delay between the onset of the strain amplitude and the relative variations of modulus, and (3) an incomplete recovery of the dynamic properties of the material when the strain energy of the low frequency signal is completely damped.

2. Materials and methods

2.1. Materials

The tests were conducted on a concrete sample measuring $15 \times 15 \times 60\ \text{cm}^3$. The composition of concrete is listed in Table 1. At the moment of test, the concrete sample was fully matured. For reference, the compressional and shear wave velocities were determined using direct transmission of an ultrasonic pulse, along the straight-line path respect to the sample width. For compressional wave velocity measurement, two ultrasonic transducers GE-Measurement & Control (model G 0,25 G code 67422, central frequency of 250 kHz) were used. For shear wave velocity measurement, two transducers Panametrics-NDT (model V151, central frequency of 250 kHz) were used. The compressional and shear wave velocities were 4056 m/s and 2483 m/s. The density of the sample was $\rho = 2350\ \text{kg/m}^3$; thus $M_o = 37.8$ GPa, and Poisson's ratio $\nu = 0.20$.

2.2. Experimental configuration

Fig. 1 shows a schematic depiction of the experimental configuration. Two ultrasonic transducers (Panametrics-NDT model V101, central frequency of 500 kHz) were placed on the sample at its middle span with a distance (d) between them, center to center, of 10 cm. A continuous sinusoidal high frequency probe was modulated by a hammer blow, while an accelerometer (Bruel &

Table 1
Mix design of concrete and properties.

Cement CEM I/52.5N (kg/m^3)	370
Water (l/m^3)	212
Fine aggregates 0/4 (kg/m^3)	774
Coarse aggregates 4/14 (kg/m^3)	1069
Compressive strength at 28 days (MPa)	53