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Dynamic acousto-elastic testing of concrete with a coda-wave probe: comparison with standard linear and nonlinear ultrasonic techniques

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ABSTRACT

The use of nonlinear acoustic techniques in solids consists in measuring wave distortion arising from compliant features such as cracks, soft intergrain bonds and dislocations. As such, they provide very powerful nondestructive tools to monitor the onset of damage within materials. In particular, a recent technique called dynamic acousto-elasticity testing (DAET) gives unprecedented details on the nonlinear elastic response of materials (classical and non-classical nonlinear features including hysteresis, transient elastic softening and slow relaxation). Here, we provide a comprehensive set of linear and nonlinear acoustic responses on two prismatic concrete specimens; one intact and one pre-compressed to about 70% of its ultimate strength. The two linear techniques used are Ultrasonic Pulse Velocity (UPV) and Resonance Ultrasound Spectroscopy (RUS), while the nonlinear ones include DAET (fast and slow dynamics) as well as Nonlinear Resonance Ultrasound Spectroscopy (NRUS). In addition, the DAET results correspond to a configuration where the (incoherent) coda portion of the ultrasonic record is used to probe the samples, as opposed to a (coherent) first arrival wave in standard DAET tests. We find that the two visually identical specimens are indistinguishable based on parameters measured by linear techniques (UPV and RUS). On the contrary, the extracted nonlinear parameters from NRUS and DAET are consistent and orders of magnitude greater for the damaged specimen than those for the intact one. This compiled set of linear and nonlinear ultrasonic testing data including the most advanced technique (DAET) provides a benchmark comparison for their use in the field of material characterization.

1. Motivation and background

The objective of this study is to investigate how a distribution of microcracks changes the acoustic response of concrete and compare the results from a suite of linear and nonlinear acoustic/ultrasonic techniques. Distributed microcracking is one of the earliest symptoms of concrete deterioration. Excessive mechanical and thermal loading, alkali-silica reaction (ASR), delayed ettringite formation (DEF) and repeated freeze-thaw (FT) cycles cause progressive volumetric micro-damage. Diagnosis and monitoring of degradation at the subcritical stages of development are essential to implementing timely and effective maintenance measures. Early damage detection in concrete demands a reliable identification of the state of distributed microcracking.

Both linear and nonlinear acoustic testing has been employed to characterize materials with distributed micro-damage. Linear ultrasonic testing relies on the gradual changes of ultrasonic measures (i.e., wave speed and attenuation) with increasing micro-damage [1]. In a medium containing a random distribution of cracks, the effective elastic modulus decreases as the density of micro cracks (defined as the number of cracks per unit volume) increases resulting in slower wave propagation. In addition, attenuation increases as a result of energy scattering. However, these changes are insignificant for low crack densities and become measurable only when the amount of micro-damage surpasses a certain threshold. For stress-induced damage in concrete, this threshold is equivalent to stress-to-strength ratios of about 0.8 (e.g., [2]). As such, linear ultrasonic techniques often fail to identify early or moderate levels of distributed damage. Nonlinear acoustic techniques, on the other hand, have shown great potential in detecting micro-damage in a wide spectrum of materials including concrete. For example, nonlinear resonance-based techniques have

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been successfully applied to detect thermal, ASR, and FT damage [3–5]. This capability stems from the sensitivity of material nonlinearity to the presence of microstructural features such as microcracks and de-bonding.

While nonlinear ultrasound hold great promise for many applications, most studies focus on one or two techniques only and a comparison of the results from the most recent techniques on the same set of samples is scarce. In this study, we document the responses from a suite of linear and nonlinear acoustic techniques on intact and stress-damaged concrete samples. The two linear techniques used are Ultrasonic Pulse Velocity (UPV) and Resonance Ultrasound Spectroscopy (RUS) to obtain ultrasonic wave velocity and homogenized elastic modulus respectively. Among the nonlinear acoustic techniques, we use Nonlinear Resonance Ultrasound Spectroscopy (NRUS) and dynamic acousto-elastic testing (DAET). NRUS measures the amplitude-dependence of resonance frequencies to estimate a nonlinear component α (non-classical softening/conditioning) averaged over the entire test sample. Thermal damage in cement, fatigue damage in composites and microcracking in bones have previously shown to result in an increase in α (e.g., [3,8]).

DAET is a relatively recent and arguably one of the most advanced methods in the field of nonlinear acoustics. DAET is the dynamic alternative of standard (quasi-static) acousto-elastic testing, where stepwise increases/decreases in static stress are replaced by a low frequency (LF) strain modulation. Compared to other nonlinear acoustic techniques, DAET provides unprecedented details on the nonlinear elastodynamic response (such as hysteresis, transient elastic softening and slow relaxation) [6]. The principles of DAET has been used for qualitative characterization of a single macro-crack [7] and ASR damage [8] in concrete. Here, we introduce a slightly modified DAET setup that both accommodates the highly heterogeneous nature of concrete and offers an alternative way of testing large samples faster than with standard DAET. We use DAET to extract simultaneously both fast and slow dynamics properties of concrete with and without distributed microdamage. In the following section (Section 2), a description of materials and employed test methods is provided. We present the test results in Section 3 and discuss our findings in Section 4.

2. Materials and test methods

2.1. Test specimens

We compare the responses of two prismatic concrete samples (0.05 x 0.05 x 0.15 m^3) of an identical concrete mix, saw-cut out of a massive concrete block (see Table 1 for material properties). To induce damage, one of the specimens was placed in a MTS loading machine and compressed along its length to 70% of the mix nominal maximum load at failure. The latter was previously measured and found to be 127.5 kN (equivalent to a compressive stress of 51 MPa).

2.2. Linear measurements (UPV and RUS)

2.2.1. UPV

Prior to inducing mechanical damage, (linear) ultrasonic compressional wave velocities were measured for both samples along their length in through transmission mode ($V_{P||}$) using a pair of 150 kHz-transducers. After damaging one sample, the test protocol was repeated to obtain the change in compressional wave velocity in the damaged sample ($\Delta V_{P||}$). We also measured compressional wave velocities at several locations across each sample. The $V_{P\perp 1}$ and $V_{P\perp 2}$ reported here correspond to the measurements across the middle and one end of samples, respectively.

2.2.2. RUS

In addition, dynamic moduli for both undamaged and damaged samples were measured using Resonance Ultrasound Spectroscopy (RUS) [9]. To do so, samples are positioned on three point-contact supports with embedded piezoelectric transducers, so that free boundary conditions can be assumed. A broadband sweep in frequency (1-100 kHz) is launched from the emitting transducer while the frequency response at the receiving transducer is measured. The frequency sweeps are repeated for different pairs of transducers and for different positions of the sample on the supports to maximize the detection of all resonances in the frequency band. The resonance frequencies are then automatically identified and assuming a perfect prismatic geometry and an isotropic sample, an inversion is performed to retrieve the homogenized elastic moduli. Details on the experimental configurations and the inversion scheme can be found in [3,9].

2.3. DAET setup and protocol

2.3.1. Setup

DAET uses a pump and probe scheme [10] (Fig. 1a). The fundamental experimental approach is to 'probe' the sample before, during and after a low-frequency perturbation of modest vibrational amplitude, hereinafter referred to as the 'pump'. The frequency of the pump is chosen such that it excites the first compressional mode of the specimen. Although this is not a necessary condition, it ensures excitations of high enough amplitude (strains of orders 10^{-6} to 10^{-5}). The strain-induced changes are probed by a pair of ultrasonic transducers (Olympus, 1 MHz-center frequency) sending low-strain (<10^{-7}) ultrasonic pulses into the medium every ΔT = 1 ms throughout the experiment. We obtain nonlinear elastic parameters by comparing unperturbed (before turning on the strain pump) and perturbed (while the strain pump is on) ultrasonic wave velocities. Following the perturbation, the probe also tracks the slow relaxation back to the initial unperturbed state (slow dynamics).

The sample is glued on a large piezoelectric disk (diameter = 5 cm, thickness = 1.25 cm) that sets the low frequency strain field within the sample. A miniature accelerometer glued at the top of the sample measures the low frequency response (Fig. 1a).

Table 1
Summary of material parameters for B1 (intact) and B8 (damaged) samples.

Method		RUS	UPV				DAET				NRUS
Parameter	ρ(kg/m^3)	C_{11} (MPa)	$V^{\perp}_{P1}$(m/s)	$V^{\perp}_{P2}$(m/s)	$V^{\parallel}_{P1}$(m/s)	$\Delta V^{\parallel}_{P}s$(m/s)	Offset R_0 (.)	Slope R_1 (.)	Curvature R_2 (.)	Enclosed area (.)	α (.)
B1	2289	33.1	3906	4080	3886	−0.5%	−0.0004	0.0002	0.6e−4	1.9e−4	−581
B8	2310	33.3	3837	4128	4011	−4.1%	−0.0022	0.0014	2.3e−4	3.5e−4	−2421
Change (%)	**0.9**	**0.6**	**−1.8**	**1.2**	**3.2**	**NA**	**481.4**	**521.8**	**277.0**	**81.6**	**316.8**
							α_{DAET} (.)	$\|\beta\|$(.)	$\|\delta\|$(.)		
						B1	−237	141	1.19e7		
						B8	−1467	933	5.12e7		
						Change (%)	**519.0**	**561.7**	**330.2**		