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Damping and velocity during conditioning and relaxation in diverse media: an experimental study

Mauro Tortello, Angelo Di Bella, and Antonio S. Gliozzi
Department of Applied Science and Technology, Politecnico di Torino, Torino, 10129, ITALY; mauro.tortello@polito.it; angelo.dibella@polito.it; antonio.gliozzi@polito.it

Charfeddine Mechri and Mourad Bentahar
LAUM UMR CNRS 6613, Le Mans Universitè, Le Mans, Cedex 9, 72085, FRANCE; Charfeddine.Mechri@univ-lemans.fr; mourad.bentahar@univ-lemans.fr

Marco Scalerandi
Department of Applied Science and Technology, Politecnico di Torino, Torino, 10129, ITALY; marco.scalerandi@infm.polito.it

Nonlinear ultrasound measurements are very sensitive to the presence of small changes in the microstructure of diverse materials. Specifically, in nonlinear mesoscopic materials, fast- and slow-dynamics effects are usually occurring simultaneously. We used an approach which allowed us to quantify fast- and slow-dynamics (during both conditioning and relaxation) almost in real time, i.e. also close to the very beginning of the conditioning process (early stages). Nonlinear and non-equilibrium parameters were extracted from the measurements and studied as a function of conditioning amplitude and conditioning time. Moreover, the functional dependence of velocity and damping was investigated from the early stages to the equilibrium state.

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I. Introduction

In nonlinear mesoscopic materials, fast- and slow-dynamics effects are usually occurring simultaneously [1,2]. The former is an instantaneous nonlinear phenomenon due to the explicit strain dependence of velocity and damping. Slow dynamics, on the other hand, is a non-equilibrium effect, governed by the dependence of the linear modulus and Q-factor on the dynamic strain level: when excited at constant strain, the sample properties vary in time ("conditioning") until they reach a new equilibrium state. When excitation is removed, the system recovers, again slowly in time, its original viscoelastic properties ("relaxation"). Both phenomena have been observed for decades and discussed for a wide variety of materials with both macro- and micro-cracks [3-5].

Conditioning and relaxation play both a fundamental role in defining the nonlinear response of hysteretic elastic media. Thus, it is of great importance to understand and quantify non equilibrium effects in order to validate theoretical models and to establish their completeness, suitability and universality. In particular, it is worth investigating the presence of correlations between the parameters describing the temporal evolution of damping and modulus of the sample under investigation. Correlations could indeed indicate that some microscopic features in the material must be identified as responsible of the physical mechanisms producing, at the same time, both softening and damping increase during conditioning. A different behavior observed in diverse materials could also be used as a tool to define nonlinear indicators for discriminating between different types of damage.

II. Methodology

II.A. Materials

Even though only data for the concrete sample are reported here, we tested several samples, representative of classes of materials with a different structure at the microscopic level. A similar behavior was observed in all investigated materials, although with some quantitative differences (see ref. [6]). The sample was in the shape of a cylinder (4 cm diameter and 16 cm length), and was drilled from a casting prepared with 340 kg of cement (CEM II A-L 42.5 R), 957 kg of sand (0-5 mm), 846 kg of gravel (5-15 mm) and 200 kg of water.

II.B. Experimental set-up

The experiments were conducted by using a waveform generator to produce ultrasonic signals defined as monochromatic waves of amplitude A_{inp} and frequency ν. After amplification through a linear amplifier (200x), the signals were transmitted to an ultrasonic transducer (with a broadband response, up to a few hundreds of kHz) acting as the emitter. A second (identical) transducer was used to detect the response of the material under test and was connected to a digital oscilloscope for data acquisition. Both transducers were glued to the sample using phenyl salicylate (salol). The linearity of the acquisition system, including transducers and coupling media, was carefully verified. In the experiments discussed here, the frequency was always chosen close to the first resonance mode of the samples.

Continuous signals were injected at low amplitude of excitation to test the material in its linear state (preconditioning) and output signals were repeatedly recorded in a short time window once stationary conditions were reached (standing wave). Afterwards, the same signal is amplified to a higher amplitude (conditioning) for a long time, up to reaching a new equilibrium state of the sample. A second set of signals is recorded at subsequent times during the conditioning process. Finally, the amplification is removed, and the relaxation process is monitored recording a third set of signals to be analyzed.

II.C. Data analysis

For each recorded signal of the three sets of data, phases and amplitudes are extracted by fitting the signals, acquired at different times, to a sinusoidal function with the same frequency as the input. Thus, we can obtain the phase and the amplitude at increasing times from the beginning of the experiment (either preconditioning, conditioning or relaxation). Note that the fitting procedure ignores the small signal distortions due to higher harmonics. These are indeed small in our case, since most of the observed nonlinearity is due to the conditioning process and is contained in the portion of the signal at the fundamental frequency [7].

Moreover, since samples are quasi-1D, an exact analytical solution can be derived for the propagation of an elastic wave in slightly nonlinear media. Therefore, we can extract the velocity and the damping coefficient of the material from the phases and amplitudes as a function of time [8].

III. Results and discussion

Fig.1 reports the evolution of velocity (a) and damping (b) as a function of time for the investigated sample. As expected, at the lowest amplitude of excitation during preconditioning (cyan symbols), both modulus and damping are constant (linear regime). As soon as the input amplitude is amplified (red symbols) the velocity is suddenly reduced by a quantity δc_{NL} (fast-dynamics effect). This reduction is followed by the conditioning phase, which lasts about 10 minutes, during which the material further softens, and the velocity further decreases by a quantity δc_{neq}. Finally, when returning to the lowest excitation amplitude (yellow symbols), the velocity increases again, but it immediately differs from the initial (t=0) equilibrium value by a quantity δc_{rlx} (relaxation). The initial value is reached again but only after a slow recovery process. An opposite behavior is followed by the damping, as shown in panel (b), for which similar parameters can be defined. The behavior reported in Fig.1 agrees very well with the results reported in the literature and it was observed in all studied materials, although with some quantitative differences which however will not be discussed here.
The parameters describing the conditioning curve have been analyzed as a function of the conditioning amplitude A_{cond}, as shown in Fig. 2. The sudden variation of velocity (and damping) due to nonlinearity and the cumulative variation due to nonequilibrium are both linearly dependent on the amplitude. However, while in the limit $A_{cond} \rightarrow 0$ we have $\delta c_{NL} \rightarrow 0$, this is not true for δc_{neq}, where $\delta c_{neq} \rightarrow 0$ when $A_{cond} \rightarrow 250\ mV$:

$$\delta\ c_{NL} = k\ A_{cond};\ \ \delta\ c_{neq} = k_0 + k_1\ A_{cond}$$

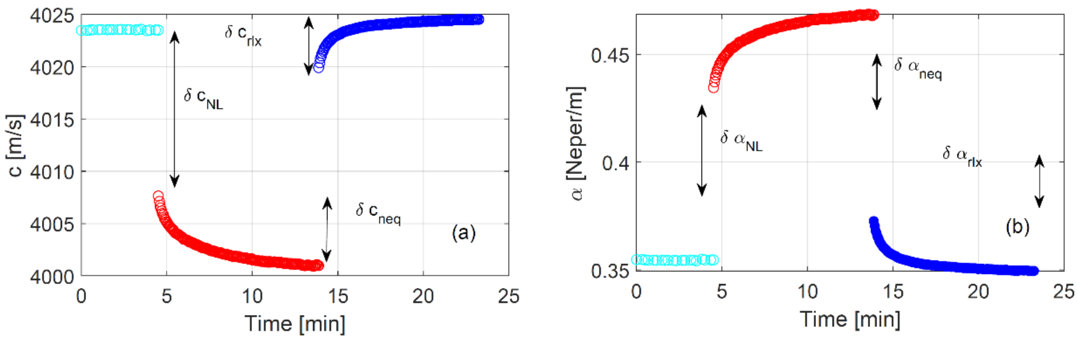

Figure 1: Evolution of velocity (a) and damping (b) as a function of time for the concrete sample. The input amplitude during preconditioning (cyan symbols) and relaxation (blue) was 50mV (before amplification) while it was switched to 1.2V during conditioning (red symbols).

The same behavior is observed for the damping variations. The presence of a threshold in amplitude for the onset of nonequilibrium effects is thus evident, as also manifested in the log-log plots reported in subplots (c) and (d) of Fig.2. While a clear linear dependence is observed for the nonlinear parameters δc_{NL} and $\delta \alpha_{NL}$ (indicating a power law with power index 1 equal to the slope), this is much less evident for the nonequilibrium parameters δc_{neq} and $\delta \alpha_{neq}$, which therefore do not appear to have a power law dependence.

Finally, the same set of data used in Fig.2 could be treated to verify the existence of correlations between the different parameters describing the evolution in time of damping and velocity during conditioning and relaxation, as shown in Fig. 3. Here, each point corresponds to the values of two parameters derived for the same conditioning amplitude. Panels (a) and (b) show that a linear correlation exists between conditioning and relaxation. Since the slope is approximately one, we conclude that, since $\delta c_{neq} = \delta c_{rlx}$ (and $\delta\alpha_{neq} = \delta\alpha_{rlx}$), the same physical phenomena involved in conditioning are reversed and involved in relaxation as well. Furthermore, the existence of a linear correlation between conditioning parameters for velocity and damping (panel (c)) indicates that damping and velocity changes, again, are likely due to the same physical features. Their behavior is qualitatively similar to that, already known in the literature, of the nonlinear parameters (panel (d)).

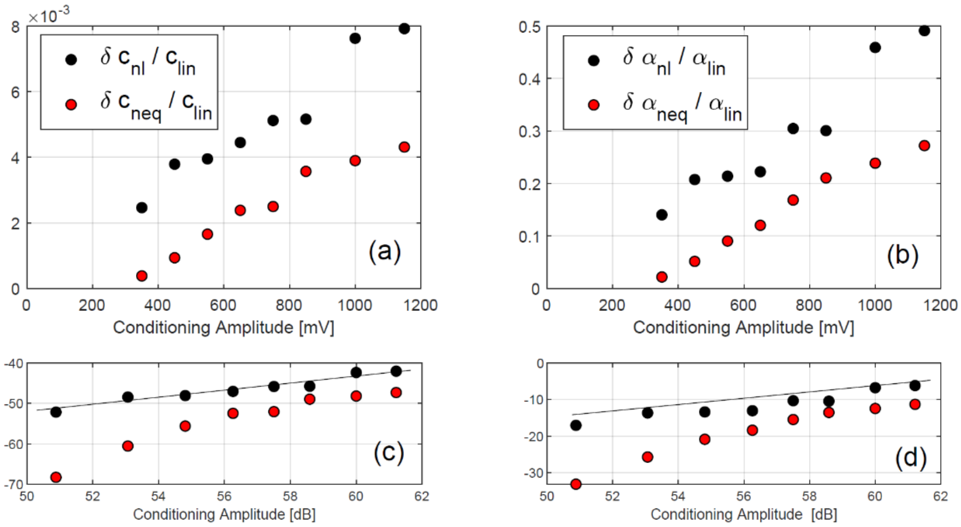

Figure 2: Dependence of nonequilibrium and nonlinear parameters of conditioning on the conditioning amplitude. Panels (c) and (d) are in log-log scale.

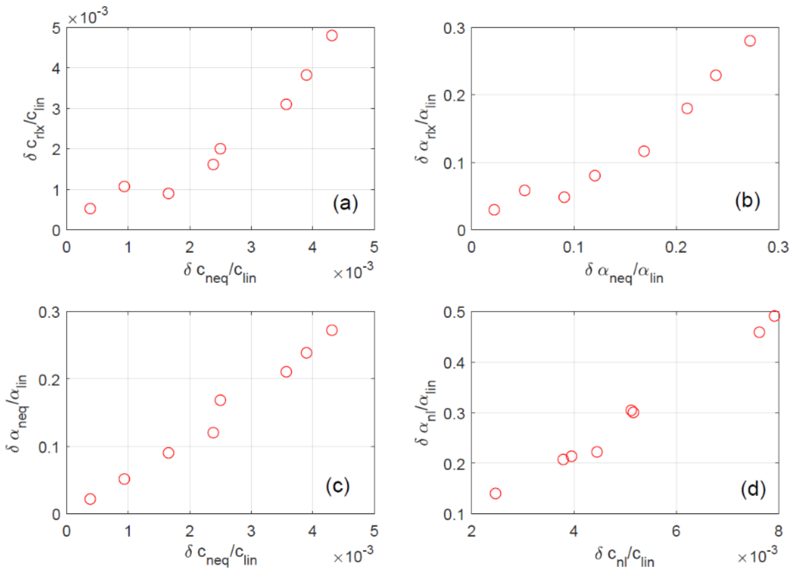

Figure 3: Correlations between relaxation and conditioning parameters for velocity (a) and damping (b). Linear correlation between velocity and damping for the conditioning (c) and nonlinear (d) parameters.

IV. Conclusion

In this paper we have quantitatively analyzed the behavior of velocity and damping during conditioning and relaxation in concrete. Three parameters have been introduced for the description of the evolution of velocity (damping): one parameter describes the fast-dynamics effects (initial sudden decrease of velocity or damping) while the second and third parameters describe the difference in velocity (damping) between an amplitude-dependent equilibrium state (conditioned state) and the linear (relaxed) state. We have shown here that:

i) A threshold seems to exist for the onset of conditioning;

ii) Correlations between the various parameters indicate that the same microscopic physical mechanism (e.g. activation of some nonlinear feature) is likely generating hysteresis for both damping and velocity.

Similar results have been found for all samples with a distributed grain structure with small microcracks (e.g. mortar, Berea and concrete), while cracked samples feature a slightly different behavior, with no clear correlations between the parameters [6].

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