Nonlinear acoustics measurements of intact and damaged samples: fast and slow dynamics

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***Abstract*—When excited by elastic waves, nonlinear mesoscopic elastic materials (for example, consolidated granular materials) show, at the same time, fast and slow dynamics effects. Here we introduce suitable parameters for quantifying them and for studying their correlations. We found that significant differences between intact and damaged samples can be observed by studying slow dynamics effects. The longitudinal profiles of the surface deformations induced by a sinusoidal excitation of a cracked sample were also investigated during different measurement configurations, showing that a considerable distortion of the original profile is induced by conditioning. These results can be useful for studying the behavior of cracks and defects in the nonclassical nonlinear regime, in view of their modeling at the microstructural level and for applications in innovative nondestructive test and evaluation techniques.**

***Index Terms*—nonlinear acoustics, consolidated granular materials, slow dynamics, nondestructive techniques**

I. INTRODUCTION

Rocks, concrete, soil and other consolidated and unconsolidated granular materials belong to the so called class of nonlinear mesoscopic elastic materials (NMEM) [1]. Besides a nonlinear stress-strain relation, NMEM also feature other characteristics like hysteresis in the stress-strain curve and "slow dynamics" behavior [2]–[7]. Moreover, also damaged linear materials may show hysteretic behavior. In relation to the hysteretic behavior, both fast and slow dynamics effects take place in NMEM when they are excited by ultrasonics waves [8]. The first are related to the instantaneous variation of physical parameters such as elastic modulus and damping [9], [10] and are due to nonlinear effects. The second are due to different physical processes, related to nonequilibrium effects. Indeed, under an excitation of sufficiently high intensity, but still small enough not to induce damage or other irreversible effects in the sample, some material properties (like modulus and damping) evolve as a function of time until they reach a new state of equilibrium that depends on the maximum strain level they are experiencing. This process is called conditioning. Then, when the excitation is removed, the material returns to its original state (relaxation). These effects, which have been known for more that two decades, however, still need to be fully understood from the microscopical point of view since very different types of materials can feature a qualitatively similar elastic behavior. But the main reason why there is a renewed interest in studying these properties is most probably the fact that slow dynamics could be used as a tool for performing Nondestructive Testing and Evaluation (NDT&E) [11], [12].

II. EXPERIMENTAL

Monochromatic signals with different amplitudes and a frequency around one of the compression modes were sent by a generator (Tektronix AFG 3022B) to a transducer glued at the base of the sample and received by an identical transducer at the other end (longitudinal modes) and finally recorded by an oscilloscope (Lecroy 324A). The transducers were MATEST C370-0 (specifically designed for measuring concrete) with a center frequency of about 55 KHz. The samples were mortar and concrete parallelepiped or cylinders, also damaged. A laser vibrometer (Polytech OFV-505) was employed for scanning, during the measurements, along the longitudinal direction of one of the damaged samples and recording the out of plane velocity. We used an approach [13] which allowed us, by recording the signal at subsequent time windows, to extract, almost in real time, the velocity and the attenuation coefficient of the material from the phase and amplitude of the detected waveform when the distortions of the signals from a pure sinusoid are small, that is, for small nonlinearities.

III. RESULTS AND DISCUSSION

Fig. 1, lower panel, reports a typical result for the evolution of velocity as a function of time measured for three measurement conditions on an intact concrete sample. The first one is preconditioning (small excitation amplitude), where there is

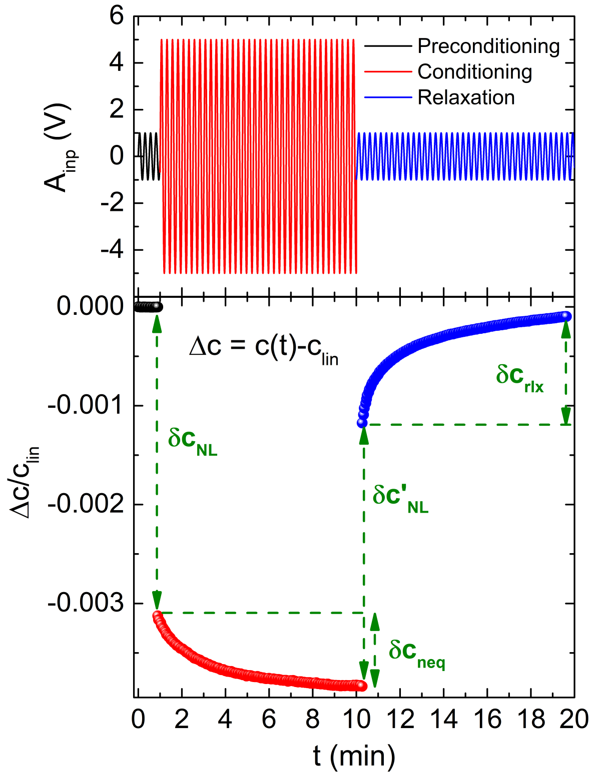

Fig. 1. Upper panel: sketch of three different experimental conditions: preconditioning (the sample is excited with a low-amplitude signal), conditioning (high excitation amplitudes) and relaxation (the excitation signal is the same as that of the preconditioning). Lower panel: experimental results showing the evolution of the relative (with respect to the linear value) variation of velocity as a function of time during preconditioning, conditioning and relaxation. The parameters introduced for describing fast and slow dynamics effects are also shown. Similar plots could be shown to describe the evolution of the attenuation coefficient as a function of time.

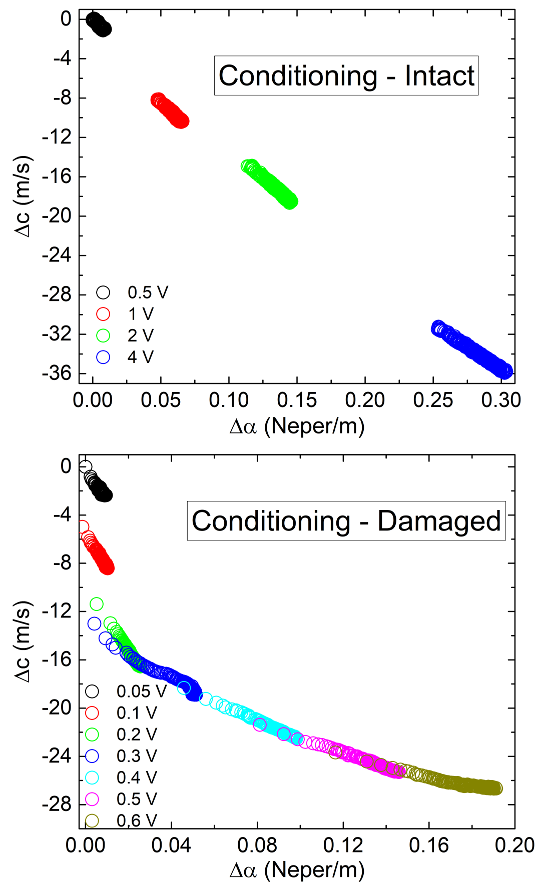

Fig. 2. Upper panel: variation (with respect to the linear value) of velocity c vs variation of the attenuation coefficient α measured at the same time during different conditioning processes described by the relevant conditioning amplitudes reported in the legend. The sample is intact. Lower panel: the same as in the upper panel but for a damaged sample.

no deviation of the propagating wave velocity from the linear value. During the second phase, conditioning, the sample is excited at higher amplitude and the velocity decreases as a function of time until it reaches a new equilibrium value. Then, during relaxation (when the sample is again excited at low amplitude), the value slowly recovers to the initial one. The immediate jump, that occurs when the high amplitude is set (or removed), is due to fast dynamics effects and can be quantified by introducing a parameter that we call δc_{NL} ($\delta c'_{NL}$). Two more parameters can also be used for describing quantitatively the slow dynamics effects, δc_{neq} and δc_{rlx} related to conditioning and relaxation, respectively. These parameters, which can also be defined for the behavior of the attenuation coefficient as a function of time, can be used to study correlations between velocity and attenuation coefficient and between conditioning and relaxation. It has been shown [10] that, for intact samples, i) all the parameters show a linear behavior as a function of the conditioning amplitude but nonequilibrium effects appear only above a certain amplitude threshold, ii) the behavior of δc_{neq} vs $\delta \alpha_{neq}$ is linear, thus indicating that the same physical features that affect the evolution of c act proportionally with the same weight in the change of α as well.

A. *Intact vs Damaged samples*

Fig. 2 shows, for both an intact (upper panel) and a damaged (lower panel) sample, a plot of the variation (with respect to the linear value) of velocity, measured at a certain time t, as a function of the relative variation of the attenuation coefficient measured at the same time. A clear difference can be seen between the two cases: the behavior of Δc vs $\Delta \alpha$ is linear for both cases but it always shows, for each conditioning amplitude, the same slope in the case of the intact sample. On the other hand, a strong dependence of the slope on the conditioning amplitude can be seen for the damaged one, thus showing that the study of these correlations can be effective in discriminating between these two different characteristics of the samples.

B. *Longitudinal profile on damaged samples: conditioning and relaxation*

Fig. 3 reports the out of plane velocity measured by scanning with the laser vibrometer along the length (16 cm)

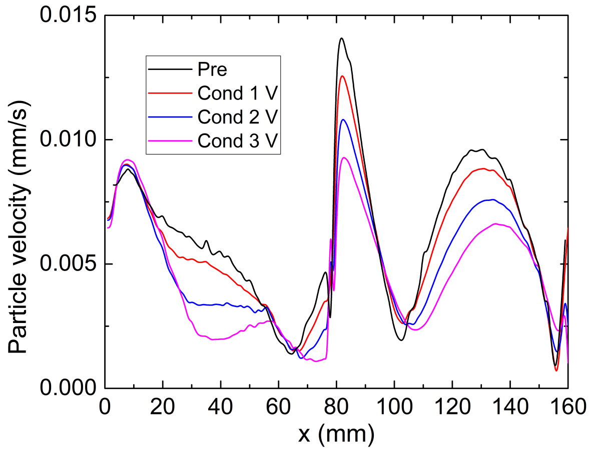

Fig. 3. Longitudinal profile measured on a cracked (at 80 mm) sample during preconditioning (black curve) and in three different conditioned states (red, blue and magenta).

of a damaged sample during the relaxed state (black line) and at three different conditioning amplitudes (red, blue and magenta lines) and for a frequency of 16 KHz. The 1, 2 and 3 V curves have been normalized by the amplitude ratio A_{pre}/A_{cond} in order to help the comparison, where $A_{pre} = 200$ mV and $A_{cond} = 1, 2, 3$ V, respectively. First of all, the crack (located at $x = 8$ cm) induces an evident deformation of the velocity distribution curve already in the preconditioned state (measured at a 200 mV excitation). The effects of conditioning, obtained by exciting the sample at higher amplitudes of excitation is huge, as shown by the decrease of the signal amplitude in correspondence of the crack and in the right half space ($x > 8$ cm). Also, the shifts of the maxima position and significant changes of the profiles are due to conditioning.

Fig. 4 shows a similar graph but now the focus is on the relaxation process. The preconditioning curve is shown (black), followed by one measured in a conditioned state corresponding to an excitation amplitude of 2 V (green), the latter again normalized by the amplitude ratio A_{pre}/A_{cond}. Then, three curves obtained at different times during relaxation are shown. It is possible to notice that, over time, the curve returns to the original, preconditioned state. In particular, the magenta curve represents the velocity profile obtained immediately after switching off conditioning, while blue and red curves have been recorded after about 20 minutes and 1 hour during relaxation. The results indicate thus a fast recovery, correspondent to the fast $\delta c'_{NL}$ recovery shown in Fig. 1, followed by a very slow relaxation process, which brings back the material to the original equilibrium state (preconditioning profile). It would be interesting to extract the value of the elastic modulus from the profile, by properly modeling the crack and compare it to the average value obtained by measuring the output signal with the transducer. Work is in progress in this regard and the results will also be compared to those obtained on intact samples.

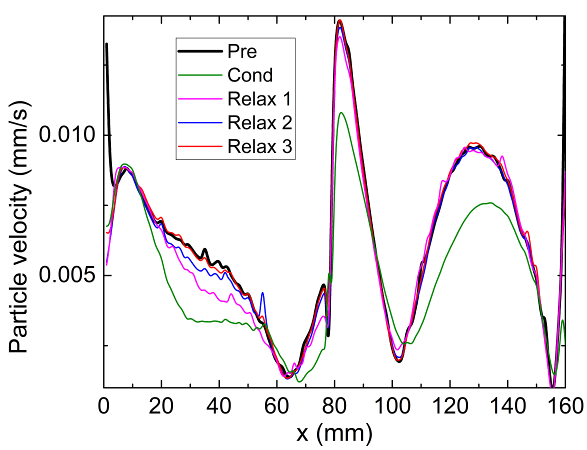

Fig. 4. Longitudinal profile measured on a cracked (at 80 mm) sample during preconditioning (black curve), in a conditioned state (green) and at different times during the relaxation process (magenta, blue and orange). It is possible to notice that the third relaxation profile fully recovers the shape of the one measured before conditioning the sample.

IV. Conclusions

In conclusion, we have shown that fast and slow dynamics effects can be handled by introducing suitable parameters capable of quantitatively describing their intensity and allowing to study correlations between them. Moreover, by looking at the correlation between velocity and attenuation coefficient, a clear difference has been noticed between intact and damaged samples. Finally, different profiles have been measured for a cracked sample in the relaxed or conditioned state, where the profile becomes more and more distorted with increasing conditioning amplitude. A model of the crack capable of describing the evolution of the profile at different conditioning amplitudes would be highly desirable, particularly in view of possible innovative applications in NDT&E.

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