Slow Dynamics Experiments in Solids with Nonlinear Mesoscopic Elasticity

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Abstract. As revealed by longitudinal bar resonance experiments, materials such as rocks and concrete show a rich diversity of nonlinear elastic behavior. As a function of increasing drive level, resonance frequencies shift downward by several percent, the resonant line shape changes, and harmonics and slow dynamics appear. Slow dynamics [1] refers to the time-dependent recovery of an elastic modulus to its initial value after being softened by large strain. In order to explore the mechanisms of nonlinear response including slow dynamics, we performed experiments on concrete and several different earth materials. The softening (conditioning) and recovery processes appear to be asymmetric. Conditioning takes place quickly; full recovery of the elastic modulus (as measured by drift of the resonance peak) takes minutes to hours, depending on the length of time the conditioning strain was applied. We find that for a wide variety of rocks and concretes, the recovery of the resonant frequency goes as log(time). Logarithmic time-dependence is a phenomenon associated with static friction and restoration of surface contacts, which in rocks probably takes place at touching crack surfaces.

INTRODUCTION

Rocks, concretes, sands, soils, ceramics, and even metals with dislocations all exhibit remarkably similar nonlinear elastic/acoustic behavior. Various measurements have shown that these materials are strongly nonlinear, hysteretic, and have memory. We call these nonlinear mesoscopic elastic materials [2].

The work reported here is an examination of the apparent "memory" exhibited by these materials, an effect termed *slow dynamics*. In almost all materials examined to date, a sample softens under a moderate dynamic strain, e. g., 10^{-6}, and returns to its original state only hours after the drive is turned off. Slow dynamics were first seen in resonance measurements [1]; up and down frequency sweeps were not the same, stopping part of the way over a resonance curve revealed a creep in the measured response, and jumps occurred when the drive was shut off and then turned on during a sweep. Slow dynamics may also have played a role and been seen in wave propagation (earthquake) measurements [3]. The results in this paper show specifically how samples soften and recover

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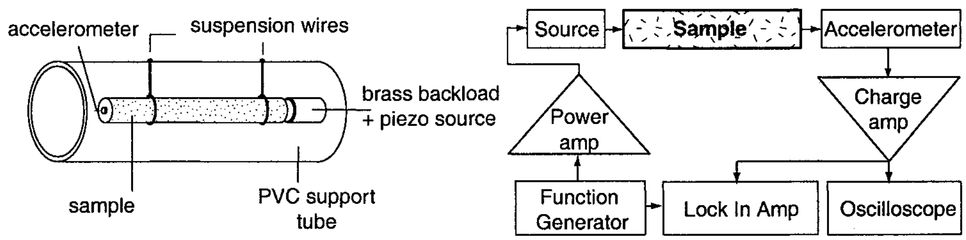

FIGURE 1. Schematic and block diagram of typical experimental arrangement.

with time and how this behavior relates to possible mechanisms of slow dynamics seen in these materials.

EXPERIMENTS

A sketch and block diagram of the experimental apparatus are shown in Fig. 1. All of the measurements were carried out with long thin bars excited in their lowest longitudinal mode (Young's mode). Sample sizes – typically 10's of centimeters – and wave speeds were such that resonance frequencies ranged from 1 to 10 kHz. The source was a PZT disk with brass backload, the receiver a small B&K accelerometer. The samples were isolated from the environment by placing them in a rough vacuum or a double insulated, sealed box filled with dry N_2. Further details about the experimental measurements can be found elsewhere [1].

A typical measurement consists of observing resonance frequency changes as various "conditioning" strains are applied and/or removed. (Resonance frequency, related to the modulus, can be measured with great precision.) By observing how fast the sample is conditioned or recovers, we hope to gain insight into the physical mechanism(s) which create slow dynamics.

RESULTS

Figure 2 shows the shifts of resonance frequency with time as a Berea sandstone sample is alternately softened and then allowed to recover. The conditioning strain was approximately 1×10^{-6}. Note that even after times of around 15 min, the sample never fully recovers to its initial stiffness (the initial resonance frequency is 2885.4 Hz). Also note that the process of conditioning and recovery is *not* symmetric (as would a capacitor during charging and discharging); the conditioning phase happens quickly, whereas the recovery part of the curve has a much different shape.

When just the recovery part of the curve is examined, a very striking result is obtained. Figure 3(a) shows raw data obtained in the first 1000 s after a conditioning strain

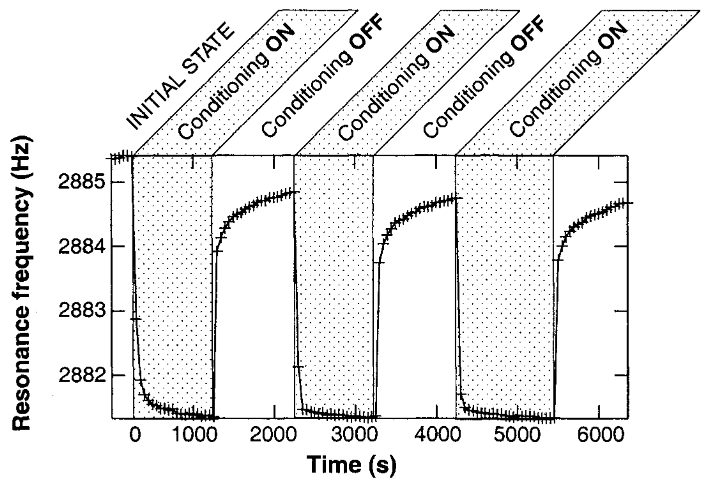

FIGURE 2. Change in resonance frequency in response to a conditioning strain of approximately 1×10^{-6}. The conditioning strain was alternately applied and turned off. Sample was a 35 cm long, 1 in diameter bar of Berea sandstone.

was turned off. When the data are plotted on semilog-x paper, the result is as shown in Fig. 3(b). *Recovery goes as the logarithm of time.*

Finally, we show log(time) recovery curves for several very different samples in Fig. 4: (a) Berea sandstone (quartz with clay) in a rough vacuum, (b) Berea sandstone at room conditions, (c) an intact concrete, (d) a damaged concrete, (e) a limestone (calcium carbonate), and (f) Fontainebleau sandstone (almost pure quartz). Despite the striking differences in the microstructure and chemistry of these samples, the recoveries all go as log(time). Recent experiments [4] have shown remarkably little deviation from log(time) behavior; residuals from a linear fit to data are only 1×10^{-6} of the asymptotic value!

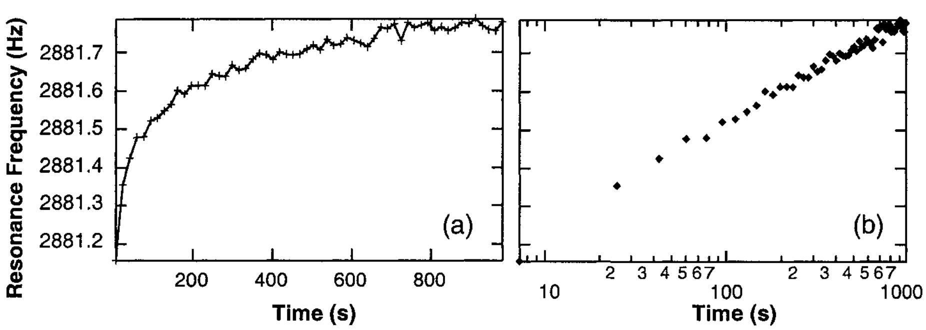

FIGURE 3. Recovery of sample—shown here as a recovery of the resonance frequency—for first 1000 s after the conditioning strain is turned off. Same sample as in Fig. 2, different day.

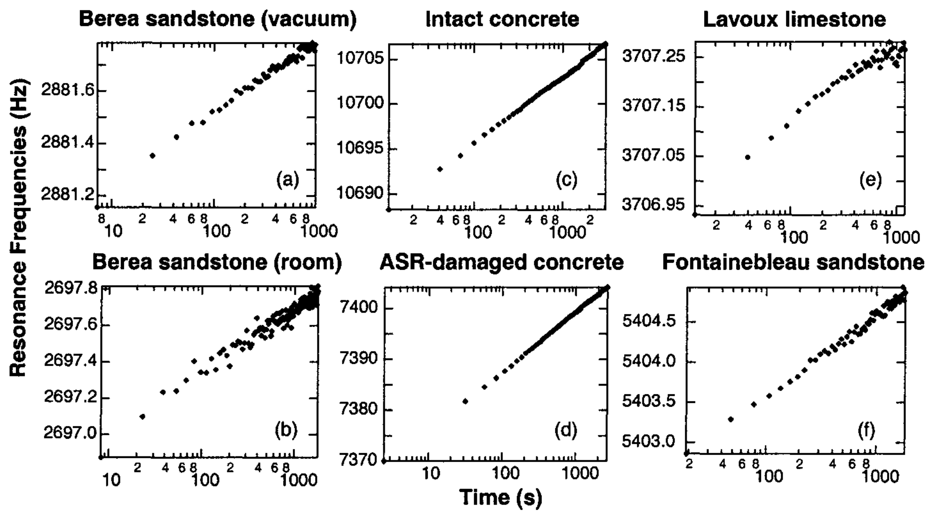

FIGURE 4. Logarithmic (time) recovery of several different samples.

DISCUSSION

A likely candidate mechanism for slow dynamics is a form of creep. Creep that is proportional to the logarithm of time is a well-known response to external stresses applied to rocks and metals. However, the driving force is always static. The slow dynamics results shown here are quite different in that the driving force is a *symmetric, oscillatory* one. One model which has been proposed [4] is based on forced rupture of the microscopic bonds leading to intergranular static friction, followed by thermally-activated "healing" of those bonds when the source of the ruptures is removed.

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