Slow Dynamics and Nonlinear Response at Low Strains in Berea Sandstone

James A. TenCate and Thomas J. Shankland§

Earth and Environmental Sciences Division, MS D443, Los Alamos National Laboratory, Los Alamos, NM 87545,
§ also at Bayerisches Geoinstitut, Universität Bayreuth, D–95440 Bayreuth, Germany
http://www.ees4.lanl.gov/Nonlinear

Abstract: The compliant features of rocks (e.g., cracks, pores) and the fluids filling them, give rise to a variety of nonlinear elastic effects. As a means of achieving large dynamic strains and amplifying otherwise small nonlinear effects, longitudinal resonance experiments on thin bars of sandstone were performed. Resonance curves were obtained by measuring acceleration at the end of the bar while sweeping frequency at a fixed drive level. As drive levels increased, resonance curves showed peak bending toward lower frequencies (softening modulus). Two very distinct nonlinear behaviors can be observed. At moderate strain amplitudes, the effects of nonlinearity are quite pronounced: rapid peak shifting and resonance curve shape changes were accompanied by slow dynamics—shapes of the nonlinear resonance curves depend on sweep direction and rate [1]. However, even at lower strain amplitudes (corresponding to motions of a few atomic diameters at the ends of macroscopic samples), nonlinearity remains in the form of frequency shifts. The different regions of the nonlinear response correspond to different types of nonlinearity, e.g., hysteretic, classical, etc. Explanations for nonlinearity at very low strain levels are being pursued.

INTRODUCTION

In their elastic properties rocks are unique and unlike most solids [2]. We observe that sandstones have a nonlinear dynamic response down to the smallest strains we have been able to measure (10^{-8}). At higher strains they become extremely nonlinear; slow dynamics (memory effects) and rapid modulus shifts are clearly seen. In the experiments seen in Fig. 1 samples are thin Berea sandstone rods, typically a few centimeters in diameter and 30 to 40 cm long. A sample is suspended by thin wires, excited by a piezoelectric disk mounted to high-impedance backload, and its response measured with an accelerometer mounted at the opposite end of the bar. To maintain a stable environment, the entire apparatus shown in the figure is placed in a rough vacuum; sample temperature is controlled by a heater tape wrapped around an independently suspended wire cage inside the support tube (not shown).

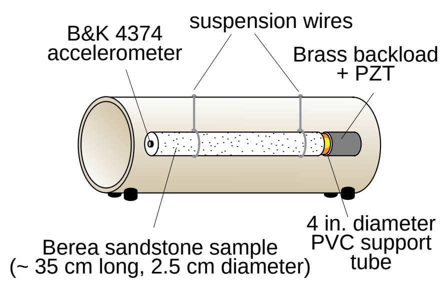

FIGURE 1. Sketch of sample mounting. Entire apparatus is placed inside a vacuum.

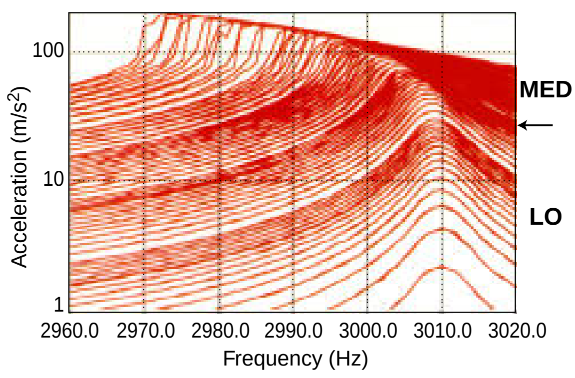

FIGURE 2. Set of resonance curves for a typical sandstone sample in air. Several different drive levels are represented and both up and down sweeps shown.

Figure 2 shows typical resonance curves for a Berea sample in air. Curves corresponding to several different drive levels are shown. At each drive level, system response is measured as the frequency is stepped up and back down. There are two (possibly three) distinct behaviors shown here. At very low strains (LO) the response appears to be linear. As shown later, the response is, in fact, *nonlinear*. Above a certain drive level (MED), the resonance frequency suddenly begins to shift rapidly downward (the modulus softens), and the upward and downward going frequency sweeps do not trace the same curve. Previously published measurements at these drive levels showed a type of memory termed slow dynamics[1]. A third region (not labeled) may occur at very large strains (which usually irreversibly damage the rock) where discontinuities and jumps begin to appear in the resonance curves.

SLOW DYNAMICS

Much of the interesting nonlinear behavior observed in the medium strain region can be attributed to slow dynamics. At high enough strains, the excitation (reversibly) changes the rock's modulus. It doesn't recover immediately from the high strain; often it takes hours, even days to return to its pre-excitation state as seen in

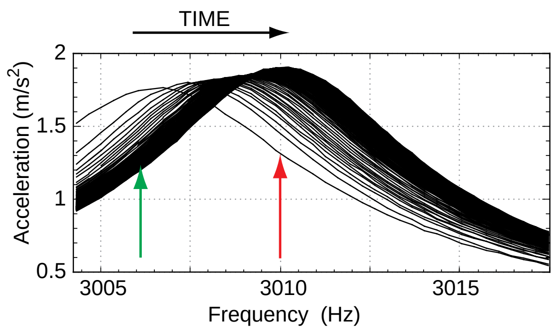

FIGURE 3. Successive resonance sweeps made after a long conditioning sweep. Initial resonance frequency before experiment is at 3010 Hz, resonance frequency immediately after conditioning strain is at 3007 Hz. Total time for recovery was approximately 10 min for this sample.

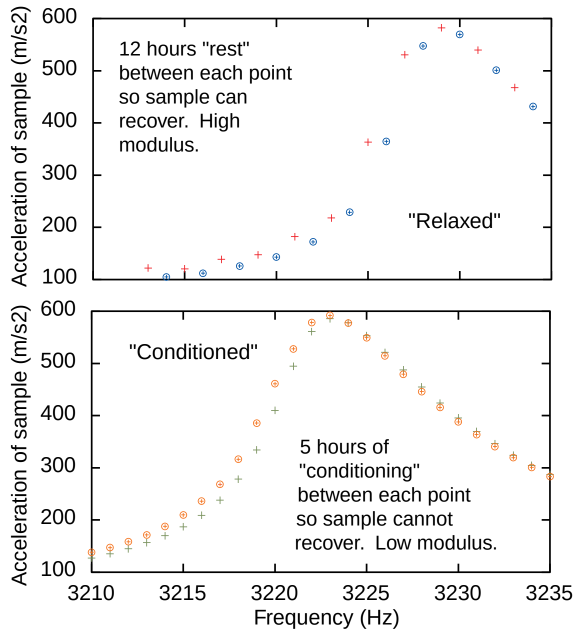

FIGURE 4. Very long sweeps. Effects of slow dynamics nearly gone, up, down sweeps are nearly identical. Top curves show up (pluses) or down (circles) sweeps with a long rest between points (top curves) or a conditioning drive between points (bottom curves).

Fig. 3. For this measurement a sample was driven at a high intensity for a fairly long period of time. Then we recorded resonance curves to measure the modulus at very low strain amplitudes as a function of time. The figure tracks the recovery.

Figure 4 shows results of two experiments designed to suppress the effects of slow dynamics using *very* long sweep times. The top plot ("Relaxed") was made by probing the rock quickly at each frequency and then allowing it to rest for 12 hours before the next measurement. Within error, the upward and downward going points lie on the same curve, i.e., the rock fully recovered between measurements. The bottom plot ("Conditioned") shows a similar pair of curves. However, for 6–8 hours between points the sample was subjected to high strain (thus softening it). Without time to recover, effects of slow dynamics again are minimal, and the modulus defined by the resonance peak is lower.

LOW STRAIN RESULTS

Figure 5 shows nonlinear results at very low strain amplitudes (limited by measurement noise of our apparatus). As strain in the rock was increased from 3×10^{-8} to 1×10^{-7}, and then back down again the resonance frequency (or modulus) actually increased (i.e., the rock got stiffer). The slight difference in up and down curves is due to a small temperature drift. Presently, we are investigating these small amplitude results to see how the results vary with temperature and humidity.

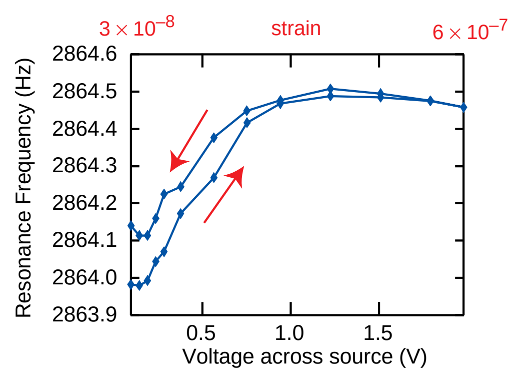

FIGURE 5. Nonlinearity at very low strains. As drive level is increased, the modulus of the sample first *increases*. The decrease (softening) continues all the way to the onset of slow dynamics.

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