Seismic-frequency attenuation and moduli estimates using a fiber-optic strainmeter

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Summary

We have developed a fiber-optic strainmeter to estimate velocities and attenuation at seismic frequencies. The two main advantages of the new system compared to strain gage techniques are the higher sensitivity to deformations (moduli) and phase lags (attenuation), and that estimates are representative of bulk values. While stress-strain measurements using strain gages or ultrasonic wave propagation sample only part of the core sample, the fiber-optic strainmeter would analyze the rock sample response to an applied stress as a whole. Still, the system is under development and the first experiment on a Plexiglas sample showed that attenuation estimates are more robust than deformation estimates due to difficulties with light intensity. Initial rock measurements are made on a dolomite sample.

Introduction

The Rock Physics and the Physical Acoustics Labs at Colorado School of Mines develop and apply new technology to analyze rock properties such as broadband compressional and shear wave velocities, elastic moduli and seismic anisotropy as a function of fluids and stresses. Another application is for seismic wave attenuation (quality factor) estimation, which could be an indicator of fluids, permeability and saturation. One of the major challenges is rock heterogeneity. Avoiding heterogeneities (grains, vugs, mineralizations, etc.) is a challenge when using semi-conductor strain gages (dimension ~ 1x5 mm) to estimate rock properties in a stress-strain experiment.

A joint research program was begun with the Colorado School of Mines and Micro-G Solutions to develop a fiber-optic strainmeter (FOS) to provide spatially averaged properties as well as higher accuracy. Using the FOS as the acquisition system for the stress-strain experiment setup would sample bulk rather than point properties as the fiber can be wrapped around the sample to average heterogeneities. Increased accuracy and sensitivity when measuring rock deformations undergoing an applied sinusoidal stress will permit better phase discrimination between stress and strain providing better measures of attenuation. The system is able to measure deformation and phase lags (strain and attenuation, respectively) as a function of frequency, from less than 1Hz to several KHz.

Previous studies have shown developments on systems to measure strains for applications in geo-mechanicals test for rock or structure failure. Butter and Hocker (1978) estimate strains on a cantilever bar by counting diffraction fringes. Schmidt-Hattenberger et al. (2003) approach geo-mechanical problems by measuring strains via a Bragg grating fiber. These two systems have been successful for their applications, but high deformation sensitivity is a requirement to compare experimental data to seismic deformations. The strain magnitudes of the two experiments previously described are not as sensitive as the FOS used for rock moduli and attenuation estimates at seismic deformations.

Fiber-optic Strainmeter Description

Figure 1 shows a basic schematic for the fiber-optic strainmeter for the Michelson interferometer geometry. A HeNe laser is shown as the light source but because the interferometer has equal lengths frequency stability is not very important. The light is split into two symmetric outputs denoted as interferometer arm I and II. The output fibers are shown wrapped around a cylinder. The ends of each output are terminated with a high reflectivity mirror so that, ideally, all of the light returns along the same fiber to the fiber splitter. The light returning from both interferometer arms is then recombined in the fiber splitter. Half of this recombined light is directed to the detector. The other half is sent back towards the laser source but is blocked by an optical isolator (not shown).

The interferometer arms are symmetric and either can be considered the reference or test arm. The output of the interferometer is simply the differential optical path length for the light in each arm. The interferometer has very high sensitivity and will provide an optical fringe every time one arm changes by an amount equal to

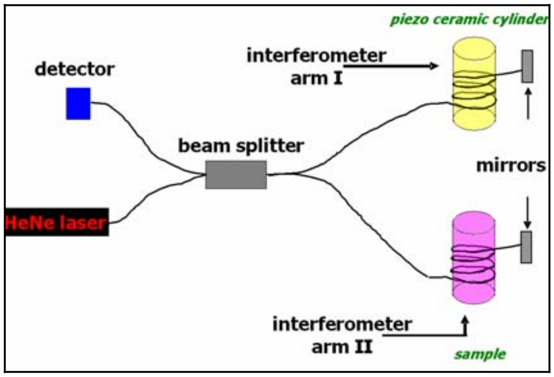

Figure 1 Schematic experimental setup for the fiber-optic strainmeter.

$\Delta=\lambda/(2n)$, where λ is the wavelength of light and n is the index of refraction of the fiber. For large changes, one could count the number of fringes or if the change is less than one fringe the change can be measured as a fraction of the full scale voltage difference corresponding to one fringe. Typical shot noise for such an interferometer with reasonable intensity beams is 10^{-3} to 10^{-6} of a fringe so that such a system should be capable of picometer displacement measurements depending upon the bandwidth of the measurement.

At very low frequencies (< 0.2 Hz) the instrument is limited due to normal temperature fluctuations that cause the fiber lengths to change differentially. In the normal mode of operation, however, the signals of interest tend to be at frequencies above a few Hz. Next we describe a way to avoid temperature fluctuations in the signal. For example, consider the case where one fiber is wrapped around a cylindrical test sample (e.g. a rock sample). A sinusoidal force (stress) is applied axially to the rock sample, and the interferometer is used to detect the change in the diameter of the rock sample. If we drive the rock such that the response is less than 1 fringe (1/3 micron), the expected signal is phase locked to the driving signal and can therefore be extracted with a phase sensitive detector. If the interferometer is at an extremum fringe (minimum or maximum) the output signal would be twice the driving frequency. If the interferometer is at a median value (side locked) then the signal would be at the same frequency as the driving frequency. Thus, it is clear that it is much easier to extract the signal if the mean value of the interferometer is locked either to an extremum or a side value so that normal temperature variations can be eliminated.

As an alternative to counting fringes to obtain the deformation of the rock, we can lock the interferometer by providing a compensating strain on one of the arms while applying stress to the other output fiber. In this case, the bandwidth of this compensation servo can be large and encompass the signal frequency so that there is no change observable on the interferometer output. The signal is then given by the deformation required to lock the interferometer. This method must be calibrated but is insensitive to fringe contrast. In our experiments the compensating deformation is given by applying a voltage to a piezo electric crystal. Recording the applied voltage can be either multiplied by different factors to provide deformation units or simply measured on a reference material in mechanical series with the sample and estimate strain ratios.

Sensitivity

Figure 2 represents the accuracy of the FOS. This sensitivity experiment consists of one piezo electric crystal being excited (strained) and a second piezo crystal compensates this deformation. The voltage (what is measured) has been transformed into deformation (amplitude) and phase angle units. The plots show that after measuring for an hour the variance for the phase is in the order of hundreds of microradians and for the deformation is in the order of hundreds of picometers. The sensitivity test showed that the FOS has a much higher sensitivity compared to the use of strain gages, which are in the order of microns. Therefore, the FOS requires smaller applied stress since it is more sensitive to the strains. The sensitivity results are encouraging and should permit us in the future to measure attenuation and velocities precisely and perhaps investigate non-linear effects in rocks as well.

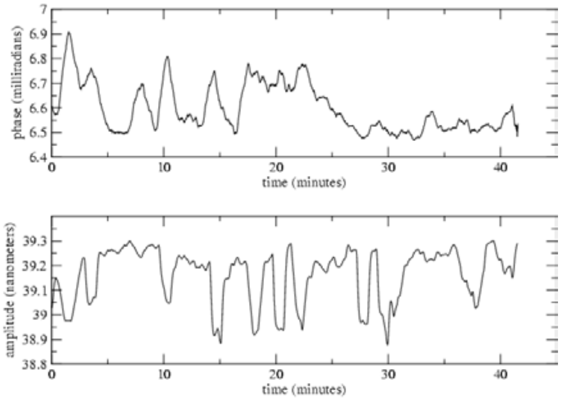

Figure 2 Strainmeter phase (top) and deformation (bottom) stability and sensitivity for an hour of measurements between two piezo electric crystals.

Plexiglas measurements:

As a preliminary (first) test to the system, three fibers are glued to a Plexiglas rod and an aluminum standard. Two were wrapped around (spiral) the Plexiglas and the aluminum, and one was set vertically on the Plexiglas. Only one of the fibers in the sample or the aluminum can be measured at a time, as there is only one free arm to be compensated by the piezo (Figure 1). In the future we would like to build two more channels to record simultaneously the three strain components. At the same time, vertical and horizontal semi-conductor strain gages are glued to the Plexiglas for comparison.

Our experimental approach measures strains in the sample and a calibrating material (aluminum) while

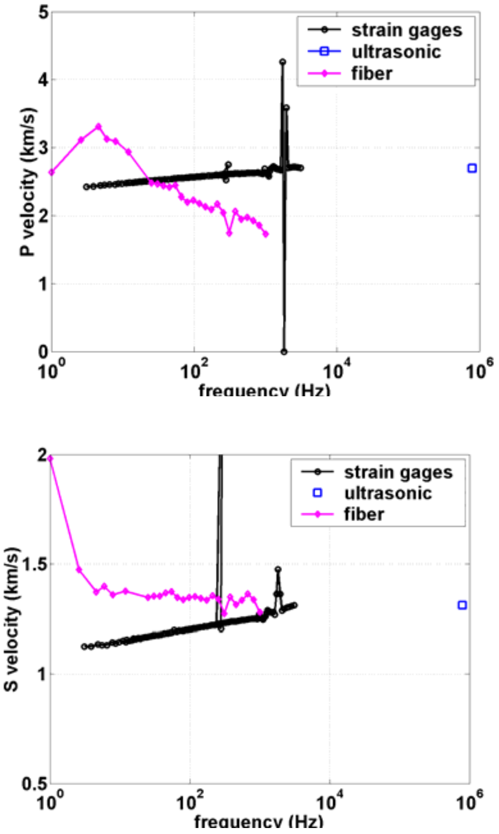

Figure 3 P- (top) and S- (bottom) wave velocities as a function of seismic and ultrasonic frequencies for the Plexiglas sample. The plots show the comparison of strain gages, fiber-optic and ultrasonic data.

applying a sinusoidal stress for a range of frequencies (Spencer, 1981, Batzle et al, 2001). Deformations are used to estimate moduli. These combined with the density give velocity. The rock is assumed linearly elastic meaning that the applied stress on the sample and aluminum standard must be equal. Phase angle lags are directly related to seismic attenuation.

The Plexiglas (sample) was set up in the same shaker (apparatus that applies axial sinusoidal stress) used for low frequency strain gage measurements (Batzle et al, 2001). The sample was measured on a laboratory bench (room pressure) for a range of seismic frequencies. Both, strain gage and fiber deformation where recorded for this setup. Moduli and latter velocities are estimated. The comparison estimates for P- and S- wave velocities using strain gages, fiber-optic, and a propagating ultrasonic wave are shown in Figure 3. The velocity values obtained from gages and fiber do not show a perfect match, but the overall bulk values are encouraging. There are a couple of possible sources of error in the strain measurements:

* Not enough light was received at the detector (mirrors did not reflect 100%).

* The fiber length glued to the sample is used to normalize deformations, and moduli are sensitive to this length. A more careful gluing and estimating the contact area (sample/fiber) is key to determine moduli values.

* The measurements were performed on a standard bench that is not isolated from vibrations that can be generated by walking, wind, etc, as an optics bench would be.

Young's attenuation values were also computed from the phase difference of the sinusoidal strains from the vertical fiber in the Plexiglas and the vertical fiber on the aluminum (Figure 4a). These measurements were performed at (warm) room temperature of about 30°C. A comparison with values obtained (on a different Plexiglas sample) from strain gages is shown in Figure 4b. A better correlation than that for velocity with respect to the use of semiconductor strain gages is observed. The reason probably is that the issue of light intensity will not significantly affect the phase estimate. Still, different Plexiglas samples can have differences in their composition and curing history giving different attenuation values (remember the gages data is from a previous experiment on another sample).

Future work:

We have shown that attenuation estimates correspond to those obtained by different methodologies, and that velocities are probably affected by light intensity or fiber contact length. Current measurements on a dolomite (with small heterogeneities) compare fiber optic and strain gage results on rocks (Figure 5). The system still must be modified for measurements to be made under pressure and with varying fluid saturations. We are also working on improving light intensity by changing the interferometer geometry where end-mirrors are not involved. The new interferometer will be designed following the Mach-Zender geometry.

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Acknowledgements

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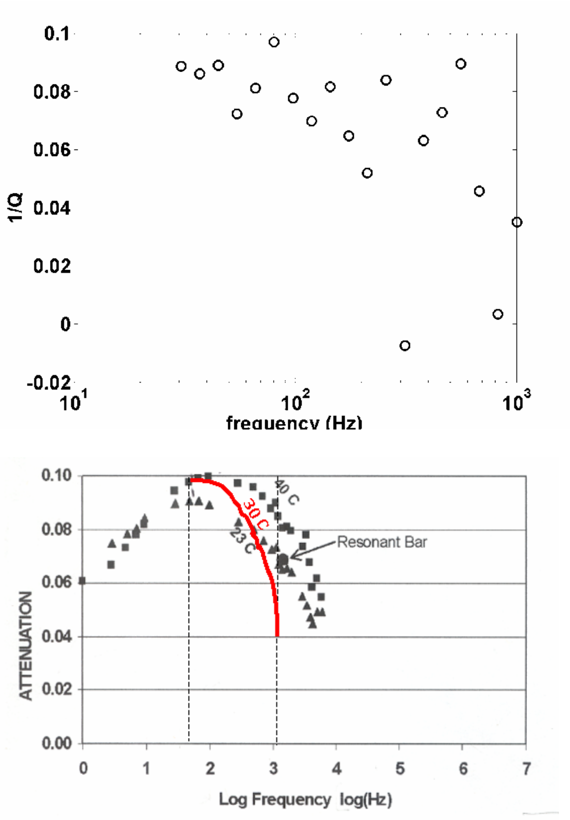

Figure 4 Attenuation (1/Q) for Plexiglas obtained from the FOS (top). Comparison of fiber-optic attenuation results (solid line) to strain gage measurements and a resonance bar experiment; these were performed on a different Plexiglas sample (bottom).

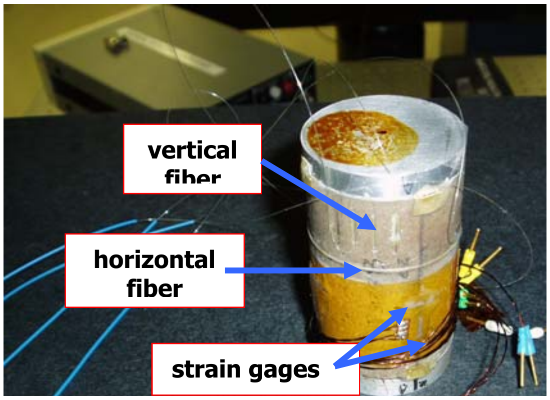

Figure 5 Dolomite sample with heterogeneities prepared with fiber-optic and strain gages. The orange layer under the strain gages is a material that acts as a fluid barrier to not damage the wires from the strain gages (resistors) in future saturation experiments.

EDITED REFERENCES

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