Fluid and rock bulk viscosity and modulus

Azar Hasanov*, Michael Batzle[†] and Manika Prasad, Center for Rock Abuse, Colorado School of Mines

SUMMARY

Compressional deformation in fluids and rocks is influenced by similar viscoelastic effects, as in shear case. In this paper we introduce the importance of bulk viscosity and modulus in frequency-dependent response of elastic velocities. We conducted experiments to measure bulk modulus and attenuation of two heavy-oil saturated rock samples by confining pressure cycling method under varying oscillation frequencies (within teleseismic frequency band 0.001 - 1 Hz), and compared these measurements to a more conventional axial stress-strain technique. We plan to extend the frequency range of the pressure cycling apparatus as well as to modify the setup in order to measure frequency-dependent bulk viscosities of viscoelastic fluids.

INTRODUCTION

The bulk modulus of any pore fluid must be used to interpret the seismic response and perform a fluid substitution for Direct Hydrocarbon Indicator analysis. However, fluids will have losses and show dispersion as a result of the viscoelastic behavior of the bulk modulus. This behavior can be described through the bulk viscosity. Bulk viscosity is distinct from the shear viscosity, but the controlling molecular motions are probably similar. In contrast to shear viscosity, bulk viscosity is rarely measured, and even poorly defined, yet it may be the dominant factor in acoustic dispersion. Attenuation and dispersion in the fluid will then be observed in any rock containing any highly viscous fluid, particularly heavy oils.

In greater scope, stress-strain low-frequency rock measurements (Spencer, 1981; Batzle et al., 2006) can have substantial errors when applied to velocities due to inaccuracies in Poisson's ratio. Direct low frequency bulk modulus measurements provide an additional measurement to calibrate the derived shear and bulk moduli from a Young's modulus experiment.
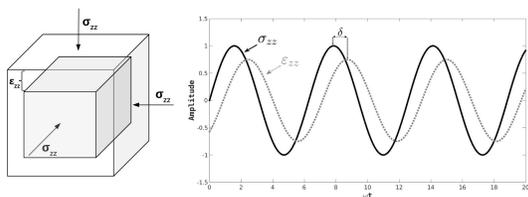

Figure 1: Schematic of the stress-strain relations in bulk deformation. This kind of behavior points to the concept of bulk viscosity in both fluids and rocks (modified after Strobl (1997)).

Any material exposed to a change in stress will undergo a strain. If the material is purely elastic, the strains will be completely linear and in phase with the applied stress. If the material is purely viscous (and Newtonian), then the strain rate is
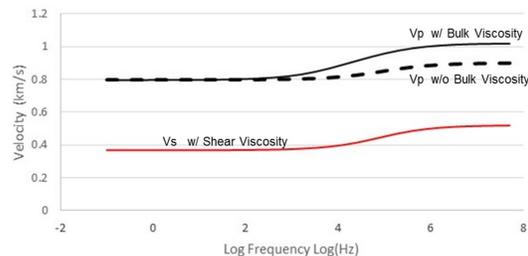

Figure 2: Schematic of velocity versus frequency for a heavy oil saturated sand.

proportional to the stress, but 90 degrees out of phase. Many of the fluids and rocks we deal with are a mixture of these two end cases. In another word, they are anelastic or viscoelastic. To some extent, these materials have a "memory" and deformation will lag stress. This translates into a frequency dependence.

Shear viscosity in fluids is very well known and has been studied in large detail. Briefly, as a shear stress is applied, the fluid begins to deform or flow. This deformation will continue as long as the shear stress is applied. A similar concept could be applied to a bulk deformation resulting from an applied hydrostatic stress. In the viscoelastic case, there will be a phase lag between the hydrostatic pressure sine wave and strain sine wave (Figure 1). This bulk viscous relaxation should be in addition to the more obvious shear relaxation. In the case of wave velocities, the frequency dispersion of shear wave (V_s) can be modeled by the viscoelastic effects due to shear viscosity. However, both the bulk modulus as well as the shear modulus are seen to have a frequency dependence (see, for example, Batzle et al. (2006); Hofmann (2006); Adam et al. (2009). Thus, simply matching the shear behavior will not completely explain the observed changes in compressional velocity (V_p). In Figure 2, we present a generalized model of V_s and V_p. Modification of the predicted response only with the shear modulus will not fully explain the changes in V_p. Hence, shear viscosity can not be the sole affecting parameter. For example, Prasad and Meissner (1992) found that saturated sediments, consisting of rounded sand grains are characterized by stronger bulk losses as compared to silt-sized quartz particles.

We conducted experiments to measure bulk modulus and attenuation of two heavy-oil saturated rock samples by confining pressure cycling method under varying oscillation frequencies (within teleseismic frequency band 0.001 - 1 Hz), and compared these measurements to a more conventional axial stress-strain technique. We plan to extend the frequency range of the pressure cycling apparatus as well as to modify the setup in order to measure frequency-dependent bulk viscosities of viscoelastic fluids.

Bulk viscosity and modulus

(a) Experimental setup used for pressure cycling measurements (after Hasanov (2014)).

(b) Heavy oil-saturated OB8 rock sample, instrumented with a pair of strain gages and encased into flexible epoxy mold.
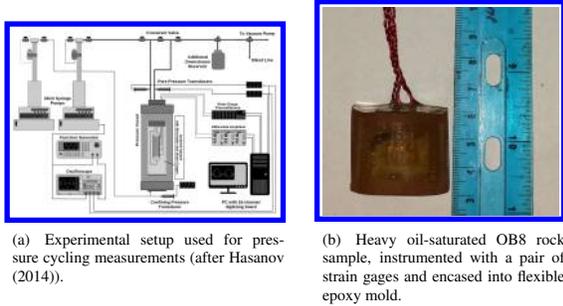
Figure 3: Pressure cycling apparatus and a sample, used in the study.

EXPERIMENTAL SETUP

We adapted the laboratory setup, developed by Hasanov (2014), for our experiments. The experimental apparatus, depicted in Figure 3(a), consists of a pressure vessel, two pressure pumps, a function generator, three pressure transducers, strain gage preconditioning modules, differential amplifiers, digitizing unit and a personal computer. In a typical experiment, a jacketed sample, instrumented with strain gages (Figure 3(b)), is mounted to the pressure vessel head and placed inside the pressure vessel, filled with hydraulic oil. Our pressure vessel can sustain confining pressures up to 69 MPa. A pressure transducer is placed at the bottom of the pressure vessel and records confining pressure. An Agilent 33250A function generator supplies analog voltage input directly into the syringe pump, which serves as the source of confining pressure. This allows the pump to generate pore pressure oscillations, amplitude, frequency and DC offset of which can be controlled with the function generator. Electrical voltage signals, generated by strain gages during a sample's deformation are filtered, amplified by Validyne SG297A strain gage preconditioning module, then digitized by the data acquisition card. The setup's upper oscillation frequency limit is currently 1 Hz due to mechanical friction within the syringe pump.

Once the samples are subjected to sinusoidally-varying confining pressure, we record the resulting volumetric strain, which lags behind the pressure signal by a phase angle Θ, which is representative of material's intrinsic attenuation. As with the axial stress-strain "low-frequency" setup (Spencer's apparatus, Spencer (1981); Batzle et al. (2006)), we utilize an aluminum sample as a calibration standard, both for bulk modulus and phase lag calculations.

RESULTS AND DISCUSSION

In the past, we have concentrated on the influence of "viscosity" (η) on wave velocity (Han et al., 2009). However, materials have both a shear viscosity (η_s) and a bulk viscosity (η_b). The Navier-Stokes equation through a lossy medium includes a viscosity term:

$$\rho \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla P + \eta \nabla^2 u \tag{1}$$

where ρ is density, t is time, and u is displacement. The more

general equation incorporates both bulk and shear viscosities (Dukhin and Goetz, 2009):

$$\rho \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla P + \eta_s \nabla^2 u + \left(\frac{4}{3} \eta_s + \eta_b \right) \nabla (\nabla \cdot u) \tag{2}$$

The acoustic relaxation times, τ, for these materials is given by:

$$\tau = \frac{1}{\rho V^2} \left(\frac{4}{3} \eta_s + \eta_b \right) \tag{3}$$

As an example, if we set η_s approximately equal to η_b, for water with a viscosity of 0.001 Pa·s (1 cP), the relaxation time is about 10^{-13} seconds. Thus, τ is directly proportional to the viscosity, which can change by many orders of magnitude. A very heavy oil at its glass point has a viscosity of 10^{12} Pa·s. This glassy oil would have a relaxation time of about 10^3 seconds; well within the seismic or logging frequency bands. This results in an attenuation coefficient for compressional waves, α_p, of:

$$\alpha_P = \frac{\omega}{\rho V^3} \left(\frac{4}{3} \eta_s + \eta_b \right) \tag{4}$$

Here, we assume the material to be thermally non-conductive to avoid the isothermal-adiabatic contributions. Dynamic measurements, including ultrasonic wave propagation, are adiabatic, whereas static measurements are generally isothermal.
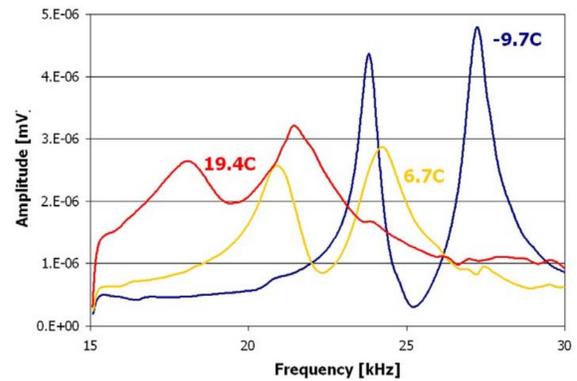

Figure 4: Resonance spectroscopy data collected on the Uvalde heavy oil. Both moduli and attenuation change with temperature. The measurement band is still fairly narrow (from Zadler (2005)).

We could attempt to measure α_P through acoustic spectroscopy, as suggested by Dukhin and Goetz (2009). We measured such a spectrum on heavy oil as a function of frequency and temperature shown in Figure 4. The peaks observed represent different vibrational modes. This technique would work well well with simple solid materials but is much more difficult with fluids with complex chemistry. A container must be used and its influence would need to be subtracted from a measured spectrum. In addition, the frequency band is actually fairly narrow (Zadler et al., 2004).

The results, obtained with our setup on two rock samples containing heavy oils at low frequencies is shown in Figure 5.

Bulk viscosity and modulus

We can compare these results to our previous measurements as shown in Figure 6. The data above 1 Hz (Log Frequency = 0) were collected with the quasi-static low-frequency system (Spencer, 1981; Batzle et al., 2006). The data below 1 Hz were collected in a separate pressure cycling system. In magnitude and frequency-dependence trend, the data from the two systems compares well.
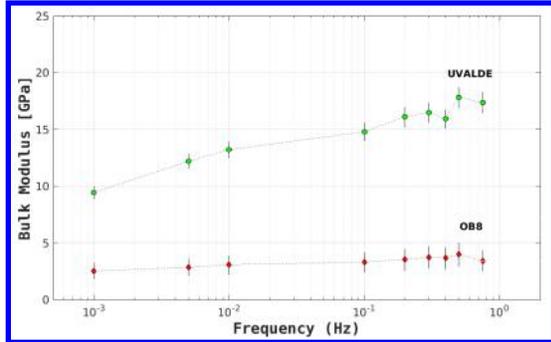

Figure 5: Measured bulk modulus as a function of oscillation frequency for the heavy oil saturated Uvalde and OB8 rock samples.
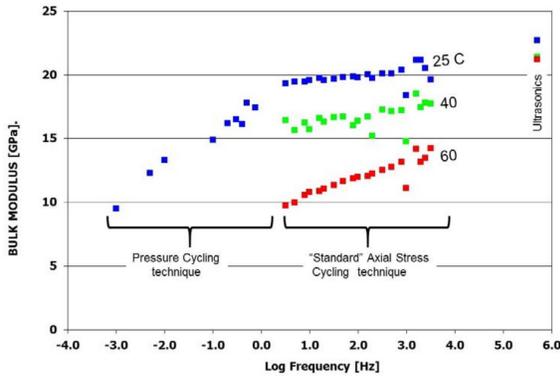

Figure 6: Comparison of pressure cycling technique with other measurements of bulk modulus for the Uvalde heavy oil saturated rock. The magnitude of the cycling technique is correct, but the frequency trend is questionable (modified after Gautam (2003)).

Attenuation can also be measured from these data:

$$\frac{1}{Q} = \tan\theta \tag{5}$$

Where θ is the phase lag between the pressure oscillations and strain oscillations. The measured θ are shown in Figure 7 for the Uvalde and OB8 rock samples containing heavy oil.

An alternative approach to calculating attenuation is to compare the total energy in the deforming system (E) to the energy lost in a cycle (ΔE) (Saxena et al., 1988; Scott-Emuakpor et al., 2010):

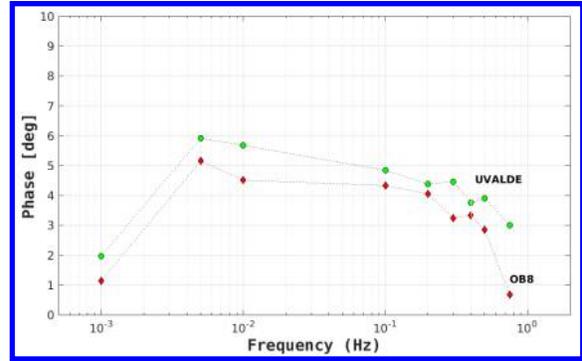$$\frac{1}{Q} = \frac{\Delta E}{2\pi E} \tag{6}$$

Figure 7: Measured phase angle between the driving stress and measured strain for both Uvalde and OB8 heavy oil saturated rocks.
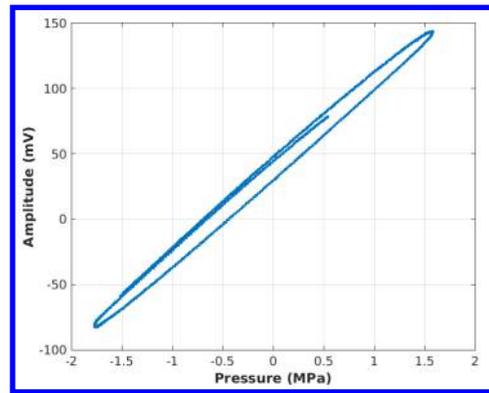

Figure 8: Example stress-strain loops at 1 mHz for OB8 heavy oil saturated sand.

Energy is calculated from the areas of a stress-strain plot as shown in Figure 8. From this plot for the OB8 sample at 1 mHz, a value for 1/Q of 0.04 is derived (Q = 25). This value is larger than the value of 1/Q = 0.021 extracted from the phase lag. The discrepancy is likely due to the variability in individual hysteresis loop areas and assumption of linearity. In most cases, the "loop" calculated loss (1/Q) is smaller than the value derived from phase angles. This comparison is shown in Figure 10.

O'Connell and Budiansky (1978) point out that the average energy (E_{ave}) should be used to calculate 1/Q rather than total energy (E). Since E_{ave} is roughly half the value of E, this would effectively double the loop phase angles in Figure 9. We expect the phase angle derived values to be more accurate due to the more extensive averaging involved.

CONCLUSIONS

Compressional deformation in fluids and rocks will be influenced by similar viscoelastic effects as in the shear case. Although considerable amount of data are available for shear viscosity and the associated changes in shear modulus, little is understood about either bulk viscosity or its influence. Fortunately, the measurements can be made in the laboratory using
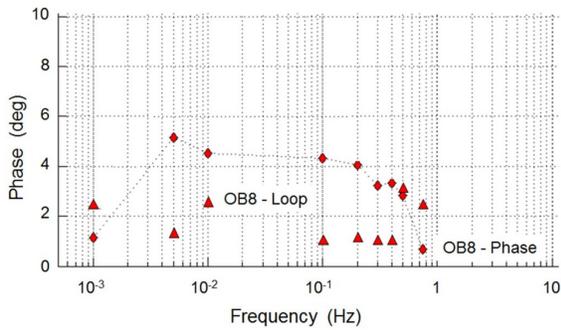
Bulk viscosity and modulus

Figure 9: Comparison of phase angles measured directly versus calculated from the hysteresis loop plots.

a variety of techniques. Dispersion and losses due to these viscoelastic components of the bulk modulus can be significant. Future work will include optimizing the measurements (amplitude, frequency range, error reduction) and testing specific cases. We also plan to expand the frequency range of our system, as well as to develop bulk viscosity measurement protocol by pore pressure cycling of viscoelastic fluids through a capillary of known permeability.

ACKNOWLEDGEMENTS

EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Adam, L., M. Batzle, K. T. Lewallen, and K. van Wijk, 2009, Seismic wave attenuation in carbonates: Journal of Geophysical Research: Solid Earth, **114**, http://dx.doi.org/10.1029/2008JB005890.

Batzle, M. L., D.-H. Han, and R. Hofmann, 2006, Fluid mobility and frequency-dependent seismic velocity—Direct measurements: Geophysics, **71**, N1–N9, http://dx.doi.org/10.1190/1.2159053.

Dukhin, A. S., and P. J. Goetz, 2009, Bulk viscosity and compressibility measurement using acoustic spectroscopy: Journal of Chemical Physics, **130**, 124519, http://dx.doi.org/10.1063/1.3095471.

Gautam, K., 2003, Fluid effects on attenuation and dispersion of elastic waves: Master's thesis, Colorado School of Mines.

Han, D.-H., J. Liu, and M. L. Batzle, 2009, Viscosity model of heavy oil with calibration of shear velocity data: 79th Annual International Meeting, SEG, Expanded Abstracts, 2115–2119, http://dx.doi.org/10.1190/1.3255274.

Hasanov, A. K., 2014, Reservoir transport and poroelastic properties from oscillating pore pressure experiments: Master's thesis, Colorado School of Mines.

Hofmann, R., 2006, Frequency dependent elastic and anelastic properties of clastic rocks: Ph.D. thesis, Colorado School of Mines.

O'Connell, R. J., and B. Budiansky, 1978, Measures of dissipation in viscoelastic media: Geophysical Research Letters, **5**, 5–8, http://dx.doi.org/10.1029/GL005i001p00005.

Prasad, M., and R. Meissner, 1992, Attenuation mechanisms in sands: Laboratory versus theoretical (biot) data: Geophysics, **57**, 710–719, http://dx.doi.org/10.1190/1.1443284.

Saxena, S. K., A. S. Avramidis, and K. R. Reddy, 1988, Dynamic moduli and damping ratios for cemented sands at low strains: Canadian Geotechnical Journal, **25**, 353–368, http://dx.doi.org/10.1139/t88-036.

Scott-Emuakpor, O., T. George, C. Cross, and M.-H. H. Shen, 2010, Multi-axial fatigue-life prediction via a strain-energy method: AIAA Journal, **48**, 63–72, http://dx.doi.org/10.2514/1.39296.

Spencer, J. W., 1981, Stress relaxations at low frequencies in fluid-saturated rocks: Attenuation and modulus dispersion: Journal of Geophysical Research, **86**, 1803–1812, http://dx.doi.org/10.1029/JB086iB03p01803.

Strobl, G. R., 1997, The physics of polymers 2: Springer.

Zadler, B. J., 2005, Properties of elastic materials using contacting and non-contacting acoustic spectroscopy: Ph.D. thesis, Colorado School of Mines.

Bulk viscosity and modulus

REFERENCES

Adam, L., M. Batzle, K. T. Lewallen, and K. van Wijk, 2009, Seismic wave attenuation in carbonates: Journal of Geophysical Research: Solid Earth, **114**.

Batzle, M. L., D.-H. Han, and R. Hofmann, 2006, Fluid mobility and frequency-dependent seismic velocity - direct measurements: Geophysics, **71**, N1–N9.

Dukhin, A. S., and P. J. Goetz, 2009, Bulk viscosity and compressibility measurement using acoustic spectroscopy: Journal of Chemical Physics, **130**, 124519.

Gautam, K., 2003, Fluid effects on attenuation and dispersion of elastic waves: Master's thesis, Colorado School of Mines.

Han, D.-H., J. Liu, and M. L. Batzle, 2009, Viscosity model of heavy oil with calibration of shear velocity data: SEG Annual Meeting, 2115–2119.

Hasanov, A. K., 2014, Reservoir transport and poroelastic properties from oscillating pore pressure experiments: Master's thesis, Colorado School of Mines.

Hofmann, R., 2006, Frequency dependent elastic and anelastic properties of clastic rocks: PhD thesis, Colorado School of Mines.

O'Connell, R. J., and B. Budiansky, 1978, Measures of dissipation in viscoelastic media: Geophysical Research Letters, **5**, 5–8.

Prasad, M., and R. Meissner, 1992, Attenuation mechanisms in sands: Laboratory versus theoretical (biot) data: Geophysics, **57**, 710–719.

Saxena, S., A. Avramidis, and K. R. Reddy, 1988, Dynamic moduli and damping ratios for cemented sands at low strains: Canadian Geotechnical Journal, **25**, 353 – 368.

Scott-Emuakpor, O., T. George, C. Cross, and M.-H. H. Shen, 2010, Multi-axial fatigue-life prediction via a strain-energy method: AIAA journal, **48**, 63–72.

Spencer, J. W., 1981, Stress relaxations at low frequencies in fluidsaturated rocks: Attenuation and modulus dispersion: Journal of Geophysical Research, **86**, 1803–1812.

Strobl, G. R., 1997, The physics of polymers, volume **2**: Springer.

Zadler, B. J., 2005, Properties of elastic materials using contacting and non-contacting acoustic spectroscopy: PhD thesis, Colorado School of Mines.

Zadler, B. J., J. H. L. Le Rousseau, J. A. Scales, and M. L. Smith, 2004, Resonant ultrasound spectroscopy: Theory and application: Geophysical Journal International, **156**, 154–169.