Seismic Dispersion in Extra-Heavy Oil Saturated Rock

Todd D. Bown*
Department of Physics, University of Alberta, Edmonton, Alberta, Canada
tbown@phys.ualberta.ca

and

Douglas R. Schmitt
Department of Physics, University of Alberta, Edmonton, Alberta, Canada

Summary

This expanded abstract presents a modern method for modeling a porous rock saturated with highly viscous liquid. Using a combination of a De Ghetto and Cole-Cole Maxwell (CCM) models, and a coherent potential approximation (CPA) effective medium theory, the acoustic velocity of carbonate rock saturated with extra-heavy oil at 22% porosity was predicted to vary ~100 m/s across a frequency range form ultrasonic (1MHz) down to seismic (50Hz) at a temperature of 20^{o}C. Results show significant velocity dispersion that would not be apparent when using Gassmann-Biot effective medium theories. The work presented here has implications for future studies to consider a more sophisticated modeling approach when dealing with extra-heavy oil as pore fluid in rock. This work may lead to help solve the problem of unexplained phenomena observed in seismic records and sonic logs in the field.

Introduction

Despite rapidly increasing exploration and production of extra-heavy oils worldwide, an understanding of the basic rock physics for rocks saturated with such oils has lagged. There are few studies in the literature that examine seismic wave propagation through heavy oil saturated rocks (Batzle et al., 2006; Leurer and Dvorkin, 2006; Gurevich et al., 2008). Interpretation of well-logs, ultrasonic measurements and seismic sections have been hampered with inconsistencies. Recently, the oil industry has been pressing ever-harder to find suitable answers to model extra-heavy oil in sedimentary formations.

Gassmann's (1951) formulas describing the static (i.e. zero-frequency) elastic behaviour are, due to their simplicity, popular and have been used extensively to combine the separate properties of rock frame, mineral, and pore fluid into a single, competent effective medium. Biot's equations (see Bouzidi and Schmitt, 2009) attempt to predict the behaviour with frequency and due to the additional parameters necessary can be problematic to apply. Although true experimental validation remains elusive (e.g. see Batzle et al., 2006) Gassmann's formulas have been assumed to work well in describing the effects of geological fluids as brines, gases, medium oils, light oils and condensates on seismic wave propagation. However problems arise in the comparison between high (e.g. laboratory, sonic logging) and low (seismic) frequencies when more viscous fluids, particularly heavy and extra-heavy oils, are the pore 'fluid' (Schmitt, 1999). Gassmann's formulas presume the fluid has a shear modulus of zero, an assumption violated by visco-elastic extra-heavy oil. The shear viscosity of such oils varies with both temperature and frequency (Batzle et al., 2006) and this can have a significant impact on the rocks observed effective moduli and acoustic wave speeds. In an attempt to better incorporate this effect, the coherent potential approximation (CPA) effective medium theory (Berryman, 1980) is explored by modelling. This approach may provide a means to correlate velocity measurements at different frequencies from ultrasonic down to seismic.

The procedure in this paper for modeling a generic extra-heavy oil is done by a De Ghetto et al. (1995) viscosity model and a Cole-Cole Maxwell (CCM) viscoelastic model (Gurevich et al., 2008). From the combination of these two models, temperature and frequency dispersions are introduced into the shear modulus of the extra-heavy oil. The shear modulus is now said to be dynamic. According to CPA theory, when combining the dynamic shear modulus of an viscous fluid with and the moduli of a rock, the fluid's frequency dispersion is imparted onto the saturated rock's effective moduli. Loosely knowing that effective moduli will be dynamic, it can be deduced that acoustic waves traveling through the such medium will also be dispersive; It is expected that a rock saturated with extra-heavy oil will have a temperature and frequency dispersion in acoustic velocity.

Theory

To calculate and gauge the viscosity for dead extra-heavy oil, an empirically derived model from De Ghetto et al. (1995) was used as our representative oil. The De Ghetto model profiled temperature and density to the viscosity η by

$$\log\cdot\log(\eta+1) = 1.90296 - 0.012619\cdot API - 0.61748\cdot\log(\tfrac{9}{5}\cdot T + 32)\,. \qquad (1)$$

where density is characteristic of degrees API gravity and T temperature is in degrees Celsius. Figure 1 displays the viscosity profile for typical extra-heavy oil of 6° API gravity. On a further note, though a good baseline average, the temperature-viscosity relationship presented by De Ghetto may not hold true for all extra-heavy oils. It is possible that compositional effects, such as those produced by biodegradation, will move the predicted viscosity away from the De Ghetto relationship.

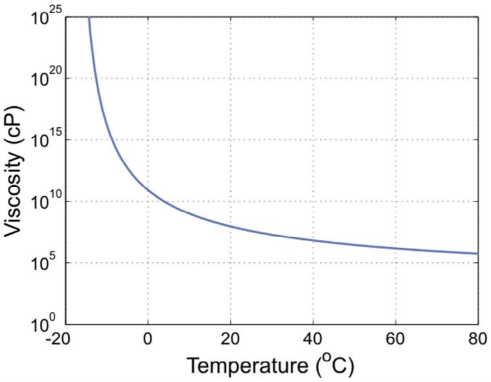

Figure 1: De Ghetto viscosity profile for dead, extra-heavy oil at 6° API gravity.

This abstract used a visco-elastic CCM model developed by Gurevich et al. (2008) to approximate the rheology of extra-heavy oil. The viscosity determined at different temperatures from the De Ghetto model was fed into the CCM model. The CCM model computed the storage modulus, (i.e., the real part of the complex shear modulus), across a range of frequencies (Figure 2). The CCM model denotes the frequency dependent, complex shear modulus μ_f as

$$\mu_f = \frac{\mu_\infty}{\dfrac{1}{(-i\omega\tau)} + \dfrac{1}{(-i\omega\tau_1)^\beta} + 1} \qquad (2)$$

$$\tau = \eta / \mu_\infty$$

where ω is the angular frequency of an acoustic signal, τ and τ_1 are relaxation times of two characteristic points on the continuous relaxation spectra, β is an adjustable parameter and μ_∞ is the (real valued) shear modulus of a material at high frequency.

Next, CPA theory was then used to calculate the effective bulk and shear moduli our saturated rock. The CPA model, determined for spherical pores (Berryman, 1980), is expressed by a system of two equations for solving effective K* and shear μ* moduli of a saturated rock

$$\begin{aligned} \varphi(K_f - K_*)P^{*f} + (1-\varphi)(K_m - K_*)P^{*m} = 0 \\ \varphi(\mu_f - \mu_*)Q^{*f} + (1-\varphi)(\mu_m - \mu_*)Q^{*m} = 0 \end{aligned} \tag{3}$$

where φ is porosity, K_f and μ_f are the bulk and shear moduli of the pore fluid, K_m and μ_m are bulk and shear moduli of the matrix material, and P and Q are invariants of the so-called Wu tensor. For the simplified case of spherical pores, the Wu tensor can be solved explicitly as

$$\begin{aligned} P^{*i} &= \frac{K_* + 4\mu_*/3}{K_i + 4\mu_*/3} \\ Q^{*i} &= \frac{\mu_* + F}{\mu_i + F} \\ F &= \frac{(\mu_*/6)\cdot(9K_* + 8\mu_*)}{K_* + 2\mu} \end{aligned} \tag{4}$$

where *i* is interchangeable for *f* and *m*. Solving the coupled equations from equation 3 was performed by an iterative approach. On a further note, the Wu tensor can be expanded and solved for pores of aspect ratios. This would be required to model more realistic sedimentary rocks, particularly complex carbonates, that contain both intercrystalline and interparticle porosity.

Examples

The calculated storage modulus for our generic extra-heavy oil via the CCM model is shown in figure 2. Our final results from CPA theory, displayed in terms of acoustic wave speed in figure 3, fused together the properties of the extra-heavy oil and carbonate rock. Inputs used for our CPA model was a rock with properties K_m = 60.5 GPa (calcite), μ_m = 29.5 GPa, and ρ_m = 2.80 g/cm^3, and extra-heavy oil with properties K_f = 3.02 GPa, 6^o API gravity and storage modulus from CCM modeling. There are two general trends in the data, a temperature increase results in a velocity decreases, and a

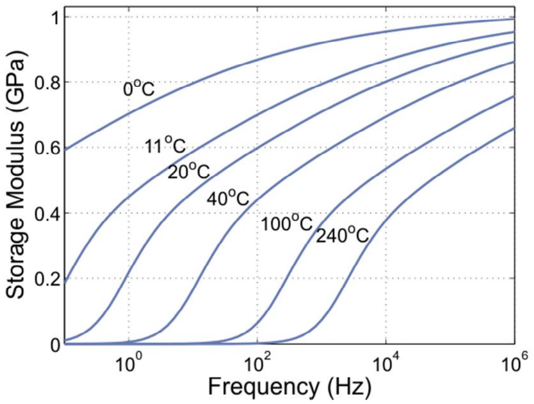

Figure 2: CCM model of the storage modulus (real part of the complex shear modulus) for extra-heavy oil. Parameters used to model the oil were μ_∞ = 1.02 GPa, β =0.2 and tau ratio of τ/τ_1 = 10.

frequency decrease results in a velocity decrease. The dispersive effects of both temperature and frequency on velocity is significant, varying over 200 m/s for both P-wave and S-wave over a temperature range of 0 ^{o}C to 240 ^{o}C and frequency range of 1 Hz to 1 MHz.

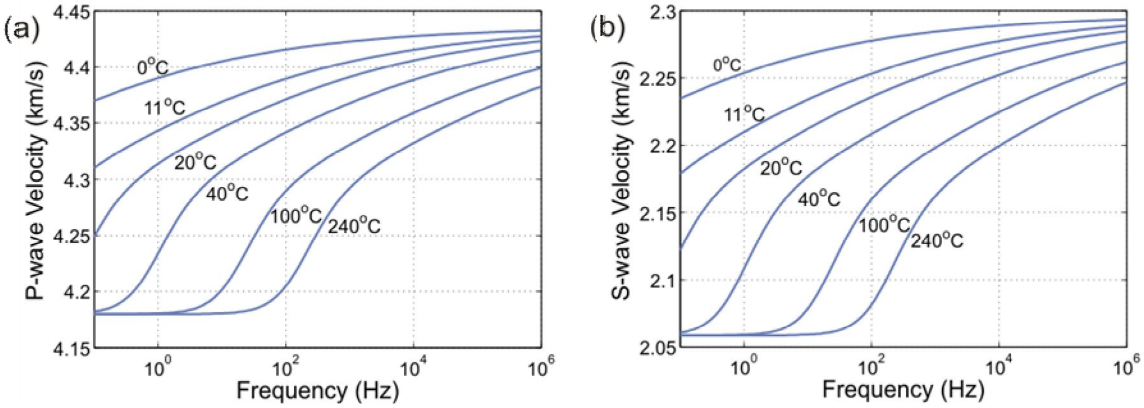

Figure 3: P and S wave dispersion in temperature and frequency for an extra-heavy oil saturated carbonate rock with 22% porosity.

Conclusion

The structure of modeling viscosity, and shear modulus for extra-heavy oil by De Ghetto and CCM models, respectively, produced a temperature-frequency dispersion in our data. CPA theory performed suitably to combine rock and pore-fluid components to predicted the effective properties of a carbonate rock saturated with a viscoelastic medium. Further work is needed to fine tune the CPA theory to include pores with aspect ratio. For rocks saturated with extra-heavy oil, this theory suggests there is significant velocity dispersion (about 10%) of the acoustic signal in both temperature and frequency. As such, care should be taken in applying the Gassmann theories to wave propagation in heavy oil saturated rocks.

Acknowledgements

This work was carried out as Bown`s term research project for Geophysics 620 in Fall 2009.

References

Batzle, M., and Hofmann, R., 2006, Heavy oils - seismic properties: The Leading Edge, 25, 750-756.

Berryman, J., 1980, Long-wavelength propagation in composite elastic media - I. spherical inclusions, II. Ellipsoidal inclusions: Journal of the Acoustical Society of America, 68, 1809-1831.

Bouzidi, Y., and Schmitt, D. R., 2009, Measurements of the speed and attenuation of the Biot slow wave using a large ultrasonic transmitter: Journal of Geophysical Research, 114, B08201.

De Ghetto, G., Paone, F., and Villa, M., 1995, Pressure-volume-temperature correlations for heavy and extra heavy oils: SPE International Heavy Oil Symposium, SPE 30316.

Gassmann, F., 1951, Elastic waves through a packing of spheres: Geophysics, 16, 673-685.

Gurevich, B., Osypov, K., Ciz, R., and Makarynska, D., 2008, Modeling elastic wave velocities and attenuation in rocks saturated with heavy oil: Geophysics, **73**, 115-122.

Leurer, K. C., and Dvorkin, J., 2006, Viscoelasticity of precompacted unconsolidated sand with viscous cement: Geophysics, 71, 31-40.

Schmitt, D. R., 1999, Seismic attributes for monitoring of a shallow heated heavy oil reservoir: A case study: Geophysics, 64, 368-377.