Wave propagation and shear wave anisotropy in partially saturated fractured rocks

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Introduction

The understanding of seismic properties of fractured systems is a key problem in applications related to hydrocarbon production and CO2 monitoring. Here, we derive a model describing frequency-dependent anisotropy in a fractured, partially saturated rock (Jin et al., 2018) by extending the theory of Papageorgiou and Chapman (2017). We show that our model has an effective fluid mobility that depends on the relative permeabilities of the saturating fluids in the rock, as well as the fluid distribution captured by a non-dimensional parameter. We interpret experimental measurements of Vp and Vs1,2 conducted by Falcon-Suarez et al. (2018), in terms of coupled squirt and patch effects through this model.

Methodology

Using an inclusion method, we describe the partially-saturated, frequency-dependent stiffness tensor of a medium with aligned ellipsoidal fractures, and its dependence on effective fluid properties, namely compressibility K_f and fluid mobility M_f. The compressibility and mobility are further dependent on fluid distribution, here quantified by a non-dimensional parameter $q \in \left[\frac{K_g}{K_w}, 1\right]$:

$$\frac{1}{K_f} = \frac{S_w}{\tilde{q}K_w} + \frac{(1-S_w)q}{\tilde{q}K_g} \qquad M_f = \kappa\left(\frac{\kappa_w}{\tilde{q}}\frac{1}{\eta_w} + \frac{q\kappa_g}{\tilde{q}}\frac{1}{\eta_g}\right), \qquad \text{with } \tilde{q} = S_w + q(1-S_w) \qquad (1)$$

where S_w is water saturation, and $\eta_{w/g}$ is the viscosity of water/gas, $\kappa_{w/g}$ their relative permeability and κ the absolute permeability of the rock. The resulting model has the form of a linear combination of two standard linear solid models: one with grain-scale squirt frequency ω_m and one with fracture-scale characteristic frequency ω_f given by

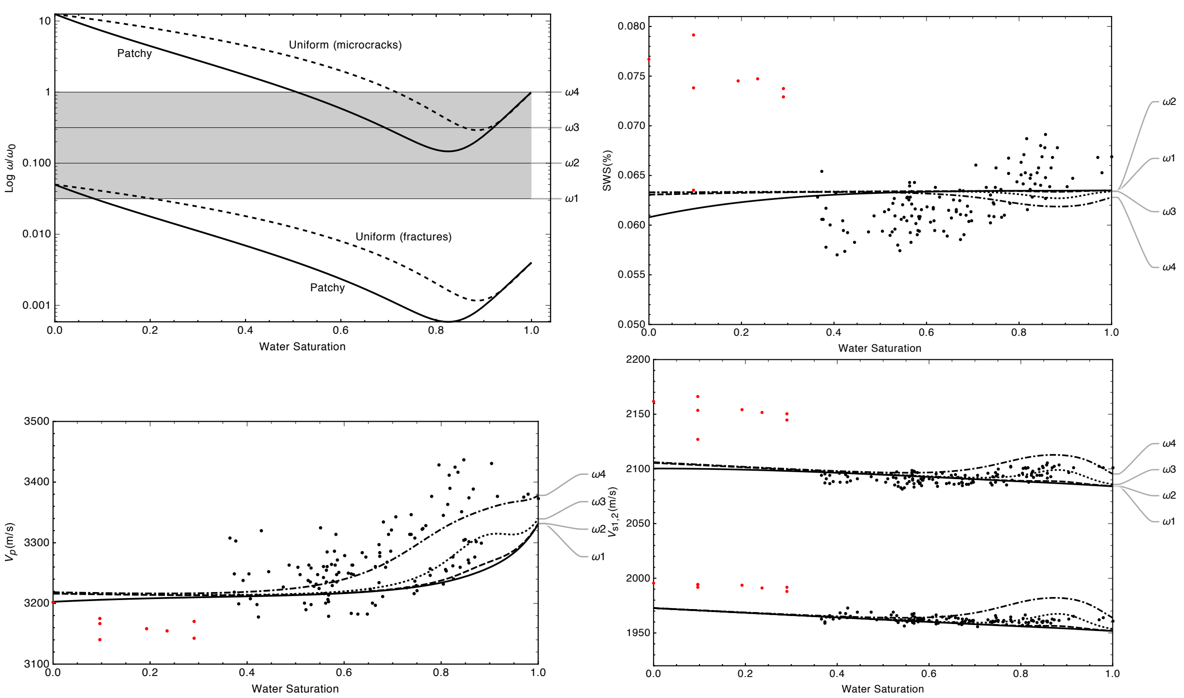
$$\omega_m = \omega_0 \eta_w M_f; \qquad \omega_f = \omega_0' \eta_w M_f \qquad \text{with } \omega_0' = \frac{\varsigma}{a_f}\omega_0 \qquad (3)$$

where ω_0 and ω_0' are the values of ω_m and ω_f at full water saturation, ς is the grain size (identified with the radii of the pore and cracks), and a_f is the fracture radius.

Results

Using the description above, we theoretically model the ultrasonic velocities obtained during flow-through (FT) and pulse imbibition (PI) experiments in a synthetic sandstone with coin-like fractures, partially saturated with CO2 and brine (see Ismael Falcon-Suarez et al., 2018 for details). We present the model predictions against the data for a set of four frequencies (ω1 - ω4) lying between the characteristic squirt flow frequency of the fractures and the microcracks in Figure 1. Note that the lowering of the characteristic frequency in Figure 1(a) at 80% saturation is the result of the scaling -by relative permeability- of effective fluid mobility. This can lead to elastic constants dispersing more at partial saturation therefore leading to a seemingly counterintuitive softening of the rock with increasing water saturation observed in both p- and s- velocities in Figures 2(c),(d).

(a) *(b)*



(c) *(d)*

Figure 1: (a) Logarithm of the characteristic frequency of standard linear solids comprising the model relative to the squirt flow frequency of water-saturated microcracks (ω0). Here the variation with water saturation for two fluid distributions (patchy or uniform) is shown. The squirt flow frequency of fractures is about 300 times lower than that of the microcracks. Four different frequencies (ω1-ω4) are used to evaluate the model the highest of which corresponds to the characteristic frequency of water-saturated microcracks (i.e. ω4=ω0) (b) Model-predicted shear wave splitting for the four different frequencies, against FT (black) and PI(red) data. Note that frequency dependence of SWS follows opposite trend to Vp, Vs1,2 (c) Model-predicted Vp for the four different frequencies, against FT (black) and PI(red) data Vp. The non-monotonic behaviour due to relative permeability is observed for ω=ω3 where a small "bump" in the velocity curve around 85% saturation is observed (d) Model-predicted Vs1,2 for the four different frequencies, against FT (black) and PI(red) data. Similarly to Vp, there is non-monotonic fluid dependence in the Vs1,2 curves because of squirt flow, at around 85% water saturation.

Conclusions

We have presented a model that describes multi-phase, frequency-dependent wave propagation in anisotropic, partially saturated rocks. In our model the squirt-flow mechanism, fluid distribution, and relative permeability effects are incorporated by means of an effective fluid modulus and mobility. Using this model, we show how ultrasonic velocities, as well as shear wave splitting corresponding to a partially saturated, fractured rock can be modelled with accuracy. Finally, we show how the dependence of the model on the relative permeability potentially leads to non-monotonic variations of shear and bulk moduli as well as SWS with water saturation.

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