Frequency dependence of fracture compliance
due to surface roughness

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Abstract — Frequency dependence of fracture compliance due to surface roughness — Seismic anisotropy provides a means to detect and characterise a fractured reservoir. The symmetry of the anisotropy is controlled by fracture orientation, while the magnitude of the anisotropy provides a measure of the total excess compliance of a fracture set. Unfortunately it is difficult to assess whether anisotropy is the result of a few large compliant fractures or due to a higher concentration of closed stiff fractures. The distinction between the models can have large implications for production, as many flow models are dependent on the cubic of the fracture aperture. Laboratory experiments by Pyrak-Nolte and Nolte (1992) have shown that dynamic compliances of natural fractures are frequency dependent and can be significantly smaller than their static values. They proposed a model to explain the frequency dependence in which natural rough fractures have an inhomogeneous distribution of compliances across their surface. This leads to a scattering induced apparent frequency dependent compliance, as different frequencies sample different subsets of compliances across the fracture. We propose a method of estimating the frequency dependence of fracture compliances due to scattering. We use the model of Hudson et al., (1997) to estimate the static compliances of a fracture modelled as an interface between two surfaces that are not in perfect contact but characterised as a planar distribution of weld points. The model is altered to allow for spatial heterogeneity in fracture compliance by replacing the input parameters with probability distributions. Using the proposed fractal scaling relationship of Worthington (2007) we scale fracture parameters from laboratory-scale to field-scale. We find that the magnitude of the frequency dependence is determined by the roughness or heterogeneity of the fracture, while the frequency band in which maximum frequency-dependence occurs is strongly controlled by the fracture’s mean static compliance. Within the seismic frequency band high frequency-dependent anisotropy due to scattering is expected for large compliant fractures, but not for closed stiff fractures. The results thus provide a potential means to differentiate between fracture- and microcrack-induced anisotropy.

INTRODUCTION

Large fractures within petroleum reservoirs have the potential to significantly enhance permeability and consequently increase production. Although seismic studies lack the resolution needed to image individual fractures, the presence of fracture sets can be inferred and characterised through the study of seismic anisotropy. The symmetry of the anisotropy is defined by fracture orientation, while its magnitude is related to the total excess compliance of the fracture set. Unfortunately it is difficult to assess whether a fracture set is composed of a few large compliant fractures, or a larger number of small stiff fractures.

Several recent investigations have reported frequency-dependent anisotropy (FDA) within petroleum reservoirs, such that the measured anisotropy decreased with increasing frequency [1-4]. Under the assumption that the anisotropy is caused by aligned fractures this would require a mechanism that reduces the apparent compliance of the fractures with increasing frequency. Two possible mechanisms to achieve this are wave induced fluid flow between fractures and pores, and scattering due to rough fractures.

The presence of an incompressible fluid within a fracture has the potential to significantly reduce its normal compliance. This effect is minimal at low frequencies, provided the rock matrix in which it is imbedded is both porous and permeable, as the fluid can simply flow out of the fracture in response to an imposed load. At high frequencies, however, the oscillations may be too rapid for the fractures to fully drain and it will appear stiff. Chapman [5] has developed a poroelastic model which shows that the frequency at which this occurs is strongly...
dependent on the porosity and permeability of the host rock, the fluid properties (e.g., viscosity and bulk modulus) and also crucially on the average size of the fractures, with larger fractures affecting lower frequencies.

Pyrak-Nolte and Nolte [6] measured apparent frequency dependent fracture compliance in lab samples. They demonstrated that the frequency dependence need not be dynamic in origin, but may simply be the result of waveform scattering while passing through a non-uniform distribution of local compliance within the plane of a rough fracture. Here we generalize these results and propose a method to model the frequency dependent anisotropy due to scattering from aligned rough fractures. The results show a dependence on the mean compliance of the constituent fractures and can potentially be used to distinguish between anisotropy produced by large or small fractures.

1 THEORY

Displacement discontinuity theory models wave propagation across a fracture as a boundary condition between two half spaces, where it is assumed that stress is continuous across the fracture but that displacements are not [7]. The discontinuity in displacement in the normal and tangential directions is proportional to the fracture compliances $Z_N$ and $Z_T$, respectively. For a wave propagating normal to a fracture the transmission coefficient is

$$T(Z_{N,T}, \omega) = \left(1 - \frac{\text{exp} \omega F_{N,T} Z_{N,T}}{2} \right)^{-1}$$  \hspace{1cm} (1)

where $\omega$ is the angular frequency, $\rho$ is the density of the matrix rock, and $V_{P,S}$ is the velocity of the wave. In general the fracture behaves as a low-pass filter on the transmitted wave with characteristic cut-off frequency

$$\omega_c = \frac{2}{\rho V_{P,S}} Z_{N,T}.$$  \hspace{1cm} (2)

Dynamic compliance can be estimated in the laboratory by matching experimentally measured transmission coefficients at known frequencies against those predicted by equation (1). In practice, however, the inferred compliance is often frequency dependent, with compliance decreasing with increasing frequency. Pyrak-Nolte and Nolte [6] argued that this could be explained as simple wavefront averaging over a non-homogeneous distribution of local compliance. In this configuration different subsets of the fracture will have different transmission coefficients, with different characteristic frequencies. As frequency increases the most compliant portions of the fracture will begin to scatter energy rather than transmit it, such that the transmitted waveform will only sample the stiffer regions, and the apparent compliance, as inferred from the transmitted wave, decreases.

Assuming that local compliance controls the local transmission coefficient, an average transmission coefficient across the fracture can be calculated as [8]

$$T(Z_{\text{app}}, \omega) = \int T(Z_{N,T}, \omega) f(Z_{N,T}) dZ_{N,T} \hspace{1cm} (3)$$

where $f(Z_{N,T})$ is the probability distribution of local compliance. The apparent frequency dependent compliances of the full fracture can then be calculated by substituting equation (3) into an inverted form of equation (1):

$$Z_{\text{app}}(\omega) = \frac{2\sqrt{1 - [T(\omega)]^2}}{\exp \frac{\omega}{V_{P,S}} [T(\omega)]}$$  \hspace{1cm} (4)

2 SCALING TO LARGER FRACUTURES

Figure 1: Laboratory and field data of fracture compliance as a function of fracture size (modified from [10]).

To calculate the frequency dependence of compliance we need an estimate of mean (static) fracture compliance and a probability distribution function that defines how compliance varies from this mean. We use the expressions of Hudson et al [9] to estimate the static compliances of fractures modelled as interfaces between two surfaces that are not in perfect contact but are characterized as a planar distribution welded zones...
separated by void areas of open fracture. The equations of normal and tangential compliance are, respectively,

\[ Z_n = \frac{\pi a^2}{4\mu} \left( \frac{\lambda + 2\mu}{\lambda + \mu} \right)^{1/2} \left( 1 + 2 \left( \frac{\lambda + 2\mu}{\lambda + \mu} \right)^{1/2} \right), \]

\[ Z_t = \frac{\pi a^2}{8\mu} \left( \frac{3\lambda + 4\mu}{\lambda + \mu} \right)^{1/2} \left( 1 + 2 \left( \frac{3\lambda + 4\mu}{\lambda + \mu} \right)^{1/2} \right), \]

where \( \lambda \) and \( \mu \) are the Lamé parameters of the host rock, \( a \) is the mean radius of the contact areas, and \( r' \) is the relative proportion of the fractured surface that consists of welded contact. These expressions are valid only for \( r' < 0.2 \). In our models we take \( r' \) to be 0.2.

A recent compilation of fracture compliance estimates at various length scales suggest that fracture compliance increases with increasing fracture length [10]. They propose a fractal scaling relationship between fracture surface properties and the average length scale. The static compliances estimated with equations (5) and (6) scale linearly with weld radius, suggesting that average weld size may act as a proxy for the length scale of the fracture.

In addition to the mean fracture compliances we also need to estimate a probability distribution to allow local compliance to vary from this mean. We assume that the local compliance is proportional to local aperture. Apertures of natural rough-walled fractures often show a skewed distribution that is approximately lognormal [11]. The shape of the distribution is controlled by the standard deviation of the log-aperture, \( \sigma \), which generally falls between 0.5 and 1.0, but may be higher for very rough fractures.

3 EXAMPLE FROM A FRACTURED GAS FIELD

Al-Harrasi et al. [4] performed shear wave splitting analysis of a microseismicity dataset from a fractured gas field in Oman. The largest magnitude of anisotropy was found within the highly fractured uppermost unit of the Natih carbonate gas reservoir with differences between the fast and slow shear wave velocities ranging mostly between 0-10% but with some measurements as high as 18%. The frequency content of the data was between 10-400 Hz, allowing for frequency dependent anisotropy analysis. The FDA effect was modelled using a frequency dependent poroelastico model (Figure 3), however, the effect of scattering was not considered. Here we use our proposed scattering model to investigate the plausible contribution of frequency dependence due to scattering.

The Natih-A reservoir has a P-wave velocity of 2800 m/s, an S-wave velocity of 1470 m/s and a density of 2400 kg/m³. Figure 4 shows the predicted frequency dependent normal compliances for various choices of \( \alpha \) (a) and mean weld radius (b). We find that the magnitude of the frequency dependence is dependent on the roughness or heterogeneity of the fracture, while the frequency band in which maximum frequency dependence occurs is strongly controlled by the fracture’s mean static compliance. The results suggest that within the frequency band typical of microseismicity (10-500 Hz) frequency dependence may be observed for static compliances in the range of \( 10^{-9} \) to \( 10^{-5} \) m/MPa.

Figure 5 shows the predicted frequency dependent shear wave splitting at various propagation angles relative to
the fracture-set normal direction. Two models are shown: one with widely spaced (5 m) fractures with static compliances around 2.5×10^{-11} m/Pa, and another with closely spaced (0.5 m) fractures with static compliances of 2.5×10^{-11} m/Pa. Both models have identical ratio of static compliance to fracture spacing, and thus have the same static effective media compliance; but the widely spaced, compliant fracture model shows greater frequency dependence.

However scattering may become more significant at higher frequency.

REFERENCES


