Effective wave dispersion and attenuation in isotropic thermoelastic media.

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SUMMARY

P-waves traveling in thermoelastic materials suffer attenuation and dispersion due to existence of the thermal wave, which is diffusive at low frequencies (mesoscopic loss) and is a truly propagation wave at high frequencies. Thus the thermal wave behaves similarly to the slow P-wave in Biot media. This work presents a Finite Element procedure to determine an effective viscoelastic medium complex long-wave equivalent to a thermoelastic material. The experiments consist on applying compresiibility and shear test on numerical samples. Each test is defined by a boundary value problem that is solved uisng the Finite Element (FE) First the procedure is validated by comparison with the case of equal layer thicknes and different Gruensen ratios. Next is analyzed the case of a layered media with varying Gruensen ratios and random layer thickness, for which not analytical solution is avalaible. This case shows an increase in pahse velocities and dissipation factors.

INTRODUCTION

Hydraulic fracturing is a standard procedure used to allow hydrocarbon production in tight gas and shale oil and gas reservoirs. It consist on injecting water mixed with sand or ceramic materia in the formation at high pressures in order to generate paths where hydrocarbons can flow to production wells. In this fashion new fractures are added to pre-existing natural ones enhancing the absolute permeability of the reservoir. Generally, this procedure generates bi-wing and planar fractures, normal to the minimum principal stresses. To simulate one stage of the fracking procedure, the numerical model combines a two-phase flow simulator, based in the Black-Oil formulation Aziz and Settari (1985); Fanchi (1997), to represent fluid injection with a breakdown criterion that follows the formation weakness zones. The flow simulator is run until the pressure reaches a threshold breakdown value at a given computational cell. Then such cell and its neighbours are fractured, i. e. their permeability and porosity are increased with prescribed values. This, in turn, induces an inmediate pressure decay in the formation. Once the planar fracture is completed, the two-phase simulator is applied to predict hydrocarbon production. At early times part of the injected water flows back before the hydrocarbon starts to be produced.

Among other approaches to numerical simulate hydraulic fracturing we mention Pak and Chan (2008), presenting a fully coupled thermal hydro-mechanical model and Zhao et al. (2014) analyzing a shale gas reservoir with large amounts of natural fractures. Furthermore, Lee and Wheeler (2018) present a genetic algorithm to optimize the design of hydraulic fracturing scenarios.

THE NUMERICAL HYDRAULIC FRACTURE PROCEDURE

The injection and production flow numerical model uses the Black-Oil formulation to two-phase, two component fluid flow allows the gas component to dissolve in the water phase. These equations are obtained by combining the mass conservation equation for each component with the two-phase Darcys law Aziz and Settari (1985). To discretize the Black-Oil equations we use the public domain BOAST simulator (Fanchi, 1997), that solves the system using IMPES finite difference technique. Thus, a CFL time step needs to be imposed Savioli and Bidner (2005).

The fracture criterium to increase porosity and permeability at a given computational cell is defined in terms of a threshold pressure value P_{bd} defined as Economides and Hill (1994).

$$P_{bd} = 3\sigma_{Hmin} - \sigma_{Hmax} + T_0 - p_H, \tag{1}$$

where T_0 is the tensile stress of the rock, p_H the hydrostatic pressure and

$$\sigma_{Hmax} = \sigma_{Hmin} + \sigma_{Tect}, \tag{2}$$

with σ_{Tect} being the tectonic stress contribution, σ_{Hmax} and σ_{Hmax} the maximum and minimum horizontal stresses, respectively, obtained as

$$\sigma_{Hmin} = \frac{\nu}{1-\nu}\sigma_V, \quad \sigma_V = g\int_0^H \rho_f \, dH, \tag{3}$$

where H is the formation depth, ν the Poisson ratio, ρ_f the formation density and g the gravity constant.

SEISMIC MODELING

A 2D viscoelastic approach is applied to simulate wave propagation in porous media Santos et al. (2011). This model is able to represent at field scales the mesoscopic attenuation and dispersion effects caused by heterogeneities of rock and fluids. It considers a single phase fluid, so its properties are computed using gas and water saturations as weighting factors. Numerically, the equation is solved by finite elements, applying an iterative domain decomposition procedure; besides a discrete inverse Fourier transform (Ha et al., 2002) computes the time domain solution.

NUMERICAL RESULTS

Validation

To validate the procedure we consider a square sample of side length 2 mm with 5 periods of alternating layers where Γ_1 takes a fix value 1.1 and $\Gamma_2 = 1.19, 1.28, 1.325, 1.37, 1.46, 1.55, 1.73, 1.82, 2.$. Frequency is 100 Hz. The sample is discretized using a 160×160 uniform mesh. The material properties are given in Table 1. (son los datos de la Figura 6) Figures 1 and 2 compare P-wave velocity and dissipation factor 1000/Q at 100 Hz obtained with the FE harmonic experiments with those predicted by the theory. A good fit is observed, better for dissipation factors than for phase velocities.

A layered medium with randon layer thickness

Next we consider two experiments for a square sample of 2mm side length with variable layer thicknesa, wdiscretized with an uniform 160x160 mesh. Figure 3 displays the ten layers sample used in the first experiment. Black corresponds to Γ_1, that is fixed at the value 1.1 and white corresponds to $\Gamma 2$, that varies according to the values in the horizontal axis in Figures.

Figures 4 and 5 display P-wave phase velocity and dissipation factors at 100Hz for the variable thickness case and a reference theoretical curve for equal thickness layers.

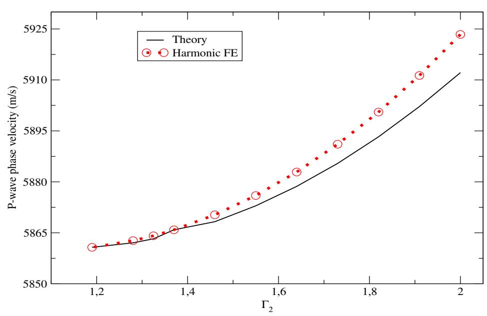

Figure 1: Theory versus FE P-wave phase velocity as function of Γ_2 for fixed Γ_1 = 1.1. The sample is square of side length 2 mm with five periods of alternating layers of equal thickness varying Γ_2 as shown in the horizontal axis. Frequency is 100 Hz.

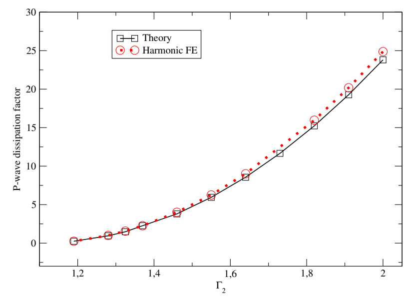

Figure 2: Theory versus dissipation factor as function of Γ_2 for fixed Γ_1 = 1.1. The sample is square of side length 2 mm with five periods of alternating layers of equal thickness varying Γ_2 as shown in the horizontal axis. Frequency is 100 Hz.

CONCLUSIONS

ACKNOWLEDGMENTS

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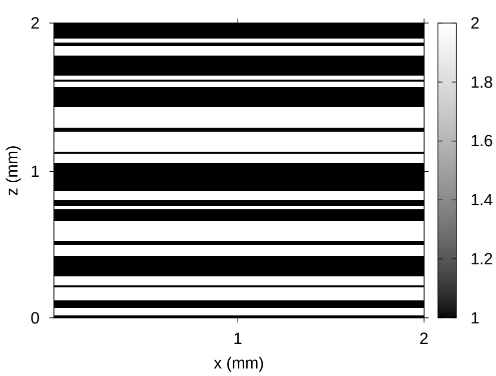

Figure 3: Illustration of a representative sample with 27 layers of variable (random) layer thickness. Side length is 2 mm. White corresponds to Γ_2, black to $\Gamma_1 = 1.1$.

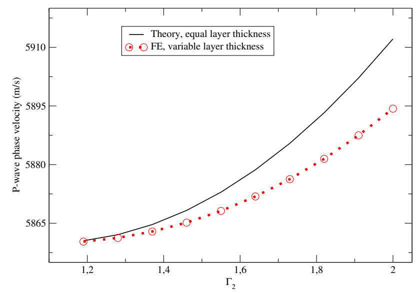

Figure 4: FE P-wave phase velocity as function of Γ_2 for fixed Γ_1 = 1.1. The FE results are for the layered sample of variable layer thickness in Figure 3. Frequency is 100 Hz.

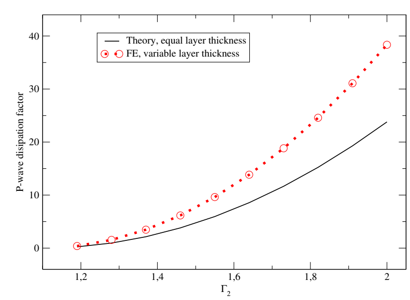

Figure 5: FE P-wave dissipation factor as function of Γ_2 for fixed Γ_1 = 1.1. The FE results are for the layered sample of variable layer thickness in Figure 3. Frequency is 100 Hz.