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Interpretation of Hydrocarbon Microtremors as Pore Fluid Oscillations Driven by Ambient Seismic Noise

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SUMMARY

Oscillations of oil in a partially saturated porous reservoir are a possible mechanism for the observed spectral modification of ambient seismic background noise above hydrocarbon reservoirs. We couple a 1D wave equation to a linear oscillator equation, which represents the oscillations of the oil within the reservoir. The resulting system of equations is solved numerically with explicit finite differences on a staggered grid in both space and time. The ambient geoseismic noise is simulated by a source term in the equilibrium equations producing a Fourier spectrum of the solid velocity at the surface including all frequencies between 1 and 10 Hz. The numerical simulations show that the oil within the reservoir always oscillates with its eigenfrequency (given a small frictional damping). The corresponding resonance peak is clearly visible in the Fourier spectrum of the fluid velocity. First results show that a smaller Young's modulus in the reservoir compared to the surrounding elastic material is necessary to transfer the oil oscillations from the fluid to the solid. For this case, the resonance frequency is also visible in the Fourier spectrum of the solid velocity at the Earth surface, because the fluid oscillations are transmitted by the elastic material to the Earth surface.

Introduction

Measurements of ambient seismic background noise above hydrocarbon bearing structures commonly show spectral modifications in the low frequency range between 1 and 10 Hz (Dangel et al., 2003). The Fourier spectra of surface velocities measured above hydrocarbon reservoirs often show a larger component around 3 Hz compared to measurements taken elsewhere. Such spectral modifications therefore allow for direct hydrocarbon indication. However, the physical mechanisms causing this spectral modification are not yet fully understood. A possible explanation is resonant pore fluid oscillations which are transferred to the elastic reservoir rock and transmitted to the Earth surface. The aim of this paper is to introduce a prototype model to simulate this behavior. This model couples an oscillator equation for the pore fluid motion with the standard elastic wave propagation equation.

Coupled wave-oscillator model

Droplets of fluid in a partially saturated porous material, such as a hydrocarbon reservoir, can oscillate in the pores (Hilpert et al., 2000). The surface tension keeps the droplet in an equilibrium position (Figure 1). If the fluid is displaced from its equilibrium, the surface tension creates a restoring force. For a simplified pore geometry as shown in Figure 1 this oscillation can be approximated by the well known second order ordinary differential equation of a linear oscillator

$$\frac{\partial^2 u_f}{\partial t^2} = -\omega_0{}^2 u_f \tag{1}$$

where t is the time, u_f is the displacement of the fluid out of its equilibrium, ω_0 is the eigenfrequency of the linear oscillator, which is calculated from material parameters describing the pore geometry and the fluid (e.g., surface tension and density). For frequently occurring physical values, ω_0 is in the low frequency range as could be demonstrated by Holzner et al. (2006). Friction between the fluid and the solid is incorporated as an additional term in the force balance equations. This term is derived from Darcy’s law of fluid flow:

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = -\frac{\varphi\eta}{\kappa\rho}\Delta v \tag{2}$$

where ρ, p, φ, η, κ and Δv are density of either fluid or solid, fluid pressure, porosity of the rock, viscosity of the fluid, permeability of the rock and relative velocity of the fluid with respect to the solid structure, respectively. Since both the fluid and the solid structure can move, equation (1) has to be formulated in terms of relative displacements. For the description of the solid movement a standard elastic wave propagation equation is used. Coupling between the elastic wave equation and the fluid oscillation equation is enabled by Darcy terms, which cancel out if both equations are added. The governing equations are:

$$\begin{aligned}
\frac{\partial v_f}{\partial t} &= -\omega_0^2 u_f + \omega_0^2 u_s - \frac{\varphi\eta}{\kappa\rho_f} v_f + \frac{\varphi\eta}{\kappa\rho_f} v_s \\
\frac{\partial v_s}{\partial t} &= \frac{1}{\rho_s}\frac{\partial \sigma_x}{\partial x} + \frac{\varphi\eta}{\kappa\rho_s} v_f - \frac{\varphi\eta}{\kappa\rho_s} v_s + \frac{1}{\rho_s} F \\
\frac{\partial \sigma_x}{\partial t} &= E\frac{\partial v_s}{\partial x} \qquad \frac{\partial u_f}{\partial t} = v_f \qquad \frac{\partial u_s}{\partial t} = v_s
\end{aligned} \tag{3}$$

where v_f, u_f, v_s and u_s are absolute fluid velocity, fluid displacement, solid velocity and solid displacement, respectively, ρ_f and ρ_s are fluid and solid density, respectively, σ_x is solid stress, F is an external source and E is the Young's modulus of the solid. The system of five equations (3) is solved using explicit finite differences on a staggered grid in both space and time (e.g., Virieux, 1986). The applied parameters are listed in Table 1.

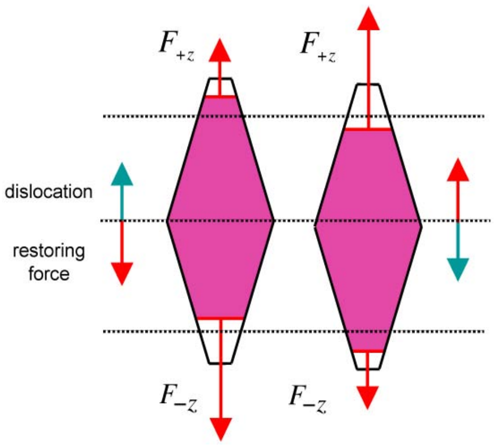

Figure 1: Simplified pore geometry. The fluid in this partially saturated pore can move out of its equilibrium position. The surface tension acts as the restoring force. Due to the simplified pore geometry the corresponding oscillation is linear.

Parameter	Symbol	Value
Eigenfrequency of oscillator	ω_0	18.85 (= 3 Hz · 2π)
Coupling term	$(\varphi \cdot \eta)/\kappa$	Reservoir: 300 Pa s m^{-2} Surrounding: 0 Pa s m^{-2}
Density of fluid	ρ_f	800 kg m^{-3}
Density of solid	ρ_s	2800 kg m^{-3}
Youngs modulus	E	Reservoir: variable Surrounding: $2 \cdot 10^{10}$ Pa
Depth of reservoir	D_{res}	300 m
Thickness of reservoir	H_{res}	40 m
Depth of external source	D_F	500 m
Model size	H_{model}	600 m with 240 nodes
Modeled physical time	t_{tot}	120 s with approx. $5.5 \cdot 10^5$ time steps

Table 1: Parameters used for all numerical runs.

Model setup

The 1D model setup represents an elastic surrounding rock and a subsurface hydrocarbon reservoir (Figure 2). A free surface boundary condition is applied at the top of the model and a nonreflecting boundary condition at the bottom (e.g., Ionescu and Igel, 2003). A point source continuous in time is applied below the reservoir. The source is a linear superposition of sinusoidal oscillations with frequencies between 0.01 Hz to 15 Hz and a frequency spacing of 0.005 Hz. The amplitudes of the superposed oscillations increase with decreasing frequency. The Fourier transform of such a source produces a similar pattern of background noise measurements in quiet areas (e.g., Aki and Richards, 1980). Coupling between the wave equation and the oscillator equation is only activated in the area of the reservoir, so that above and below the reservoir normal elastic wave propagation takes place.

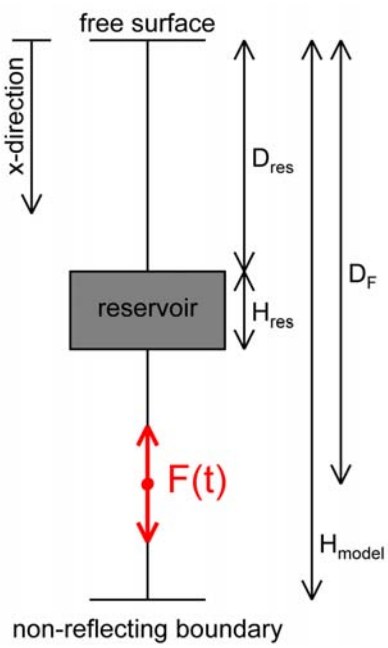

Figure 2: Model setup for all simulations. Outside the reservoir the model is linear elastic whereas in the reservoir the modified equations (3) apply and oscillations of the fluid can take place.

Numerical results

With the model described above several numerical simulations were performed. All simulations were run for 120 seconds physical time. For a model with no hydrocarbon reservoir, i.e. a purely homogeneous linear elastic model, the spectrum of the solid velocity at the surface is identical to the spectrum of the external source and is not shown here. Figure 3 and 4 both show spectra of simulations with a reservoir. In the first simulation the reservoir has the same Young's modulus than the surrounding material. In order to clearly demonstrate the phenomenology of the coupling effect a large contrast of the reservoir properties compared to the environment was chosen in the second simulation, i.e. the Young's modulus is 100 times smaller than the surrounding material.

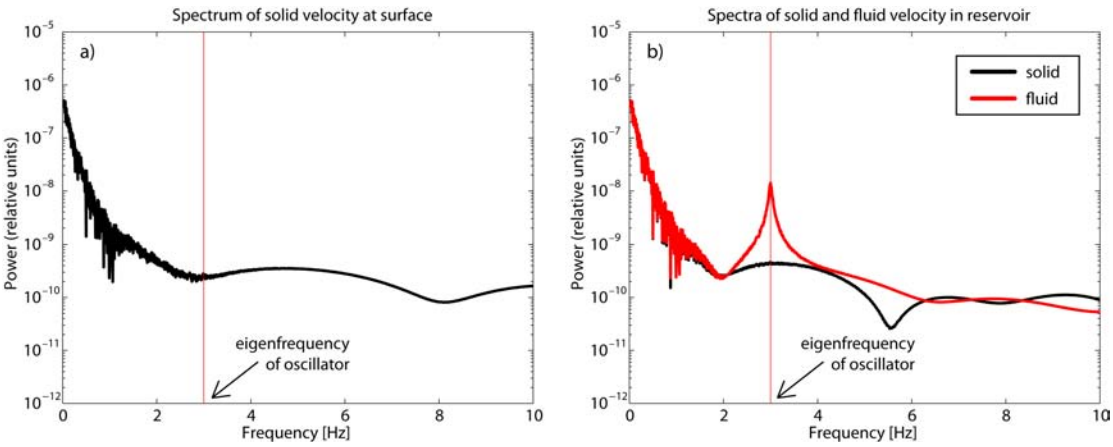

Figure 3: Spectra of solid velocity at the surface (a) and in the reservoir (black line in b) for a model with a hydrocarbon reservoir represented by an oscillating fluid. Red line in b) shows the spectrum of the fluid velocity in the reservoir. Vertical red line indicates the eigenfrequency of the linear oscillator (fluid).

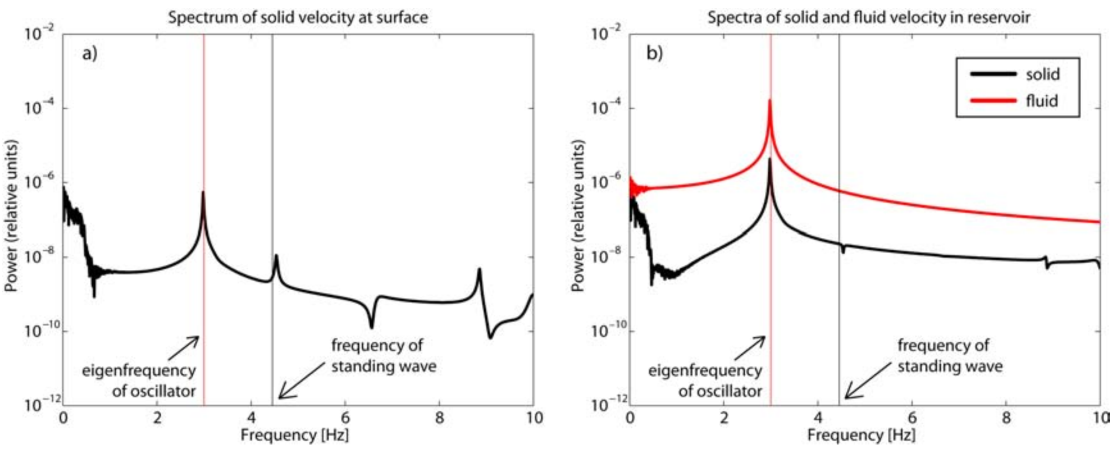

Figure 4: Spectra of solid velocity at the surface (a) and in the reservoir (black line in b) for a model with a hydrocarbon reservoir represented by an oscillating fluid and a smaller Young's modulus. Red line in b) shows the spectrum of the fluid velocity in the reservoir. Vertical red line indicates the eigenfrequency of the linear oscillator (fluid). Vertical black line indicates the standing wave resonance between surface and reservoir.

For both models the eigenfrequency of the fluid is clearly visible in the Fourier spectrum of the fluid velocity in the reservoir (red line in Figures 3b and 4b). However, the oscillation of the fluid is not transmitted to the solid in the first model (no peak at 3 Hz in Figure 3a). Using a smaller Young's modulus in the reservoir allows the oscillation to be transmitted to the solid, and therefore to the surface (peak of the black lines at 3 Hz in Figures 4). The contrast in Young's modulus also produces standing waves between the surface and the reservoir which generate a new resonance frequency (second peak in Figure 4a).

Conclusions

The spectral modifications of ambient seismic background noise above hydrocarbon bearing structures have been observed predominantly in the low frequency range around 1-10 Hz. Therefore a physical explanation for this spectral modification should have a general character which is independent of local peculiarities. The parameters that determine the eigenfrequency of the fluid oscillation around 3 Hz in our model are pore size, pore saturation, surface tension and fluid density. If these parameters do not vary orders of magnitude between different reservoirs, the same modifications around 3 Hz can be expected. The 3 Hz oscillation of the fluid only appears when the frictional coupling between the solid and the fluid is weak enough. If the coupling is too strong, the critical damping limit is reached. The fluid moves in phase with the solid and no oscillation can take place. In simulations shown above the coupling term is set to a value small enough for the fluid to develop oscillations.

Although the fluid always oscillates with its eigenfrequency (given a small coupling term) this oscillation is not always transferred to the solid. The small coupling term necessary for the oscillation to take place weakens the transfer to the solid. In this case no modification in the surface spectrum is visible. A weak elastic medium (small Young's modulus) in the reservoir is needed to enable this transfer. The impedance contrast generated by the weak elastic reservoir produces standing waves between the Earth surface and the reservoir and within the reservoir itself. These standing waves act back on the fluid oscillation and therefore amplify the transfer to the surface.

In the future we will elaborate our coupled wave-oscillator model and in particular explore further possibilities for coupling mechanisms in order to provide quantitatively realistic models which can be verified by real data.

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