Low frequency spectral modification of geoseismic background noise due to interaction with oscillating fluids entrapped in subsurface porous rocks

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Abstract

Studies of passive seismic data in the frequency range below 20Hz have shown that the frequency content of the ever-present seismic background noise changes above hydrocarbon reservoirs. Different explanations for this observation have been proposed. In this study, the effect of oscillating pore fluids, i.e. oil, on the seismic background noise is investigated. A non-wetting fluid drop entrapped in a pore can oscillate with a characteristic eigenfrequency. Capillary forces act as the restoring force driving the oscillations. A 1D wave equation is coupled with a linear oscillator equation, which represents these pore fluid oscillations. The resulting linear system of equations is solved numerically with explicit finite differences.

The most energetic part of the seismic background noise, i.e. frequencies around 0.1-0.3Hz, is used as the external source. This part is presumably related to seismic surface waves generated by ocean waves. It is shown that the resulting elastic wave initiates oscillations of the fluid drops. The oscillatory energy of the pore fluid is transferred continuously to the elastic rock matrix. In consequence, seismic waves in the elastic rock carry a second frequency, the eigenfrequency of the pore fluid oscillations on top of the applied external frequency. Both frequencies can be measured at the earth surface. The presented model is considered as a possible explanation for observed spectral modifications above hydrocarbon reservoirs. Time evolution of the pore fluid oscillations seems to be related to the thickness of the hydrocarbon reservoir.

Example of real data

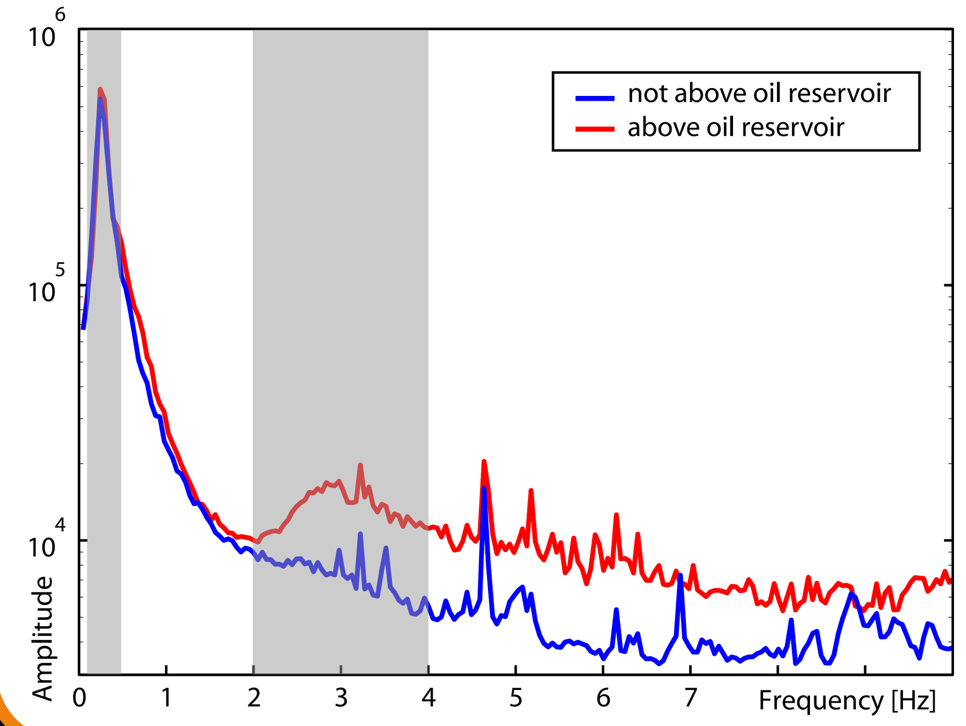

Figure 1: Spectra of passive measurements of seismic background noise above (red) and nearby (blue) a proven oil reservoir. Spectraseis survey for Petrobras, Potiguar Basin, Brazil, 2004. Frequency with highest energy (0.3Hz) is used as external source in numerical simulations.

Please help yourself

Pore fluid oscillations

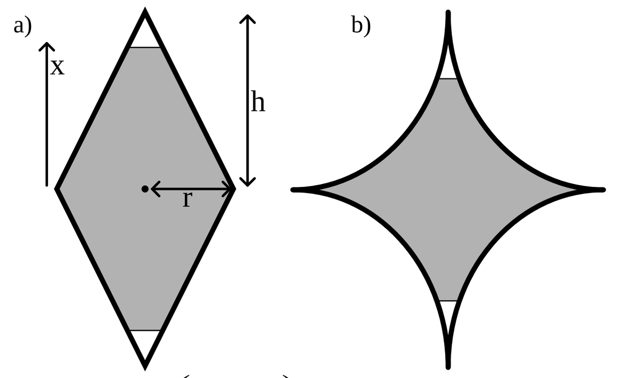

Figure 1: Two types of simplified pore geometries. Gray fluid fills the pore only partially. This way oscillations of the fluid are possible. Geometry a) results in a linear relation between displacement and resotring force, i.e. a linear oscillation. Geometry b) results in a non-linear oscillation.

$$F = 2\pi\gamma r\left(\frac{x}{h}-1\right), \quad f = \frac{\partial F}{\partial x} = 2\pi\gamma\frac{r}{h}$$

$$m \approx \frac{2}{3}\pi r^2 h\rho^f, \quad \omega_0 = \sqrt{\frac{f}{m}} = \sqrt{\frac{3\gamma}{h^2 r\rho^f}}$$

Equations 1: Surface tension force, spring constant, mass and eigenfrequency for linear pore geometry.

Coupling of pore fluid oscillations with elastic rock

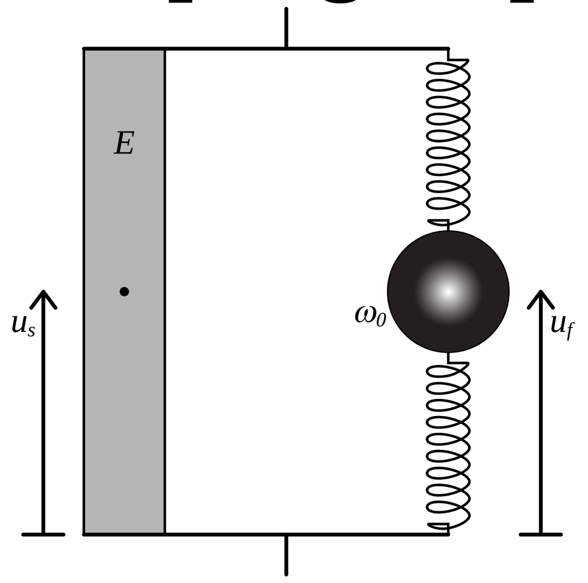

Figure 3: Schematic rheological model for the coupling between elastic deformation and pore fluid oscillations. The elastic bar with Young's modulus E is coupled with a linear oscillator of eigenfrequency ω_0. Two displacements have to be considered, one for the elastic subsystem u_s and one for the oscillatory fluid subsystem u_f.

$$S\phi\rho^f\frac{\partial^2 u^f}{\partial t^2} = -S\phi\rho^f\omega_0^2\left(u^f-u^s\right)$$

$$(1-\phi)\rho^s\frac{\partial^2 u^s}{\partial t^2} = \frac{\partial}{\partial x}\left(E\frac{\partial u^s}{\partial x}\right) + S\phi\rho^f\omega_0^2\left(u^f-u^s\right)$$

Equations 2: Coupled linear system of equations for the two unknown displacements u_s and u_f.

Numerical model setup

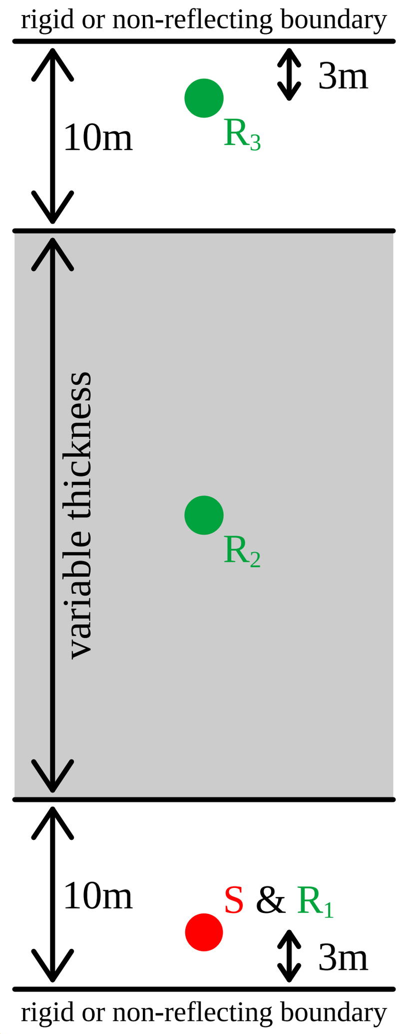

Figure 4: 1D model setup for numerical simulations consists of three receivers R_1-R_3 and one source S identical with position of receiver R_1. Shaded area (i.e. the reservoir) is described by coupled system of Equations (2), the rest is purely elastic. Lower and upper boundaries can be rigid (zero displacement) or non-reflecting.

Table 1: Parameters used in numerical simulations. Parameters not listed in this table are explained elsewhere.

Symbol	Value
h	$5 \cdot 10^{-3}$ m
r	10^{-3} m
γ	10^{-3} N m^{-1}
ω_0	18.85 (= 3Hz $\cdot 2\pi$)
ρ^f	800 kg m^{-3}
ρ^s	2800 kg m^{-3}
E	$2 \cdot 10^{10}$Pa
ϕ	0.3
S	0.9
Ω	1.89 (= 0.3Hz $\cdot 2\pi$)

Energy conservation and transfer

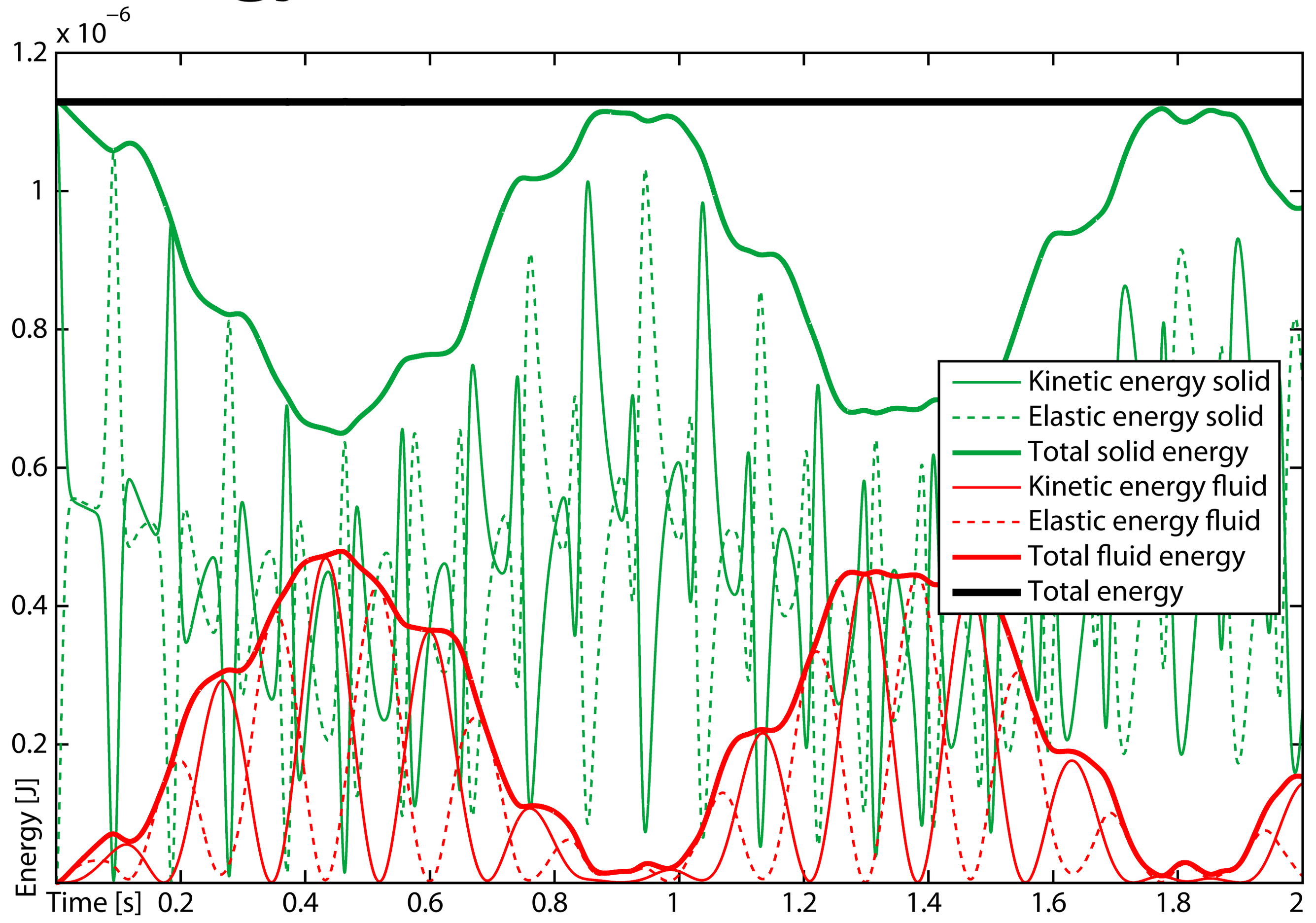

Figure 5: Time evolution of the four different energies in the system. For this simulation only the 120m thick reservoir area of the model in Figure 4 was used without the elastic layers and with two rigid boundaries. No external source was applied but a Gaussian curve for the solid velocity was used as initial condition. The total energy, i.e. the sum of all energies (thick black line) stays constant over time. The energy in the system is conserved.

Numerical spectra over time

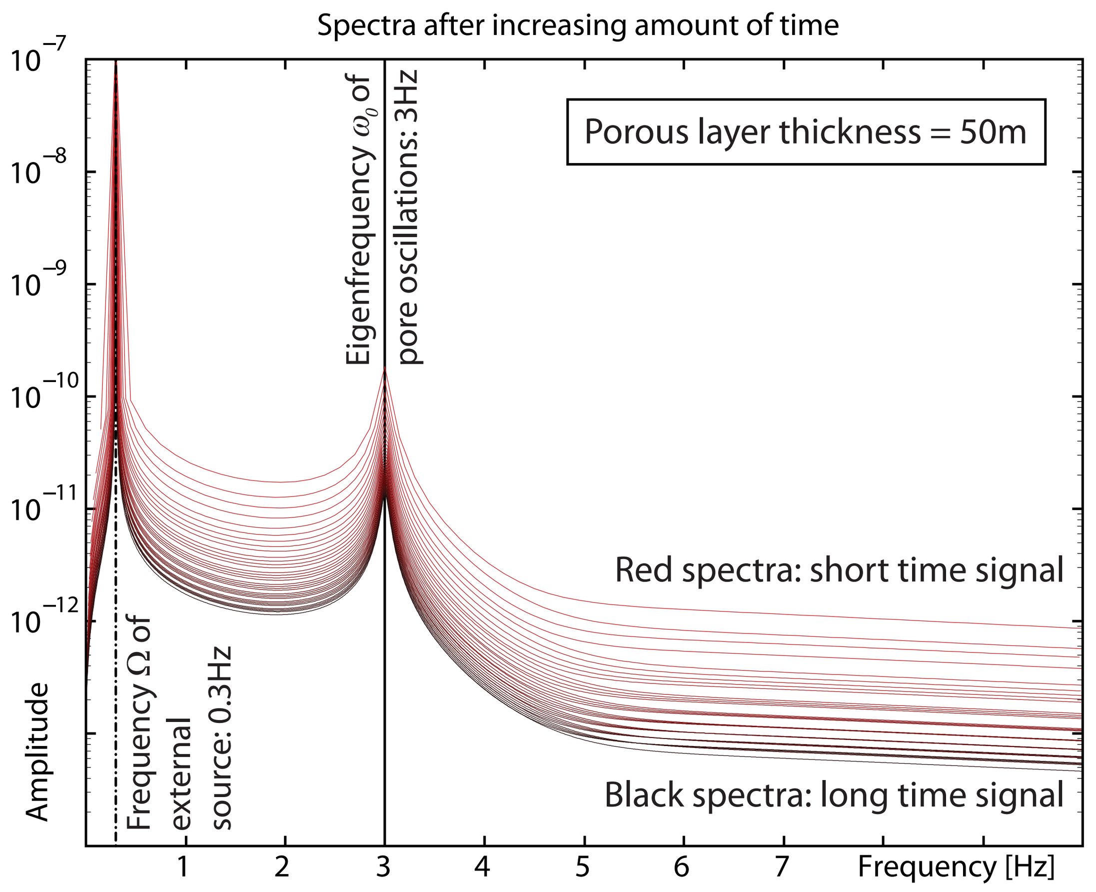

Figure 6: Spectra of solid velocity at receiver R_3 for a 50m thick porous layer. Different spectra are calculated after different simulation lengths. Longest time signal is 120s (black spectra), shortest is 3.5s (red spectra). Dash-dotted vertical line: Frequency of external force; Solid vertical line: Eigenfrequency of pore fluid oscillations.

Changing thickness of reservoir

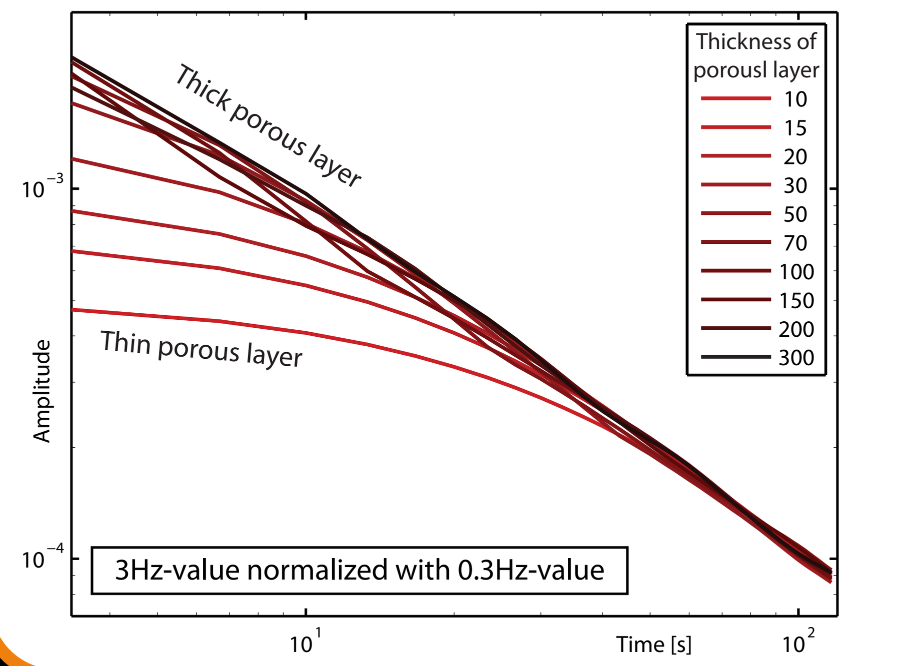

Figure 7: Time evolution of amplitude ratio between 3Hz-peak and 0.3Hz-peak in the spectra in double-logarithmic representation. Different colors represent different porous layer thicknesses. Spectra are calculated with the solid velocity time signal at receiver R_3.

Conclusions

Micro-scale pore fluid oscillations can transfer enough energy to the elastic solid rock to change the frequency content of the large-scale seismic background noise in the low frequency range.

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