Interpretation of Hydrocarbon Microtremors as Nonlinear Oscillations Driven by Oceanic Background Waves

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Summary

Hydrocarbon Microtremor Analysis (HyMAS) identifies the presence of hydrocarbon containing geological structures by analyzing low frequency seismic background wave signals. A possible interpretation of this reproducibly observable phenomenon is the excitation of hydrocarbon related resonances. Synthetic spectra produced by basic linear and non-linear one-dimensional models of an oscillating liquid filled porous medium show characteristic features of measured HyMAS spectra when oceanic background waves around 0.1-0.2Hz are assumed to be the external driving force.

Introduction

Hydrocarbon Microtremor Analysis (HyMAS) is an innovative technology identifying the hydrocarbon content of geological structures by analyzing low frequency background wave signals (see Holzner *et al*. (2005)). Hydrocarbon indicating information is extracted from spectral modifications of naturally occurring background waves in the 0.1 – 20 Hz range interacting with hydrocarbon bearing porous structures. As a direct hydrocarbon indicator, HyMAS is an ideal complement to 2D and 3D seismic structural imaging technologies. Its efficacy has been proven at more than 15 sites worldwide (see Dangel *et al*. (2001)) as well as by recent land pilots in Austria and Brazil (see Holzner *et al.* (2005) and Macedo *et al.* (2005)) from which typical HyMAS data of a weak and a strong signal indicating low and high hydrocarbon potential are shown in Figure 1.

A general approach towards an explanation of such behavior is the phenomenological interpretation as a driven linear (Figure 2) or non-linear oscillator, which has been successful in many other cases of oscillation phenomena. In order to explore the feasibility of such an approach, synthetic spectra are generated by numerical modeling and variation of model parameters. For these investigations "linear" and "non-linear" refer to the generalized spring constants of the restoring capillary forces in the liquid filled pores which enable the oscillations.

Since the specific shapes of the pores are not of major importance as long as the conditions for linear or nonlinear spring constants are satisfied, two simple poro-mechanical models often used in literature were chosen as examples (see Hilpert *et al* 2000).

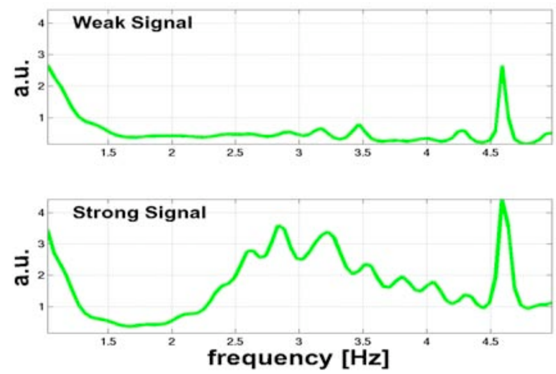

Figure 1: After suitable data processing both in the time and frequency domains the HyMAS value can be determined as the peak value of the frequency power density spectrum, in this case near 3 Hz, taken from the vertical velocity component of the measured signal. The trace on top shows a low HyMAS value, while the trace on the bottom represents a high HyMAS value in arbitrary units. The measurement locations were about 2 km apart. The peak at about 4.6 Hz is due to a nearby artificial noise source. The signal increase towards lower frequencies is due to the ever-present strong ocean wave peaks between 0.1 - 0.2 Hz, the dominant component of the background spectrum. Note that the frequency separation of the fine structure wiggles corresponds to the frequency of the oceanic wave peak which is likely to be caused by a non-linear interactions discussed below.

Linear model

A bi-conical pore geometry as shown in Figure 3 is used for the linear model, while the spherical pore shape as shown in Figure 5 represents the nonlinear case.

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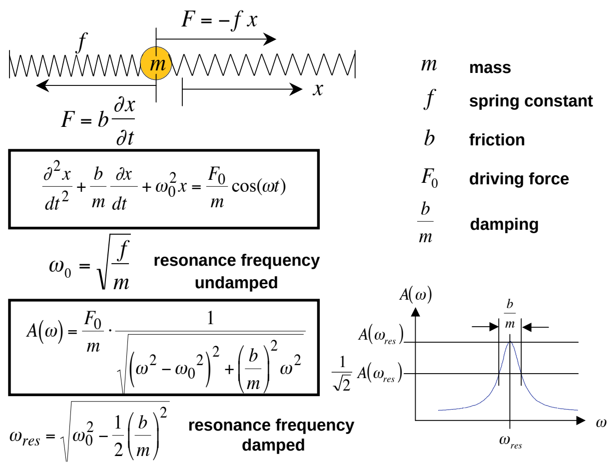

Figure 2 : General description of a one-dimensional driven oscillator along the x-direction with its second order differential equation and resonance response function.

The bi-conical pore geometry has the advantage of providing a linear spring constant for the restoring force which is independent of the dislocation of the liquid along the z direction. In equilibrium, the capillary forces which are proportional to the length of the oil/rock contact line (ORCL) balance each other. For small displacements of the liquid, the lengths of both ORCL change in such a way that the related capillary forces $F_z = F_{+z} + F_{-z}$ always add up to a restoring force which enables oscillations.

Neglecting gravity, which would mainly shift the equilibrium position, and assuming nearly filled pores, an oscillation frequency according to the one-dimensional oscillator model can be estimated. The spring constant

$$f = \frac{\partial F_z}{\partial z} = \gamma \frac{2\pi r}{h} \quad \text{and mass} \quad m = \frac{2}{3} r^2 \pi\, h\, \rho_L$$

lead to the resonance frequency

$$\nu = \frac{1}{2\pi}\sqrt{\frac{f}{m}} = \frac{1}{2\pi h}\sqrt{\frac{6\gamma}{r\,\rho_L}}$$

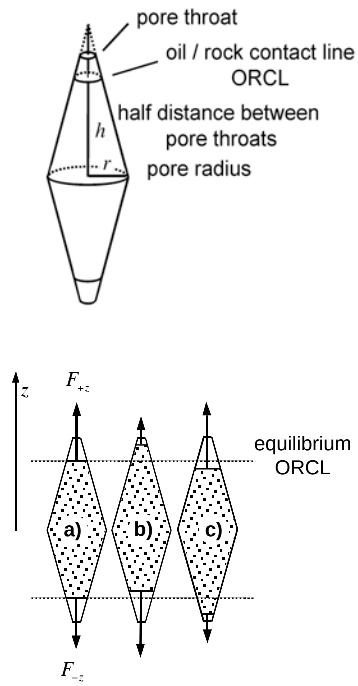

Figure 3: Schematic representation of a simple bi-conical pore geometry which enables low frequency oscillations of the contained liquid along the *z*-direction. The liquid surface boundary forms the oil/rock contact line (ORCL) between the oil and water phases as well as the water wetted pore surface where capillary forces occur. a) liquid in equilibrium: the capillary forces F_{+z} in positive and F_{-z} in negative z direction balance each other; b) Situation after a small displacement of the liquid in the positive z-direction: F_{+z} has decreased and F_{-z} has increased compared to the equilibrium. The resulting restoring force drives the liquid back along the negative *z*-direction towards its equilibrium position; c) same as b) with dislocation in the negative z-direction.

The observed value of ν = 3 Hz is compatible with realistic values of the relevant parameters given in Table 1. Also, the value for the vertical component of the ground velocity of about 10^{-6} m/s measured at the surface represents the value which can be expected from the superimposed signal of pores contained in a reservoir of 20 m thickness and 1000 m depth and a porosity of 0.2. The general shape of the measured spectrum shown in Figure 1 can be fitted when a suitable distribution of the parameters of Table 1 is introduced. Figure 4 shows, as an example, how the sharp-peaked spectrum of a single oscillator approaches the wider observed shape as a function of the width "sigma" of the assumed log-normal parameter distribution.

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surface tension of oil	$\gamma = 10^{-3}\ \frac{\mathrm{N}}{\mathrm{m}}$
density of oil	$\rho_L = 8 \cdot 10^2\ \frac{\mathrm{kg}}{\mathrm{m}^3}$
pore radius	$r = 10^{-3}\ \mathrm{m}$
half distance between pore throats	$h = 5 \cdot 10^{-3}\ \mathrm{m}$

Table 1 : Parameter values for poro-mechanical model

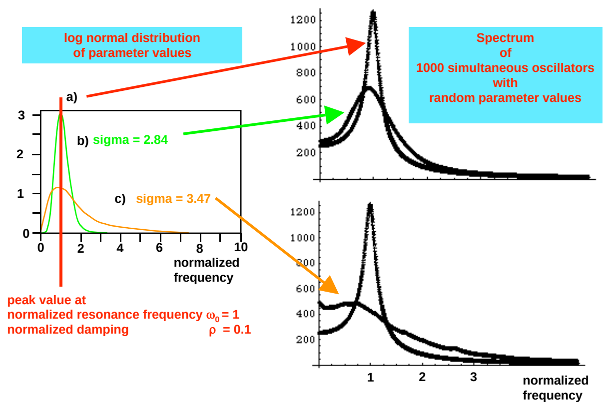

Figure 4: Numerical simulation of the superimposed spectrum of 1000 linear harmonic oscillators for three different parameter distributions: a) all oscillators with normalized resonance frequency at ω_0=1 and damping ρ=0.1 ; b) both resonance frequency and damping vary according to a log-normal distribution with sigma = 2.84; c) both resonance frequency and damping vary according to a broad log-normal distribution with sigma = 3.47.

Nonlinear model

For the explanation of the fine structure wiggles shown in Figure 1 non-linearity in the above model is introduced by allowing for a more general pore shape, e.g. spherical as shown in Figure 5. This defines a more general, non-linear spring constant in a natural way. Such nonlinearities actually provide the more common case in nature (Hilpert *et al.* (2000) and references to Oh and Shatterly (1979) and Payatakes *et al.* (1980) therein).

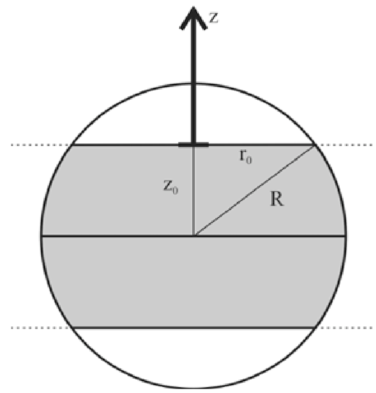

Figure 5: Schematic representation of a spherical pore geometry which enables low frequency oscillations of the contained liquid along the *z*-direction.

Similar to the bi-conical case shown in Figure 3, the liquid surface boundary forms the oil/rock contact line and the restoring capillary forces drive the liquid back along the *z*-direction towards its equilibrium position after an initial dislocation. While the bi-conical pore geometry leads to a linear spring constant for the restoring motion, the spherical pore geometry results in a nonlinear spring constant that depends on the dislocation and therefore leads to a non-linear restoring motion.

The non-linear spring constant depending on the filling level z_0 is given by

$$f = \frac{\partial}{\partial z}\left(\gamma 2\pi r(z)\right) = 2\pi\gamma \frac{\partial}{\partial z}\sqrt{r^2-(z_0+z)^2} = -\frac{2\pi\gamma(z_0+z)}{\sqrt{r^2-(z_0+z)^2}}$$

which leads to the non-linear one-dimensional differential equation

$$\frac{\partial^2 z}{\partial t^2} + \frac{b}{m}\frac{\partial z}{\partial t} + \frac{2\pi\gamma(z_0+z)z}{m\sqrt{r^2-(z_0+z)^2}} = \frac{F_0}{m}\cos(\omega t)$$

The filling-level dependent oscillation mass and frequency are

$$m = \frac{4}{3}\pi r^3 \rho_L \frac{\left(3r^2 z_0 - z_0^3\right)}{2r^3}$$

and

$$\omega_0 = \sqrt{f/m} \approx \sqrt{\frac{2\pi\gamma z_0}{m\sqrt{r^2-z_0{}^2}}}$$

The synthetic spectra obtained from the nonlinear model are displayed in Figure 6 for different filling levels. The one-peak spectrum of the linear case splits up into several peaks which are separated by the driving oscillation frequency.

The frequency of the spectrum shifts toward larger values as the filling level approaches full saturation. Note that these features need a certain transient time to build up, as is demonstrated in Figure 7.

Conclusion

In conclusion, it has been shown that the phenomenological model of a driven one-dimensional linear and nonlinear oscillator can provide a natural interpretation of characteristic spectral features empirically attributable to hydrocarbon reservoirs. Good agreement between the numerical modeling results and the observations is achieved for realistic parameter values using the dominant part of the ever present background wave spectrum, the seismic wave field around 0.1-0.2 Hz caused by oceanic waves, as the driving force for the oscillations.

References

Holzner, R., Eschle, P., Zürcher, H., Lambert, M., Graf, R., Dangel, S. and Meier, P.F., Applying microtremor analysis to identify hydrocarbon reservoirs, First Break, May 2005, vol. 23, p. 41-49.

Dangel, S. *et al.*, Phenomenology of tremor-like signals observed over hydrocarbon reservoirs, Journal of Volcanology and Geothermal Research, 2003, vol.128, p. 135-158.

Macedo I., Dittz R., Santos de Oliveira A., Holzner R. and Graf R., Observation and modeling of seismic background noise, Ninth International Congress of the Brazilian Geophysical Society, 11-14 September 2005, Salvador - Bahia, Brazil.

Hilpert, M. et al., Capillarity-induced resonance of oil blobs in capillary tubes and porous media, Geophysics, 2000, vol. 65, p. 874-883.

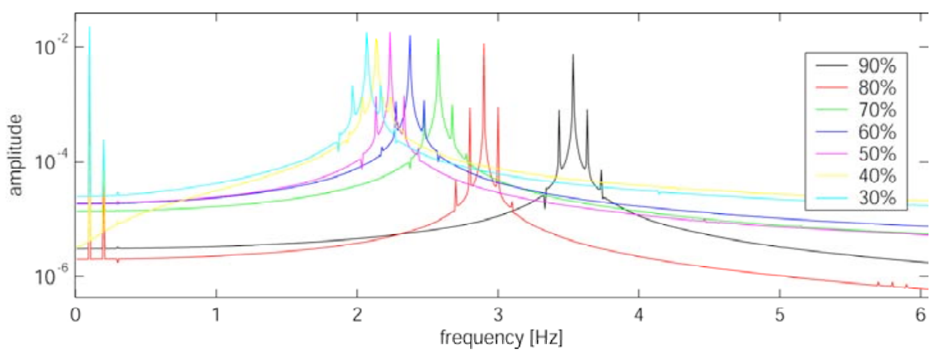

Figure 6: Spectrum of nonlinear oscillations in a spherical pore for different filling levels between 0.3 and 0.9 of the pore liquid. The frequency spacing of the multiple peaks is a typical feature of nonlinear systems and corresponds to the frequency of the driving oscillation at 0.1 Hz, which also produces its own overtone at 0.2 Hz. For demonstration reasons, the damping was set to zero which leads to sharper peaks.

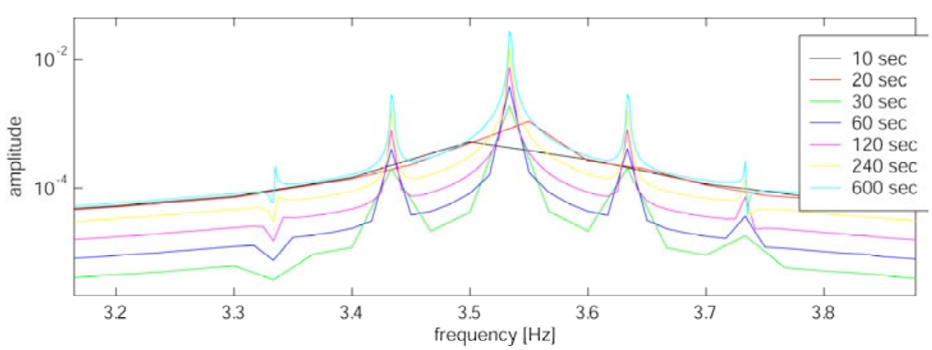

Figure 7: Development of the spectrum of nonlinear oscillations in a spherical pore during 600 s for filling level = 0.9 of the pore liquid. The frequency spacing of the multiple peaks is a typical feature of nonlinear systems and corresponds to the frequency of the driving oscillation at 0.1 Hz. Natural oscillation frequency of pore: n =3.527 Hz, mass of liquid in pore m = 2.64 ·10-5 kg.