Experimental evidence of the relation between the Biot-Gassmann modulus and the bulk modulus measured by DARS (Differential Acoustic Resonance Spectroscopy) of oil-saturated rocks

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Summary

A set of 23 oil-saturated samples were used for Differential Acoustic Resonance Spectroscopy (DARS) measurements. In these experiments the bulk modulus of a sample is determined by the change in the resonance frequency of a tube due to the introduction of the sample. DARS experiments on porous samples confirm the perturbation theory by Morse and Ingard. For sealed porous samples, good agreement between the Biot-Gassmann modulus and the DARS bulk modulus was obtained. For open-pore samples the DARS bulk modulus is governed by the relative fluid motion at the outer wall. Measurements based on more realistic in-situ conditions (pressurized samples with multi-constituent properties) should lead to revisions of the theory, and enhance the use of DARS for reservoir characterization.

Introduction

Scaling from laboratory to seismic frequencies is not trivial and there is imminent need for low-frequency laboratory data. Acoustic Resonance Spectroscopy is an established methodology that is used by the National Bureau of Standards to measure the velocity and quality factor of fluids. Harris (1996) proposed to adapt this method to measure the velocity and quality factor of sound in rocks in the sonic frequency range. Differential Acoustic Resonance Spectroscopy (DARS) is an experimental method based on the change in the acoustic resonance frequency of a fluid-filled tube due to the introduction of a foreign object in the tube. The resonance frequency of the fluid-filled tube is proportional to the ratio of the sound velocity in the surrounding medium and the length of the cylinder. For example, for liquids with velocities in the order of 1000 to 1500 m/s, the resonance frequency of a 0.5 m open-ended cylinder is 1000 - 1500 Hz.

Applications of the DARS method involve the estimation of the acoustic attenuation of porous rocks by Harris et al. (2005), the estimation of the flow properties of porous rocks by Xu et al. (2006) and Xu (2007), and the determination of the physical mechanism responsible for the measured compressibility by Vogelaar et al. (2008).
Recently, Vogelaar (2009) demonstrated that the DARS set-up provides a complementary technique to measure the sample bulk modulus at low frequencies (1 kHz).

The purpose of this paper is to show the experimental relation between the so-called Biot-Gassmann modulus and the sample bulk modulus measured by DARS. If, in addition, a theoretical framework could be established, the potential benefit to the oil industry would be profound.

Laboratory set-up

The DARS set-up discussed in this paper is at the Stanford Wave Physics Laboratory. A schematic lay-out of the equipment is shown in figure 1.

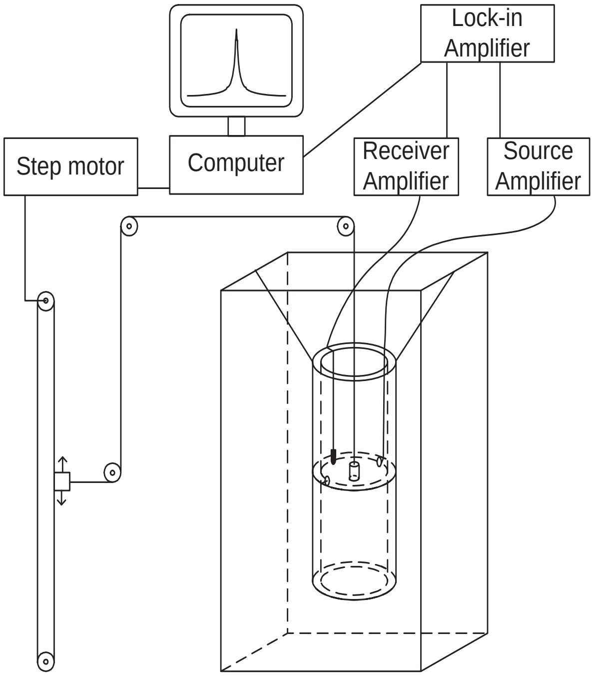

Figure 1: Schematic lay-out of the DARS set-up. The rectangular box is the oil-filled container in which a hollow cylinder is hung. The two sources are drawn as two opposite open circles in the cylinder wall, whereas the receiver is schematized as a bullet at 90◦ from the sources. The test object (small cylindrical sample) is hung on a thin nylon wire in the sources-receiver plane (the so-called pressure antinode), but can be moved vertically along the axis of the cylinder using the step motor.

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The resonator is a cylindrical open-ended Aluminum tube. Two piezoelectric ceramic frequency discs are used to excite vibrations in the oil. The sources are embedded in the wall in the middle of the tube facing each other. A small calibrated hydrophone is used to measure the pressure. The source and receiver are amplified and connected to a lock-in amplifier. The lock-in amplifier is controlled and automated by a computer. The step-motor is also controlled by the computer to provide an accurate and repeatable positioning of the sample. This system was conceived and first built by Harris (1996) and updated by Xu (2006).

Sample description

The set of investigated porous samples is the variety of 23 consolidated natural and artificial rocks. Their rock physical properties, measured with the conventional methods are given in table 1. All samples are fully saturated with 5 cSt silicone oil, which is identical to the fluid filling the container, see figure 1. For the purpose of this experiment, the pores of the tested samples are initially open, so that the pore-fluid can communicate with the surrounding fluid. The second batch of DARS measurements is on the same samples, but now with the outer surface carefully sealed by means of an epoxy resin.

Pressure perturbation

The DARS method is based on the pressure perturbation of the empty tube due to the introduction of a foreign object in the tube. The density and compressibility of the foreign object differ from the values in the surrounding medium. Morse and Ingard (1968) derived an expression for the perturbed normal mode due to the scattering of a small object within a resonator. The perturbed resonance frequency is determined by the rms pressure-amplitude distribution and the velocity-amplitude distribution over the sample. This change in frequency is related to the change in compressibility of the system, which is on its turn related to the bulk modulus of the sample. For details we refer to Vogelaar (2009) and references therein.

Experimental results porous samples

We compare the bulk modulus of the open and sealed samples obtained by the DARS technique with the conventional Biot-Gassmann modulus of the saturated rock. This latter modulus is calculated from the porosity and the bulk moduli of the grains and the saturating fluid. In addition, the bulk and shear modulus of the matrix are needed. These are calculated from the dry rock density and the dry compressional and shear wave velocites in the usual manner. The Biot-Gassmann modulus of each sample is given in the third column of table 2.

Next, we apply the DARS method on the oil-saturated samples. We first measure the resonant frequency of the empty cylinder, followed by the equidistant measurements of the sample-loaded cylinder at various positions along the cylinder's axis. The empty resonant frequency and sample-loaded resonant frequency at the middle position are used to calculate the DARS bulk modulus of the porous sample. The DARS bulk modulus for the samples with open pores and those for the sealed samples are also shown in table 2. We observe a large variety in bulk moduli.

From the table, we find that the DARS bulk modulus of the sealed samples is generally higher than the DARS bulk modulus of the samples with open pores. Obviously, sealed samples are stiffer than samples with open pores, since fluid flow is restricted in the former.

Sample ID	Density [kg/m^3]	Permeability [mD]	Porosity [%]
SSA04	2086 ± 1	362 ± 18	20.80 ± 0.01
SSB07	1847 ± 1	2748 ± 6	28.56 ± 0.01
SSC05	2317 ± 2	0.74 ± 0.04	11.75 ± 0.04
SSF02	1930 ± 1	2666 ± 26	26.78 ± 0.01
SSG01	2004 ± 1	1862 ± 12	24.29 ± 0.01
YBE03	2111 ± 5	182 ± 1	18.94 ± 0.02
VIF01	1603 ± 7	11928 ± 137	37.99 ± 0.02
VIC05	1497 ± 10	25557 ± 2783	42.86 ± 0.03
QUE09	2067 ± 7	2214 ± 4	21.89 ± 0.01
B1P13	2132 ± 4	330 ± 3	20.06 ± 0.05
CAS16	2159 ± 2	5.51 ± 0.01	18.66 ± 0.03
B1N20	2119 ± 3	205 ± 1	20.62 ± 0.01
COL23	2357 ± 4	0.77 ± 0.03	11.44 ± 0.03
BEN27	2010 ± 7	1151 ± 4	24.11 ± 0.02
B2P30	2144 ± 2	161 ± 1	19.52 ± 0.01
B2N32	2164 ± 3	92.7 ± 1.7	19.03 ± 0.02
FEL36	2039 ± 4	10.1 ± 0.1	23.02 ± 0.02
NIV44	1847 ± 1	6544 ± 132	30.18 ± 0.02
UNK50	2245 ± 2	0.09 ± 0.00	15.84 ± 0.05
NN356	2195 ± 3	1.50 ± 0.08	16.99 ± 0.04
NN458	2225 ± 1	5.76 ± 0.19	15.75 ± 0.02
GL160	1884 ± 2	17935 ± 1031	34.02 ± 0.01
GL261	1895 ± 3	18324 ± 613	35.57 ± 0.01

Table 1: Rock physical properties of the porous materials under study obtained from independent laboratory measurements: dry density, the Klinkenberg corrected permeability, and the porosity. The error is the standard deviation of the measurements.

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Biot-Gassmann versus DARS bulk modulus

In figure 2, we cross plot the Biot-Gassmann modulus with the DARS bulk modulus of the open samples. We observe that this DARS bulk modulus is generally lower than the Biot-Gassmann modulus for all samples.

Xu et al. (2006) estimated the flow properties in porous media with a model for dynamic diffusion and related the effective compressibility (measured with DARS) to permeability. He found that the permeability of the sample greatly influences the DARS-compressibility.

Sample ID	Bulk modulus open sample [GPa]	Bulk modulus sealed sample [GPa]	Biot-Gassmann modulus [GPa]
SSA04	4.1 ± 0.4	8.7 ± 1.6	9.6 ± 0.5
SSB07	3.0 ± 0.2	14.3 ± 4.0	15.3 ± 0.7
SSC05	10.2 ± 2.2	17.6 ± 5.8	16.5 ± 0.8
SSF02	2.9 ± 0.2	6.9 ± 1.0	7.9 ± 0.4
SSG01	3.3 ± 0.2	10.1 ± 2.1	9.5 ± 0.5
YBE03	5.6 ± 0.7	11.0 ± 2.5	11.1 ± 0.5
VIF01	2.3 ± 0.1	6.0 ± 0.8	5.2 ± 0.2
VIC05	1.9 ± 0.1	3.7 ± 0.3	3.4 ± 0.2
QUE09	3.3 ± 0.2	10.3 ± 2.2	10.1 ± 0.5
B1P13	5.5 ± 0.6	9.8 ± 2.0	12.3 ± 0.6
CAS16	9.3 ± 1.8	9.1 ± 1.8	8.8 ± 0.4
B1N20	4.3 ± 0.4	8.2 ± 1.4	9.9 ± 0.5
COL23	9.1 ± 1.8	13.0 ± 3.4	14.8 ± 0.7
BEN27	3.4 ± 0.2	13.6 ± 3.7	12.7 ± 0.6
B2P30	5.5 ± 0.7	9.7 ± 2.0	12.8 ± 0.6
B2N32	6.2 ± 0.8	11.5 ± 2.7	12.3 ± 0.6
FEL36	6.4 ± 0.9	9.2 ± 1.8	12.1 ± 0.6
NIV44	3.2 ± 0.2	12.1 ± 3.0	7.9 ± 0.4
UNK50	8.5 ± 1.5	14.1 ± 3.9	15.9 ± 0.8
NN356	9.3 ± 1.8	12.9 ± 3.3	13.9 ± 0.7
NN458	13.6 ± 3.7	18.3 ± 6.2	20.0 ± 1.0
GL160	2.5 ± 0.1	5.0 ± 0.5	8.8 ± 0.4
GL261	2.5 ± 0.1	5.6 ± 0.7	10.0 ± 0.5

Table 2: Bulk moduli of the fully oil-saturated samples. The bulk moduli of the open and sealed samples are determined using the DARS method with a different sample surface condition. Their error reflects the uncertainty in the system. The Biot-Gassmann modulus is calculated from independent laboratory measurements.

To further investigate this claim, we cross plot the Biot-Gassmann modulus with the DARS bulk modulus of the sealed samples. The results are shown in figure 3. We observe a good agreement between the DARS bulk modulus of the sealed samples and the Biot-Gassmann modulus. Apparently, the bulk modulus measured with DARS is dependent on whether or not the pore fluid is allowed to communicate with the surrounding fluid. The mechanism responsible for the bulk modulus measured with the DARS set-up is a combination of the bulk modulus of the saturated frame and fluid flow.

Future work on DARS should concentrate on investigating the theoretical relation between the DARS bulk modulus of open samples and relative fluid flow.

Conclusions

Differential Acoustic Resonance Spectroscopy (DARS) experiments on porous samples confirm the perturbation theory. DARS can thus be used successfully to determine the bulk modulus of those samples at tube resonance frequencies (around 1 kHz). If the sample is sealed at the outer surface, the closed-pore boundary conditions apply, and the Biot-Gassmann modulus of the sample is measured. The bulk modulus of porous samples with open outer pores is determined by the relative fluid motion at the sample's outer wall. This leaves open the question whether DARS can be used for estimating reservoir properties, such as permeability and gas volume content.

Acknowledgements

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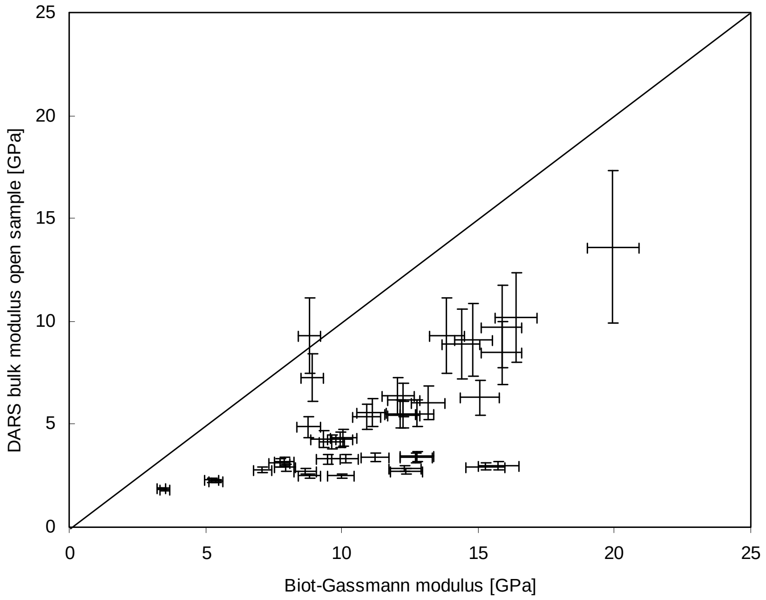

Figure 2: Cross-plot of the Biot-Gassmann modulus and the bulk modulus of the porous samples with open pores obtained by the DARS method.

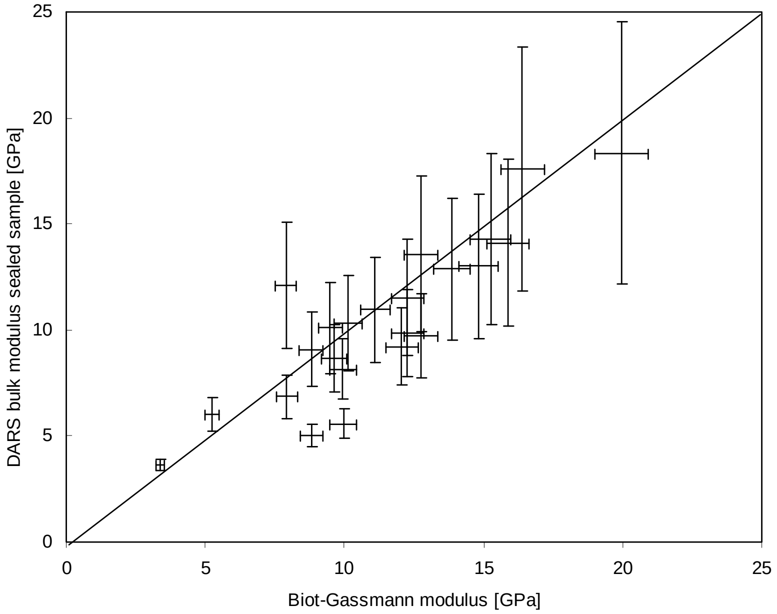

Figure 3: Cross-plot of the Biot-Gassmann modulus and the bulk modulus of the sealed porous samples obtained by the DARS method.

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