Velocity dispersion in sandstone under partially saturated conditions

Introduction

Seismic Rock Physics is an interdisciplinary study as a “bridge” linking seismic data (attribute parameters) to oil reservoir property (elastic parameters). At present, the ultrasonic transmission method is the mostly used laboratory measurement technique to determine the acoustic properties of fluid-saturated reservoir rocks, and further dispersion studies are implemented via the ultrasonic method-based measurements. However, the frequency of seismic data is less than 100Hz, which is obviously different from the laboratory ultrasonic band, and the seismic response characteristics of the reservoir rock under different frequencies also show different characteristics. Many theories have been developed to predict and interpret the seismic wave dispersion in fluid-saturated reservoir rocks. These theoretical models play important roles in understanding the dispersion mechanism on seismic wave propagation, however, still remain unconstrained by experimental data due to the scarcity of laboratory measurements, especially at low seismic frequency range.

To obtain the direct laboratory-scale dispersion measurements, we laboratory have developed systematic measurement techniques to investigate the elastic properties of rock, which cover frequency bands from seismic frequency range to ultrasonic range (also known as the multi-band measurement techniques system). This system contains stress-strain measurement method and traditional ultrasonic method. In order to ensure the accuracy of the experimental data, we have done a great deal of tests on known material and made great progress. It can be seen that the multi-band measurement techniques system is able to provide reliable experimental data. Then, we conducted experiments on two conventional sandstones to investigate the influence of different fluids on the seismic wave dispersion.

Apparatus introduction and Sample description

1. Multi-band measurement techniques. The system provides great potential to clarify the features of wave dispersion and attenuation in the reservoir rocks from seismic to ultrasonic frequency range, especially due to the presence of fluid. There are two kinds of experimental methods: ultrasonic pulse transmission method and stress-strain method. High frequency measurement is based on ultrasonic pulse transmission method, through P&S ultrasonic transducers at both ends of the sample to obtain propagation time. Low frequency measurement is based on stress-strain method, namely recording the forced deformation exerted on rock samples through extensional and axial resistive strain gauges, and then combining the strain on the reference Aluminum standard, the elastic modulus will be obtained (see Fig.1(a)). Typical signals are of very good quality as shown in Fig.1(b). Technical details concerning the low-frequency system can be found in their previous work (Batzle et al., 2006).

![Figure 1](image)

**Figure 1** A stress-strain measurements-based forced deformation system. (a) Schematic of the low frequency forced deformation system, and an improved assembly of combining resistive strain gauges.
for monitoring the extensional and axial deformation and built-in pulse transmission transducer stack; (b) Typical responses of extensional and axial strain gauges on a test sample and aluminum standard.

2. Sample description. The samples we used are two conventional sandstones from the same drill-core with the depths at 2970.55m below sea level. The well is located in Jidong oilfield, the north area of the Bohai sea bay, China. The two samples obtained from the same drill-core have very similar mineral components and physical properties, as shown in Figure 2, Table 1. Thus, in the experiment, one sample is used for saturated water, and the other is used for saturated glycerin. The result of comparison on dispersion analysis is entirely caused by different fluids. The available samples comprise these two sandstones with varying porosity (20.54%-21.17%), permeability (115.876-116.267mD), and grain density (2.064-2.084g/cm3), as shown in Table 1. The samples are cylindrical, 38.2mm in diameter and 60.3 to 61.8mm in length. Table 1 summarizes the physical characteristics for two samples. Porosity and permeability are measured using standard helium porosimetry and air permeability equipment at atmospheric pressure. Fig.3 shows thin sections of these conventional sandstones. The cores have experienced a series of digenesis, such as mechanical compaction, pressure solution, cementation, and dissolution. The samples S1 and S2 have dolomite, dolomitization is evident from high porosity and high permeability because dissolved grains or fossils become pore space, increasing the connectivity between pores, thus increasing permeability. The mineral compositions retrieved from X-ray diffraction analysis are summarized in Table 1.

![Figure 2 The sandstone samples](image1)

![Figure 3 Thin sections for our sandstone samples.](image2)

**Table 1** Physical properties and petrological data for the sandstone set of the sandstone samples. Mineralogy was obtained from XRD analysis and are reported in percent per volume.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
<th>Grain density (g cm⁻³)</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>38.2</td>
<td>61.8</td>
<td>2.084</td>
<td>20.54</td>
<td>116.267</td>
<td>2970.55</td>
</tr>
<tr>
<td>S₂</td>
<td>38.2</td>
<td>60.3</td>
<td>2.064</td>
<td>21.17</td>
<td>115.876</td>
<td>2970.55</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay mineral (%)</td>
<td>Quartz (%)</td>
<td>K-feldspar (%)</td>
<td>Plagioclase (%)</td>
<td>Dolomite (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S₁</td>
<td>5.8</td>
<td>33.8</td>
<td>8.3</td>
<td>41.4</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>S₂</td>
<td>5.9</td>
<td>33.5</td>
<td>8.1</td>
<td>41.7</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>Humidity (%)</td>
<td>Injected fluid</td>
<td>Viscosity (cP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S₁</td>
<td>23</td>
<td>65</td>
<td>water</td>
<td>1.0087</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S₂</td>
<td>23</td>
<td>65</td>
<td>glycerin</td>
<td>1410</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tests with sandstones

We divided the two samples into two groups, one sample was used for water-saturated experiment, and the other sample was used for glycerin-saturated experiment (Table 1). Two samples are all measured at low (seismic: 2–2000Hz) and ultrasonic frequencies (1MHz), however, the fluid injected
into the samples is different. Saturation is determined by the pore volume and the volume of injected fluid. The pore volume can be obtained by the sample volume and porosity, moreover, the volume of injected fluid is accurately controlled by a Teledyne ISCO pump. All testing procedures were carried out at room temperature (23 ± 2°C) and humidity (65 ± 2% r.h).

1. Tests under water-saturated conditions. The first test was on S1. We measured and compared the elastic modulus under different water-saturated conditions. The measurement results are shown in Fig.4. During the experiment, our sample can be seen as a two-phase (gas/water system) medium. On the basis of Gassmann equation, the effective modulus of the pore fluid is determined by the minimum fluid component, namely, the effective modulus of the pore fluid is approximately equal to the modulus of the gas. Only when the saturation is very high, the effective modulus of the pore fluid is equal to the modulus of the fluid. However, the bulk density of the rock keep growing with the increase of saturation, and the result is that the compressional wave velocity significantly decreases until reaching high saturation, then \( V_P \) will suddenly increase caused by the effective modulus of pore fluid burst (Fig.4). Fig.4 also shows that the variation of velocity with saturation in low frequency (2-2000Hz) is not consistent with the result of ultrasonic (1MHz). \( V_P \) measured at ultrasonic frequency increase with saturation increased. This implies that more than one rock-fluid mechanism works. When the frequency of the loaded pulse wave is higher, the increment of pore pressure induced by pulse wave can’t reach the equilibrium, and pore pressure is in the non-relaxation state, so as to harden the rock skeleton. This explains that \( V_P \) measured at ultrasonic frequency is higher compared with the value measured in the low frequency.

![Figure 4](image)

**Figure 4** Elastic parameters and velocity of S1 as a function of frequency at different water-saturated conditions by injection. Measured \( V_P \) and estimates of the velocities using Gassmann’s equation

2. Tests under glycerin-saturated conditions. After that, the second test was on S2. The experimental procedure is the same, yet the only difference lies in the choice of injected fluid. That is to say, S1 is selected for Water injection, and S2 is selected for glycerin injection. Measured \( V_P \) under different frequency bands as a function of glycerin saturation are shown in Fig.5. It shows that the regularity of compressional wave velocity with saturation is not consistent with the test results of S1. Classically, the viscosity of glycerin is far higher than that of water, so the fluid mobility of the S2 is lower than that of the S1 (according to Table 1). We found dispersion is strong and well within the seismic band at relatively lower fluid mobility. This means that S1 fall in the low-frequency regime, and the velocity dispersion curves of S2 shift to the low frequency by comparing with S1. In other words, lowering mobility increases the relaxation time needed for fluid equilibration, thus lowering the dispersion frequency.
Figure 5 Measured $V_p$ and estimates of the velocities using Gassmann’s equation in $S_2$ as a function of frequency with glycerin saturation. At about 30 Hz position, variation regulation of velocity with saturation is transforming in the unsaturated state.

Conclusions

We present data over a broad frequency band to investigate velocity dispersion under different saturation. These measurements demonstrate that dispersion can be significant and is strongly influenced by fluid mobility. We observe that the dispersion curve shows a systematic shift to lower frequencies with decreasing fluid mobility (increasing viscosities). Lowering fluid mobility increases the relaxation time needed for fluid equilibration, thus lowering the dispersion frequency. Generally, permeability of rock and viscosity of fluid can span several orders of magnitude; mobility also can vary by numerous orders of magnitude. In this paper, the sandstones have higher porosity and thus high permeability, so these rocks should fall in the low-frequency regime. This provides a great opportunity for us to observe the dispersion curve shift to low frequency. In contrast, most sedimentary rocks (shales, siltstones, tight sandstones and carbonates etc.), having low mobility can only fall in the high-frequency regime, even in typical seismic exploration frequencies.

Acknowledgments

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References

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