差分共振声谱法测量岩石声学参数方法研究

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摘 要 给出了一种测量岩石声学属性的新方法——差分共振声谱法。该方法的原理是通过测量待测岩石样本对共振腔共振频率的扰动来计算待测岩石样本的声学参数。首先详细介绍了差分共振声谱法的基本理论,然后用COMSOL有限元模拟软件对18个已知参数的岩石样本的共振进行了正演模拟,进而用模拟结果进行反演计算,得到了比较好的结果。

关键词 差分共振声谱 共振频率 有限元 体积模量
中图法分类号 P631.54; **文献标志码** A

The interpretation of the acoustic properties of rock from acoustic responses at field-seismic frequencies has been discussed for decades. For conventional travel time measurements, because of the size of the sample , the frequency is constrained to be in the ultrasonic range. For field sonic logs, the frequency is much lower than ultrasonic, in the kilohertz range. This disparity between routine acoustic and seismic measurement techniques makes it difficult to couple and interpret information at different frequencies. The goal of the Differential Acoustic Resonance Spectroscopy (DARS) is to measure the acoustic properties of rock in kilohertz range.

The bulk modulus describes the resistance of the sample to volume change under applied hydrostatic stress. In rock mechanics, the standard way to estimate the bulk modulus of a rock sample is to measure the density and the ultrasonic p-and s-wave velocities of the sample and then calculate the bulk modulus :

$$K=\rho\left(V_P^2-\frac{4}{3}V_S^2\right) \tag{1}$$

Where K is the bulk modulus, ρ is density, V_P and V_S are the p-and s-wave velocities of the material, respectively. This method is widely used for nonporous and dry porous materials. However, for fluid-saturated porous samples, the velocity measurement results are influenced by the effect of pore fluid inertia at high frequencies. The high-frequency effects of pore fluid on the bulk module of porous materials has been studied for decades, especially as it relates to the attenuation of seismic waves in fluid-saturated porous media. Biot (1956a, b; 1962a, b) established a model to describe the solid-fluid interaction in a porous medium during wave propagation[1—4]. Research on Biot theory demonstrated that his prediction overestimated the bulk modulus and underestimated the measured attenuation at low-frequencies. Mavko and Nur (1975, 1979) proposed a microscopic mechanism, due to microcracks in the grains and/or broken grain contacts[5,6]. When a seismic wave propagates in a rock having a grain-scale broken structure, the fluid builds up a larger pressure in the cracks than in the main pore space, resulting in a flow from the cracks to the pores, which Mavko and Nur (1975) called "squirt flow." Therefore, the passing wave results in pore pressure heterogeneity in the porous medium, and the pore fluid is driven to flow at pore-scale distances to release the locally elevated pressure. A model to describe this

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mechanism, which can be applied to liquid-saturated rocks, was provided by Dvorkin *et al* (1995)[7]. The squirt-flow mechanism seems capable of explaining much of the measured attenuation in the laboratory at ultrasound frequencies. Pride, Berryman and Harris (2004) pointed out, however, that it does not adequately explain wave behavior in the seismic frequency range. The inertial effect of the pore fluid on the high frequency measurements, *e. g.*, time of signal flight, of porous media limits their application in field seismic data interpretation. To evaluate the physical properties, *e. g.*, the compressibility or bulk modulus, of earth materials at frequencies close to field seismic, Harris (1996) proposed a Differential Acoustic Resonance Spectroscopy approach [8,9].

The resonance frequency of a cavity is dependent on the velocity of sound in the contained fluid. In the DARS experiment, we first measure the resonance frequency of the fluid-filled cavity. Then, we introduce a small sample, *i. e.*, rock, into the cavity and measure the change in frequency. Fig. 1 illustrates an example of the cavity responses with and without the tested sample. Through a combination of calibration and modeling, we determine the compressibility of the sample from the frequency shift.

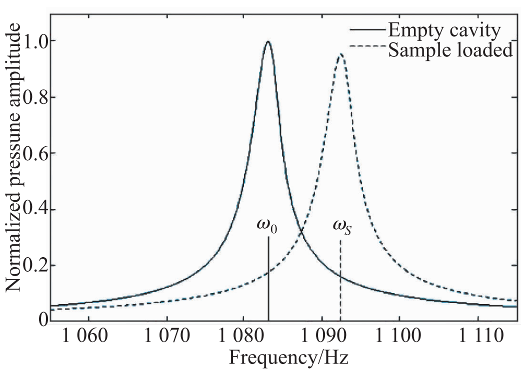

Fig. 1 DARS responses with and without a tested sample. Parameters ω_0 and ω_S are the resonance frequencies of the empty and sample loaded cavity

1 Theory and derivation

The introduction of the sample perturbs the resonance properties of the otherwise empty cavity. Under the influence of the perturbation, the empty pressure p_1 in the fluid changes top_2, and the resonant frequency shifts from ω_1 to ω_2. We use the acoustic wave equation to estimate first-order changes in resonance frequency as follows:

$$-\kappa_1\omega_1^2 p_1 = \nabla \cdot \left(\frac{1}{\rho_1}\nabla p_1\right) \tag{2}$$

$$-\kappa_2\omega_2^2 p_2 = \nabla \cdot \left(\frac{1}{\rho_2}\nabla p_2\right) \tag{3}$$

Where $\kappa_i = 1/(\rho_i c_i^2)$ are the compressibility parameters. The differential Eq. 2 and Eq. 3 can be solved with the boundary conditions of $\nabla p = 0$ at the boundaries of the cavity and $p = 0$ at the open ends of the cavity. Multiplying Eq. 2 by p_2 and Eq. 3 by p_1, and integration over the cavity volume (V_C), we have

$$-\int_{V_C}\kappa_1\omega_1^2 p_1 p_2 \mathrm{d}V = \int_{V_C}\nabla \cdot \left(\frac{1}{\rho_1}\nabla p_1\right)p_2 \mathrm{d}V \tag{4}$$

$$-\int_{V_C}\kappa_2\omega_2^2 p_1 p_2 \mathrm{d}V = \int_{V_C}\nabla \cdot \left(\frac{1}{\rho_2}\nabla p_2\right)p_1 \mathrm{d}V \tag{5}$$

With further manipulation of eq. 4and eq. 5 and application of boundary conditions ,we get

$$\omega_2^2 - \omega_1^2 = -\omega_2^2\frac{\kappa_2 - \kappa_1}{\kappa_1}V_S A - \omega_1^2\frac{\rho_2 - \rho_1}{\rho_2}V_S B \tag{6}$$

where

$$A = \frac{1}{V_S}\frac{\int_{V_S}p_1 p_2 \mathrm{d}V}{\int_{V_C}p_1 p_2 \mathrm{d}V};$$

$$B = \frac{1}{V_S\rho_1\kappa_1\omega_1^2}\frac{\int_{V_S}\nabla p_1 \nabla p_2 \mathrm{d}V}{\int_{V_C}p_1 p_2 \mathrm{d}V}。$$

If the sample is placed at a pressure antinodes, where $\nabla p = 0$,then the calibration constant B in eq. 6 vanishes. At this location, we can write eq. 6 as

$$\delta\omega = [\kappa_2/\kappa_1 - 1]V_S A' \tag{7}$$

Where and $A' = -A/2, \delta\omega = (\omega_2 - \omega_1)/\omega_1$. As mentioned above, we can use a standard sample to find coefficient A'. Therefore, the compressibility of an unknown sample can be quantified by the perturbation it causes to the DARS cavity.

2 Finite element simulation of DARS

To better under the DARS theory, numerical modeling on DARS is desirable. This article carries out a comprehensive simulation study using the finite element method. Commercial software COMSOL is used in this simulation.

The key component is the cylindrical cavity, which is immersed in a tank filled with fluid. We use a three-dimensional cavity to simulate the cavity, so that we can have highest numerical accuracy and find out key physics features of the DARS technique. In the modelling, we assume that the wall of the cavity is rigid and reprensent the cavity's open-ends using the free boundary condition(pressure equals to zero).

Fig. 2 shows the DARS model used in our simulation. The rock sample's diameter and length are 0.056 m and 0.05 m. The sample is placed at the center of the cavity. The fluid being used in the current system is Dow 200 silicone oil whose nominal acoustic velocity and density are 986 m/sec and 918 kg/m^3, respectively.

This DARS simulation is an Eigen-frequency problem. For the empty cavity (the acoustic property of the sample is the same as the surrounding fluid), the resonance frequency of the first mode is 1 140.394 Hz. We then introduce a sample and investigate how the resonance frequency chances as the sample property changes. When the sample is placed at the center of the resonator, the acoustic pressure dominates, and the sample's smaller compressibility increases the frequency compared to that of the resonator without the sample. Table 1 lists the sample parameters and simulated data.

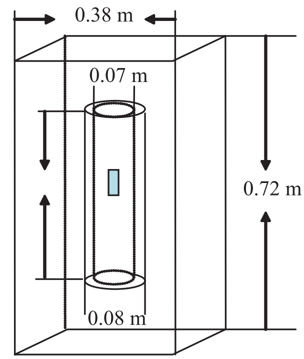

Fig. 2 Three-dimensional DARS model used in the finite element simulation

The simulated data in table 1 are used for calculating the compressibility of the rock samples. Then we compared the DARS-estimated compressibility of the 18 samples with those given compressibility. The results are shown in fig. 3.

Table 1 Sample parameters and resonance frequencies at certain decimated data points.

No.	Sound speed/ ($m \cdot s^{-1}$)	Density/ ($kg \cdot m^{-3}$)	Frequency/Hz
1	960	960	1 141.541
2	980	1 000	1 143.025
3	1 000	1 040	1 144.358
4	1 040	1 080	1 146.13
5	1 080	1 120	1 147.656
6	1 200	1 180	1 150.656
7	1 400	1 250	1 153.731
8	1 600	1 350	1 155.76
9	1 800	1 450	1 157.068
10	2 000	1 540	1 157.932
11	2 400	1 600	1 158.858
12	2 800	1 800	1 159.493
13	3 000	1 900	1 159.701
14	3 500	2 000	1 160.00
15	4 000	2 100	1 160.186
16	5 000	2 300	1 160.389
17	6 000	2 500	1 160.488
18	7 000	2 700	1 160.541

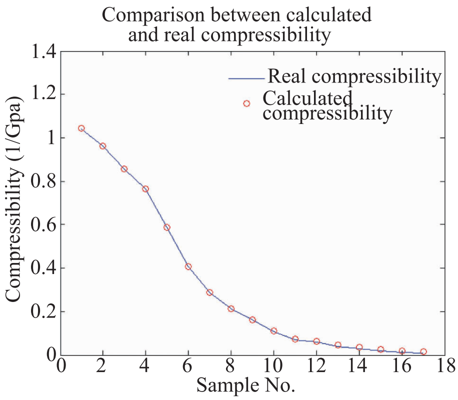

Fig. 3 The calculated compressibility and real compressibility

The horizontal axis is the number of the sample and the vertical axis is compressibility. The calculated compressibility agrees with the given compressibility very well. These results strongly indicate that the DARS can be used to measure the physic properties of rock.

3 Conclusions

This methodology for nondestructive measurement allows for rapid, accurate measurement of the compressibility of small samples, based on this newly developed DARS system. By analyzing the difference between fundamental modes with and without a sample, we can characterize the acoustic properties of the sample. Rock samples were measured using DARS at the frequency near 1 kHz that is close to the high-resolution field seismic frequency scope. The simulated results from eighteen samples validated the perturbation theory.

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Acoustic Measurement of a Rock Sample Using Differential Acoustic Resonance Spectroscopy

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[**Abstract**] A new acoustic method of estimating property in rocks is presented. This method, called Differential Acoustic Resonance Spectroscopy or DARS, was based on measureing the changes in resonces of a cavity that is perturbed by the introduction of the sample. The change in the resonant frequency was used to characterize the velocity and acoustic properties of the rock sample. The numerical Differential Acoustic Resonance Spectroscopy simulation using the finite element (FE) method in COMSOL is developed.

[**Key words**] Differential Acoustic Resonance Spectroscopy resonance frequency finite element method bulk modulus