Ultrasonics 56 (2015) 294–302

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Laboratory measurement of elastic anisotropy on spherical rock samples by longitudinal and transverse sounding under confining pressure

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ARTICLE INFO

Article history:
Received 16 April 2014
Received in revised form 10 August 2014
Accepted 12 August 2014
Available online 27 August 2014

Keywords:
Elastic anisotropy
Hydrostatic pressure
Ultrasonic sounding
High pressure
Longitudinal and shear waves

ABSTRACT

Knowledge of shear wave velocities in loaded rocks is important in describing elastic anisotropy. A new high-pressure measuring head was designed and constructed for longitudinal and traversal ultrasonic sounding of spherical rock samples in 132 independent directions under hydrostatic pressure up to 60 MPa. The velocity is measured using a pair of P-wave sensors and two pairs of S-wave sensors (T_V/R_V and T_H/R_H) with perpendicular polarization. An isotropic glass sphere was used to calibrate the experimental setup. A fine-grained anisotropic quartzite sample was examined using the P- and S-wave ultrasonic sounding. Waveforms are recorded by pairs of T_P/R_P, T_V/R_V and T_H/R_H transducers in a range of confining pressure between 0.1 and 60 MPa. The recorded data showed a shear wave splitting in three basic structural directions of the sample. The measurements proved to be useful in investigating oriented micro-cracks, lattice (LPO) and shape-preferred orientation (SPO) for the bulk elastic anisotropy of anisotropic rocks subjected to hydrostatic pressure.

1. Introduction

Laboratory research into rock samples is focused on understanding the influence of lithology, porosity, confining pressure, anisotropy and degree of fracturing on P- and S-wave velocities.

The anisotropy of rocks may be caused by: (1) lattice (or crystallographic) preferred orientation (LPO), (2) preferred morphological or shape-preferred orientation of inclusions (SPO) [1,2], (3) preferred orientation of micro-cracks/pores, (4) thin layers of isotropic materials with different elastic properties [3], or (5) the combination of the above mentioned parameters. The anisotropy of mechanical properties also depends on the stress level and on the system of acting forces – uniaxial force, confining pressure, etc. [4,5], several methods can be used to study elastic anisotropy experimentally: ultrasonic sounding [1,6], the neutron diffraction method [7], or modal analysis of rock samples which enables calculation of the longitudinal V_P and shear V_S wave velocities of anisotropic rocks based upon experimentally established grain orientation distribution functions [8]. Traditionally, anisotropy of rocks under atmospheric and high pressures has been investigated by means of P-wave ultrasonic sounding in three mutually perpendicular directions on samples in the form of a cube or prism [1,9], or by P- and S-wave sounding [10,11]. Very often, polyhedron-type samples such as octadecahedrons, tetratrioctahedrals [12–14] and/or cubes with beveled edges [15,16] are used. Cylindrical samples are mostly used to determine elastic anisotropy [17–20] and other quantities as well.

The study of the velocity anisotropy of V_P on spherical samples provides more complete information of the velocities in any direction both under atmospheric and high hydrostatic pressures [21–28].

Elastic velocities for many crustal rocks have been determined by ultrasonic experiments using high-pressure apparatus [29–31]. These experimental studies have provided compression and shear wave velocity data to assess the petrological characteristics of the lower parts of the continental crust.

Simultaneous V_P and V_S measurements have been conducted in recent ultrasonic experiments on crustal rocks [32–34]. Elastic moduli of solids have been also calculated by means of resonant ultrasound spectroscopic techniques [35–37]. Nevertheless, such a study requires samples without porosity or fluids.

The purpose of this paper is to describe a new high-pressure system for the laboratory study of rocks by P- and S-wave ultrasonic sounding of spherical samples under confining stress up to 60 MPa.

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http://dx.doi.org/10.1016/j.ultras.2014.08.015
0041-624X/

2. Technical solution

So far, the directional dependence of velocity anisotropy in spherical samples under hydrostatic pressure of 0.1 MPa up to 400 MPa has been studied only by using P-wave velocity sounding, as described in [24].

This paper deals with a significant improvement of this system, which enables measurements also by using two pairs of perpendicularly oriented shear wave transducers. Measurements can presently be made in 132 independent directions under hydrostatic pressure up to 60 MPa.

The mechanical design of the measuring system enables movement of the spherical sample and the transducers by two-step motors. All moving mechanical parts are located inside the pressure vessel. A schematic drawing of the new transducer measuring arrangement is shown in Fig. 1A. Three pairs of transducers (T_P/R_P, T_H/R_H and T_V/R_V) are used for ultrasonic sounding by means of the pulse-transmission method. The angle between the individual transducer pairs is 15 degrees, which corresponds with the measuring step of the high-pressure head. The contact surfaces of the sphere and transducers are covered by a high-viscosity layer (Sonotech, shear wave gel) to transfer the shear-wave energy from the T_H and T_V transducers to the sample and subsequently to R_H and R_V.

The sensor polarization is determined according to the sphere's rotation axis. The measuring system uses one pair of P-wave transducers with flat contact surfaces, denoted by P, which record longitudinal waves. A piezoceramic Noliac pill, N51 4.5 mm in diameter and 0.5 mm thick, is used in the transducer. Their resonant frequency was about 2 MHz. There are also two pairs of perpendicularly oriented shear wave transducers with horizontal T_H and vertical T_V polarization. Noliac tablets, N55, L2.5 – W2.5 – TH1, of size 2.5 × 2.5 mm and 1 mm thick, with 0.8 MHz resonant frequency, are used in flat contact sensors. All transducers have similar point contact with the spherical sample but due to the shear wave gel used; the real contact of the sensors is not point contact but quasi-point one, which may have a diameter of roughly 1 mm or more. Predominant wavelength of recorded signals was about 1–2 mm.

The contact surfaces of the transducers are covered by shear-wave couplant as well. Using two pairs of shear-wave transducers provides better discrimination of the individual shear-wave components propagating through the anisotropic sample. When setting up a new ultrasonic sounding position/direction, due to the high-viscosity layer covering the spherical sample and transducers, the step motors cannot rotate the sphere or the arms fitted with 3 pairs of transducers. To change the position of transducers, the measuring head has to be equipped with one miniature DC motor (Maxon, diameter 8 mm), which is used to eliminate the contact between the sphere and transducers. After setting up a new measuring position, the DC motor re-establishes the contact between the transducers and the sample. As the restoring force of the transducers is controlled by the current of the DC motor, nearly identical contact conditions between the sensors and sample are preserved at all measuring points at one level of acting hydrostatic pressure. The restoring force is given by switching off DC motor current at an identical level. Eliminating the contact between the sample and transducers has several advantages: 1. It enables transducer and sample movement to set up a new transducer positions. 2. It prevents the high-viscosity layer from being wiped off in the course of transducer movement. 3. Calibration measurements proved that the high-viscosity layer remains on the sphere surface during the entire measuring procedure. During sample preparation, the sample and contact surface are carefully covered by shear-wave gel at a temperature of 40 °C to assure very thin and uniform spreading of the shear-wave gel. All measurements are done at 22 °C. Using the Maxon DC motor brings only one limitation it can only be used up to 60 MPa of hydrostatic pressure. As this is a miniature DC motor with a planetary four-stage gear, filling the inner parts of the motor with oil produces high friction of all individual parts, which results in a significant increase in the no-load current, which reaches nearly 80% of the maximum continuous current. Due to this fact, use of the new measuring set up is currently limited to a hydrostatic range between 0.1 MPa and about 60 MPa. As this is the range of hydrostatic pressure at which all cracks close, so that the modified measuring setup records the most important part of this process anyway. At one transducers' position, P, SV and SH waveforms are recorded. Note

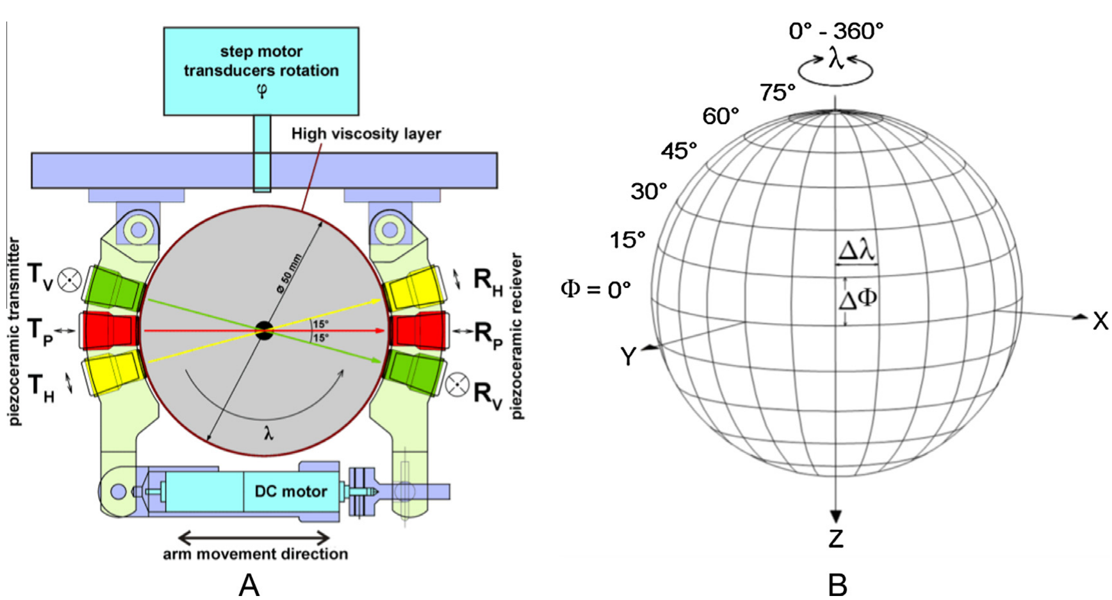

Fig. 1. A: schematic plot of the measuring setup. T_P, R_P – pair of longitudinal piezoceramic transducers (T-transmitter, R-receiver); T_V, R_V – pair of shear-wave transducers with vertical polarization; T_H, R_H – pair of shear-wave transducers with horizontal polarization. λ – angle of sphere rotation, Φ – angle of arm rotation, step motor to rotate arms with transducers, DC motor – motor to eliminate and re-establish contact between the sphere and transducers to enable arm movement and position the sphere and transducers. B: measuring net projection on the sphere surface, arm inclination Φ = 0–75° in steps of 15°, sphere rotation λ = 0–360° in steps of 15°.