Estimation elastic properties on core samples using ultrasonic travel-time tomography measurement with robotics application: preliminary study on laboratory model

Vani Mutia Sari, Tedy Setiawan, Fatkhan, T. A. Sanny
Geophysical Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia
E-mail: vani.mutiasari@gmail.com

Abstract. Ultrasonic travel-time tomography using laboratory model were performed in this preliminary study. The measurement was calibrated using a known velocity laboratory model representing an iron with P-wave velocity \((V_p)\) 5920 ms\(^{-1}\). Source and receiver transducers were equally spaced around the model. In the first measurement, the source position was at point 1, and receivers at points 2 to 16. In the second measurement, the source position was at point 2, and receivers at points 3 to 1. The measurements were repeated, and a total of 240 ray path were recorded. Then, the travel-time data inverted and reconstructed to get tomogram using a MSIRT (Modified Simultaneous Iterative Reconstruction Technique) algorithm. Each pixel tomogram represents a point velocity at ray path intersections. It is important to have at least one intersection for each pixel, so each pixel represents an average velocity. The use of robotic instrument provides precise and efficient results in data measurements despite errors between 1% and 3% at the time of motor rotation. The ultrasonic tomography using robotics equipment proves to be helpful in obtaining accurate measurement.

1. Introduction
Tomography (derived from the Greek word “tomos”, meaning section, and “graph”, meaning image) is an application of nondestructive testing to view the interior of a body without penetrating its surface by physical means. This method of imaging is used widely in the medical field using X-Rays to create a cross-sectional image, e.g. abdominal, cardiac, maternity, gynecological, urological and cerebrovascular examination, breast examination, and small pieces of tissue as well as in pediatric and operational review.

Geophysical tomography can utilize different radiation sources such as X-Ray, electrical resistivity, reflection, seismic and ultrasonic. The radiated energy is passed through a medium and measured in slightly different ways, producing transforms that display different physical information in the cross-section. In X-Ray tomography the cross sectional image is of the boundaries within a medium such as cracks in rock. In electrical resistivity tomography the tomogram, shows the resistivity through the medium. Reflection tomography measures reflected ultrasonic waves as they bounce off of interfaces within a body. Seismic tomography is very similar to ultrasonic tomography [1]. The difference between these two methods of tomographic imaging is the frequency ranges used. Seismic tomography utilizes low frequency waves to measure structures within the earth. The low frequencies correspond to long wavelengths which are capable of traveling long distances. Ultrasonic tomography is used more for
laboratory monitoring systems. Ultrasonic waves have small wavelengths which can resolve small structures, however ultrasonic waves attenuate quickly and can therefore only be transmitted over short distances. And this study discusses about ultrasonic tomography on core samples.

Ultrasonic waves are acoustic waves which have two types of longitudinal wave (P-wave) and transverse wave (S-wave) with frequency ranges from 20 kHz to 1 GHz [2,3]. Nowadays, the utilization of ultrasonic waves has grown in various fields in science and technology. Ultrasonic waves are frequently employed for two main methods, such as Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM). Although both methods have different variables and applications, however the principle used remains the same, i.e. detecting a defect or unconformity in an opaque object. So far, the NDE research has evolved into many specific methods, including ultrasonic tomography. There are two types of NDE applications that are commonly used ultrasonic waves, low-frequency Bulk Acoustic Wave (BAW) and Source Acoustic Waves (SAW). The BAW is utilized to perform ultrasonic tomography using transducers that are divided into transmitters and receivers. Two pairs of transducers (transmitter and receiver) P and S-waves are utilized to observe the propagation of ultrasonic waves. The transducer is made of piezoelectric material to convert electrical signals from voltage (V) and electric current (I) to compressive force (F) and average velocity (v). There are many variety of material to make piezoelectric and these materials still develop, ranging from quartz (SiO3), poled-ceramic, lead-zirconate (PZT), to the most rigorous for laboratory scale are lithium niobate (LiNbO3) [4].

The velocity between one transmitter and receiver transducer pair represents an average velocity along that ray-path. By conducting a tomographic survey where multiple ray-paths are measured at different orientations across the sample, many velocities along the different ray-paths can be found. These velocities are then inverted to produce a velocity profile along the plane being measured. The values of the compressional and shear velocities (Vp and Vs) obtained, and the density of rocks can be used to calculate the other elastic parameters, such as Vp/Vs, Poisson’s Ratio (σ), Shear Modulus (µ), Bulk Modulus (K), Young’s Modulus (E), Mu-Rho (µρ), and Lambda-Rho (λρ) [5,6,7].

Previous studies of ultrasonic tomography on core samples of rocks are applied in mining engineering to investigate the distribution of fractures [8,9], and in civil engineering to identify grout injection in porous medium [10]. Ultrasonic tomography is used to know defects on the framework of aircraft and railway wheels [3,11,12]. The same measurement technique is also developed in this research.

2. Robotic Measurement

Ultrasonic tomography utilizes an ultrasonic wave as a source. In this study it assumes that wave path is a straight line. Furthermore, the average velocity of ultrasonic wave propagation between transmitter and receiver is expressed as object projection conducted on many angles. To reconstruct a tomographic image, measurements of travel time are made at various angles from transmitter (T) to receiver (R). The measurement diagrams are as Figure 1.

![Tomography Measurement Block Diagram](image)

The measurement system uses transducer V103RM (P-wave) and V153RM (S-wave), pulser receiver 5072PR, preamplifier 5676, and digital oscilloscope NI-PCI5911. Transducers are used frequency of 1MHz that are set to have different distances. On average a measurement result of P-wave velocity on iron medium
is of 5920 ms\(^{-1}\) that is close to reference value. Figure 2(a) shows computer used for controlling robotic measurement system.

Picking first break is applied for calculating P- and S-wave velocity [9,10]. Calculating P and S-wave velocities manually and by using the robotics tool are obtained by measuring distance from transmitter to receiver. The distance is the same for manual calculations and with the robotics instrument. Calculating distances are obtained by using the MATLAB program operation for a cylindrical sample model with a diameter of 4.5 cm divided into 16 measurement points. The sample consists of three different layers of resin-iron-resin. Measurements with the robotics instrument are applied on the iron medium because the location is in the middle of the sample. In addition, the iron has a reference velocity and has a good wave velocity response, making it easier for analysis.

3. Measurements of Core Samples
Before measuring core samples, it is necessary to calibrate the transducers, i.e. by attaching the transmitter and the receiver transducer directly. This needs to be conducted to determine the reference input waveform and delay time [9]. As a result from this calibration, there is no delay time for both P- and S-wave. In addition to calibrate, it was also conducted measurements to check reliability of transducers using water as a medium. Ultrasonic velocity measurements on water medium with glass containers (glass diameter 6.62 cm), has given a result that the water velocity of about 1574.3 ms\(^{-1}\) as shown in Figure 3. Figure 4 shows a flow chart of ultrasonic tomography measurement.

First measurement test of a core sample is measurements of five-data sets that are divided into three types based on transmitter-receiver distance. The core sample is cylindrical in shape with diameter of
4.5 cm and is divided into 16 points. One data set consists of 16 measurements. The first set is cross measurement, the second is three quarters cross and the third is a quarter cross. The cross measurement that can be described as follows transmitter is point 16 and receiver is point 8. After finishing one measurement, the core sample was turned 22.5° using the robotic instrument that was controlled by computer. Then it conducted measuring other points until one data set completed. Other two type measurements are also similar to the cross measurements. Figures 5 a, b and c show to give illustrations for straight path measurements. To test quality of ultrasonic tomography data, measurement experiments were conducted with two types of observations. The first is fully manual measurements, whilst the second is a combination of manual measurements and the robotic measurements at certain points.

![Figure 5. Illustrations of straight path measurement data using the robotic instrument: (a) cross, (b) three quarters cross, (c) quarter.](image)

Figure 5 illustrates iron model used in this preliminary study, and Figure 7 show the cross plots of iron measurement results. The red curve is measurement values using the robotic instrument, while the blue curve is conventional measurement values. Then, the reference plot is indicated by the black curve at a value of 5920 m$^{-1}$. In general, measurements with robotic instrument (blue curve) have a more horizontal trend toward the reference value (blue curve). The value of the obtained velocity is also close to the reference velocity. This further strengthen hypothesis that with the robotic instrument can provide more precise and accurate results.

![Figure 6. Iron model used in this preliminary study, with diameter 4.5 cm.](image)

![Figure 7. Graph plots of cross measurement results.](image)

Using MSIRT (Modified Simultaneous Iterative Reconstruction Technique) method developed by Sanny and Sassa [13], all ray paths were calculated from a pair of transmitters to receivers. Figure 8 illustrates ray path of ultrasonic tomography measurement data, and measurement at different orientations across the sample (Figure 5). Figure 9 displays that on the outside circle there is improvement of quality data with relevant results. Colours of outer cells are originally red and become
darker in colour toward the dark red. Dark red represents a value of approximately the reference velocity used 5920 ms\(^{-1}\). Measurement results obtained have improved in terms of quality.

**Figure 8.** Ray path of ultrasonic tomography measurement data.

**Figure 9.** P-wave ultrasonic tomogram.

To provide a more detailed error description for the iron measurements, Table 1 shows error calculations using least square method for three parts [9,13], i.e. cross, quarter, and three quarters cross. The table of calculation errors provide better results on cross error calculations. This significant error provides the fact that, measurements using the robotic instrument can contribute positively to obtain quality data. Better point placement provides better travel time picking, so the calculation of wave velocity closes to the reference velocity.

**Table 1.** Table of errors

| Orientation of ray-oath | Error |
|-------------------------|-------|
| Cross                   | 0.490 |
| Quarter                 | 2.229 |
| ¾ Cross                 | 1.026 |

4. Conclusion
An approach to estimate the elastic properties of core samples using ultrasonic travel-time tomography has been discussed. The use of robotic instrument provides precise and efficient results in data measurements despite errors between 1% and 3% at the time of motor rotation. The ultrasonic tomography using robotics equipment proves to be helpful in obtaining better measurements, the calculation of wave velocity closes to the reference velocity. To improve estimation the elastic properties of core samples, in the next research will be used other materials, and application on core samples. Up-scaling core measurements needs to be considered when comparing to logs or seismic data.

**References**
[1] Cosentino PL, Capizzi P, Martorana R, Messina P, and Schiavone S 2011 *J. Geophysics* P1-8
[2] Adams J, Molle H, and Warren JD 2011 *New York. Springer Science LLC*
[3] Balvantin A, and Baltazar A 2011 *Mexico. 5th Pan American Conference for NDT*
[4] Cheeke J, and David N 2002 *Florida CRC Press LLC*
[5] Castagna JP, Batzle ML, and Eastwood RL 1985 *J. Geophysics* 50 P571-581
[6] Mavko G, Mukerji T, and Dvorkin T 1998 *New York. Cambridge University Press*
[7] Vernik L, and Nur A 1992 *J. Geophysics* 57 P727-735
[8] Falls SD, Carlson SR, Chow T, and Young RP 1992 *J. of Geophysical Research* 97 P6867-6884
[9] Johnson WB 2004 *Virginia Polytechnic Institute and State University USA. Master of Science Thesis*
[10] Jorne F, Henriques FMA, and Baltazar LG 2014 *J. Construction and Building Materials* 66 P494-506
[11] Klinger C, and Bettge D 2013 *Elsevier* 35 P66-81
[12] Leonard KR, Malyarenko EV, and Hinders MK 2002 *Inverse Problems* 18 P1795-1808
[13] Sanny TA, and Sassa K 1996 *J. of Applied Geophysics* 35 P117-131