Ultrasonic measurements on thin samples: numerical modelling

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SUMMARY

Ultrasonic pulse velocity method is a standard method for measuring elastic properties of rock cores in laboratories. Cylindrical plugs of 40-100 mm length are usually used for such measurements. It was recently shown that thin disc samples (~15 mm in length) were suitable for such measurements in the case of an advanced experimental set-up. Here we present results of numerical simulations to support the outcome of the previous work and to improve the understanding of wave propagation in the samples during laboratory ultrasonic measurements. The finite element method within Abaqus/Explicit (Dassault Systemes, Simulia) is used to simulate wave propagation along the experimental rig and the rock sample caused by transmitted ultrasonic pulse. The computational domain mimics the real geometry. The results of the numerical modelling prove that an S-wave transducer also produces a compressional wave that propagates along the sample and can be recorded by a receiver. Simulations are performed for three configurations used in real laboratory experiments. The numerically simulated waveforms are compared with the signals, recorded during laboratory experiments. Simulated travel times of elastic waves are in a good agreement with experimentally obtained results.

Key words: Ultrasonic measurements, rock physics, numerical modelling, Abaqus, FEM.

INTRODUCTION

Calibration of log and seismic data in laboratory is important in exploration and requires elastic properties of rocks to be known. Ultrasonic pulse velocity method is a standard method for measuring elastic properties of rock cores in laboratories. A pulse generated at the frequency of about 1 MHz propagates through the tested sample and the transit times of compressional and shear waves (P- and S-wave respectively) are recorded and used to calculate the compressional and shear wave velocities of the sample. To duplicate subsurface conditions, ultrasonic measurements are to be conducted under the *in situ* confining pressure (Hughes and Cross 1951, Blake et al. 2012). Thus the dimensions of the samples are determined by the geometry of a pressure cell. Usually cylindrical samples with 25-38 mm in diameter and 40-100 mm in length are used for ultrasonic measurements (Steward and Peselnick 1977, Stesky 1985, Blake et al. 2012). Shorter samples are generally not used to avoid near field effect. A comprehensive description of a pulse transmission technique including its major limitations was given by Birch (1960).

Ultrasonic measurements of elastic properties of thin samples (<40 mm) are also often required. Thin discs are used for measurements of dielectric permittivity of rocks (Josh et al., 2012) and ultrasonic measurements on the same samples are important for their comprehensive characterization. Another example when reliable measurements of ultrasonic velocities on thin samples are of practical importance is saturation and desiccation experiments (e.g., Ferrari et al. 2014), which are time-consuming especially when such experiments are done on full-length samples of 40-100 mm. The use of thin discs (38 mm in diameter and ~15 mm in length) allows significant reduction of the saturation/desiccation time needed for stabilizing of a saturation level. Several studies used thin samples for ultrasonic measurements (Kono et al. 2009, Kitamura et al. 2013). However, the reliability of the results obtained on such samples has not yet been validated. Here, we introduce an experimental set-up for ultrasonic measurements on thin samples and obtain travel times of compressional and shear waves for discs ~15 mm in length. We further perform numerical simulations to prove that such thin samples are suitable for reliable ultrasonic measurements. We obtain simulated waveforms of transmitted signal and compare them with the waveforms recorded at the receiver during the experiment. The results of numerical simulations allow validation of experimentally measured P- and S-wave arrival times.

METHOD

Ultrasonic measurements were performed using the experimental technique described by Lebedev et al. (2013). We use V153 1MHz/.5″ transducers (Olympus Panametrics-NDT™) working in shear mode (S-transducers). The experimental set-up inside pressure cell is shown in the Figure 1. An extra polymethyl methacrylate (PMMA) cylinder is added to fit a thin sample into the pressure cell. The sample and the PMMA are placed between two polyether ether ketone (PEEK) cylinders. Source and receiver transducers are mounted to the opposite sides of this set-up. As a result we transmit ultrasonic pulse through nonhomogeneous layered medium. Presence of contacts between different materials within the set-up leads to rapid dissipation of S-wave's energy. Therefore, it could be tricky to recognize the S-wave at the recorded waveform as it might be contaminated by previously arrived oscillations.

In this work we use S-transducers to emit ultrasonic pulse as it was shown that such technique allows registration not only S-wave but P-wave as well (for more details see Lebedev et al., 2013). However, source S-transducer converts transmitted electrical signal to mechanical displacement parallel to its surface. For modelling we assume that the source transducer has only shear displacement and we neglect any displacements of its surface in directions other than direction of transducer polarity. To obtain the initial waveform emitted by the source transducer, the source and receiver were put into direct contact. Recorded signal shown in the Figure 2 is in a good agreement with the technical description of the transducers. We convert the recorded electrical signal into the mechanical displacement and use it as a boundary condition for the modelling.

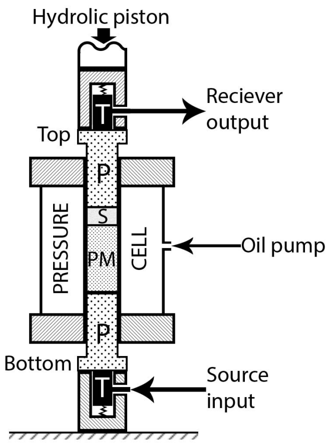

Figure 1: Scheme of pressure cell and experimental set-up. T – transducers, P – PEEK cylinder, PM – PMMA, S – sample.

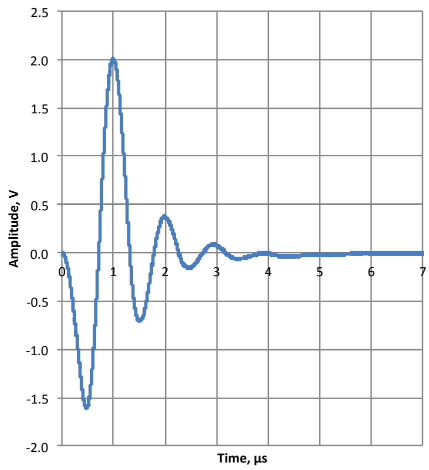

Figure 2: Recorded signal. Source and receiver transducers are in direct contact.

Numerical simulations using finite element method within Abaqus/Explicit (Dassault Systemes, Simulia) is performed to prove our approach for picking of P- and S-wave arrivals. The computational domain copies the geometry of the experimental set-up (Figure 3). We restrict displacement in the Z direction of the edges of the top and bottom surfaces. Due to the perfect transducers assumption we consider the geometry to be symmetric with respect to the X direction. Thus the modelling is performed within the domain representing a half of the real set-up. Transmitted ultrasonic pulse is introduced as a displacement of the middle part of the domain's bottom surface in the Y direction. The time-dependent amplitude of the displacement is defined according to the recorded signal from the source transducer (Figure 2). The transmitted signal is obtained by averaging of the simulated displacement of the receiver nodes (Figure 3). This signal is processed in order to convert mechanical displacement into output electrical signal and to compare the data with experimentally obtained waveforms.

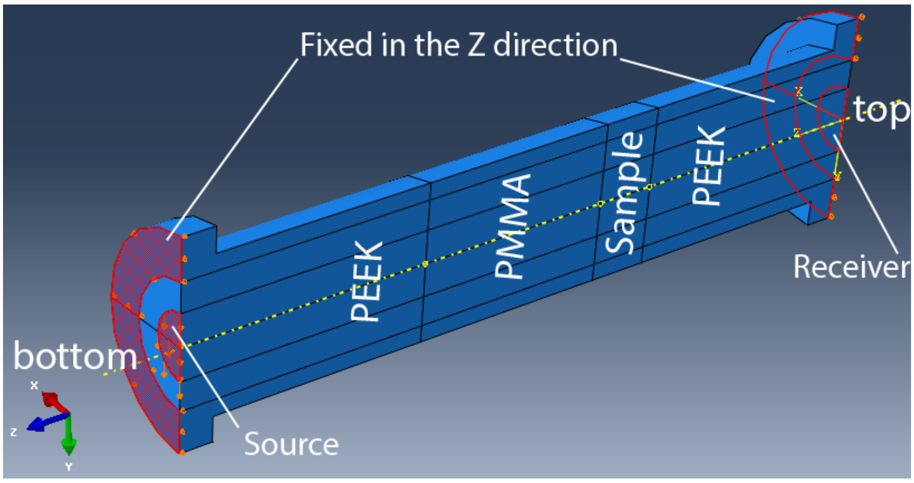

Figure 3: Computational domain with highlighted regions of fixed area, source and receiver. Boundary conditions are applied to YZ plane to introduce symmetry in the X direction.

We model wave propagation through three different configurations of the set-up: (1) a solid aluminum cylinder (52 mm in length; 38 mm in diameter); (2) a PMMA cylinder (48.16 mm in length, 38 mm in diameter) placed between two PEEK cylinders (62.43 mm and 58.62 mm in length, both are 38 mm in diameter); (3) a thin aluminum disc (14.32 mm in length, 38 mm in diameter) with additional PMMA cylinder placed between two PEEK cylinders. We divide the computational domain into several parts according to the real geometry of a given set-up and assign the elastic properties of the relevant material to each part.

It is important to choose proper size of spatial cells and time steps to achieve accurate numerical simulation results. To capture elastic wave propagation 5-10 cells per one wavelength are reasonable. As the slowest wave is an S-wave propagating in PMMA (~1400 m/s) and the frequency is 1 MHz, the element size should be $1\text{-}5\cdot10^{-4}$ m. Time step $\Delta t < 10^{-7}$ s is chosen according to Courant–Friedrichs–Lewy condition.

We make following assumptions to build the numerical model:

1. Transducers are perfect and their surfaces move only in Y direction;
2. All material are elastic (no viscous behavior);
3. Contacts between different parts within the set-ups are perfect (no slip).

RESULTS AND DISCUSSION

An example of simulated elastic wave propagation in the solid aluminum cylinder is presented in the Figure 4. Displacement of particles in the Y direction corresponds to the shear wave transition. S-wave propagation through layered medium in time is presented in the Figure 4a. Moreover, P-wave propagating in Z direction is initiated by displacement of the source in Y direction. Displacement of particles in the Z direction is presented in the Figure 4b. Positive and negative Z-displacements are observed at the opposite sides of the source. Thus compressional dipole is emitted and propagates through the media with P-wave velocity. It causes displacement of the receiver at the top of the domain in the Y direction (Figure 4c). Therefore, we are able to register P-wave arrival using S-transducers.

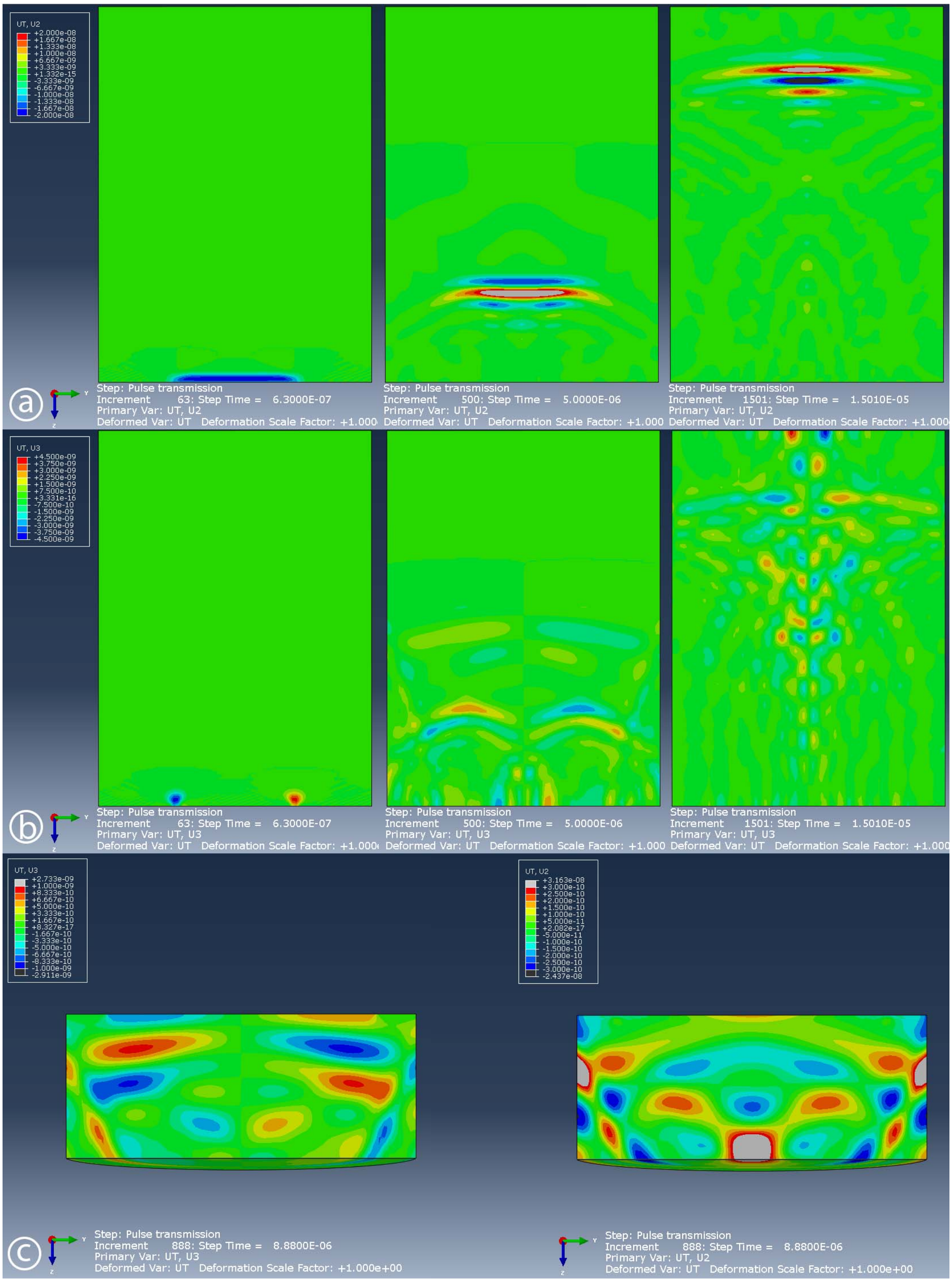

Figure 4: Simulated wave propagation in solid aluminum cylinder. a) Displacement of particles in the Y direction (U2); b) displacement of particles in the Z direction (U3), initiation and propagation of the compressional dipole; c) top part of the domain, left – U3, right – U2 at the same moment of time.

We consider that the receiver transfers only Y-displacement into the form of electrical signal. Average Y-displacements of the receiver nodes converted into the form of electrical signal are plotted in the Figure 5 in comparison with experimentally obtained waveforms for three different set-up configurations. The times of P- and S-wave arrivals could be easily picked. Travel times of compressional and shear waves in experiments and simulations match well with each other. Modelling results help picking the S-wave arrival in case of thin aluminum disc as the experimental signals are contaminated with reflected P-wave arrivals.

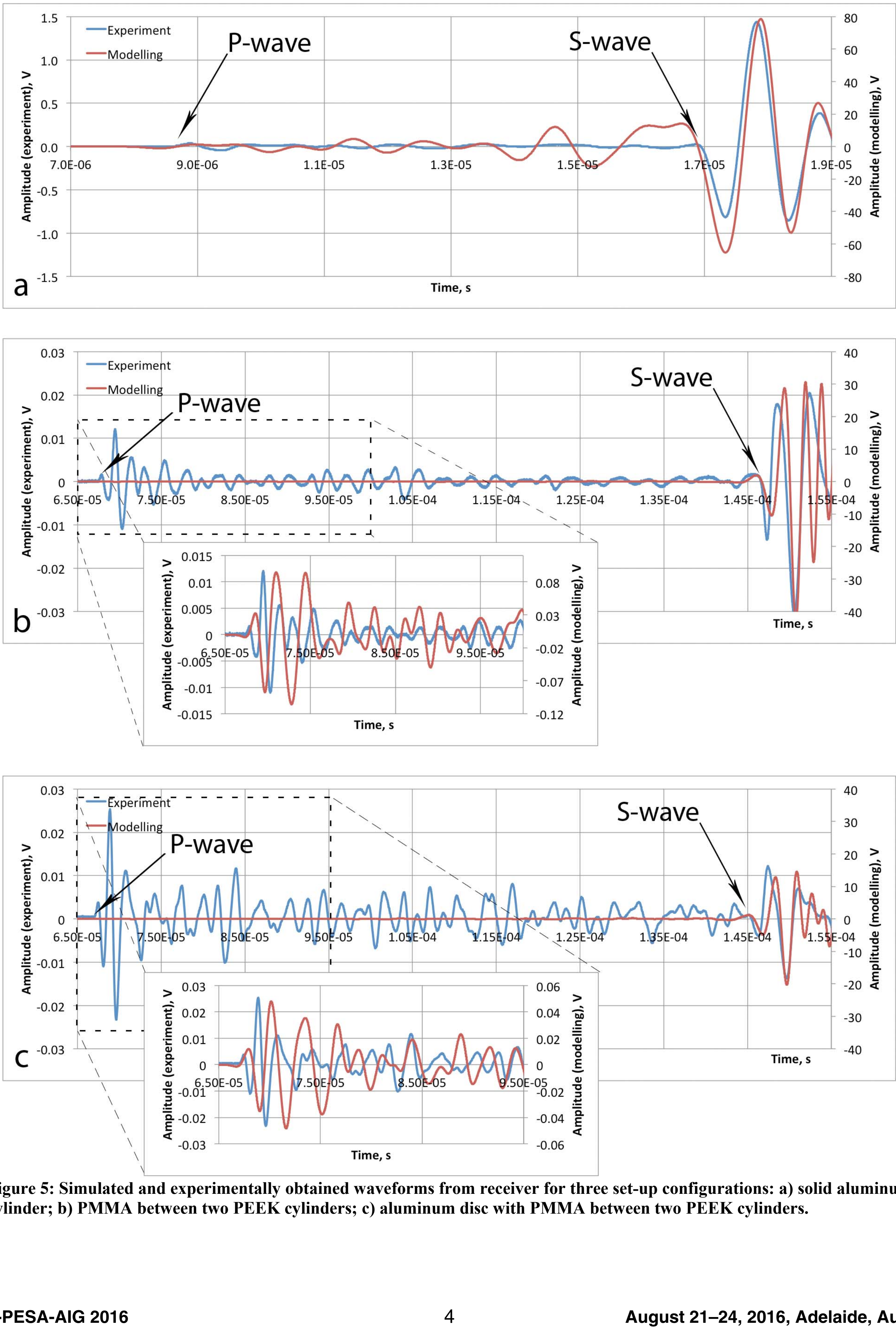

Figure 5: Simulated and experimentally obtained waveforms from receiver for three set-up configurations: a) solid aluminum cylinder; b) PMMA between two PEEK cylinders; c) aluminum disc with PMMA between two PEEK cylinders.

The amplitude of waveforms is much higher for simulated data. This relates to the set material properties for modeling and assumed perfect contacts between different purely elastic materials. We use elastic media without viscosity or damping, so dissipation of energy is not taken into account. We post-process simulated waveform for the set-up with aluminum disc (Figure 5c in red colour) and introduce time-dependent exponential dissipation. Obtained result is presented in the Figure 6.

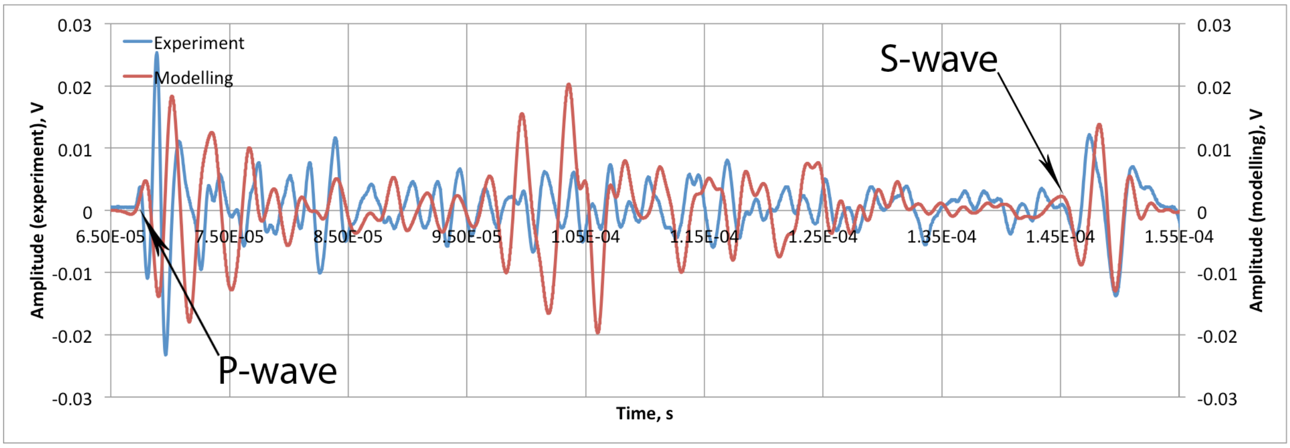

Figure 6: Waveforms obtained for PEEK / PMMA / aluminum disc / PEEK set-up. Comparison of experimentally obtained waveform and simulated waveform with exponential dissipation of amplitude.

Furthermore, differences in frequencies are observed for experimental and simulated waveforms, especially for P-wave oscillations. This could be related to the assumption about perfect source of transmitted pulse or/and utilisation of not fine enough mesh in numerical modelling. Further model development and refinement is necessary.

CONCLUSIONS

Numerical modelling of waves propagations through the set-up used in advanced ultrasonic measurement experiments reveals validity of the approach for registering P- and S-wave arrivals using a pair of S-transducers. Simulations are performed for three configurations used in real laboratory experiments. Simulated travel times of elastic waves are in a good agreement with experimentally obtained results. Advanced modelling is needed to take into account the real behavior of source and receiver of ultrasonic pulse and dissipation of energy within the system.

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