EFFECT OF AMPLITUDE ON WAVE PROPAGATION

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SUMMARY

It is common to use ultrasonic techniques to measure elastic properties of the porous media. However, conventional methods are unable to measure local strain in ultrasonic wave. This is not clear how the velocity of wave depends on its amplitude. In this work we, 1) measured the particle displacement in the ultrasonic wave using a Laser Doppler Interferometry (LDI) and 2) measured changes of P-wave velocities with wave amplitude for elastic (Aluminium), viscoelastic (Polymethylmethacrylate), and granular media (dried Gosford sandstone). We checked this phenomena using a conventional ultrasonic receiver and linked this changes to a local strain in wave. The study indicated that for a sandstone sample by increasing of local strain produced by an ultrasonic wave from $7*10^{-6}$ to $2*10^{-5}$ the P wave velocity increase by 0.7%. We also analysed the accuracy of velocity measured using LDI as a receiver and compare the results with that using conventional transducers. Moreover, the effect of proper couplant of the sample and the transducer was investigated in details.
Key words: Ultrasonic, P wave, strain amplitude, Laser Doppler Interferometry

INTRODUCTION

Strain amplitude effect on wave propagation investigated previously in various studies (Johnson et al 1996, Ten Cate et al 1996, Van Den Abeele et al 1997, Zinszner et al 1997, Tutuncu et al 1994, 1998a, 1998b, Ostrovsky et al 2001). However, such studies are mostly focused on wave attenuation rather than wave velocity. Limited experimental studies carried out on this effect on velocity dependence on strain provide ambiguous results. Winkler and Nur, (1982) show that the velocity of the waves decreases with the increase of the strain, however Mashinskii (1994, 2004 and 2005) observed increasing of wave velocity with wave amplitude and related that phenomena to microplastic effects in elastic modulus. In both mentioned works the strain amplitude has been estimated and not directly measured. To investigate this phenomenon we measured the strain amplitude inside an ultrasonic wave directly by a Laser Doppler Interferometry (LDI) and observed an increase of the P-wave velocity with an increase of the strain.

METHOD AND RESULTS

The LDI experiments employed laser equipment and ultrasonic facilities. To determine the compressional-wave velocities ultrasonic pulse transmission technique had been used on the samples; Polymethylmethacrylate (PMMA), Gosford sandstone and Aluminium (Table 1). The ultrasonic system includes of pair P-wave transducers with a nominal centre frequency of 1 MHz, to generate and detect P-wave, 5077PR Pulser and Receiver units (Panametrics-Olympus), and digital oscilloscope Tektronix TDS 2022C (200MHz). The Laser Doppler Interferometry set up contains of Vibrometer OFV-5000 Modular, Vibrometer Controller, Vibrometer Sensor Head OFV-503 (Politec Ltd.), and noise cancelling platform (Figures 1). Equipment was synchronized by 5077PR pulser-receiver. For each media, the transmitter-receiver configurations have been fixed on the centre of the cube surface.
Figure 1 shows the set-up of the experiment using LDI as a receiver of wave. The piezoelectric transducer was used as source of P-waves. It was directly glued by a "superglue" at the middle of the sample. As a receiver the LDI was used. The LDI measures the rate of the displacement (particle velocity) of the surface in a small area (around 0.3 mm in diameter). Thus to calculate the displacement, the recorded waveform was integrated over time. The measurement point was selected on the opposite side to the source, and was in the middle of the surface. We applied square shape pulse of different voltages from 100 to 400V to the piezoelectric source to generate ultrasonic waves with different amplitude but the same frequency of 1 MHz. At this frequency the wavelengths in the PMMA, Aluminium and Gosford sandstone will be 2.7, 6.2, and 3.1 mm respectively.
To measure the equipment delay ("deadtime") at different output voltage, the centre of naked transducer has been monitored by LDI. The set up for measuring the "deadtime" for LDI and ultrasonic equipment is demonstrated in Figure 2. The "deadtime" for ultrasonic also measured by direct transducer –to- transducer contact using the superglue. Such "deadtimes" were subtracted from all first waves' arrivals. LDI and ultrasonic "deadtimes" for range of voltages is presented in Figure 3. The results indicate that by increasing the applied voltage from 100V to 400V the ultrasonic "deadtime" increases from 0.32µs to 0.33µs and LDI "deadtime" decreases from 3.92 µs to 3.93 µs. The change of the "deadtime" is mainly due to changes in internal electronics circuits inside the 5077PR Pulser and Receiver.
Different coupling fluid are commonly using in the ultrasonic measurement. We investigated the effect of couplant on first arrival of the ultrasonic wave. Figure 4 shows the arrival times in Gosford sandstone measured at different voltages applied to the source in two

cases: 1) viscous couplant and 2) solid like couplant (glue) . We can see that if the transducer was not glued to the sample (i.e. there is an uncontrollable gap between the sample and the transducer) the "deadtime" is fluctuated. This is not the case if the transducer was glued to the sample. Moreover, as we measure the displacement of the surface if transducer is glued to the sample the displacement increases linearly with increasing of the applied voltage. If we use viscous fluid, such displacement will be not proportional to applied voltage. This result has been check with PMMA sample (Figure 5). We can see that the displacement in ultrasonic wave is proportional to applied voltage in this case**.**

We performed the measurements of the velocity using LDI and piezoelectric transducer as a receivers. Firstly we measure a first arrival using LDI and to do that we measured 5 points on the surface of the sample (laser beam focus points) and then the average velocity over these points by LDI was calculated. Figure 7 shows the measurement of first arrivals of this 5 points along one line with the same diameter of the piezoelectric crystal inside the transmitter transducer. Then we glued the receiver in the same position. The results of the measurement are shown in the Figure 8. We can see that velocities measured by both methods are very similar in the case of Aluminium and PMMA for both applied voltages (100V and 400 V), however there is some difference (up to 7%) for granular medium (sandstone). This may be due the fact that the transducer measures the "average" arrival of the wave over big area (diameter of 19 mm), but LDI measures much smaller area (0.3 mm diameter). For that particular reason we chose ultrasonic transducer – to- transducer method for accurate velocity measurement for Gosford sandstone.

	Gosford sandstone	*PMMA*	*Aluminium*
Density (g/cm3)	2.23	1.2	2.69
Length (mm)	20.6	50	40.3
P-wave velocity (m/s)	3259	2755	6404

Table 1, Properties of the tested material in this study

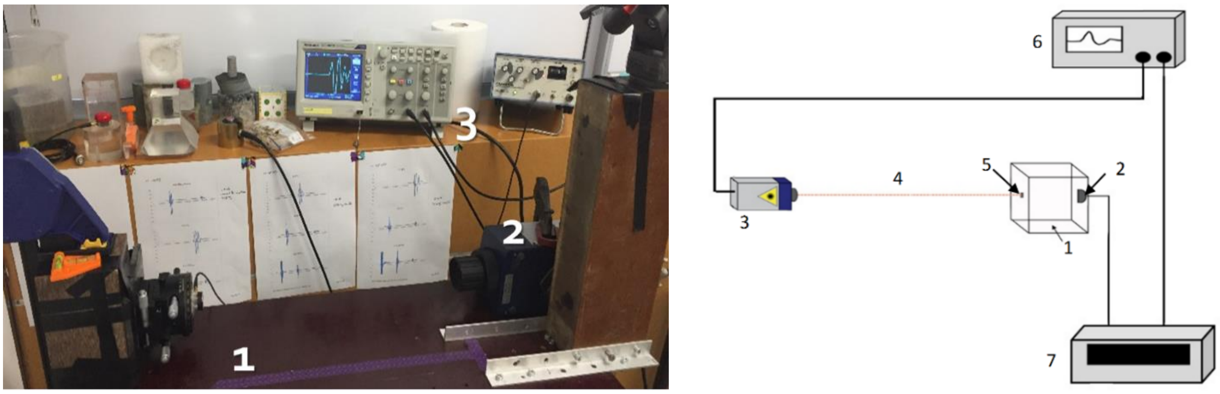

Figure 1. (left) Experimental set up; 1: Laser Doppler vibrometre, 2: special noise-cancelling platform, 3: ultrasonic equipment, (right) schematic experimental setup. 1: sample, 2: source of elastic waves, 3: laser Doppler interferometer, 4: laser beams (emitted and backscattered), 5: focus point, 6: acquisition system device, and 7: pulse generator.

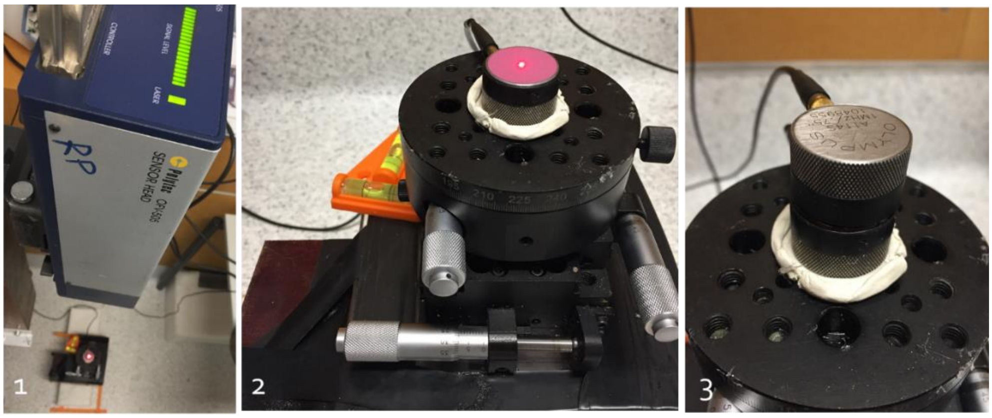

Figure 2. Measurements of equipment delays ("deadtime"): LDI (1) LDI setup (2) Laser beam focused on centre of source transducer; Transducer-to-Transducer (3) transducers were glued to each other to guarantee the good direct contact

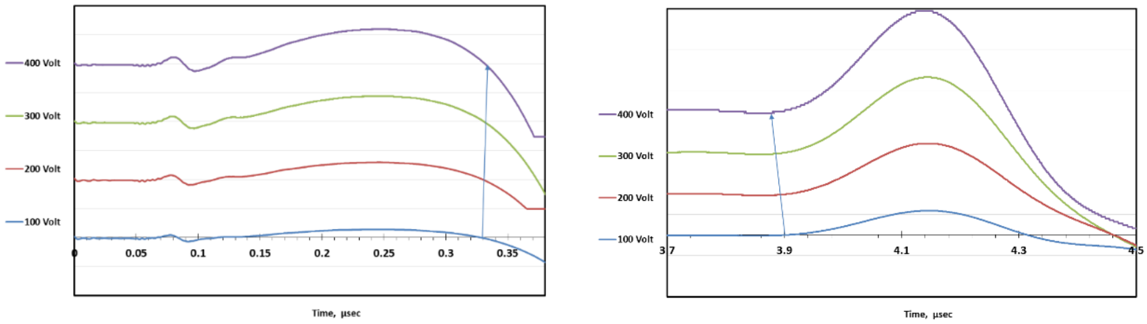

Figure 3. Ultrasonic (left) and LDI (right) signal "deadtime" for 4 ranges of amplitudes

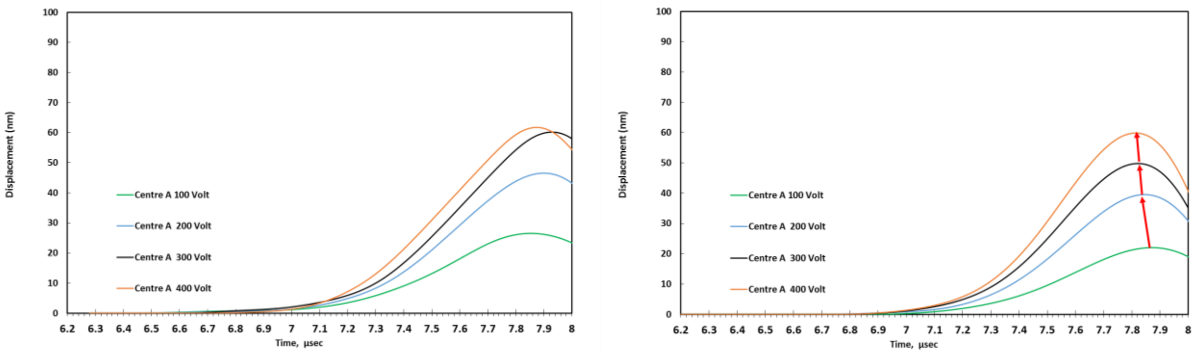

Figure 4. Very viscous fluid coupling (left) vs modified coupling (superglue) (right) in Gosford sandstone.

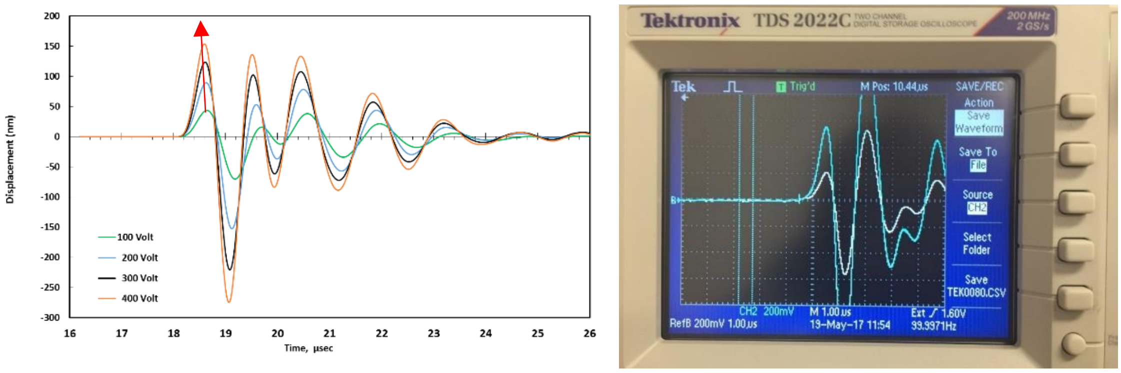

Figure 5. (left) PMMA amplitude displacement for full waveform measured by LDI, (right) oscilloscope measurement of changes in first arrival, blue line indicates the 200V and white line is 100V

We define the strain (Ɛ) inside a wave as:

$\varepsilon = d/\lambda$,

Where **d** is the maximum particle displacement from the position of equilibrium and **λ** is the wavelength.

To analyse the effect of strain on P-wave velocity Gosford sandstone has been selected. Results are shown in the Figure 9. We increase voltage applied to the source from 100 to 400 V, and we observed the increase in strain in the wave and the increase in wave velocity. By changing of the strain from $7*10^{-6}$ to $2*10^{-5}$ the velocity increases by 0.7%. This should mentioned that no confining pressure was applied to the sample in this test except for a small weight (0.5 kg) for a better coupling.

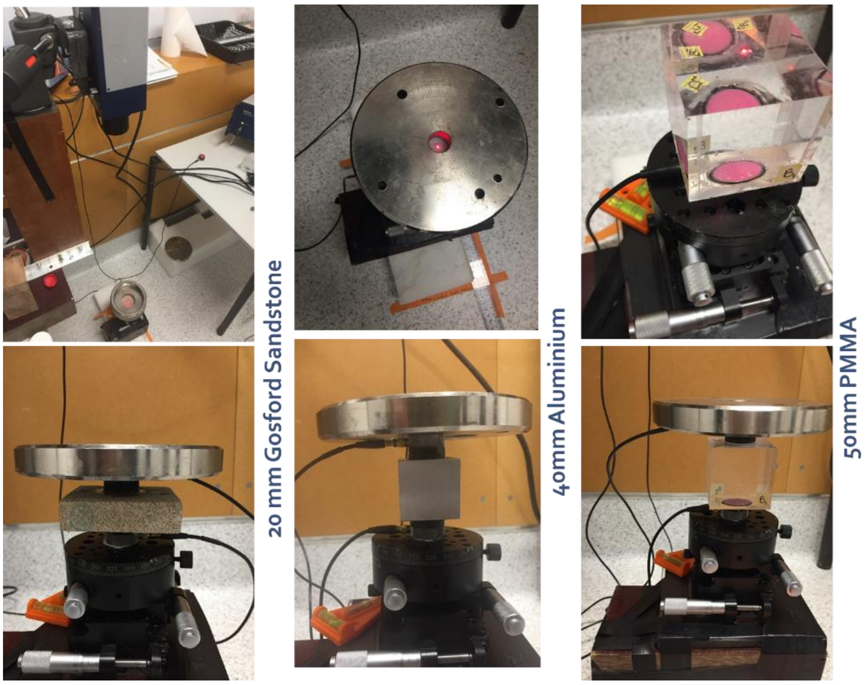

Figure 6. Set up for measuring the velocity by ultrasonic equipment and changing the receiver from LDI to transducer for all samples: upper row- LDI measurements, bottom row – ultrasonic measurements.

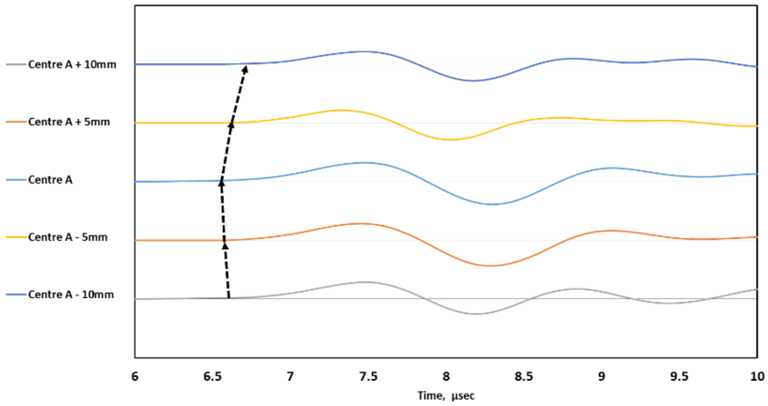

Figure 7. First arrival measurements by LDI along one line on the surface of Gosford sandstone to calculate the average velocity by LDI.

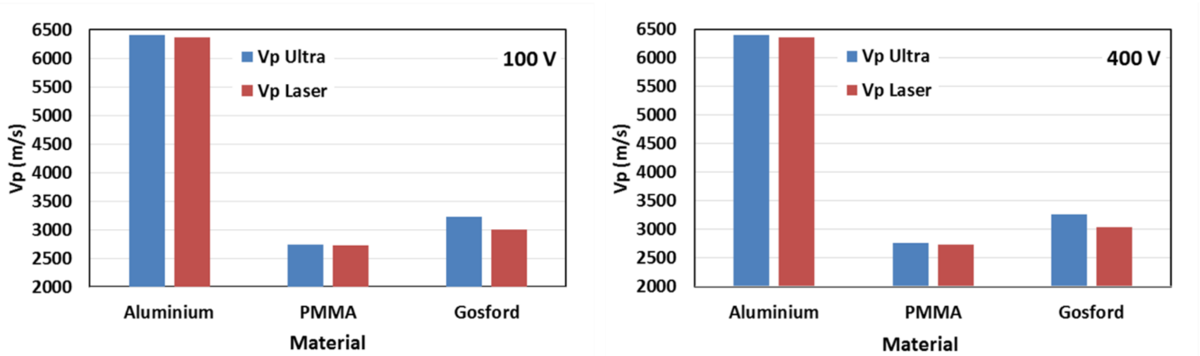

Figure 8. Velocity variation measurement by LDI and ultrasonic for Aluminium, PMMA and Gosford sandstone on voltages of 100 and 400

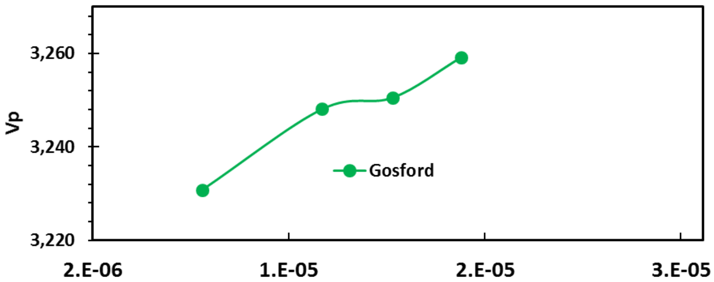

Figure 9. P wave velocity vs strain amplitude in ultrasonic wave for Gosford sandstone. Voltages applied to transducer are 100V, 200V, 300V, and 400V.

CONCLUSIONS

We directly measured the strain inside ultrasonic wave generated by a piezoelectric transducer at different voltages applied to transducer. We observed the increase in the velocity with strain inside the wave by 0.7% for Gosford sandstone by increasing the local strain produced by an ultrasonic wave from $7*10^{-6}$ to $2*10^{-5}$. Using the same transducer as a source of ultrasonic wave, we measured the velocity using a second transducer and LDI as a receivers of wave. We find out that the velocity measured by pair of transducers is more reliable in a case of granular medium, and the results of measurements are identical for elastic materials.

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