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Visualization and measurements of wave propagations in slurry hammers

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ABSTRACT

We are studying strongly-coupled fluid-structure interaction generated by a stress wave propagating along the surface in the slurry (mixture of water and solid particles) adjacent to a thin solid shell. This is realized, experimentally, through projectile impact along the axis of a slurry-filled tube. We have tested polycarbonate tubes with 52 mm inner diameter and 4 mm wall-thicknesses. A steel impactor is accelerated to 1 m/s by gravity and strikes a polycarbonate buffer within the tube located at the top of the slurry surface. Strain gages measure hoop strains every 200 mm and pressure transducer records reflected pressure at the closed end of the specimen tube. Since we use the polycarbonate tube, we can visualize original distribution of solid particles inside the specimen tube and motions of particles due to the propagation of slurry hammer for low volume fraction cases. Wave speeds obtained in our experiments decreased as volume fraction of particles of calcium carbonate increases while theoretical wave speeds proposed by Han et al. (1998) for a slurry hammer are independent on the fraction. Reflected pressure reduces when a volume fraction of particle increases while the impulse calculated by integrating reflected pressure histories just slightly reduces with the fraction increasing.

1 Introduction

The propagation of coupled fluid and solid stress waves in liquid-filled tubes is directly relevant to the common industrial problem of water hammer [1, 2, 3]. Two failure occurred in nuclear power plants due to detonation loading inside the pipe system; Hamaoka-1 NPP in Japan, Brunsbüttel KBB in Germany [4]. In these accidents, detonable mixtures were accumulated by radiolysis and water is present near the explosion. It is quite likely that the impact-loaded water interacted with the tube wall and caused a fluid-structure interaction and escalated the damages during the explosions.

When a shock in a liquid propagates perpendicular to submerged structure, flexural waves are generated in the structure. The main wave propagation mode is flexural wave in the structure which can be closely coupled to a pressure wave in the liquid. To investigate this type of coupling, we are using projectile impact and thin-wall water-filled tubes to generate stress waves in the water that excite flexural waves in the tube wall, see Fig. 1.

We have been using this configuration to study [5, 6] elastic and plastic waves in water-filled metal and polymer tubes. The theory of water hammer and our previous studies show that the extent of fluid-solid coupling in this geometry is determined by a non-dimensional parameter.

$$\beta = \frac{KD}{Eh} \tag{1}$$

where K is the fluid bulk modulus, E is the solid Young's modulus, D is the tube diameter, and h is the wall thickness. In this case, the coupling is independent of the blast wave characteristics and only depends on the fluid and solid properties and geometry. The Korteweg waves travel at a speed (Lighthill [7])

$$c = \frac{a_f}{\sqrt{1+\beta}} \tag{2}$$

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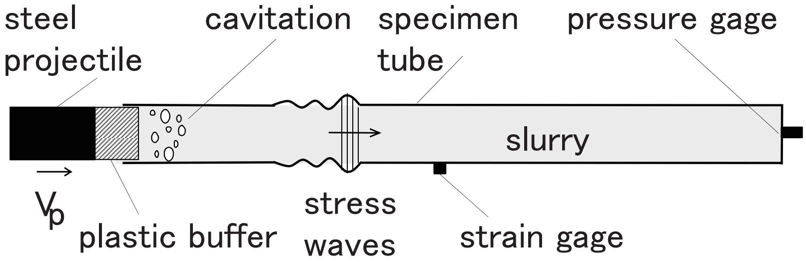

Figure 1: Schematic diagram of axi-symmetric water-in-tube configuration for generation of tube flexural waves coupled with stress waves propagating in the water.

which, depending on the magnitude of β, can be significantly less than the sound speed a_f in the fluid or the bar wave speed $\sqrt{E/\rho_s}$ in the tube. The parameter β is sufficiently large in our experiments that we obtain significant fluid-solid coupling effects. Previous experiments [8] on flexural waves excited by gaseous detonation are superficially similar to the present study but these have all been in the regime of small β.

The current study reports results for slurry-hammer as elastic wave propagation generated by low-speed impacts. The present work extends in a systematic fashion our previous studies [5, 6, 9] in which we used metal tubes or composite tubes. The dynamic interaction between solids and fluid for homogeneous slurries has been studied by several researchers [10, 11]. In their formulations, solid particles are modeled without detail observation during the wave passage. In the present study, we used polycarbonate tubes so that we can visualize particle motions inside the tube and discuss effects of particles on the wave speeds and pressure loadings.

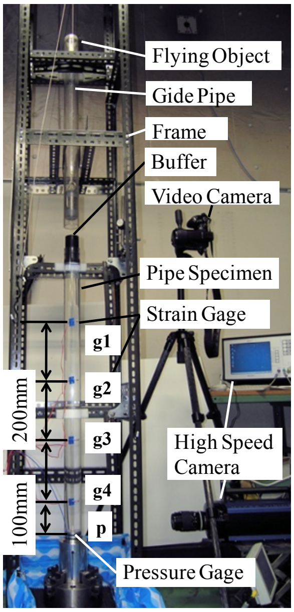

Figure 2: Picture of free-fall test facility.

Experimental Methods

We built a free-fall facility to perform experiments on the fluid-structure interaction as shown in Fig. 2. The guide tube for the projectile is mounted vertically above a specimen polycarbonate tube filled with water or slurry. The 50 mm diameter and 1.5 kg steel projectile is accelerated by a gravity up to 1 m/s; reflected pressure recorded at the closed bottom end is about 0.6 MPa. A high-speed digital camera (FC100, Casio) is used to measure the projectile

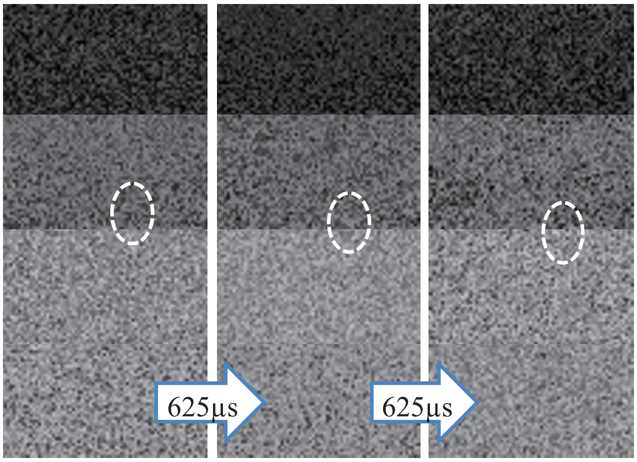

Figure 3: Particle motions after the passage of slurry hammer wave.

speed at the impact. The average projectile speed dropping from 100 mm height is 0.71 m/s. A high-speed video camera (HPV-1, Shimadzu) is used to observe the particle motions due to wave propagations and determine particle speeds just after the passage of the wave by post-processing the images (see Fig. 3). Obtained particle speed is 0.49 m/s and does not change in the range less than volume fraction of 0.2%.

The impact-generated stress waves cause the tube to deform and the resulting coupled fluid-solid motion propagates along the tube and within the water or the slurry. The deformation of the tube is measured by strain gages oriented in the hoop direction and the pressure in the water is measured by a piezoelectric transducer mounted in an aluminum fitting sealed to the bottom of the tube (Fig. 4). The specimen polycarbonate tube has 52 mm inner-diameter and 60 mm outer-diameter and 4 mm wall-thickness. Strain gages are mounted to measure the hoop strain of the polycarbonate tube at 200 mm increments. The bottom of the tube is fastened to an aluminum bar mounted in a lathe chuck that is placed directly on the floor.

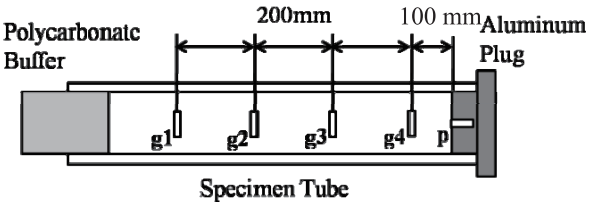

Figure 4: Schematic of test specimen tube with buffer, pressure transducer (p), and strain gages (g1-g4).

The projectile is not completely ejected from the guide tube when it impacts a polycarbonate buffer placed on the water surface. A gland seal is used to prevent water and slurry moving through the clearance space between the buffer and specimen tube. In this fashion, the stress waves due to the impact of the projectile are transmitted directly to the water surface inside the specimen tube. Slurry is prepared by mixing water and calcium carbonate particles (CaCO3, averaged diameter 6 μ m, density 2.7 g/cm^3, up to 600 g).

2 Results and discussion

Figure 5 shows hoop strain histories for a water case without particles measured at locations g1 to g4 as given in Fig. 4. The red trace in Fig. 5 is the pressure history and since this is obtained in the solid end wall, the pressure values are enhanced over those for the propagating wave due to the effects of reflection at the aluminum-water interface. In Fig. 5, the strain signal baselines are offset proportional to the distance from the buffer bottom. The blue line indicate the leading edge of the primary (main) stress wave front. The primary wave speed is 412 m/s. The subsequent reflection of the primary waves from the bottom and re-reflection from the buffer can be observed

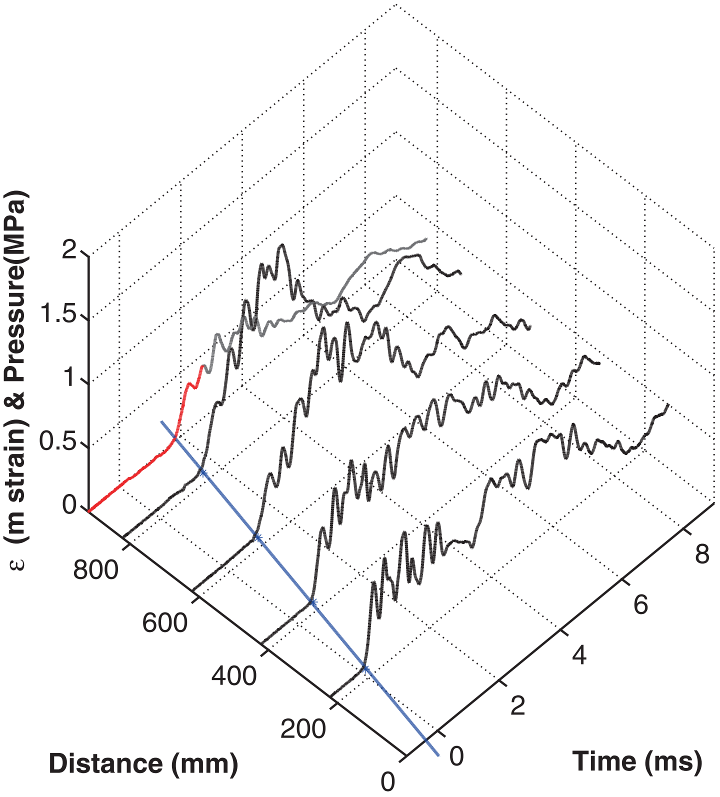

Figure 5: Strain and pressure histories for shot 062, $C_V = 0\%$, water case.

as distinct strain pulses. Peak pressure at the front is 0.57 MPa.

Hoop strain histories for a slurry case is presented in Fig. 6. This figure is drawn in the same manner as Fig. 5. Volume fraction of particles is 11.3% and total 600 g of particles are mixed in the water. Each experiment of slurry is conducted within a minute after mixing so that we can measure the slurry hammer at homogeneous conditions. The frontal wave speed is 246 m/s and is slower than that of the water case. The peak pressure is 0.40 MPa and is lower than that of the water case. We found that the tube is expanded before the arrival of the main stress wave. Since there is no expansion for the water case, this is unique for the slurry hammer case.

Figure 7 shows the relation between the slurry-hammer speed and the volume fraction of the particle. As the volume fraction increases, the speed decreases from 400 m/s to 250 m/s. Han et al. [11] proposed the equation to predict the speed of the slurry hammer for homogeneous mixture. In their equation, the slurry-hammer speed is calculated with the water and the particle speeds. We substituted the buffer and the particle speeds into their equation as the water and the particle speeds and obtained the theoretical values. The theoretical estimation is presented in the Fig. 7. With increasing the volume fraction, experimental results decreases more than theoretical estimations. First, we used the particle velocity obtained in the case for low volume fraction (0.2%) due to the limitation of the particle visualization. Therefore, there is a posibility that the particle speed dramatically changes as the volume fraction increases. The other reason for the disagreement is considered to be caused by scattering of frontal waves due the the presence of particles.

The relation between the frontal peak pressure and the volume fraction of particles is given in Fig. 8. Experimental results indicated that the peak pressure does not change by increasing the volume fraction of the particles. Theoretical results also shows the weak dependence on the volume fraction. Since there was the presence of particles near the buffer, the buffer motion was strongly affected by the particles, which results in dispersion of the peak pressure. The peak pressure can be estimated by the product of the density of slurry, wave speed, and the boundary speed

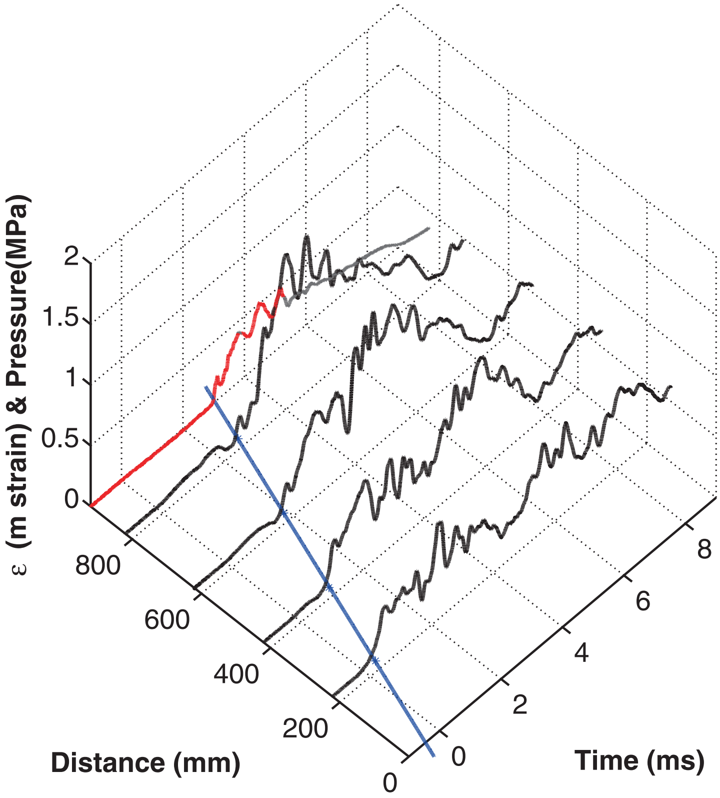

Figure 6: Strain and pressure histories for shot 062, $C_V = 11.3\%$, slurry case.

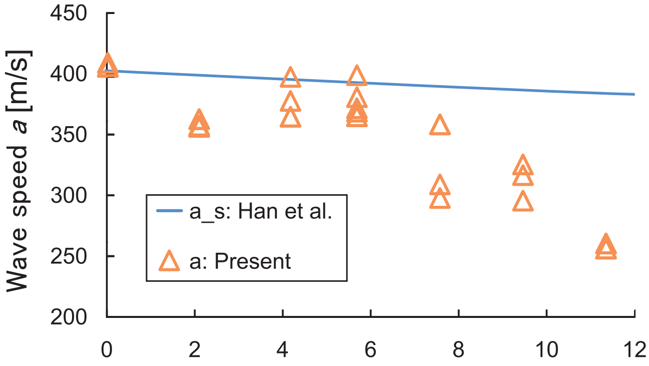

Figure 7: The relation between the slurry-hammer speed and the volume fraction of particles C_V.

(the buffer speed). Figure 9 is obtained by substituting the experimental wave speed into the equation for the peak pressure. As shown in this figure, peak pressure decreases as the volume fraction increases. If the scattering becomes dominant due to the presence of particles, it is reasonable that the peak pressure decreases as the volume fraction increases.

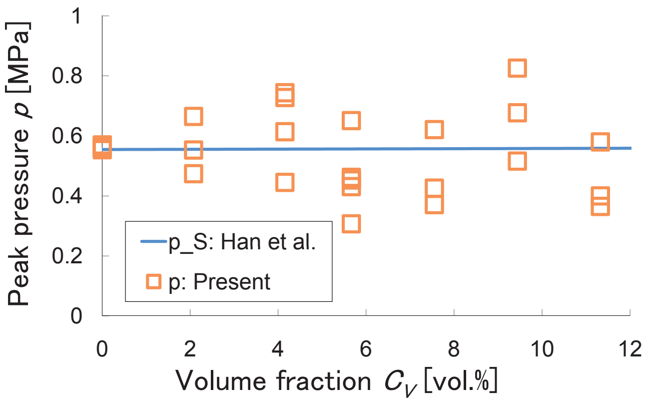

Figure 8: The relation between the peak pressure and the volume fraction of particles C_V.

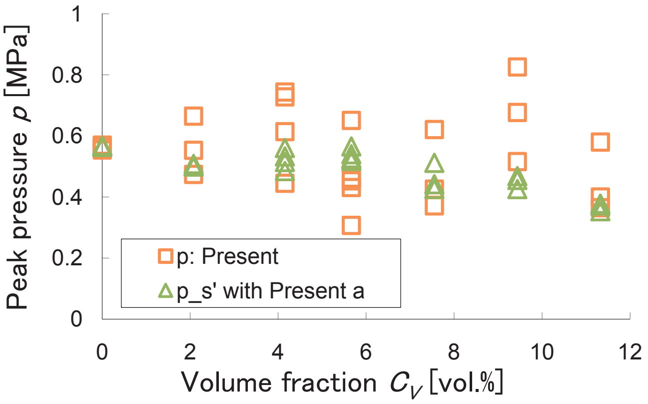

Figure 9: The relation between the peak pressure and the volume fraction of particles C_V estimated from wave speeds.

3 Summary

We used projectile impact to study the propagation of coupled structural and pressure waves in slurry-filled polycarbonate tubes. The main disturbance travels at a Korteweg speed for water case but becomes slower as the volume fraction of particle increases. The wave speeds in experiments indicated the difference from the theoretical estimations proposed by Han et al. Peak pressure in experiments shows weak dependence on the volume fraction and agree with the trend of the theoretical estimations.

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