FLUID-SOLID INTERACTION DURING A SHOCK WAVE IMPACT ON A CONVERGING COMPOSITE STRUCTURE

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1 Background

Shock focusing in water is of interest in many applications, and in particular for marine structures subjected to dynamic loading events. In general, a naval vessel has many convergent sections, for example the rudder-hull junction, propeller shaft(s) and bow thrusters. If a nearby explosion would generate a shock wave that can enter the convergent sections and focus as it converges to the apex, tremendously high pressures can be generated. Here, we are investigating a so-called worst case scenario and we define this as a scenario where the shock wave reflections off the surrounding confinement are minimized in order to allow for a maximum of energy contained in the shock wave to reach the focal region. A geometric shape that minimizes reflections is given by a logarithmic spiral [1]. This particular geometry has been used in previous investigations for shock focusing in air, both in experiments, [2], and in numerical simulations, [3]. In this paper we present results from converging shocks in water contained in convergent geometries made of aluminum, polycarbonate and fiber composites.

2 Experimental setup

The experimental setup consists of a gas gun, a visualization system and the specimen. The specimen is formed by a water-filled convergent cavity that is sandwiched between two windows and a square-shaped piston that is used to seal-off the entrance to the water chamber. Figure 1 depicts the gas gun setup and Figure 2 shows the two types of specimens used in this study. In Figure 2 (a) a sketch of the solid polycarbonate sample is shown. The convergent region in the core material is filled with water and sandwiched between two polycarbonate windows. Figure 2 (b) shows a thin-walled carbon fibre sample that will be filled with water and sandwiched between the same type of windows as the solid polycarbonate core.

The so-called Bowden-Brunton method [4] is used to generate the shock wave in the water. A 220 g projectile launched from the gas gun impacts the rear part of the plunger at the specimen and generates stress waves that will create a shock wave in the water. The shock generated in the water results in both pressure (longitudinal) and shear (transversal) waves in the surrounding material. In turn, the shear and pressure waves in the solid interact with the water, creating a coupled problem.

To visualize the shock focusing process a 10-inch diameter Z-folded schlieren system was used. The schlieren technique is a qualitative technique that visualizes changes in the index of refraction due to compressibility effects of the shock medium, e.g. a change in density or pressure. The schlieren setup seen from above is shown in Figure 3, and the schlieren technique is explained in detail by Settles, [5].

Earlier results on shock focusing in water with different types of core materials using a convergent 22 degree wedge-shaped geometry have been reported earlier by Eliasson et al, [6]. From this work, it is clear that the type of material plays an important role in the shock focusing process. A "fast" material such as aluminum (compare longitudinal and transversal wave speeds inside the core material to the incoming shock Mach number) generates cavitation inside the water-filled section, while a "slow" material such as Solitane deforms the surrounding material more easily.

3 Worst case scenario

The worst case scenario, i.e. no reflections off the boundary, was introduced by Milton and Archer, [1], and is given by a logarithmic spiral. The shape of the curve can be represented by the following equation

$$r = \frac{L}{\cos\chi} e^{\frac{\chi-\theta}{\tan\theta}} \qquad (1)$$

where L is the characteristic length of the duct, χ is the characteristic angle of the duct, and θ and r are the polar coordinates, see Figure 4.

The characteristic angle χ depends on the Mach number of the incoming shock wave, M_s. In order to find the appropriate shape for a water-filled logarithmic spiral for an incoming shock Mach number of M_s =1.1 Whitham's geometrical shock dynamics (GSD) was used, [7]. With GSD, we are able to express the characteristic angle, χ, in terms of known parameters given by the incoming Mach number, M_s, and constants from the equation of state for water. In this study, we used a stiffened equation of state, also referred to as the Tamman equation of state, [8], given by the following expression

$$e = \frac{p + \gamma_\infty p_\infty}{\rho(\gamma_\infty - 1)} \qquad (2)$$

where e is the internal energy, p is the pressure, ρ is the density and γ_∞ and p_∞ are constants. The constants are chosen such that the speed of sound in water using the stiffened equation of state is the same as that for the speed of sound in water for room temperature in the laboratory.

4 Pressure measurements

To quantify the experiments and to be able to compare results and validate numerical solvers, polyvinlyidene difluoride (PVDF) gauges are being developed in the lab [9]. PVDF film is a piezoelectric material which can turn a dynamic mechanical change such as change in shape due to an ambient pressure into electrical signals. There are several properties of PVDF sensors which make them suitable for these experiments;

- Wide frequency range (0.001-109 Hz). This is crucial for shock wave applications, because the pressure changes very fast.
- Vast dynamic range (can measure pressure up to GPa range).
- Low acoustic impedance (close match to water).
- Can be fabricated with ordinary lab tools. No special equipment needed.
- Relatively cheap when compared to commercial hydrodynamic-shock sensors.

For each one of the PVDF gauges, calibration of its dynamic response is needed, due to individual differences from the fabrication process. To calibrate them, a hydrodynamic shock tube [10] is used. The only difference between a hydrodynamic shock tube and a common gas shock tube is that water is filled into the driven section of hydrodynamic shock tube. A commercial pressure sensor with exceptionally fast response time (1 µs, Model 113B31 ICP Dynamic Pressure Sensor) is used to calibrate the PVDF sensors in the hydrodynamic shock tube. In Figure 5 (a), the driven part of the hydrodynamic shock tube is shown. There are three transducers attached to the shock tube, where the middle one is the commercial transducer and the two on each side of it are laboratory made PVDF transducers. In Figure 5 (b) a typical pressure response from two laboratory PVDF sensors are compared with the commercial transducer. It is seen that the lab-made sensors are working and are as fast as the commercial sensor.

5 Test samples

The fiber carbon composite samples have been prepared and pressure measurements are now work in progress and quantitative results will be presented at the ICCM 18 meeting.

At first, a simpler geometrical shape with planar walls and an apex in the form of a half circle was built, see Figure 6. This preliminary test sample was built using four layers of material. Holes for pressure transducers have been drilled and the windows consist of 1 inch thick polycarbonate, see Figure 7.

The logarithmic spiral made of a solid polycarbonate block is shown in Figure 8 (a). It is made of a 1 inch thick core material with 1 inch thick polycarbonate windows. The logarithmic spiral for this sample is matched to an incoming shock Mach number of M_s =1.1.

6 Results

Schlieren images from a shock test with the solid logarithmic spiral sample made of polycarbonate can be seen in Figure 8 (b) and (c). Figure 8 (b) shows a schlieren image of the sample before the impact and Figure 8 (c) shows the sample during a shock test. A large dark area outside the logarithmic spiral cavity is observed and this is due to cavitation of the thin liquid film in between the windows and the core. The light is blocked out by the cavitation bubbles. Cavitation is also seen inside the logarithmic spiral cavity, which is due to the rarefaction wave from either the motion of the piston or the deformation of the fluid-solid interface.

8 Conclusions and future work

The schlieren technique works well for a qualitative understanding of the shock event and these images can be used as a comparison and validation of numerical simulations that will be performed as part of the future work of this project.

The laboratory made pressure transducers are working and results from both the solid polycarbonate core and the thin-walled fiber carbon composite will be compared and presented at the ICCM 18 meeting.

Our simulations will be performed using OVERTURE, a computational framework developed by a group from LLNL [11]. OVERTURE is a package of finite difference codes for solving partial differential equations on curvilinear overlapping grids using adaptive mesh refinement. Here we will be using a multi-physics solver to take the fluid-structure interaction into account. The Euler equations with a stiffened EOS, equation (2), are used in the fluid domain and linear elasticity is assumed in the solid domain. Preliminary numerical results on aluminum cores show that three-dimensional effects are very important to take into account. The change in maximum pressure for a three-dimensional compared to a two-dimensional logarithmic shape is on the order of twelve times larger. A snapshot of the numerical simulations for a two-dimensional logarithmic shape made of aluminum is shown in Figure 9. A detail worth noting is that the shock front is not perpendicular to the fluid-solid interface. The reason for this is the following: due to the high hydraulic pressure behind the shock wave, the solid will be deforming and moving away from its original shape. In order to match the tangential velocity of the fluid along the shock front at the boundary, the shock wave must have an angle with the undisturbed boundary. This phenomenon is not visible if the solid part of the simulation is omitted and instead treated as a rigid boundary.

To study the three-dimensional effects using experiments, we have constructed three-dimensional test models. The three-dimensional test models will be equipped with pressure sensors only because no visualizations can be done.

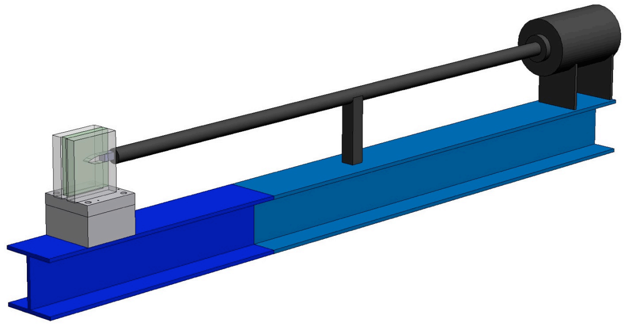

Fig. 1 Experimental setup consisting of a gas gun and the sandwich structured specimen.

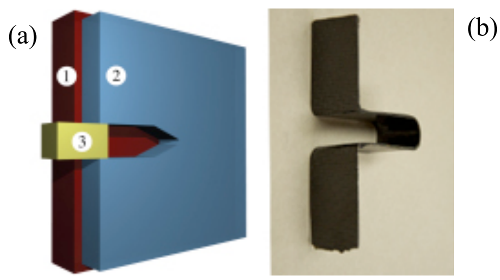

Fig. 2. (a) An illustration of the sandwich structure with a water-filled wedge. (1) polycarbonate window, (2) core with water-filled wedge, and (3) piston that the projectile impacts upon. (b) The thin-walled composite sandwich structure without windows and piston.

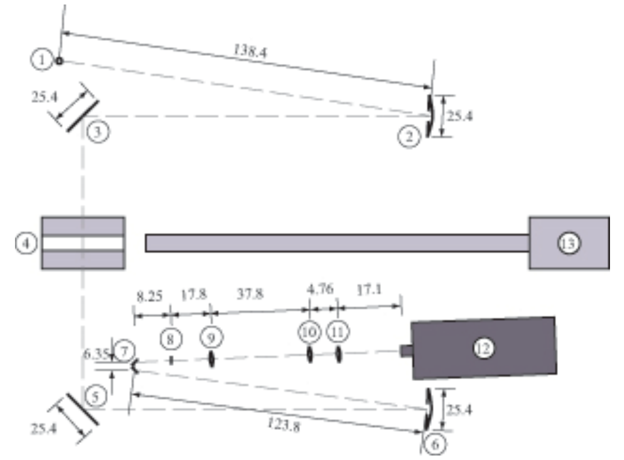

Fig. 3. An overview over the optical setup seen from above. (1) Spark source, (2) 25-cm spherical mirror, (3) 25-cm flat mirror, (4) sample, (5) 25-cm flat mirror, (6) 25-cm spherical mirror, (7) two mirrors, (8) knife edge or color filters, (9) 300-mm achromatic lens, (10) 200-mm achromatic lens, (11) 200-mm lens, (12) Nikon DSLR camera, (13) gas gun. The grey dashed line shows the light path. Distances are given in centimeters.

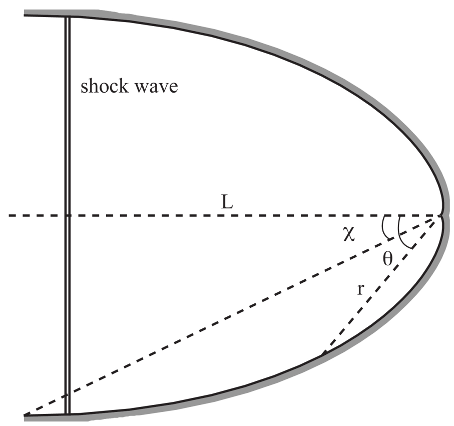

Fig. 4. Logarithmic spiral given by equation (1).

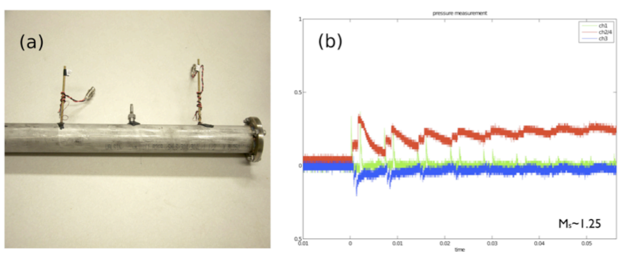

Fig. 5. (a) Pressure sensors attached onto the high-pressure part of the hydrodynamic shock tube. Left and right: lab-made sensors. Middle: Commercial PCB pressure sensor. (b) Sensor responses during shock event. Green and blue: lab-made sensors. Red: PCB pressure sensor.

Fig. 6. The first test version with a half circle apex made of fiber composite sample. The sample consists of four layers of material.

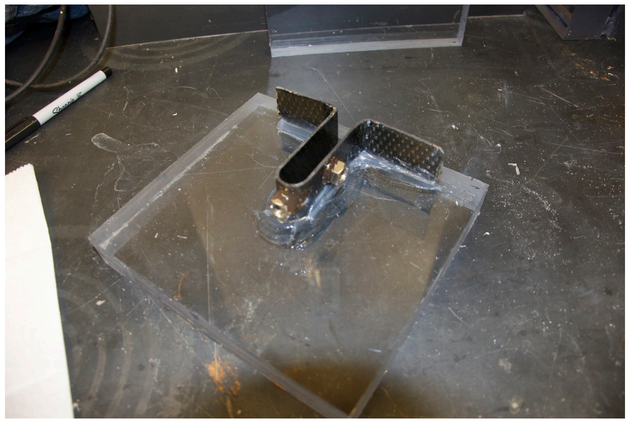

Fig. 7. The four layer carbon fibre sample is glued between polycarbonate windows and prepared with holes for pressure transducers.

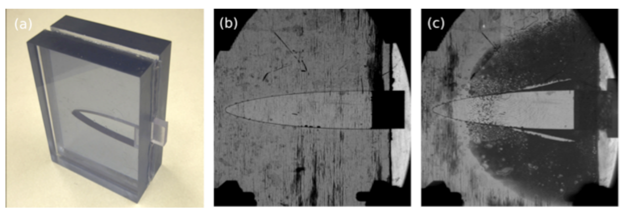

Fig. 8. (a) A typical example of our three-part test model. (b) - (c) Schlieren image of the model before and during shock.

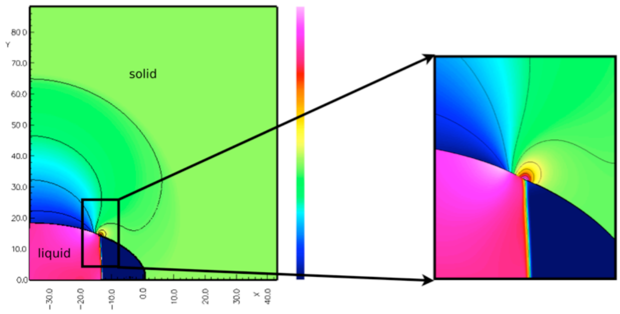

Fig. 9. Snapshot of fluid-structure interaction simulation. The solid material (green base color) is aluminum. Divergence of displacement is plotted in the solid part, and pressure is plotted in the fluid part. Right: Oblique shock front along the boundary.

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