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Investigation of shock wave focusing in water in a logarithmic spiral duct, Part 1: Weak coupling

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ABSTRACT

Shock focusing in water is a phenomenon that can occur during the impact of a shock wave generated by an underwater explosion onto any type of convergent marine structures. To predict the dynamic material response of the marine structure, it is important to understand the shock wave dynamics during the focusing event. In this paper, both experimental investigations and numerical studies of two-dimensional shock focusing in water are presented. Here, a convergent geometry given by a logarithmic spiral curve is used to focus the shock waves. In the experiments, the interaction between three types of materials and the shock wave in water is explored by using high-speed photography. Distinct features of such flows are unveiled. Three scenarios have been considered in simulations: a rigid structure where only the water-filled region is taken into account, a fluid–structure interaction problem in which the surrounding material responses are included, and an axisymmetric simulation to determine the three-dimensional effects.

1. Introduction

Shock focusing is a fundamental tool to generate extreme conditions at the focal region. It is utilized in both basic research and various applications such as in the study of shock stability, implosion fusion reactors and medical treatment for kidney stones (Gardner et al., 1982; Lindl et al., 1992; Chaussy et al., 1980). Shock focusing typically occurs because of the reflection from complex boundaries surrounding the shock focusing media or inhomogeneities of the flow field (Sturtevant and Kulkarny, 1976). For example, a planar shock front becomes curved as it propagates inside a shock wave lithotripter, a reflector in a particular shape used to generate a focused shock wave to destroy kidney stones (Mulley, 1986). Many analytical, experimental and numerical studies have been conducted on shock focusing. Most of the work focused on the generation and stability of cylindrical and spherical converging shock waves in gases (Guderley, 1942; Perry and Kantrowitz, 1951; Takayama et al., 1987; Schwendeman and Whitham, 1987; Eliasson et al., 2008). In recent years, the use of shock wave focusing in biomedical applications has increased. Examples are shock wave lithotripsy (Mulley, 1986; Gerald, 1997; Weiland et al., 2007) and drug delivery by shock waves (Kato et al., 2000; Doukas and Kollias, 2004). The working medium for both of these applications is water or a water solution. In general, shock focusing in water generates much higher pressures than shock focusing in air, due to the increase in density and speed of sound in water as compared to air (Ridah, 1988; Fleck and Deshpande, 2004).

An application of particular interest to the navy is shock loading from underwater explosions (UNDEX). UNDEX poses a tremendous threat to all kinds of naval structures. In particular, shock wave focusing from UNDEX can take place in several convergent sections on a naval vessel, such as rudder–hull junction, propeller shaft and bow thruster. The main factor that influences the focusing behavior of the shock wave in water is the geometry of the convergent sections, as suggested by previous studies of shock focusing (Schwendeman and Whitham, 1987; Coleman and Saunders, 1989; Eliasson et al., 2007). Other factors, such as the shock strength and the material properties of the surrounding section, also play a critical role in determining the focusing effects of the shock wave.

In order to obtain an upper limit of the most severe conditions that UNDEX can generate, we propose to study shock focusing in geometric shapes leading to a maximized energy at the focal region. The geometric shape chosen for this study is given by a so-called logarithmic spiral which was presented first by Milton and Archer (1969). Since the shape of the shock front far enough away from an UNDEX event can be approximated to be planar,

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all simulations in this paper starts with a planar incident shock wave.

Furthermore, multiphase interactions including liquid–gas interaction and liquid–solid interaction are common in shock focusing applications. For example, a study on superseismic loading shows that the fluid–solid interface deflection induced by the shock impact can result in modified fluid dynamics (Arienti and Shepherd, 2002). In general, multiphase interactions are challenging for both experimental and numerical investigations. In experiments, ultrafast diagnostic methods are needed in order to characterize the fluid and solid dynamics simultaneously (Espinosa et al., 2006; Giordano et al., 2005). In simulations, strategies to take the effects of coupling between the fluid and the solid phase have been developed (Shin, 2004; Giordano et al., 2005; Young et al., 2009) and are available in many different simulation packages.

Here, we present results of shock focusing in a water-filled convergent section surrounded by a bulk material using both experiments and numerical simulations. The experiments consist of shock focusing in a water-filled convergent section surrounded by different types of bulk materials: polycarbonate, aluminum and polymethylmethacrylate/methacrylate (PMMA). The plastic materials are used because they are transparent and simultaneous wave propagation in the sample and inside the water-filled region can be obtained. The metallic sample is closer to the materials that are used in many marine applications. Three different types of simulations are presented and compared to experiments: (i) a two-dimensional rigid confinement, (ii) a two-dimensional multiphysics simulation that takes both the water in the convergent section and the surrounding solid material into account, and (iii) an axisymmetric rigid confinement. A two-dimensional rigid simulation is chosen because it should give the ideal maximum pressure at the focal region, providing an upper limit on e.g. maximum density and pressure close to the focal region, and it provides an understanding if the boundary can be assumed to be rigid or not. The two-dimensional fluid–structure simulation shows the importance of enabling energy from the incident shock wave to being distributed to the core material, as is the case in the experiments. It also shows how much the maximum pressure is reduced by assuming a linear elastic response of the surrounding structure. The last set of simulations, axisymmetric, indicates the importance of taking three-dimensional effects into account.

2. Experimental technique

Experiments are performed using an impact technique where a projectile from a gas gun impacts onto the experimental specimen. The projectile impact leads to generation of a propagating shock wave in a water-filled convergent section in the experimental specimen. As the shock wave propagates into the convergent section it will focus and generate very high pressures at the focal region. Two different schlieren visualization techniques are used to capture the shock dynamics and the interaction with the surrounding material during the focusing phase: single-shot photography with high resolution and high-speed photography.

The experimental setup consist of a gas gun, a 25.4 cm-diameter Z-folded schlieren imaging system, and the experimental specimen. The experimental technique and the visualization system have been explained elsewhere in detail (Wang and Eliasson, 2012; Wang et al., 2013), and will be only briefly explained here. The experimental specimen is shown in Fig. 1. The core material with a convergent water-filled section is sandwiched between two transparent optical quality polycarbonate windows measuring $182 \times 205 \times 12.7$ mm. The shape of the convergent cavity is given by a logarithmic spiral and this shape was chosen due to its ability to focus a shock wave with minimal reflections (Inoue et al., 1993, 1995). The shape is derived using Whitham's geometrical shock dynamic theory (Whitham, 1974) based on a shock Mach number $M_s = 1.1$ with a stiffened equation of state (Wang and Eliasson, 2012). The length of the convergent cavity, also referred to as the characteristic length of the logarithmic spiral, is set to $L = 114$ mm, Fig. 1. A polycarbonate blocker is placed at the entrance of the convergent section to prevent the water from leaking out. The core materials are made of polycarbonate, aluminum or PMMA, and the windows are made of polycarbonate. The edges between the windows and the core are sealed with silicone to prevent water leakage from the specimen. Special care is taken to remove any bubbles in the water-filled region before an experiment.

Details of the wave propagation through the blocker and the experimental specimen along with shock Hugoniot curves for the various materials involved are carefully explained in our earlier work (Wang and Eliasson, 2012).

2.1. Single-shot photography

High-resolution single-shot photographs are taken with a Nikon D90 SLR camera with a AF-S Nikkor 18–105 mm zoom

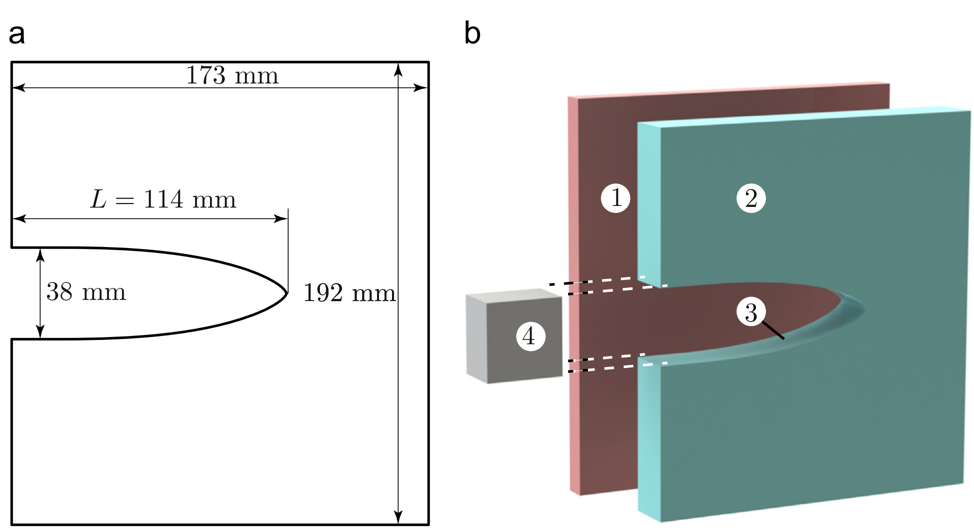

Fig. 1. (a) Experimental core and exploded view of the assembly. The core thickness is 25.4 mm for the aluminum and polycarbonate samples. For the PMMA samples, this thickness is 6.3 mm. (b) Exploded specimen assembly with (1) transparent window (only one is depicted for clarity), (2) core, (3) water-filled convergent section, and (4) blocker placed at the entrance of the cavity to serve as impact site and to prevent water from leaking out.