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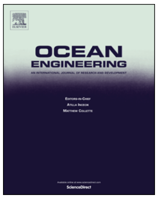

Numerical simulation of underwater explosion near air–water free surface using a five-equation reduced model

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ABSTRACT

Underwater explosion phenomena is a complicated problem, however, it has different and important applications. This type of explosion includes strong shock waves with generation of low pressure cavitation's zone and deformable interfaces. The main objective of this article is simulation of interaction of shock wave with interface of two-phase gas–liquid flow and capturing the complicated interface generated from explosion. For this reason, a five equations reduced model is considered with using a new cavitation model including gravity force effect. From the numerical point of view, a Godunov method was applied using HLLC solver. By using MUSCL-Hancock strategy, second order accuracy is achieved. To verify the developed computer code, a one dimensional shock tube test case and two test cases including one dimensional cavitation in open tube and a two dimensional underwater explosion where its experimental results can be found in the related literature are used for comparison to justify the obtained results. The comparison of the results confirms an excellent accuracy of the numerical results. The proposed new cavitation model, on the other hand, is capable of calculating low pressures and simulating the dynamic creation and evolution of the bulk cavitation below the free surface.

1. Introduction

Underwater explosions near structures and a sea free surface are of practical importance in many fields. The underwater explosion effects on nearby structures initially which can be considered as a high-pressured shock and a cavitation collapse. For the underwater explosion (UNDEX) analysis, water is supposed to be compressible, homogenous and unable to sustain shear stress. Some advanced software codes have been developed specifically for simulations of UNDEX and fluid–structure interactions including LS-DYNA (Hallquist, 1999). MSC.Dytran includes structural parts and/or computational fluid dynamics (CFD) parts and is used for short-term transient analyses. The CFD solver of MSC. Dytran software uses an Eulerian method and employs a finite volume method to discretize the governing conservation laws equations. These equations are integrated in time by a first-order explicit dynamic scheme.

As underwater explosion initiates, due to the tension created behind the rarefaction wave, cavitation can take place and some part of the water is splashed upwards, creating a "spray dome."

One most important type of cavitation is a bulk cavitation. The bulk cavitation is created by the compressive shock wave reflecting from the free surface. As the incident shock wave reflects from the free surface, it creates a reflected tension, or rarefaction wave. This reflected tension makes low pressure area. The bubbly cavitation is excited by rarefaction wave. This process tends to expansion of corresponding zone because of micro-bubble growth in that zone (Davydov and Kedrinskii, 2008). The characteristics of bulk cavitation area are dependent on the amount, kind and depth of the explosive charge. The very low pressure in the cavitation zone is required to be modeled via coupling to a cavitation model. Otherwise negative pressure will appear in numerical results. It is true that negative pressure can be registered both in a liquid and in a cavitation zone but due to the numerical restriction of equation of states the phenomenon cannot be simulated and the code will fail. Some one-fluid models that have been proposed to model the bulk cavitation are cut-off model (Chen and Heister, 1994), vacuum model (Tang and Huang, 1996), Schmidt model (Schmidt, 1997) and Qin model (Qin et al., 1999). The specifications of these models have been mentioned in detail in Refs. Liu et al. (2004) and Xie et al. (2006).

For simulating the underwater explosion the employed numerical method must be able to capture gas–liquid interface (water–air interface) accurately. Generally underwater explosion is a compressible multi-phase flow problem. To simulate these

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problems, two classes of methods have been developed as: sharp interface methods and diffuse interface methods. Sharp interface methods are based on Lagrangian viewpoints. In this framework, the computational cell moves and deforms with the flow interface. However, for some fluid flows, deformations are unbounded and resulting mesh contortions can make the Lagrangian numerical schemes inaccurate (Scheffer and Zukas, 2000). For eliminating these drawbacks a robust method called Arbitrary Lagrangian–Eulerian (ALE) developed to reduce the mesh deformations of Lagrangian method but the effect has still some limitation (Farhat and Roux,1991) and (Kim and Shin, 2008). Also, Lagrangian and ALE methods have more computation cost in comparison to the Euler method. Eulerian methods use a fixed mesh and Euler equations with an additional equation for tracking or reconstructing the material interface. The most common Eulerian sharp interface methods for capturing of interfaces are the volume of fluid (VOF) method of Hirt and Nichols (1981), the ghost fluid method of Fedkiw et al. (1999) and a level set approach (Mulder et al., 1992). Recent applications of the VOF, the ghost fluid method and the level set method to complex free surface flows have been presented for example in Löhner et al. (2006) and Kleefsman et al. (2005) and de Sousa et al. (2004) and Di Mascio et al. (2007). Recently a combination of level set and ghost fluid method was developed by Terashima and Tryggvason (2009). A drawback of these schemes is that the particular implementation can become rather difficult. Numerical simulations of underwater explosion near free surface are made by Petrov and Schmidt (2011). In their study, the flow in each medium is explained in terms of the Euler equation with the conditions of matching on the free surface. Recently, underwater shock and free surface interaction were studied by Xie et al. (2007). In their work the wave propagation and refraction at the free surface were simulated by the ghost fluid method (GFM) and modified ghost fluid model (MGFM). They include a one fluid model of cavitation to improve their method capability in cavitation modeling.

Other numerical methodology which is going to be used in this article is a diffuse interface method. See for example Abgrall (1996), Saurel and Abgrall (1999) and Saurel et al. (2009). In these methods diffuse interfaces appear as a consequence of numerical diffusion. Kapila five-equation two-fluid model has shown good potential for the numerical simulation of interfaces separating compressible fluids as well as wave propagation in compressible mixtures Kapila et al. (2001). They proposed the sound velocity as $\frac{1}{\rho\hat{c}^2}=\frac{\alpha_1}{\rho_1 {c_1}^2}+\frac{1-\alpha_1}{\rho_2 {c_2}^2}$ for the five-equation model. This sound velocity is also well-known as Wood sound velocity. Saurel et al. (2009) declared that this mixture sound speed has a non-monotonic variation with volume fraction. A bad consequence of the Wood speed of sound appears when a pressure wave interacts with a diffuse interface.

Allaire et al. (2002) proposed five-equation model for the simulation of interfaces between compressible interfaces. This model is very similar to five equation model proposed by Kapila et al. (2001) and Murrone and Guillard (2005), except that its equation for the volume fraction is different. Ansari and Daramizadeh (2013) used Allaire et al. (2002) model for modeling different compressible two-phase flows and shock interface interaction cases. The high accuracy of the results presents good performance of the model.

This study aims to develop a numerical procedure for simulating detailed events of a two-dimensional (2D) underwater explosion near a free surface. Therefore, the proposed method must deal simultaneously with different physics such as cavitation and interaction of shocks with gas/liquid (air–water) free surface interfaces. In present work for simulating underwater explosion and shock wave interaction with interfaces, five equations reduced model proposed by Allaire et al. (2002) is coupled with a new cavitation model and the gravitational effects are taken into account. The previous Schmidt and Qin cavitation models are based on Wallis sound relation. This sound relation is not applicable with the considered five-equation model because of non-monotonic behavior (Saurel et al., 2009). From numerical viewpoints a HLLC numerical method is applied to solve all conservative equations. By using MUSCL-Hancock strategy, second order accuracy is achieved.

The features of the proposed cavitation model are as follows:

1. Simplicity of the present method.
2. The independence of the proposed model to sound velocity and difficulties caused by non-monotonic behavior of some sound velocities.
3. Good performance of the model during creation and evolution of cavitation.
4. Ability to pressure field and volume fraction estimation in cavitation zone and derivation of the related iso-counters with high accuracy.
5. In the proposed model, all the phases are considered to be compressible and constant density assumption has not been used.

The remainder of this paper is organized into six sections. In Section 2, the reduced five-equation formulation and equation of states and appropriate sound relation are presented. In Section 3, the new cavitation model and its formulation are derived. In Section 4, the numerical method is presented, with more attention for the phase advection equation. In Section 5, numerical results are discussed, for one shock-tube problem and two underwater explosion problems. Section 6 concludes the obtained results.

2. Five equations reduced model

A five equations reduced model is composed of two mass equations, a mixture momentum equation and a mixture energy equation (Allaire et al., 2002) and (Murrone and Guillard, 2005). These equations are written in a conservative formulation, while the first equation of this model is a non-conservative equation for the volume fraction which contains a non-conservative term involving the divergence of the velocity. The equations are as follows:

Volume fraction evaluation equation:

$$\frac{\partial \alpha}{\partial t}+\vec{u}.\vec{\nabla}\alpha=0 \tag{1a}$$

Mass conservation equations for gas and liquid phases:

$$\frac{\partial\left(\alpha_g\rho_g\right)}{\partial t}+\nabla.(\rho_g\alpha_g\vec{u})=0 \tag{1b}$$

$$\frac{\partial(\alpha_l\rho_l)}{\partial t}+\nabla.(\rho_l\alpha_l\vec{u})=0 \tag{1c}$$

mixture momentum conservation equation:

$$\frac{\partial\left(\rho\vec{u}\right)}{\partial t}+\nabla.(\rho\ \vec{v}\ \otimes\ \vec{u})+\vec{\nabla}P=0 \tag{1d}$$

mixture energy equation:

$$\frac{\partial(\rho E)}{\partial t}+\nabla.((\rho E+P)\vec{u})=0 \tag{1e}$$

where α, ρ, u, P, E, e are the volume fraction, density, velocity, pressure, total energy and internal energy, respectively. The