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Cross validation of analytical and finite element models for Hydrodynamic Ram loads prediction in thin walled liquid filled containers

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ABSTRACT

To reduce the vulnerability of both civilian and military aircraft, it is important to take the Hydrodynamic Ram pressure into account when designing their fuel tanks. Hydrodynamic Ram is especially dangerous for thin walled lightweight structures that cannot be armoured due to weight penalty reasons. Similarities in bubble behaviour between Hydrodynamic Ram and underwater explosion situations were observed in recent high-speed tank penetration/water entry experiments. A confined version of the Rayleigh–Plesset equation – which is classically used for incompressible bubble dynamics analysis (including underwater explosion) – was developed to simulate a bubble created by a Hydrodynamic Ram event induced by projectile penetration at ballistic speed in a confined geometry filled with a liquid. In the present work, the authors validate the proposed confined Rayleigh–Plesset equation for application on a spherical container thanks to quasi-incompressible ALE finite element simulation results. Then to determine the effect of liquid compressibility on confined bubble dynamics, the authors compare predictions of bubble radii obtained with the confined Rayleigh–Plesset equation with the prediction obtained using compressible finite element simulations. Eventually, the authors discuss differences in the bubble dynamics and hydrodynamic loads predictions obtained with the two approaches.

1. Introduction

In the event of an impact of high speed/high energy projectiles on liquid filled tanks, the container may suffer large hydrodynamic loads that could possibly rupture the entire structure. This impact scenario is referred to as Hydrodynamic Ram. This scenario is especially dangerous for thin walled structures that cannot be armoured due to weight penalty reasons. There is an insistent need for tools to model hydrodynamic effects that occur during a Hydrodynamic Ram for not only military (vulnerability requirement) but also civilian aircraft design (safety reasons). Numerical modelling of Hydrodynamic Ram dynamics would allow us to improve the survivability of structures with respect to this particular threat.

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Generally, during the impact of a projectile in a large container, the cavity created by the drag of the projectile will be enclosed by the surrounding liquid, and a large bubble will be created as in Deletombe et al. (2013), Disimile et al. (2009), and Lecysyn et al. (2010). This bubble behaves in the same manner as gas bubbles generated by other means (Fourest et al., 2014). The stages of bubble dynamics during Hydrodynamic Ram events first described by Ball (1985) are in agreement with those described by Fuster et al. (2009) for other cavitation problems, i.e. *expansion stage, deceleration stage, initial compression, implosion, and rebound*. These oscillating bubble processes have been investigated for a long time. Extensive experimental and theoretical studies have been carried out on that subject, first motivated by the discovery that bubbles are a source of damage (erosion caused by cavitation, Philipp and Lauterborn, 1998; rupture due to underwater explosion, Cole, 1945; etc.), and more recently for the beneficial aspect of cavitation (micro-surgery, Venugopalan et al., 2002; Vogel, 1997, and chemical reaction, Hauke et al., 2007). In these phenomena two potential sources of damages have been identified in the literature. A collapsing bubble emits a shock wave in the liquid and if the bubble is near a solid boundary, it will develop a liquid jet (Plesset and Chapman, 1971; Lauterborn and Bolle, 1975; Chahine et al., 1994). This jet originates from the opposite side to the solid boundary, penetrates through the bubble and impacts the solid boundary at high velocity.

There are two main differences between Hydrodynamic Ram bubbles and bubbles created by other means. Firstly, in Hydrodynamic Ram phenomena the bubble is generated in a closed container. This container is usually sufficiently small for the liquid medium not to be considered infinite, with sufficient distance between the bubble and each wall so that no hydrodynamic jet is formed towards the walls. However when bubbles are in a closed container, an additional cause of damage arises, that is the bursting of the container under the solicitation generated by the bubble growth (Deletombe et al., 2013). In the first approximation if the liquid is assumed incompressible, the container may suffer a large deformation in order to accommodate the gas bubble expansion (maximal radius of 120 mm for a 7.62 mm NATO bullet impacts at 850 m s^{-1} in Deletombe et al., 2013).

Secondly, in Hydrodynamic Ram events the bubble is generated by projectile drag, hence it is dependent on the projectile parameters. Deletombe et al. (2013) presented experiments of the impact in water of non-academic projectiles (7.62 mm NATO bullets) at ballistic speed (850 m s^{-1}). They enlightened the effect of the tumbling of projectiles on the cavity shape during Hydrodynamic Ram events. During tumbling the projectile transmits its momentum more quickly to the liquid medium. An extreme case would be an instantaneous and homogeneous transfer that would lead to a spherical cavity bubble. On the other hand, a projectile that cannot tumble will transfer its kinetic energy more slowly and will create a more elongated cavity shape in its wake as in Varas et al. (2009a). Bless (1979) observed that the pressure resulting from the tumbling of the projectile could be five times greater than the one observed in a case without tumbling. Deletombe et al. (2011) performed pressure measurements for 7.62 mm bullet impacts on water filled tanks, and observed greater pressures during the drag stage than during the subsequent cavity growth stage but in shorter times. They nevertheless concluded that none of these stages could be neglected for the sizing of structures because they could both induce significant impulse.

The present work focusses on the cavity growth and collapse stages in the case of tumbling projectiles. However the tumbling of projectiles is particularly difficult to correctly simulate with available numerical tools. The most advanced numerical simulations of this phenomenon presented in the open literature deal with non-deformable projectiles. In these simulations the main difficulty comes from the large deformation of the fluids during the simulation. Anyway the whole sequence of events up to the collapse (that might take up to 30 ms) is not entirely simulated. To deal with such a difficulty, explicit finite element codes were developed which can simultaneously handle Lagrangian and Eulerian formulations in a compatible way for different sub-domains or mediums within a given fluid–structure problem. Lagrangian formulation can be used for instance for the projectile and the container and either an Eulerian formulation in a Coupled Euler Lagrange approach (Varas et al., 2009b, 2012a,b; Artero-Guerrero et al., 2013; Sareen et al., 1996) or a particular (SPH) approach (Varas et al., 2009b; Sauer, 2011) can be used for the fluid medium. Different approaches exist to couple the Lagrangian and Eulerian domains. Conform meshing can be used (merged nodes at the interface), to create coupling, or contact interfaces (penalty methods, Lagrange multipliers, etc.) of many different types. For instance in the simulations from the literature, the interaction between the solids and the fluids is done using a penalty based approach.

Another approach has been chosen in the present paper that consists in studying this complex phenomenon with analytical models. Pioneer studies on the subject were carried out by Morse and Stepka (1966), Stepka and Morse (1963), Stepka et al. (1964, 1965), Stepka (1966). They identified the factors that affect the structural loading during an Hydrodynamic Ram event. These factors can be organised with respect to the three media: the projectile (shape, size, and material), the tank wall (thickness, material, pre-stress, and protective structure) and the liquid properties. They tried to determine the effects of the different parameters on the survivability of tanks. However they could not clearly establish a correlation that could embrace the effects of all parameters. The present authors proposed an approach based on the classic Rayleigh–Plesset equation that describes the dynamics of a single gas bubble in an infinite liquid domain. The Hydrodynamic Ram bubble dynamics observed in Deletombe et al. (2013) were described using a modified version of the Rayleigh–Plesset equation introducing confinement effects of a spherical container on the bubble dynamics. This model has been applied to experiments presented in Deletombe et al. (2013) with the calibration of the structure response in Fourest et al. (2014). Then it has been applied to one of these tests with the structure response approximated using analytical plate formulae in Fourest et al. (2015). The obtained results are promising, however this analytical model has not yet been validated against experiments or numerical simulations in 1D conditions, furthermore the model used in this approach is incompressible. The effect of liquid compressibility on unconfined bubble dynamics is known to be mainly important during