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Breaking wave impact on a floating body with air bubble effect

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ABSTRACT

The hydrodynamic problem of a breaking wave impacting on a floating body with air bubble effect is modelled based on the incompressible velocity potential theory, which is solved using the boundary element method in the time domain. To avoid the numerical inaccuracies due to the sharp temporal and spatial variations of velocity and pressure at the initial stage of impact, a dual system is adopted. The simulation close to the impact zone is conducted in a stretched coordinate system, while away from the impact zone the deformation and propagation of incoming overturning wave is simulated in the physical coordinate system. The continuities of both pressure and velocity are enforced at the interface of two zones. When the impact zone is no longer small, the dual systems will be merged and the simulation will be undertaken in one single domain. The air bubble trapped between the breaking wave and the solid surface is taken into account based on the assumption that the trapped air undergoes an adiabatic process. An auxiliary function method is used to decouple the nonlinear mutual dependence of fluid loading, body motion and bubble deformation. Simulations are undertaken for cases related to breaking wave impact in various engineering problems, including a solid coastal wall, a freely floating ship cross section, a floating breakwater and a tension leg platform. Detailed results for pressure, free surface profile, bubble deformation and body motion are provided, and their physical implications are discussed.

1. Introduction

The breaking wave is a spectacular phenomenon in the sea. It evidently occurs when there are cyclones, storm surges, tsunami, etc., but it also occurs in mild sea conditions, for example, when a wave meets an obstacle in its path or interacts with other waves. Impact by the breaking wave can pose a great risk to a structure in the ocean, such as a ship, an offshore platform and a breakwater, due to impact produced high loading on the structure. In extreme conditions, a ship may capsize or break, a platform and breakwater can be damaged. Thus the safety, reliability as well survivability of an ocean structure in such a scenario are some of the major concerns in design.

Fluid flow characteristics, including the spatial distribution and temporal variation of velocity, pressure, free surface, during the breaking wave impact are highly complex. When a wave front hits a solid structure, its path is suddenly blocked. The flow direction has to turn sharply, which means a very large acceleration and therefore a very large pressure gradient. The physical process of wave front impact has been demonstrated by Bagnold (1939), Nagai (1961) and Cooker and Peregrine (1995). Various methods have been developed to account for this physical process. Tanizawa and Yue (1992) assumed that

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the solid surface was 'invisible' to the liquid when the wave front arrived at the wall, and the wave would pass the invisible body without any hindrance. Only when the area between the two intersection points of the wall with the undisturbed wave was not small, it would then be taken as the initial wetted surface, and the impact would start at this moment. Zhang et al. (1996) treated the initial impact stage as a self-similar problem. The wave front was approximated as an asymmetric liquid wedge, and the impact velocity was assumed to be a constant and perpendicular to the wall. The wave profile away from the impact was assumed to vary exponentially. Wu (2007a) used a stretched coordinate system method for wave front impact on a wall, and Wu (2007b) subsequently considered the impact by a large liquid droplet on a wall and on a solid wedge. Duan et al. (2009) considered the impact of a wedge shaped wave front on the corner of a coastal wall. The present work considers a two dimensional (2D) breaking wave impact on a floating body or fixed coastal wall. When the section of the structure does not change rapidly, for example near middle section of a slender ship, the two dimensional approximation can be used for impact in the beam sea, similar to the strip theory for ship motion. The result of the 2D theory is expected also to shed some insights into the general 3D problems.

It is generally accepted that the kinetic properties of fluid, especially impact velocity, is the most influential factor for the process of breaking wave impact during impingement onto a structure. However, many scholars have also demonstrated that the entrapped air cavity plays a significant role as well in the physical process of breaking wave impact. The effect of the trapped air pocket was included. The air pocket was assumed to undergo rapid contraction and expansion, and therefore pressure and volume would change adiabatically. An early work is that by Bagnold (1939), in which a wave tank experiment was undertaken. He found that the shock pressure of a thin air pocket was much larger than that of a thick pocket, and when the thickness of air cushion exceeded half of its height, the shock pressure could be neglected. Hattori et al. (1994) investigated the effect of air bubble on wave impact pressure through an experiment. It was observed that the impact pressure with air bubbles was much larger than that without air bubbles. They also found that the characteristics of impact pressure were closely related to the trapped air bubble. The magnitude and frequency of pressure oscillation for the case of the thin pocket being trapped by the breaking wave were much larger than those corresponding to the thick air pocket. When the thick air pocket was trapped, the pressure measured from the sensor would reach a peak rapidly, and after that, it would oscillate with a decreasing amplitude due to the air pocket pulsation. Other typical experimental work on breaking impact includes those by Blackmore and Hewson (1984), Bullock et al. (2001), and Peregrine (2003).

Earlier work on breaking wave impact is based on various approximations, such as Wagner theory (Wagner, 1932) and the method of matched asymptotic expansions (Cointe and Armand, 1987). These approximation methods have been effective for many engineering problems. However, there are also various limitations. A more recent work is that by Song (2015). She used the velocity potential theory with fully nonlinear boundary conditions on the deforming water surface. The trapped air bubble effect and its deformation with time were included based on the assumption of an adiabatic process. A dual coordinate system method was used. The stretched system (Wu, 2007a) was used in a small area of the impact zone at the initial stage to account for the rapid temporal and spatial variation, and physical system was adopted away from the impact zone. Continuity conditions for pressure and velocity were enforced at the interface of two regions. Simulations were undertaken for impact on a fixed wall with air bubble effect.

There are other related works on breaking wave impact using both experiment and numerical simulations. Manjula et al. (2015) examined the response of a slender vertical cylinder under breaking wave loading by a series of model experiments. The cylinder was fixed at the top but was left free on the bottom. Other experimental work includes those by Ma and Li (2002) for the impact on vertical cylinders in shallow water, Stanczak and Oumeraci (2012) on the surface erosion of a dike slope, and by Hu et al. (2017) on the truncated wall in a wave flume. Computational fluid dynamics (CFD) techniques have also played an important role in dealing with breaking impact with large deformations of free surface and air bubble. Bredmose et al. (2015) investigated the scaling and aeration effects on violent breaking water impacts with trapped air based on compressible-flow theory. Choi et al. (2015) solved the modified Navier–Stokes equations with wave reaction force and dissipation term in a dissipation zone to investigate breaking wave impact forces on a vertical cylinder and two inclined cylinders. Kamath et al. (2016) simulated the breaking wave impact, induced by the variation of water depth, on a slender cylinder in a three-dimensional numerical wave tank based on the open source CFD model.

The above studies have significantly advanced our understanding regarding the characteristics of breaking wave impact. However, much of work with air bubble is for a fixed body. In fact, it is more common for wave to impact on a floating body which moves under the wave excitation. Some new physical features may arise due to body motion, which leads to some new challenges in the numerical simulation. A particular feature is that the breaking wave impact loading, the motion and deformation of bubble and its corresponding pressure oscillation are fully and nonlinearly coupled. In present work, we shall develop a two dimensional numerical technique for breaking wave impact on a floating body with air bubble. The incompressible velocity potential theory is used for the liquid flow. The neglected compressibility may be important for a very short period of time (Khabakhpasheva and Wu, 2007). However, during this period the momentum exchange from wave to body is relatively small for cases which we consider, and therefore the compressibility effect of liquid can be ignored. Fully nonlinear boundary conditions are adopted on the deforming free surface and bubble surface, which are tracked by the time stepping method. At each time step, the velocity potential problem is solved by the boundary element method (BEM). The dual coordinate systems (Song, 2015) are adopted at the early stage of impact. The auxiliary function method (Wu and Eatock Taylor, 2003) is used to decouple the nonlinear mutual dependence of fluid loading, body motion and bubble deformation. The method and numerical procedure are verified through the convergence study and comparison for wave impact on a fixed body, reflecting a coastal wall. Extensive numerical results are provided in various case studies, to account for some typical features related to a freely floating ship, a floating breakwater constrained by nearly horizontal cables and a TLP constrained by two vertical tendons. Results are analysed and their physics associated with breaking wave impact on floating bodies are discussed.