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Water entry of cylinders and spheres under hydrophobic effects; Case for advancing deadrise angles

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ABSTRACT

The results of an experimental investigation of water entry of spherical and cylindrical shaped objects with hydrophobic surfaces are presented in this work. The test specimens have a varying deadrise angle. Drop tests have been set up for studying slamming by dropping test objects from various heights toward water surface. Different fluid dynamics phenomena like jet formation, cavity formation, water splashing and flow separation on solid surfaces are investigated and compared with under hydrophobic effects. From digital images captured using a high speed camera, pileup coefficients and splash velocities are measured. It is observed that flow separation occurs earlier with hydrophobic surfaces causing no pressure pulse occurrence on the solid surface at larger penetration depths. Hydrophobicity also causes larger pileups with faster jet flows indicating more kinetic energy transference to the fluid. Along with high speed imaging, the impact loads are calculated and compared with when hydrophobicity is present via strain gauge measurements. It is found that the peak strain values during slamming are smaller with hydrophobic surfaces promoting a reduction in the impact forces while distributing the pressure pulses on a larger wetted area.

1. Introduction

The problem of water impact, which involves the interaction of a structure with a fluid with free surface, has been studied experimentally and theoretically for almost a century. This impact problem, more commonly known as slamming in ocean engineering, either concerns the impact of a floating structure on the sea surface (bottom slamming) or the impact of water waves on ships and other marine structures (breaking wave slamming). Von Karman (1929) and Wagner (1932) are the pioneers in the field of predicting impact forces and pressure distribution during water entry. They developed their method by using potential flow theory in order to estimate the loads acting on a landing seaplane. Since then, their method has been taken as a starting point for numerous researchers and improved to give better results in similar cases and related problems that experience slamming loads. Preventing structural damages and increasing manoeuvrability in ship design, reducing arrival times and increasing fuel efficiency in ship operation, and improving missile entrance into water are few examples to emphasize the importance of the improved understanding of the impact forces and the parameters involved in such slamming events.

The study of fluid-structure interaction during a slamming event has been widely influenced by analytical and numerical models developed for basic geometrical shapes (wedge, cone, sphere, cylinder or flat plate) entering into water since Von Karman's and Wagner's first formulas developed on vertical entry of a wedge. In this method, the pressure and the force acting on a wedge during impact is calculated by applying the momentum theorem, i.e. some of the initial momentum of the body gained until the impact is transferred to a certain mass of water, called the added mass. The problem with this method is that it is valid only on certain deadrise angles and not valid at larger submergences due to the difficulty in calculating the added mass. Many researchers have extended the work of Von Karman and Wagner to different three dimensional geometries. Extensive experimental work has been done to validate these analytical and numerical models. Most of the experimental studies have focused on two-dimensional impact problems with emphasize of the hydrodynamic aspects of such water entry. Experimental measurements of slamming events have been carried out mostly by drop tests where a rigid or non-rigid body is dropped from a certain height creating a desired entrance velocity onto still water. The main aim of such experiments is to investigate the pressure distribution during the impact. An extensive review on the subject has been given by Abrate (2013). Chuang (1967) performed experiments by dropping wedges to characterize the effects of deadrise angle and the entrained air between free surface and the body for

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deadrise angles less than 3°. Chuang (1969) later extended Wagner's theory to axisymmetric bodies and also performed experiments with cones to investigate the three-dimensional effects of slamming (Chuang and Milne, 1971). Lin and Shieh (1997) experimentally investigated the flow pattern during penetration and the pressure characteristics of a cylinder during water impact. Huera-Huarte et al. (2011) studied slamming for small deadrise angles and confirmed the trapped air phenomenon significantly cushions impacts with angles less than 5°. Faltinsen (2000), Cooper and McCue (2011), and Panciroli et al. (2012) carried out their drop tests on non-rigid panels and deformable wedges to study hydroelasticity. Zhao and Faltinsen (1993) developed a nonlinear BEM for two-dimensional bodies with a jet flow approximation and applied it to rigid wedges with deadrise angles between 4° and 81°. Battistin and Iafrati (2003) studied the water impact of two-dimensional and axisymmetric bodies by developing a fully nonlinear BEM taking into account the jet formation at the intersection of the body contour and the free surface. Yettou et al. (2006) performed drop tests to study two-dimensional flow situations and investigated the influence of the drop height thus entrance velocity, the deadrise angle and the mass of the wedge. De Backer et al. (2009) studied the impact of axisymmetric spheres and cones. Okada and Sumo (2000) measured the strains on aluminum plates in water entry. Panciroli et al. (2015a) carried out an experimental study on water entry of curved rigid wedges. Campbell and Weynberg (1980) and Miao (1988) carried out forced cylinder impact experiments and derived empirical relations for the slamming forces and provided an empirical slamming coefficient, Cs.

More recently, in much smaller scales, the impact and spreading dynamics of liquids on solid surfaces have been extensively studied for Newtonian and non-Newtonian fluids. The outcome following impact is evinced to three different forms in liquid impact on solids; spreading, rebounding, splashing. Previous studies has showed that drop deformation depend strongly on surface properties. And it is shown that there are fundamental differences in the hydrodynamics of these impacts between hydrophilic and hydrophobic surfaces. The impact dynamics of slamming on hydrophobic surfaces are unexplored.

1.1. What happens during slamming?

Slamming impact has an impulse character and produce high magnitude local pressure pulses (around hundreds of kPa) which are very short in duration, followed by a lower magnitude residual pressure lasting tens of milliseconds. This pressure distribution rapidly travels across the immersed body surface making a maximum at the solid-fluid interface at the location where the water jet is formed. This water jet propagates along the surface of the immersing body. From the theory and the experiments, it is known that the maximum impact pressure is proportional to the square of the entrance velocity of the body and is always reached in the vicinity of the waterline. The pressure pulse magnitude and the propagation speed are critically dependent on the impact velocity and deadrise angle of the impacting body. The faster the velocity and the lower the deadrise angle it has, the higher the impact force it encounters. These parameters along with the total drop mass and the total volume (buoyancy force) are the main factors shaping the water uprise and splash characteristics.

Following Von Karman's and Wagner's approach, staying within the framework of potential flow theory, slamming forces can be calculated by conducting momentum analysis with the concept of added mass, i.e. the force acting on a rigid body is equal to its added mass multiplied by its acceleration. In Von Karman's approach, water uprise is completely neglected. Wagner (1932) modified Von Karman's formula to take the piled-up water into account. Thus, Wagner's approach gives a larger impact force prediction and is assumed to be more accurate. But the water jet flow, so the splash, is still neglected in his approach. Because in momentum analysis, it is shown that the flux of momentum going into the jet is much smaller compared to the flux of momentum going into the remainder of the fluid in the asymptotic solution. In conclusion, Von Karman's formula underestimates the impact force, while Wagner's formula overestimates it (Cointe and Armand, 1987) for rigid bodies. On the other hand, the conservation of energy dictates us that the rate of change of the energy within the fluid plus the energy loss due to water uprise and splash at the free surface is equal to the work performed by the moving body. Cointe and Armand (1987) investigated the water uprise and the jet flow in detail. According to the asymptotic analysis, half the energy transferred from the body to the fluid is imparted to the main flow and the other half is to be found within the jets developing near the intersections (Cointe et al., 2004). The jet flow (and splash) and the spray at the first contact creates nonlinear effects during the impact (Cointe and Armand, 1987). Panciroli et al. (2015a) investigated the flow physics during water entry of curved wedges via PIV analysis and concluded that between 60% and 80% of the energy transferred to the fluid during the impact is imparted to the risen water, which accounts for the pile-up and the spray jets. Experimental results show that these nonlinearities in the equations of motion as the body penetrates the free surface play an important role in the hydrodynamics of the impact.

From the literature it can be said that an accurate prediction of the impact force can be made under the general simplifying assumptions such as incompressible and inviscid fluid, irrotational flow, no body flexibility, no aeration in flow, no surface tension. Knowing that the maximum impact loads are experienced at the very beginning of impact, these assumptions are not adequate to obtain a right solution to the problem since there are some other effects to be considered. For example, Van Nuffel (2014) investigated the effect of flexibility on cylinder impacts and concluded that the flexibility in the test object decreases the measured pressure and force data. The effect of the surface properties of the entering body on slamming is not fully understood yet. Guzel and Korkmaz (2015) showed the differences in splash characteristics during the impacts on hydrophobic surfaces.

1.2. Effect of hydrophobicity

If a water droplet resting on a solid surface forms a characteristic contact angle of larger than 90°, the surface is named as hydrophobic, otherwise hydrophilic. Superhydrophobic surface is referred to have contact angles exceeding 150° and the roll-off angles (hysteresis) less than 5°. In the wetting state of Cassie-Baxter's, water particles sit on a mixture of solid and air and cannot penetrate into between the corrugations on the solid surface, thus causing air pockets to be trapped under it, resulting in less contact area between the solid surface and the water. If there is only air under the droplet, it is predicted to be a contact angle of 180°. Coating can also induce similar corrugation on solid surfaces, causing water drops to move or even bounce during interactions with solids.

From the literature, it is known that hydrophobic surfaces can cause slippage as water flows on them. Therefore, hydrophobic surfaces reduces the drag in microscale flows for both laminar and turbulent flow regimes (Daniello et al., 2009). A parameter often used in the literature to quantify the drag reduction is the slip length. The slip length is defined as the ratio of the velocity of the water layer in contact with the surface (slip velocity) to the velocity gradient at the surface, in another words, the distance inside the solid wall for which the velocity profile of a flowing water vanishes. At high Reynolds number flows, hydrophobic surface's direct effect on the drag force acting on a moving object seems disappointingly small (Duez et al., 2007). But in the phenomenon associated with the entry of a solid body into a liquid, the surface wetting properties determine the way the liquid connects to the solid to form the contact line, demonstrating that the unique properties of superhydrophobic surfaces are indeed capable of modifying the macroscale hydrodynamics (Duez et al., 2007). Duez et al. (2007) carried out experiments by impacting spheres and showed that hydrophobicity promotes air entrainment.