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Aeration Effects on Hydrodynamic Loads of Circular Cylinder's High-speed Water Entry

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The water entry of two-dimensional circular cylinder at high-impact velocity is studied numerically. The flow model treats the fluid as a compressible mixture of air and water with homogeneous material properties. A high-resolution Godunov-type method is employed to solve the governing equations numerically. The impact loads in both pure water and aerated water conditions are investigated. The aerated water is modeled using the analogy with problems of shock wave propagation in compressible foam. It turns out that the impact force is found to increase with the velocity, as expected, and the aerated gas has a significant reduction on the impact load.

INTRODUCTION

Predicting the hydrodynamic loads of high-speed entry is one important aspect in the design of aeronautical and aerospace structures. The load during the impact period is characterized by huge transient pressures, which may potentially damage the structure (Faltinsen, 1993). Assuming inviscid and incompressible fluid, as in the first-order approximation, the pioneering works on water entry originated from von Kàrmàn and have been extended by taking the pileup of the water surface into account using a linearized asymptotic analysis. The second-order Wagner theory was proposed by Korobkin (2007) and Oliver (2007) for the impact of a liquid parabola onto a rigid flat plate. By applying the linearized free surface boundary conditions on the horizontal plane at the splash-up height and imposing the body boundary condition on the actual position of the body, Zhao and Faltinsen (1993) obtained the numerical solution of the boundary-integral equation. Following the same initial-boundary-value formulation, a conformal mapping technique was successfully used to solve the water impact of general two-dimensional sections (Mei et al., 1999). The inviscid and incompressible liquid is considered in all these analytical approaches.

The nonlinear jet flow in the intersection region between the body and free surface was investigated using asymptotic matching by Howison et al. (1991). For wedges and a section with flare, it was found that the local jet flow at the water intersection does not play an appreciable role in the overall dynamics of the impact (Zhao and Faltinsen, 1993).

Besides this, many researchers were devoted to propose a numerical approach to predict the impact. Using the boundary element method, water entry of an arbitrary section and axis-symmetrical bodies was solved (Zhao et al., 1996; Iafrati et al., 2000). The smoothed particle hydrodynamics method is introduced to study water entry problem by Oger et al. (2006), and Sames et al. (1999) adopted the volume of fluid method to predict impact load and simulate the free surface deformation.

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Compared with higher-order analysis and fully nonlinear numerical solutions, the first-order Wagner theory predicts the contact region reasonably well (Korobkin, 2007; Oliver, 2007); however, the first-order prediction of the hydrodynamic force is significantly higher than the measured ones (Verhagen, 1967; Chuang, 1970). According to von Kàrmàn, the expected maximum pressure at the start of impact is associated with the acoustic pressure $P_{\max} = \rho_w C_w V$, where ρ_w is the density of the water, C_w is the sound speed of the water, and V is the impact velocity. Many reasons have been investigated regarding the differences. One of the underlying reasons for the difference between the measured pressure and the theoretical one is the air cushion effect. Lu et al. (2000) studied the elastic body deformation, and Wu et al. (2004) analyzed the free fall motion of a wedge. The existence of bubbles entrained in the water, for many reasons in reality, may have great influence on the impact loading as well (Ma et al., 2016).

Small air bubbles exist in the realistic upper layer of ocean water; the amount of air volume can reach an order of 0.5% of the sea water (Lamarre and Melville, 1991; Wu, 2002). As illustrated in Fig. 1, the sound speed of air-water mixture is sensitive to the volume fraction of air in the mixture α. For example, even 0.1% air can dramatically reduce the sound speed from 1,500 m/s to 375 m/s. The low speed of sound in aerated water means the effect of compression is worth considering, especially in the high-speed water entry problem. Even for low-speed water entry problems, experimental results show that the impact load in aerated water is smaller than that in pure water for a flat plate drop test in pure and aerated water (Ma et al., 2016).

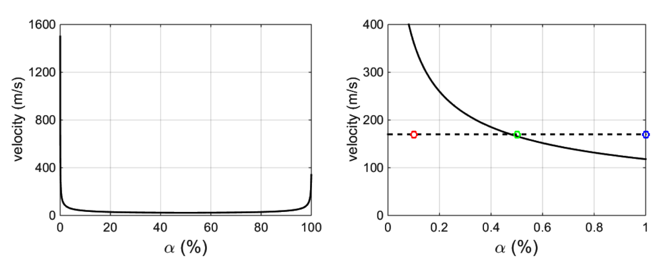

Fig. 1 Sound speed in the water-air mixture: The red, green, and blue points denote the situations where the impact velocity is $Ma = 0.5$ and the aeration levels α are 0.1%, 0.5%, and 1.0%, respectively.