International Journal of Multiphase Flow 85 (2016) 48–56

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow

Unsteady characteristics of cloud cavitating flow near the free surface around an axisymmetric projectile

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ARTICLE INFO

Article history:
Received 10 October 2015
Revised 21 April 2016
Accepted 21 May 2016
Available online 26 May 2016

Keywords:
Cloud cavitating flow
Free surface
Large eddy simulation
Cavity shedding
Wave elevation

ABSTRACT

The effect of free surface on unsteady cloud cavitation is important for high-speed surface vehicles, However, previously published experimental and numerical works regarding this topic are limited. In this paper, a typical launching experiment is performed with the presence of free surface. A numerical approach is established by using large eddy simulation and volume-of-fluid methods. Firstly, unsteady evolutions of the cavity and re-entry jet are obtained in both experimental and numerical results, which agree well with each other. Results indicate that the cavity evolution on the upper side of projectile is remarkably different compared to the lower side under the free-surface effect. For instance, on the upper side, cavity growth is slower, the velocity of the re-entry jet is higher, the cavity sheds faster, and the position of shedding cavity collapse is closer to the main cavity. Secondly, the effect of the free surface is studied by analyzing the constraint variation. Because the flow stream around the upper surface is thin, changing its direction under the effect of pressure difference inside and outside the cavity is easy. Non-axisymmetric collapse features generate a mass of strong vortexes on the cylindrical surface, and the non-uniform distribution of high pressure region is also one of the most important factors to induce lateral and vertical forces on the projectile. Finally, the heights of wave elevation in cases with and without cavitation are compared. The presence of cavitation leads to an increase in wave height, but the increment is about half the thickness of the cavity. This finding indicates that the actual constraint effect is between the effects of the infinite water field and the fully free condition.

1. Introduction

Cavitation is one of the main obstacles in increasing the speed of surface vehicles. In particular, when the interaction between free surface and cloud cavitating flow is involved, the problem becomes complicated. On the one hand, the free surface may affect the dynamic behavior of cloud cavitation such as development and shedding. On the other hand, the evolution of cloud cavitation region can affect wave elevation as well. Relevant studies in literature are limited and the understanding of the interactions is still inadequate (Faltinsen, 2005).

By contrast, a considerable amount of research has been conducted on cloud cavitating flow by neglecting the effect of free surface. Experimental research is mostly conducted in cavitation water tunnels.The flow motion and structure such as cavity shedding and re-entry jet are investigated by using the high-speed camera, particle image velocimetry and X-ray (Stutz and Legoupil, 2003; Stutz and Reboud, 1997, 2000). These tools are important in revealing mechanisms and validating the computational results. Several cavitation models used by numerical simulations have been established in the framework of homogeneous multiphase flow to describe the mass transfer of phase change, and many applications have been achieved (Merkle et al., 1998; Singhal et al., 2002; Kunz et al., 1998). In simulations of turbulence effect, Reynolds averaged Navier–Stokes equations and turbulence models with physical modifications have been widely used for engineering applications. Approaches such as modified renormalization-group k-ε turbulence model (Coutier-Delgosha et al., 2007a, 2003a, 2003b, 2007b; Zhou and Wang, 2008), filter-based model (FBM) (Wu et al., 2005), partially averaged Navier–Stokes (PANS) method (Hu et al., 2014; Huang and Wang, 2011; Ji et al., 2014, 2013), are widely used. In recent years, large eddy simulation (LES), which can capture considerable details of large-scale turbulent eddies in the flow field with high accuracy, has been adopted for research on cavitating flows and some promising results have been published

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.05.013

(Bensow and Bark, 2010; Dittakavi et al., 2010; Gnanaskandan and Mahesh, 2015; Huang et al., 2014; Ji et al., 2015; Roohi et al., 2013; Wang and Ostoja-Starzewski, 2007; Yu et al., 2014).

Research on the effect of free surface on cavitation is lacking in literature. Producing a stable free surface is difficult in a cavitation water tunnel, which is why credible experimental results are rare. There were some early experiments carried out by Dawson (1959). They studied the evolution of supercavitating flow around a wedge-shape hydrofoil near the free surface and obtained the overall forces as one of the results. However, the cavitating flow in the experiments was generated by ventilation under low-velocity restriction in the tunnel. Theoretical analysis and numerical simulation are the primary research methods used at present. Potential flow theory and volume-of-fraction (VOF) method are often adopted to study the effect of free surface on the flow field around hydrofoils (Karim et al., 2014; Liang et al., 2013; Xie and Vassalos, 2007). Early research which investigates the effect of submersion depth on the length of supercavitation based on linearized theory can also be found in the book of Franc and Michel (2005). Based on consistency between theoretical models on the free surface and cavitation, Faltinsen and Semenov (2008) established a numerical approach within a unified framework on the supercavitating flow near the free surface. The effects of depth, Froude number, cavitation number and other parameters of cavitation shape and lift based on calculation results are discussed. Bal et al. presented a boundary element method (Bal, 2007, 2011; Bal and Kinnas, 2002) for cavitating hydrofoils near a free surface, which was also extended to the applications of surface piercing cavitating hydrofoils, including a tandem case. The effects of Froude number, cavitation number and submergence depth of the hydrofoil from free surface have also been discussed. The effect of the free surface was also considered in some research on supercavitating flow in shallow water (Amromin, 2007; Chen et al., 2011). The aforementioned works are mostly limited to the study of stable cavitation, particularly supercavitation. However, research on instable cavitation near the free surface is still very difficult, because appropriate means of validation are inadequate.

In this paper, a typical launching experiment is performed, and a numerical approach using VOF and LES methods on the cloud cavitating flow near the free surface is established. Experiments and simulations are performed on typical cases around an axisymmetric projectile. Numerical methods are validated by comparing results with underwater launching experiments. The unsteady non-axisymmetrical characteristics of cavity evolution are obtained. The effects of free surface on re-entry jets, cavity shedding and the effects of cavities on wave elevation are both studied.

2. Experimental setup

2.1. System principle

The launching system is established on the basis of the SHPB technology (Wei et al., 2011) . Projectiles are driven by the stress wave by using the SHPB system (as shown in Fig. 1). The projectile can be transiently accelerated to reach 30m/s in less than 50μs. It is very difficult to generate a free surface and keep it undisturbed before flowing around the model in a cavitation water tunnel. However, by using the present method, the free surface keeps static before launching. The distance that the projectile moves during the acceleration process is less than 3% of the projectile diameter. Therefore the disturbance during launching is very slight and can be neglected. It is appropriate for investigating the cavitating flow near the free surface.

The present experimental method still has some disadvantages. The launching speed of model is set by adjusting the pressure in the air chamber with high pressure. However, the propagation of stress wave is insensitive to contact and friction conditions, so the launching speed disperses under the same pressure in the air chamber. Actually, exact speed values need to be obtained by analyzing the model motion in images.

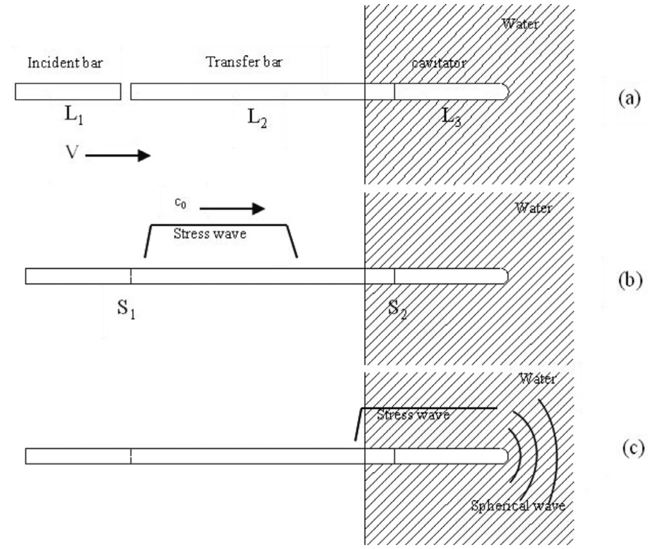

Fig. 1. Launch process schematic.

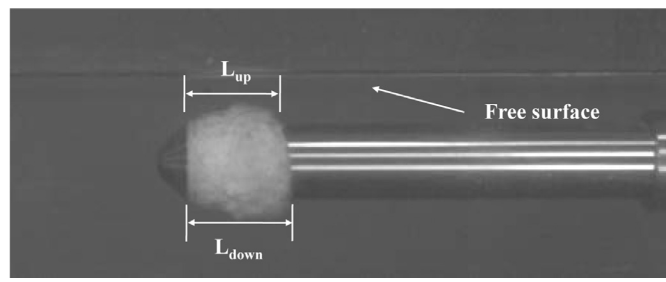

Fig. 2. Typical cavitation photograph.

2.2. Projectile model and typical experimental condition

The projectile used in this study is a slender cylinder with a conical head and made of polished stainless steel. The total length is 246 mm, the diameter is 37 mm and the conical angle is 90°.

As shown in Fig. 2, a photograph of typical cavitation can be obtained using a high-speed camera with 25,000 frames per second(FPS). In a typical experiment, the distance between the free surface and the upper side of the projectile is 17 mm, and an analysis of obtained images indicates that the speed is approximately uniform at 17.8 m/s. The temperature is 20 °C. The cavitation number can be calculated as

$$\sigma = \frac{p_\infty - p_v}{\frac{1}{2}\rho_l v_\infty^2} = 0.62 \tag{1}$$

where p_∞ is the pressure in open air, p_v is the saturated vapour pressure , ρ_l is the liquid water density and v_∞ is the speed of projectile. Under the present condition, the projectile is small and fast, the pressure difference between the upper and lower regions caused by gravity is much smaller than the flow dynamic pressure , as $\frac{\rho_l g d}{\frac{1}{2}\rho_l v_\infty^2} = 0.0023 \ll 1$. Therefore, the variation in cavitation number in the y direction caused by gravity can be neglected.

The shoulder and tail cavities with shedding bubbles are clearly shown. The cavity is nonaxisymmetrically affected by the free surface. Therefore, the length on the upper and lower sides of the cavity is measured, as shown in Fig. 2. The precision of the length and