Ocean Engineering 84 (2014) 228–236

Contents lists available at ScienceDirect

Ocean Engineering

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

A study on the collapse of cavitation bubbles surrounding the underwater-launched projectile and its fluid–structure coupling effects

Yiwei Wang [a], Lijuan Liao [a], Tezhuan Du [a], Chenguang Huang [a,*], Yubiao Liu [a], Xin Fang [b], Naigang Liang [b]

[a] Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
[b] The State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 26 February 2013
Accepted 5 April 2014
Available online 13 May 2014

Keywords:
Cavitating flow
Collapse
Coupling effect
Numerical simulation
Underwater launch

ABSTRACT

The unsteady cavitating flows surrounding the projectile during the underwater launch process are numerically and experimentally analyzed to investigate the collapse mechanism of the cavitating bubbles and its coupling effect with the vibration of the structure. We have examined the evolution of unsteady cavitation around the shoulder and tail of a rigid projectile when it is vertically launched. Navier–Stokes equations are solved with a mass transfer cavitation model using multi-block sliding mesh. Numerical results of the surface pressure change and the fluctuation in the exit-water phase have a fair agreement with the experimental data. The mechanism for the occurrence and evolution of cavitation collapse is investigated through flow field analysis. The generation of collapse pressure is simplified as the water layer accelerating and impacting the wall, and a physical model is established. In addition, from the dimensional analysis we observed that the bending fracture is the major potential damage form of structure, and the natural frequency of structure is a key factor to the coupling effect. Finally, a simplified process of the projectile with initial traverse velocity is studied by a fluid–structure interaction approach. The results demonstrate that the coupling effect between vibration deformation and collapse pressure is significant to enlarge the vibration amplitude.

1. Introduction

During the underwater launching process of high speed projectiles, cavitation takes place in the low pressure region (Brennen, 1995; Blake and Gibson, 1987) around the projectile. And the cavitation bubbles collapse when the projectile is exiting the water. High pressure pulses are generated, which have significant influence on the motion and vibration of the projectile. Correspondingly by the remarkable fluid–structure coupling effect, the pressure distributions and flow patterns are affected by the motion and vibration of the projectile as well.

Cavitation around hydrofoils and axisymmetric bodies have been widely studied (Coutier-Delgosha et al., 2007; Bensow and Bark, 2010; Owis and Nayfeh, 2004). Investigations of bubble collapse in classic papers mostly focus on the single bubble collapse, which can be traced back to the beginning of last century (Besant and Ramsey, 1913). As the development of the experimental and numerical methods, researchers have found that complex phenomena such as jets and shock waves are generated when bubble collapses, and may damage the structures as cavitation erosion (Lauterborn and Kurz, 2010; Lauer et al., 2012; Quinto-Su and Ohl, 2009). However, in the cavitation flow field around hydrofoils or projectiles, the cavitating region is filled with a huge amount of small bubbles, which is extraordinarily different from the phenomenon of single bubble collapse. Saito and Sato (2003) observed the collapse process of cavitating bubbles around a cylinder and the impact on to the structure, then classified and characterized different collapse. Quan et al. (2008) simplified the collapse of the bubbles surrounding an exiting-water projectile into collapse processes of ring bubbles on the sections, and also investigated the mechanism and influence factors of the collapse pressure.

As mentioned above, bubble group collapse is mainly researched by simplified and qualitative methods. The characteristics and mechanism of bubbles collapse when projectiles go through the free surface are still lack of clear description. Furthermore, hydro-elastic researches mostly concentrate on pipe flow and hydraulic machinery applications (Tijsseling and Vardy, 2005; Young, 2007, 2008; Münch et al., 2010), however, collapse-vibration coupling effect is rarely studied by now.

In the present paper, we have numerically studied the vertical launch process of a projectile, investigated the characteristics of bubble evolution, analyzed the mechanism, provided a physical model for bubble collapse and discussed the influence of collapse–vibration interaction.

---

* Corresponding author. Tel.: +86 1082543811; fax: +86 1082544256.
E-mail address: huangcg@imech.ac.cn (C. Huang).

http://dx.doi.org/10.1016/j.oceaneng.2014.04.014

Nomenclature

L	length of the projectile
D	diameter of the projectile
v	velocity of fluid
$v_{\max}$	the maximum value of the axial velocity of the projectile
v_r	velocity in the radial direction
v_c	radial velocity of fluid at the collapse point
v_a	advancing speed of collapse along the projectile
c	sound speed of the water layer
t	time
ρ	density
ρ_{water}	density of water
p	pressure
p_c	peak value of collapse pressure
P_∞	far-field pressure in the air region
P_g	the gas pressure in the cavitation region
$\widetilde{L}$	dimensionless length of projectile defined by $\widetilde{L} = L/D$
$\widetilde{v}$	dimensionless velocity defined by $\widetilde{v} = v/v_{\max}$
$\widetilde{c}$	dimensionless sound speed defined by $\widetilde{c} = c/v_{\max}$
$\widetilde{t}$	dimensionless time defined by $\widetilde{t} = t/(D/v_{\max})$
$\widetilde{\rho}$	dimensionless density of the mixture fluid defined by $\widetilde{\rho} = \rho/\rho_{\mathrm{water}}$
C_p	pressure coefficient defined by $C_p = p/(\frac{1}{2}\rho_{\mathrm{water}} v_{\max}^2)$
m	the mass of the projectile
I	the moment of inertia of the projectile
ω_i	the circular frequency of the i-th order vibration model of the projectile
φ_i	the shape of the i-th order vibration model of the projectile
σ_y	the yield strength of the material of the projectile
Coordinate X	initial axial direction of the projectile in which the projectile launches
Coordinate Y	traverse direction in which the projectile moves before launching

2. Numerical methods

The typical process studied in the present paper is as shown in Fig. 1, which mainly consists of: (1) Near-tube phase (as shown in Fig. 1a): the high pressure gas under the projectile pushes it to accelerate and out of the tube. (2) Cruise phase (as shown in Fig. 1b): while the projectile runs inside the water, the motion is free and only dominated by the hydrodynamic forces. (3) Exiting-water phase (as shown in Fig. 1c): the projectile exits the water and passes through the free surface.

The RANS equations of the single fluid/multiphase model are adopted with the Singhal cavitation model (Singhal et al., 2002) to simulate the phase change. RNG k–ε model is modified as Dular et al. (2005) suggested to change the formula of turbulent viscosity. The unsteady numerical simulations are performed based on the finite volume method with the SIMPLEC scheme. The equations are discretized by a first order implicit scheme in time and a second order upwind scheme in space.

The computational domain is axisymmetric and the projectile is launched along the axial direction as *Coordinate X*. A multi-block structured mesh is adopted as shown in Fig. 2. The sliding-mesh method is used to represent the relative motion between the projectile and the tube. Variables are interpolated at the interface between the inner and the outer block. In addition, the mesh layer at the interface A and B is automatically split and collapsed to make sure the total region invariable. The height of first layer surrounding the projectile is set as $D/10\,000$, where D is the diameter of the projectile. The wall $Y+$ is approximately equal to one (as shown in Fig. 3).

3. Experiment setup

In order to validate the simulations, experiments are carried out as well in a vertical underwater launching system consisting of the tighten water tank, the launch device, the projectile model and the measuring system to probe the pressure evolution at typical positions on the surface of the projectile (as shown in Figs. 4 and 5). In the launch experiment, the piston is pushed by compressed air, propels the projectiles to accelerate and move vertically. Cavitation generated in the low-pressure regions around the shoulder of projectiles evolves unsteadily and collapses after exiting water. Pressure

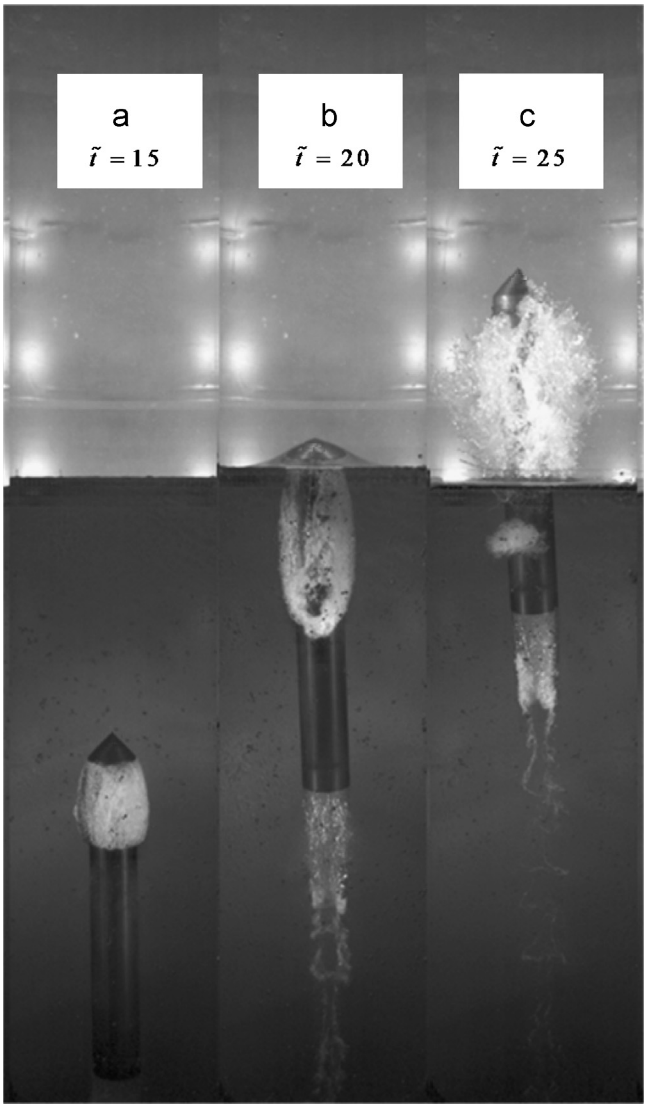

Fig. 1. Photographs in different stages of a typical launch experiment.