

On the non-equilibrium dynamics of cavitation around the underwater projectile in variable motion

Y Chen, C J Lu, J Li, X Chen, Z X Gong

School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, 200240, China

E-mail: cyofjs@sjtu.edu.cn

Abstract. In this work, the dynamic behavior of the non-equilibrium cavitation occurring around the underwater projectiles navigating with variable speed was numerically and theoretically investigated. The cavity collapse induced by the decelerating motion of the projectiles can be classified into two types: periodic oscillation and damped oscillation. In each type the evolution of the total mass of vapor in cavity are found to have strict correlation with the pressure oscillation in far field. By defining the equivalent radius of cavity, we introduce the specific kinetic energy of collapse and demonstrate that its change-rate is in good agreement with the pressure disturbance. We numerically investigated the influence of angle of attack on the collapse effect. The result shows that when the projectile decelerates, an asymmetric-focusing effect of the pressure induced by collapse occurs on its pressure side. We analytically explained such asymmetric-focusing effect.

1. Introduction

Partial cavitation usually appears around the shoulder the underwater projectiles navigating near sea surface. The deceleration of projectile caused by propulsion problem may result in the unstable evolution and collapse of the cavity, which will significantly affect the hydrodynamic loads acting on the projectile's body.

The primary objective of this work is to investigate the dynamic behavior of the cavity in non-equilibrium state around several underwater projectiles, which is induced by the instantaneously variable motion of the projectiles. The numerical works were carried out by solving the one-fluid compressible RANS equations using the commercial CFD package 'ANSYS FLUENT 14.0'. The cavitating flow is computed using the cavitation model suggested by Zwart et al. [1].

2. Problem statement

The axisymmetric underwater projectiles with three kinds of head form were studied. The projectiles move in an infinite stationary water area. A constant pressure is specified at the downstream boundary to adjust the initial cavitation number σ . The motion of the projectiles is achieved by dynamic mesh technique. The initial velocity of the projectiles, U_{b0} , is specified as 30 m/s. Then the projectile is decelerated to an ultimate velocity $U_{bt}=20$ m/s in 0.2 s, with the law: $U_{bt} + (1-t/0.2)^3(U_{b0} - U_{bt})$.

3. Results and discussion

3.1. Evolution of non-equilibrium cavity during variable motion of projectile



Figure 1 presents the evolutions of the cavity during the decelerating motion and the following uniform speed period. The evolutions on the projectiles are basically similar but have some differences. The large-scale of separated flow around the blunt-nose projectile makes the secondary cavities to grow and collapse periodically and endlessly. However, the relatively smooth noses of the other two projectiles make the secondary cavities to gradually reach quasi-steady state after times of oscillation.

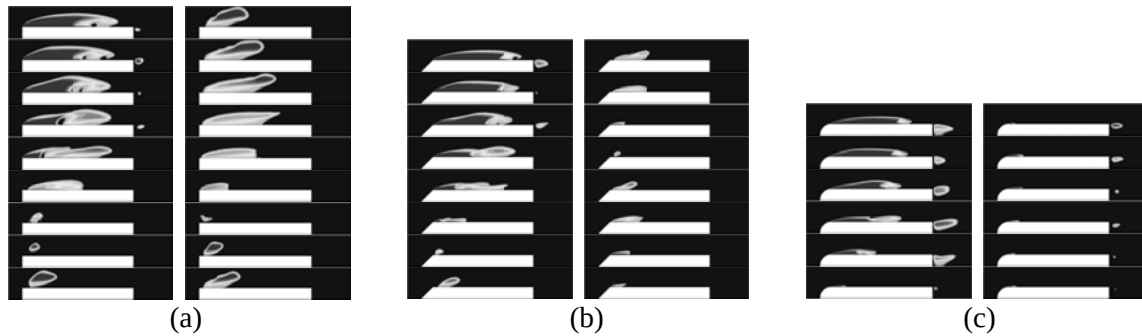


Figure 1. Evolution of the cavities around the projectiles: (a) blunt-nose projectile, $\sigma=0.3$; (b) conic-nose projectile, $\sigma=0.25$; (c) hemispheric-nose projectile, $\sigma=0.2$.

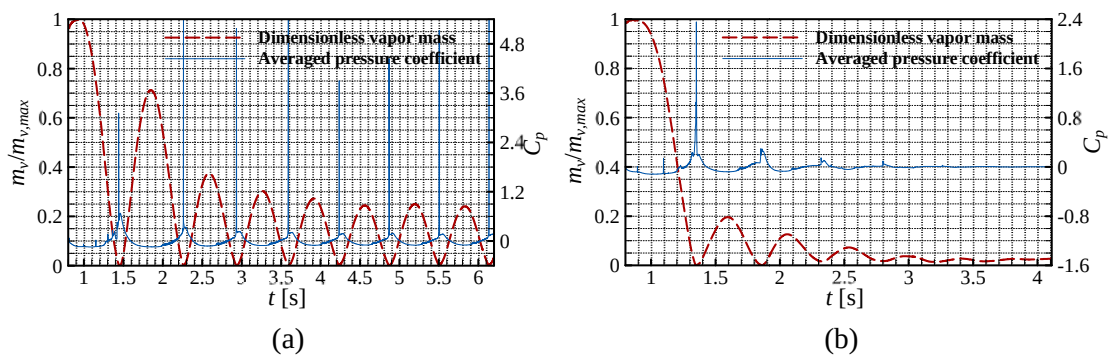


Figure 2. The correlation between the total vapor mass and the averaged pressure in far field: (a) blunt-nose projectile; (b) conic-nose projectile.

We obtained the time histories of the total vapor mass and the averaged pressure coefficient on the upstream boundary, as shown in figure 2. In the case of the conic-nose projectile, a strong pressure peak appears around the first collapse, and each of the following valleys on the curve of vapor mass corresponds to an individual pressure peak. However, as for the blunt-nose projectile, the cavitation reaches a periodic state without damping after four or five times of oscillation.

For cavitating flows in dynamic equilibrium, the disturbed pressure p'_∞ instead of p_∞ should be related to the change-rate of the cavity. We assume that when the cavity has irregular shape, its collapse effect on the averaged pressure in far field is similar with that of a spherical cavity having the same volume. Here we propose the definition of the equivalent radius, $\tilde{R}$, using the instantaneous cavity volume $V_c(t)$, and establish a correlation between the averaged pressure coefficient and the change-rate of the specific kinetic energy of collapse:

$$\tilde{R}(t) = \left[\frac{3}{4} \frac{V_c(t)}{\pi} \right]^{\frac{1}{3}} \quad (1)$$

$$C_p \sim E(\tilde{R}) = \left[\tilde{R} \frac{d^2 \tilde{R}}{dt^2} + \frac{3}{2} \left(\frac{d\tilde{R}}{dt} \right)^2 \right] / \left(\frac{1}{2} U_{b0}^2 \right) \quad (2)$$

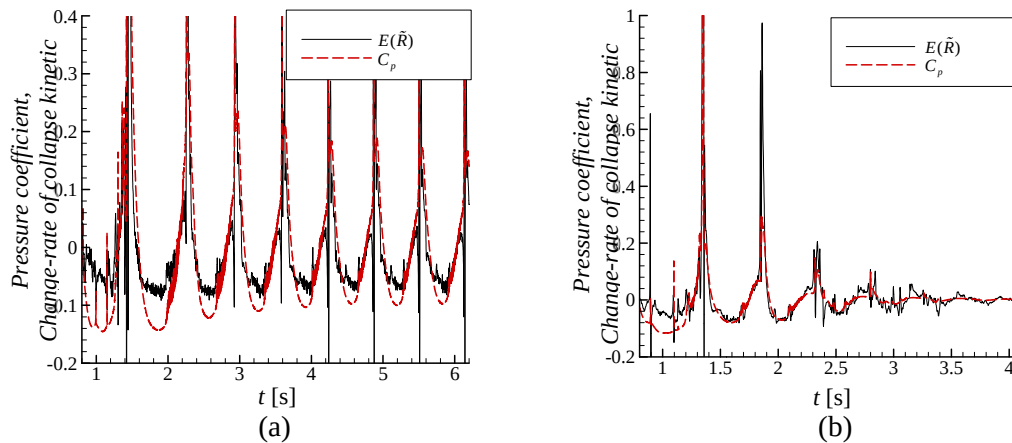


Figure 3. Comparison between the averaged pressure coefficient in far field and the change-rate of the specific kinetic energy: (a) blunt, $\sigma_0 = 0.30$; (b) conic, $\sigma_0 = 0.25$.

Figure 3 presents the comparison between these two dimensionless quantities. The two curves are in good agreement in the shape and position of their main peaks.

3.2. Asymmetric-focusing effect of the collapse-induced pressure

We find if the projectile navigates with angle of attack, the collapse will entirely move to the pressure side of the projectile even if the angle is small, different with traditional cavitation theory [2].

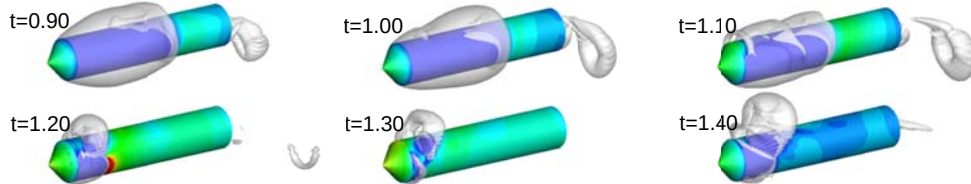


Figure 4. Evolution of the cavity shape and the pressure on projectile's surface ($\sigma_0 = 0.3$, $\alpha = 2^\circ$).

Figure 4 shows the cavity evolution around the projectile navigating with $\alpha = 2^\circ$. The filled contours of the pressure on projectile's surface are shown as well. The collapse produces a small block of high-pressure region on the pressure side. This phenomenon is unusual in common sense.

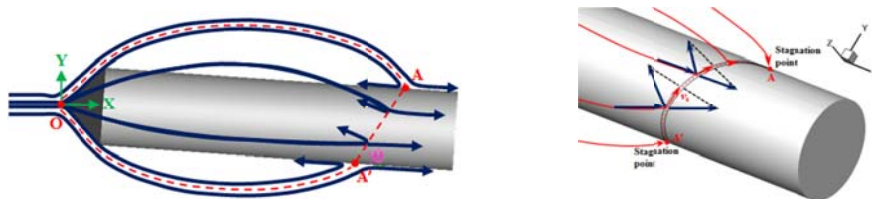


Figure 5. Diagram of the streamlines on an idealized cavity and the velocity along the closure.

We consider an ideal cavity whose shape is like ellipsoid [3]. It is well known that the re-entrant jet produced is reflected at the closure line [4]. By using the Cauchy-Lagrange integration in the reference frame fixed on the projectile, in the stage of the asymmetric focusing after the deceleration stops, the pressure difference between the stagnation points “A” and “A'” can be written as:

$$\delta p = \rho_l \frac{D}{Dt} \delta \varphi = \rho_l \frac{D}{Dt} \int_{A'A} V_s ds \quad (4)$$

In section 3.1, it has been proven that the change-rate of the equivalent radius of cavity, $\tilde{R}$, has good correlation with the variation of pressure. It is considered that the length and the thickness of cavity tend to be isotropic when they are small enough. Since the annular cavity is converted into a spherical cavity of equivalent radius, L_{OA} and $\tilde{R}$ are related as:

$$\frac{dL_{OA}}{dt} \sim O\left(\frac{\sqrt{\tilde{R}}}{\sqrt{R_n}} \frac{d\tilde{R}}{dt}\right) \quad (5)$$

The relation between the magnitude of the minimal axial component of the jet velocity V_j and the corresponding maximal velocity on the closure line is:

$$V_{s,max} = V_{j,min} \frac{\cos(\theta - \alpha)}{\cos(\pi - 2\theta + \alpha)} \quad (6)$$

This equation can also be expressed as $V_{s,max} = C(\theta)V_{j,min}$. The integration of the velocity along the closure line is in scale with the maximal velocity $V_{s,max}$:

$$\int_{A'A} V_s ds \sim O(\bar{V}_s R_n) \sim O(V_{s,max} R_n) \quad (7)$$

The re-entrant jet reflects on the closure line “AA’”, thus $V_{j,min}$ should be greater than or at least not be lower than dL_{OA}/dt . The following relation exists:

$$V_{j,min} \approx \left| \frac{dL_{OA}}{dt} \right| \quad (8)$$

After putting all the above-mentioned equations together, the pressure difference between “A’” and “A” is in proportional relation to a composite expression of the equivalent radius $\tilde{R}$ and its change-rates:

$$\delta p \sim \rho_l \sqrt{R_n} \frac{D}{Dt} \left(\sqrt{\tilde{R}} \left| \frac{d\tilde{R}}{dt} \right| \right) = -\rho_l \sqrt{R_n} \left[\sqrt{\tilde{R}} \frac{d^2 \tilde{R}}{dt^2} + \frac{1}{2\sqrt{\tilde{R}}} \left(\frac{d\tilde{R}}{dt} \right)^2 \right] \quad (9)$$

The $\tilde{R}$ satisfies the Rayleigh equation, and it's easy to obtain its change-rates in the above equation. Finally we have found that corresponding difference of pressure coefficient can be estimated as follows, given $\tilde{R}_0/\tilde{R} \gg 1$:

$$\delta C_p \sim \frac{2}{3} \sigma \sqrt{\frac{R_n}{\tilde{R}}} \left(\frac{\tilde{R}_0}{\tilde{R}} \right)^3 \quad (10)$$

Acknowledgments

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