The effect of cavitation on the hydrofoil dynamic characteristics

J Yang¹, L J Zhou¹, Z W Wang² and F L Zhi¹

¹ College of Water Conservancy and Civil Engineering, China Agricultural University, Beijing, 100083, China
² Department of Thermal Engineering, Tsinghua University, Beijing, 100084, China

E-mail: zlj09@263.net

Abstract. Cavitation in hydraulic machinery usually causes a change of fluid dynamic characteristics. In order to predict the effect of cavitation on hydrofoil characteristics, the cavitation around a hydrofoil was studied numerically. The full cavitation model and a modified RNG $k\varepsilon$–turbulence model were used. The finite volume method with the SIMPLEC scheme was used to discretize the time-dependent equations. The second-order upwind scheme was used for the convection terms with the central difference scheme used for the diffusion terms. Fluid dynamic characteristics including cavity’s length, shedding frequency, pressure coefficient and lift and drag force coefficients features in a range of cavitation number were analyzed. Computations were made on the three-dimensional flow field around a NACA66 hydrofoil at 8° angle of attack. The recording force signals exhibit periodic behaviours with the time. And the cavity shedding frequency increases with the cavitation number, however the length of cavity decreases with the cavitation number, which result in changing of lift-drag ratio. Especially for larger cavitation numbers, the lift drag ratio of cavitation field is getting closer and closer to that of non-cavitation field.

1. Introduction

The cavitation on the hydraulic machinery usually causes change of fluid dynamics characteristics. It brings undesirable effects on the hydrofoils, such as unstable load on the blade or hydrofoil [1, 2], resulting in the reduction of efficiency.

Many works have been done to understand the mechanism of hydrofoil cavitation. It has been found that an increase of lift coefficient can be observed when cavitation occurs [2, 3], and it keeps rising with the increase of cavity width until reaches maximum at the cloud detachment, then it decreases abruptly when the cavity collapses [4, 5]. Robert et al. [3] found that lift and drag coefficients are functions of cavitation number at constant angle of attack by experiment. As the cavitation number reduces, the cavity on the hydrofoil become larger, and the drag coefficient reaches a maximum and then decreases. However, the lift coefficient decreases rapidly. And the decrease of drag coefficient merely causes a reduction in the slope of the lift/drag ratio curves. Amromin et al. [6] has shown that the partial cavitation on the suction side of the hydrofoil OK-2003 does lead to drag reduction and a significant increase in the lift drag ratio within a certain range of cavitation number and within a three-degree range of angle of attack. Song et al. [7] conjectured that cavitation bubble first occurs at the point of minimum pressure near the nose when the lift coefficient is the maximum. With the bubble cavity slides down the foil, the lift decreases to a minimum when it arrives at the tail of the foil. Many researchers believe that the lift and drag coefficients fluctuate in cycles with...
the periodic growth and shedding of cavity, and they all have the same frequency. Arndt et al. [8] concluded that sheet cavitation and its transition to cloud cavitation results in a highly unstable flow which can induce significant fluctuation in the lift, and the amplitude of the fluctuation can exceed 100% of the lift in steady state. In addition, Kawakami et al. [9] believed that water quality appears to have a significant effect on cavitation behavior, for gas content has a strong influence on the spectral characteristics of lift and surface pressure measurement. Arndt et al. [10] also observed a new effect of the perturbation frequency on the lift and drag fluctuation, as well as on the time-average cavity length by experiments.

Since the shedding of cavitation has a significant effect on the flow, in the present work the unsteady cavitating flow over a 3-D hydrofoil is numerically simulated, and the effect of cavitation on the lift and drag coefficients and cavity length are analyzed in detail. The simulation will be presented at angle of attack 8 deg and Reynolds number of 8x10^5, but varying the cavitation number.

2. Governing equations and cavitation model

The homogeneous gas-liquid two phase full cavitation model proposed by Singhal et al. [11] as adopted in this work. The fluid was assumed to be a mixture of liquid, vapor, and nocondensable gases and the density is a function of vapor mass fraction, which is computed by solving a transport equation coupled with the mass and momentum conservation equations.

The continuity and the momentum equations for the mixture are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial x_j} \right) \right]$$

Where, $\rho , u , p$ are the mixture density, velocity and pressure respectively, $\mu$ and $\mu_t$ are the laminar and turbulent viscosities. The mixture density, $\rho$ is defined as:

$$\frac{1}{\rho} = f_v \rho_v + f_{ncg} \rho_{ncg} + \frac{1-f_v-f_{ncg}}{\rho_l}$$

Where, $f_v$, $f_{ncg}$ and $f_l$ are the mass fractions of the constituent components of the mixture and $\rho_v, \rho_{ncg}$, and $\rho_l$ are the densities of the constituent components of the mixture. The mass transfer between the liquid and vapor is defined:

$$\frac{\partial \rho \alpha_v}{\partial t} + \nabla \cdot (\rho \alpha_v \vec{u}) = \nabla \cdot (\rho f_v \vec{u}) + \frac{\partial (\rho f_l)}{\partial t} + R_v - R_c$$

$$R_v = C_v \sqrt{k} \rho_l \rho_i \sqrt{\frac{2 \max (p-p_r,0)}{3 \rho_i}} f_v$$

$$R_c = C_c \sqrt{k} \rho_l \rho_i \sqrt{\frac{2 \max (p_c-p,0)}{3 \rho_i}} (1-f_{ncg} - f_v)$$

Here, $R_v$ stands for the vaporization and $R_c$ stands for the condensation processes, respectively. The empirical constants are $C_v = 0.02$, $C_c = 0.01$ and the surface tension $\lambda = 0.0717 N/m$. The standard RNG $k-\varepsilon$ turbulence model fails to accurately predict the separation and collapse of the cloud cavity. Coutier-Delgosha et al. [12] presented that standard RNG $k-\varepsilon$ turbulence models over-prediction of eddy viscosity in high vapor concentration regions. So the influence of compressibility of the two-phase medium on turbulence was considered by using a modified turbulence viscosity coefficient which related to the vapor and liquid densities in the cavitating region.

$$\mu_t = f(\rho) \frac{C_r k^2}{\varepsilon}$$
The finite volume method with the SIMPLEC scheme was used to discretize the time-dependent equations. The second-order upwind scheme was used for the convection terms. The PRESTO scheme was used for the pressure interpolation. The QUICK scheme was used for the vapor mass fraction transport equation.

3. Hydrofoil geometry and boundary conditions

Figure 1. Calculation domain and boundary conditions. Figure 2. Mesh around the hydrofoil.

The hydrofoil geometry and boundary conditions are the same as previous referred experimental data [5]. The calculation domain (see Figure 1) was divided into seven blocks in a structured grid, the grid around the hydrofoil is shown in Figure 2. The classical boundary conditions for incompressible flows were used with an imposed inlet velocity and a fixed outlet pressure. The other faces were set to be non-slip walls.

4. Calculated result and analysis

Firstly, the variations of the lift and resistance coefficient and the pressure pulsation with the periodic cavity evolution were analyzed. Figure 3 shows the results of the cloud cavitation of \( \sigma = 1.25 \) in suction side at a 8° angle of attack. The iso-surface for a 10% vapor volume fraction was chosen because it is the best correlation to the real cavity shape [13]. The key parameters like the cavitation number lift coefficient, the pressure coefficient and the resistance coefficient are defined as follows:

Cavitation number: \[ \sigma = \frac{p_\infty - p_c}{0.5 \rho V_c^2} \]

Pressure coefficient: \[ C_p = \frac{p - p_\infty}{0.5 \rho V_c^2} \]

Lift coefficient: \[ C_L = \frac{L}{0.5 \rho V_c^2 A} \]

Resistance coefficient: \[ C_D = \frac{D}{0.5 \rho V_c^2 A} \]

In this simulation, the evolution of the lift and drag coefficient and the cavity shape were given in Figure 3. It shows the sheet cavity has two times shedding. In the first shedding, the cavity breaks off from the mid of the foil chord, then the rest cavity continues to grow, and the shedding cavity moves towards the downstream with the main flow. However, the cavity completely sheds off from hydrofoil head in the second shedding, after that a new cavity period begins and repeats the last one. The continuous cycles of cavity growth and shedding result in periodic lift and resistance coefficient perturbations as shown in Figure 3 (a). t1~t8 shows the typical instantaneous of one cavity evolution cycle. The lift coefficient is more affected than the drag coefficient in the growth stage of the sheet cavity, which has higher pulsation amplitude. One can also note from Figure 3(a) that the lift and drag coefficient amplitude of these pulsations increases with cavity length. The pressure fluctuation is also given in Figure 3(c), t1~t2 show the last cycle is nearly finished and a new cavity cycle begins, the cavity starts to grow from the head of foil and the lift coefficient gradually increases simultaneously. The growth stage will last till t4 when the cavity reaches to the maximum length. We will see the maximum lift of the amplitude occurs at this moment. Then the sheet cavity approaches 75% chord and part of the cavity is broken off by the reentrant jet. So the lift coefficient appears to decline from t4~t5. After the first cavity shedding, the lift coefficient increases rapidly with the residual cavity keeping on growing, as t5~t6 shows. The cavity length is close to the maximum around t6 so the lift coefficient reaches to the
maximum too. Later, the cavity is broken off again and the lift coefficient decreases during t6–t7. Eventually the sheet cavity is cut off near the leading edge of the hydrofoil, the lift coefficient drops to the lowest value in t7. Then a new cavity growth cycle begins and the lift coefficient rises again (see t8). It is also marked out the pulsation processing of monitor point in the suction side from t1 to t8 in Figure3(c). As we all know, when the foil is covered by cavity, the pressure will drop to the saturation pressure, and the pressure will increase while the cavity sheds or collapses. So in time t4, the cavity length and the lift coefficient reach maximum while the average pressure should be minimum as shown in Figure3(c), most of the monitor points are in lower pressure value. The situation is reversed in t7. The spectral analysis of lift oscillations are illustrated in Figure 4. There are two frequencies, 11Hz and 4.13Hz, which represent two shedding in one cavity period. The presented results agree reasonably well with Jean-Baptiste et al.’s data, with a predicted shedding cycle frequency of 10.75Hz, compared to the frequency of 11.02Hz. The higher frequency 11Hz reflects the first small vortex shedding, and the lower one 4.13 means the bigger cavity shedding. As analyzed above, the maximum lift occurs at the time of maximum cavity length, so the effect of the first small vortex shedding on the lift and drag coefficient is smaller than the secondary bigger shedding. That’s why both of the lift and drag forces have the main frequency of 4.13Hz.

Figure3. The lift and drag fluctuations (a) and wall-pressure pulsations (c) in one cavity evolution cycle (b) under cavitation number1.25.

It is important to emphasize the lift to drag ratio in different cavitation numbers. As shown in Figure 5, the effects of cavitation number on the lift and drag behaviour are analyzed. The lift to drag ratio almost increases linearly with the cavitation number. That shows the lift to drag ratio will drop with the cavitation develop. And the more seriously the cavitation develops, the more significant the amplitude of lift to drag ratio descends. That is to say, a lift to drag ratio close to the theoretical value in non-cavitating flow can be achieved under a larger cavitation number.
Figure 4. The spectrum of lift and drag coefficients of hydrofoil.

Figure 5. The relationship between cavity shedding frequency and cavitation numbers.

Figure 6. The relationship between cavity length and cavitation numbers (right).

Figure 7. The variation of pressure coefficient in suction side (left).

Figure 8. The variation of lift to drag ratio with cavitation numbers (right).

In Figure 6 the correlation of cavity frequency and cavitation number is presented. The frequency increases with the cavitation number. This can be explained by cavity length and flow field pressure under different cavitation number. In Figure 7, the time-averaged pressure coefficient vibration in suction side of hydrofoil is given. The pressure coefficient is gradually increasing from the leading edge to the tail of the hydrofoil and the flow field will have higher average pressure in larger cavitation number. The first point has low pressure coefficient since the area of leading edge is basically covered by the cavity. The more close to the trailing edge, the higher pressure coefficient will be. With the increasing cavitation number, the pressure coefficient gradually increases from $p_5$ to $p_{10}$. So the cavity growth will be limited. The cavity length will be shorter and shorter. And the shedding frequency is higher with cavitation number. On the contrary, as the cavitation number reduces, the time-averaged pressure becomes lower, the cavity growth and shedding stage become longer, resulting in lower shedding frequency. That is verified in Figure 8. As previous predicted the maximum cavity length decreases when the cavitation number increases.

5. Conclusions

The cavitating flow around a three dimensional hydrofoil is simulated using a transport equation based model and a modified RNG $k-\varepsilon$ turbulence model. The hydrofoil dynamics characteristics including the lift and drag force coefficients features, the cavity’s
length, the shedding frequency and the pressure fluctuation in a range of cavitation number are analyzed.

When the cavitation occurs, the lift and drag force will fluctuate with the evolution of cavity growing and breaking off. In the stage of cavity growth, the lift and drag coefficient will increase simultaneously. And the lift and drag coefficient will reach to the maximum as the cavity length becomes the longest. When the cavity shedding begins, the lift coefficient will decrease rapidly. The lift to drag ratio increases with the cavitation number, because the cavity length will decrease with the cavitation numbers, which results in the changing of lift-drag ratio. The more seriously the cavitation develops, the more lift and drag ratio reduces. For a larger cavitation number, the cavitation has little effect on the flow, so the lift drag ratio of cavitation field will get closer and closer to that of non-cavitation field.

The cavity characteristics in different cavitation numbers are also given. The results show the cavity shedding frequency and the cavity length will increase with the cavitation number. That’s because the average pressure is higher with cavitation number increasing, which blocks the cavity growth, then the growth and shedding processing will be shorter and shorter, so the shedding frequency will rise.

**Acknowledgements**

The authors thank the National Natural Science Foundation of China (No. 51279205), and National High Technology Research and Open Research Fund Program of State Key Laboratory of Hydroscience and Engineering (No. sklhse-2012-E-01) for supporting present work.

**References**

[1] Kjeldsen M, Arndt R and Effertz M 2000 ASME. J. Fluids Eng 122(3) 481-7
[2] Mohammad J and Izadi 2009 Numerical analysis of water suction effect on lift and drag coefficient of a hydrofoil with cavitation Proc. of FEDSM2009 (Colorado, USA, 2-6 August 2009)
[3] Kermeen R W 1956 Water tunnel tests of the naca661-012 hydrofoil in noncavitating and cavitating flows Pasadena Report No. 47-7
[4] Leroux J B, Astolfi J A and Billard J Y 2004 J. Fluids Eng. 126(1) 94-101
[5] Leroux J B, Delgosha O C and Astolfia J A 2005 Phys. Fluids 17(5) 1-20
[6] Amromin E, Kopriva J, Arndt R and Wosnik M 2006 ASME. J. Fluids Eng. 28(5) 231-6
[7] Song C and Qin Q 2001 Numerical simulation of unsteady cavitating flows Proc. 4th Int. Symp. on Cavitation (Pasadena, California, USA, 20-23 June 2001)
[8] Arndt R, Song C, Kjeldsen M, He J and Kelle A 2000 Instability of partial cavitation: A numerical experimental approach Proceedings of 23rd symposium on naval hydrodynamics (Val de Reuil, France, 15-16 September 2000)
[9] Kawakami D T, Qin Q and Arndt R 2005 Water quality and the periodicity of sheet/cloud cavitation. Proc. of FEDSM2005 (Houston, Texas, USA, 19-23 June 2005)
[10] Arndt R and Amromin E L 2008 ASME. J. Fluids Eng. 130(3) 1-7
[11] Singhal A K, Athavale M M, Li H Y and Jiang Y 2002 ASME J. Fluids Eng. 124 617-624
[12] Delgosha O C, Reboud J L and Fortes-Patella R 2003 ASME J. Fluids Eng. 125 38-45
[13] Dular M, Bachert R, Staffel B and Sirok B 2005 European Journal of Mechanics B/Fluids 24 522-538