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NUMERICAL SIMULATION OF CAVITY OVER HYDROFOIL BY USING BOUNDARY ELEMENT METHOD BASED ON POTENTIAL FLOW

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ABSTRACT: *In this paper numerical study of cavity over hydrofoils is considered by using boundary element method based on potential flow. For this purpose hydrofoil and cavity surface are approximated by panels. Then sources and doublets are distributed over these surfaces. In this method the length of cavity is assumed constant. A set of equations are obtained by applying boundary conditions over the hydrofoil and cavity surface with closing cavity condition, which they are solved together. An important advantage of this method is getting the answer in a short period of time along with low cost computations. Also, there is a good agreement between numerical and experimental results that shows the accuracy of this method.*

1. INTRODUCTION

Cavity is one of the most interest phenomena. The simplest definition of cavitation is phase change of liquid to vapor because of reducing pressure. Generally, there are some distortion effects because of cavity, but in some cases we can have some useful effect from cavitation such as reduce drag force by producing super cavity around a moving body in an incompressible flow. Helmholtz described the first model for super cavity in 1868. Then Kirchhoff solved the flow over a vertical plate in 1869 and then it was modified by Rayleigh in 1876[1]. Woods described a methods based on potential flow (1951). He used open vortex model for studying cavity over a flat plate at an angle of attack. The main results for three dimensional model of cavity were presented by Kinnas and Fine in 1990[2]. In peresent work cavity flow assumes as a non-viscous irrotational potential flow. In this view, cavity flow over the hydrofoil is considered as a big bubble which covers all the zones of cavitation. So, we ignore the micro-bubbles and assumes the pressure inside of the cavity being constant. In this case, vorticity is very small on boundary of cavity and by a good approximation could assume that the flow is potential around the cavity[3]. Both partial and super cavity are considered here.

2. Formulation

A hydrofoil with a partial cavity is shown in figure 1,in which the cavity is started at point D and ended at L. Super cavity over the hydrofoil is shown in figure 2. The flow around the cavity and foil in both cases is described by velocity potential function φ .This flow is irrotational and non-viscous so, φ satisfie the Laplas equation.

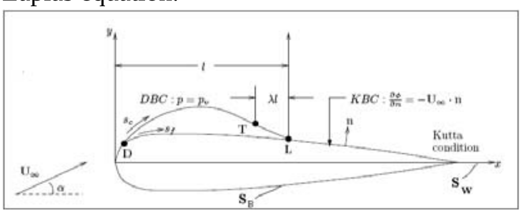

Fig. 1. Partial cavity over a 2-D hydrofoil at an angle of attack

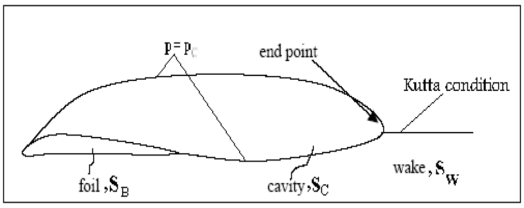

Fig. 2. Super cavity over a 2-D hydrofoil and the position of Kutta condition

For both two cases we can use boundary condition over the surface of hydrofoil and cavity.In general we can approximate constant pressure inside the cavity and it is equal to vapor pressure p_v. Then dynamic boundary condition can be applied by equating pressure coefficient, cavitation number or tangential velocity to a constant number. At trailing edge of hydrofoil we can apply the Kutta condition or Morino and Kao condition:

$$\mu_w = (\Delta\varphi)_w \qquad (1)$$

In which $(\Delta\varphi)_w$ is potential jamping at trailing edge. Boundary condition over the surface of hydrofoil and cavity is written as:

$$\nabla\varphi \,.\, n = 0 \qquad (2)$$

Which is the kinematic boundary condition. At the end of cavity we can use regenerative pressure model. In this method, the velocity of transition zone (between the point T and L in fig.1) can be calculated from:

$$q_{tr} = U_\infty \sqrt{1+\sigma}(1 - f(s_f)) \qquad (3)$$

which s_f is the arc length of hydrofoil surface below the cavity and measures from separation point.The function $f(s_f)$ is defined as below:

$$f(s_f) = \begin{cases} 0 & s_f \prec s_T \\ A(\dfrac{s_f - s_T}{s_L - s_T})^\upsilon & s_T \le s_f \le s_L \end{cases} \qquad (4)$$

In which A $(0 \prec A \prec 1)$ and υ $(\upsilon \succ 0)$ are two arbitrary constant numbers [2]. In addition, we can apply another condition for the height of cavity at the end point:

$$h(s_L) = 0 \qquad (5)$$

For super cavity the simple close model can be used [4]. In this model we have:

$$h(s_{cep}) = 0 \qquad (6)$$

This means that the thickness of cavity at the end point is zero. In addition, we can use Kutta condition at the end of cavity.

2.1. Integral and decretize form of equations

Potential function φ can be written as distributed dipoles and sources over the boundary. So:

$$\varphi(x) = U.x + \int_{s_c} q(\xi)\varphi_s ds - \int_{s_b+s_c} \mu(\xi)(n.\nabla\varphi_s)ds - \int_{s_w} \mu_w(\xi)(n.\nabla\varphi_s)ds \qquad (7)$$

In which $q(\xi)$ and $\mu(\xi)$ are the strength of source and dipole, respectively. φ_s is potential of source with strength of unity which located on position x. μ_w is the strength of dipole on wake surface (s_w). The descretized form of equation (11) is:

$$\varphi_i = u.x_i + \sum_{j=1}^{N_c} q_j \alpha_{ij} + \sum_{k=1}^{N} \mu_k \beta_{ik} + \mu_w \beta_{iw} \qquad (8)$$

The coefficients α and β are:

$$\alpha_{ij} = \frac{1}{2\pi}\int_{s_j} \ln r \, ds \quad , \quad \beta_{ik} = \frac{1}{2\pi}\int_{s_k} \frac{\partial \ln r}{\partial n_k} ds \qquad (9)$$

where 'r' is the distance between two point x and ξ. For complete set of equations, we need another equation. This equation can be obtained by the closing condition for cavity.
We can use thin airfoil theory and relate cavity height to source strength of the panel which is obtained by Kinnas and Fine for partial cavity as:

$$q_c(1 - f(s_f))\frac{dh_c}{ds_c} = \frac{\partial\varphi}{\partial n} \qquad (10)$$

where $\dfrac{\partial\varphi}{\partial n}$ indicate source strength. By integrating over cavity surface, we have:

$$h_c(s_c) = \int_0^{s_c} \frac{1}{q_c(1 - f(s_f))}\frac{\partial\varphi}{\partial n} ds_c \qquad (11)$$

At the end point we have:

$$\int_0^{s_c} \frac{q}{q_c(1 - f(s_f))} ds_c = 0 \qquad (12)$$

The descretized form of this equation is:

$$\sum_{j=1}^{N} \frac{q_j}{(1 - f(s_f))} \Delta s_j = 0 \qquad (13)$$

q_j and s_j are source strength and cavity length up to panel of j, respectively. For super cavity:

$$q_c \frac{dh_c}{ds_c} = \frac{\partial \varphi}{\partial n} \qquad (14)$$

By integrating:

$$\sum_{j=1}^{N} q_j \Delta s_j = 0 \qquad (15)$$

where Δs_j is the length of a panel and q_j is source strength on panel.

3. Results and discussion

For validation of this method, pressure distribution over an airfoil (ONERA-120) is compared with experimental results of Kourta[5] in figure 3. The angle of attack is $\alpha = 3.4^\circ$. As shown, there is a good agreement between numerical and experimental results. In addition, the numerical results of partial cavity are compared with Laberteaux experiments[6] in figs 4 and 5. The airfoil is NACA0009 and about 100 panels are considered. Stagnation point over the airfoil is at $L_D = 8.856 \times 10^{-3}$ which has good agreement with experiment. In these figures relative height of cavity is plotted as a function of relative length at an angle of attack 5° and 7°.

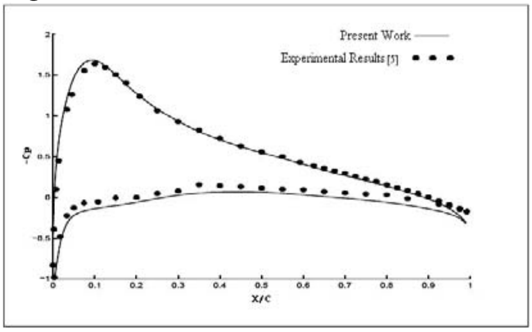

Fig. 3. Pressure distribution over hydrofoil ONERA-120 and $\alpha = 3.4^\circ$

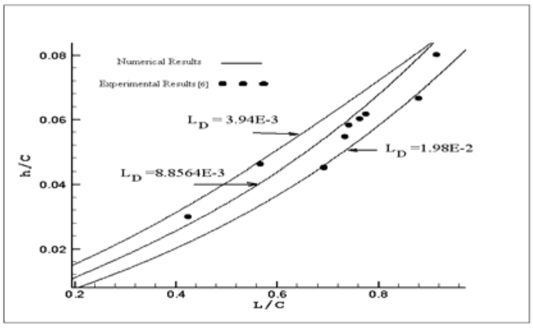

Fig. 4. Effect of separation point position on cavity height over NACA0009 and $\alpha = 5^\circ$

In figure 6 , the history of convergence for several panels is shown. As seen the rate of convergence is very high in this method.

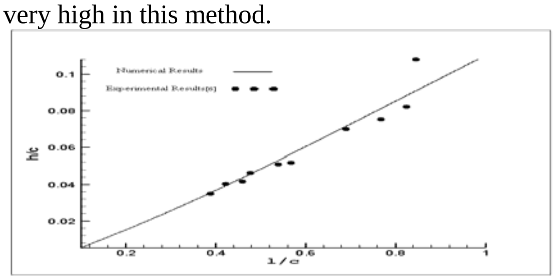

Fig. 5. The results of NACA0009 for $\alpha = 7^\circ$

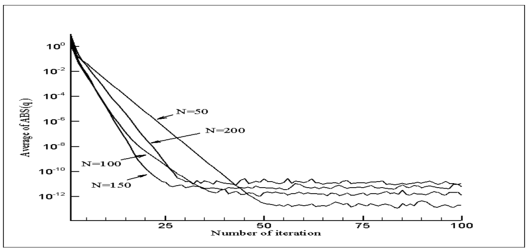

Fig. 6. History of convergence (N=The number of panels)

The configuration of cavity over the hydrofoil with $L/C = 0.5$ and $\alpha = 3^\circ$ is shown in figure 7. Pressure coefficient for this condition is shown in figure 8. In figure 9, the numerical and experimental results for the case of super cavity over a flat plate are shown. The results are for $\alpha = 4^\circ$ and 8°. Lift coefficient for this case is shown in figure 10. A good agreement can be seen in these figures. The results show that the variables L/C and $\frac{c_l}{(\pi\alpha/2)}$ are functions of α/σ, however, independent of angle of attack, just like the experimental results [8].

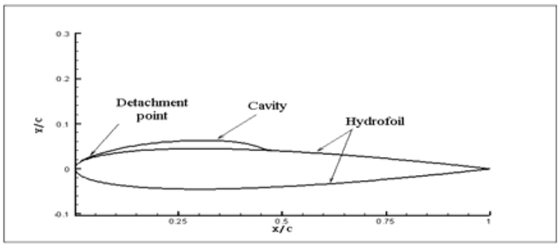

Fig. 7. Configuration of cavity for $L/C = 0.5$, $\alpha = 3^{\circ}$

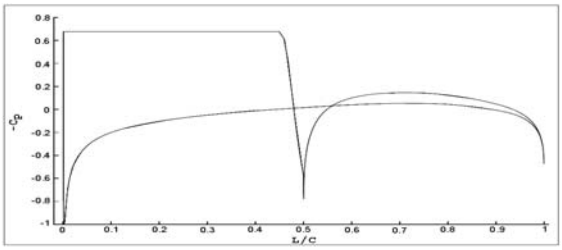

Fig. 8. Pressure distribution over NACA0009

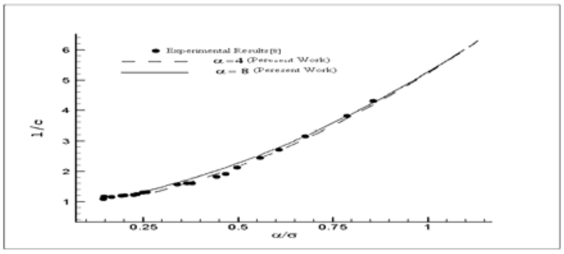

Fig. 9. Cavity length as a function of α/σ

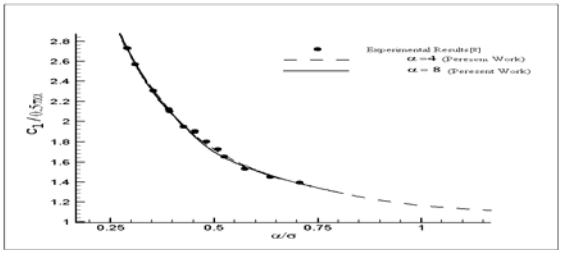

Fig. 10. Lift coefficient as a function of α/σ

For hydrofoil NACA0009, the cavity length and c_l are plotted as a function of α/σ for $\alpha = 4^{\circ}$ and 8° in figures 11 and 12. As shown, c_l and relative cavity length are independent of angle of attack. The experimental results [8] confirm these results.

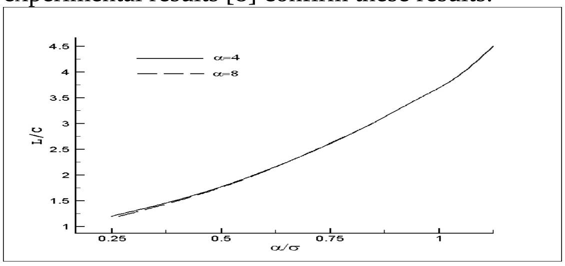

Fig. 11. Relative cavity length on NACA0009

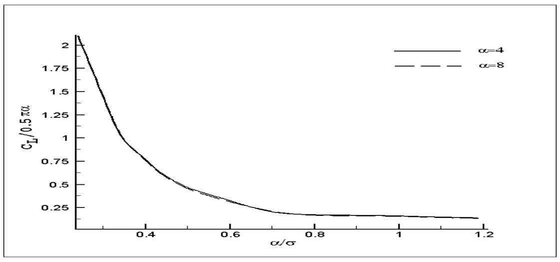

Fig. 12. Lift coefficient on NACA0009

4. Conclusions

In this work we applied potential flow theory for numerical modeling of partial and super cavity over the hydrofoils. In this view, the cavity was considered as a bubble. The results showed the good accuracy of this method. In addition, the rate of convergency in this method was very high. So, we can conclude that, this is a very useful method for predicting characteristics of cavities over hydrofoils in various conditions. It is proved that the results of super cavity have better agreement with experimental results than the partial cavity results, because the flow is more stable in super cavity.

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