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การคำนวณคลื่นที่เกิดจากการเคลื่อนที่ของแพนน้ำ

Calculation of wave generated by hydrofoil

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บทคัดย่อ

สัมประสิทธิ์แรงยกบนแพนน้ำจะแปรเปลี่ยนไปตามความเร็วของการเคลื่อนที่และระดับความลึกจากผิวน้ำ การแปรเปลี่ยนจะเกิดขึ้นมากสุดเมื่อแพนน้ำอยู่ใกล้ผิวน้ำ ทั้งนี้สืบเนื่องมาจากอิทธิพลของผิวอิสระ (ผิวน้ำ) แรงพลศาสตร์ที่กระจายอยู่บนแพนน้ำนี้สามารถคำนวณโดยใช้ระเบียบวิธี *Doublet lattice* ร่วมกับฟังก์ชันของกรีนที่สอดคล้องกับเงื่อนไขเชิงเส้นของนอยแมน-เคลวิน ณ ตำแหน่งเฉลี่ยของผิวอิสระ ด้วยวิธีการนี้สามารถคำนวณแรงดันบนผิวแพนน้ำ สัมประสิทธิ์แรงยกและรูปร่างของผิวอิสระ ทำการคำนวณหาสัมประสิทธิ์แรงยกบนแพนน้ำแบบ *Circular arc* ที่มีสัดส่วนความชะลูด 5.11 และความเร็ว *Froude* number 4.3 ที่ระดับความลึกและมุมปะทะต่างๆ ซึ่งผลลัพธ์เชิงตัวเลขมีความสอดคล้องกันเป็นอย่างดีกับผลการทดลอง และกับผลการคำนวณด้วยระเบียบวิธีอื่น

Abstract

The hydrodynamic lifting coefficients of hydrofoil vary according to Froude number and depth of submergence. Strong variations of the above coefficients are occurred when hydrofoils are situated near the free surface. Doublet lattice method with Green's function, which satisfies Neumann-Kelvin boundary condition at the mean position of free surface, is used for computing the pressure distributions over the surface. Consequently, the lifting coefficients and wave pattern can be calculated. Numerical results obtained correspond well with experiment data for circular arc hydrofoil of aspect ratio of 5.11 and Froude number of 4.3, at many different depths of submergence and angles of attack.

1. Introduction

In classical ship theory, the main resistance to ship moving in water consists of wave making resistance and resistance due to incident wave. The performance of ship, especially from economic point, depends directly upon the reduction of those resistances. One of the common method to improve the performance of many fast moving vessels, is using of hydrofoil, such as HYSUCAT[1]. So the calculation of hydrodynamic force produced by hydrofoil is necessary. This calculation is very complicated because of free surface effect, particularly in lifting problem. Lift coefficients is generally dependent on both of speed (represented by Froude number) and depth of submergence [2]. However, the aerodynamics theory can be applied to compute hydrodynamic force by including free surface condition. The examples of these calculations are works of Kaplan[3], Johnson [4], Furuya[5] and Thiart[6]. They used *lifting line method* to estimate hydrodynamic force for many different situations.

In this paper, the doublet lattice method is applied by using Green's function, which satisfies Neumann-Kelvin boundary condition at mean position of free surface. The Green's function proposed by Guevel and Bougis[7] is used. The numerical calculation was developed by Nontakaew[8]. Two advantages of using this method are; it can be simply applied to arbitrary form of body and be able to compute the thickness effect of hydrofoil. However, the effect of thickness is not taken into account in present study. Because the thickness effect for the case of hydrofoil is less significant. The Numerical results are validated by comparing with experiment data of circular arc hydrofoil with aspect ratio of 5.11 and Froude number of 4.3, at many different angles of attack and depths of submergence [9]. And, the effect of Froude number is compared with calculation of Thiart[10].

The objective of this paper is to continue the work of Nontakaew[11], Kittisanwuttiwetya[12] and Tiaple[13], for studying hydrodynamic phenomenon produced by hydrofoil. The reduction of wave resistance and sea-keeping abilities may be improved by installing lifting elements to the ship hull.

2. Numerical method

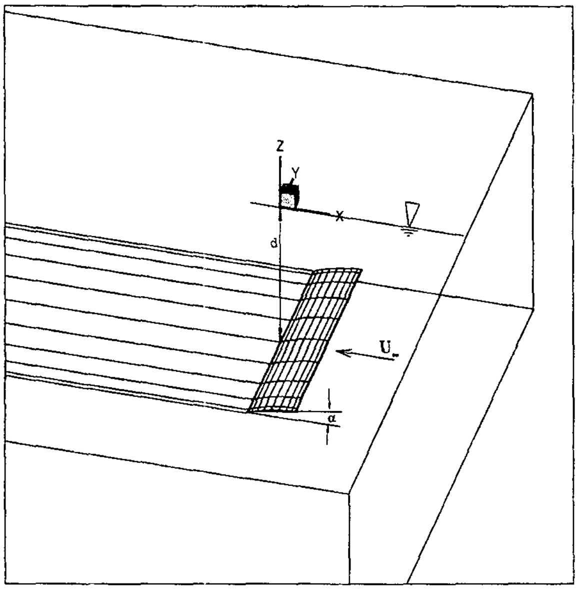

Figure 1. Fluid domain and coordinate system

The fluid surrounding the hydrofoil is assumed to be incompressible, invicid and irrotational flow. The velocity potential can be written as:

$$\Phi(\vec{x}) = \phi(\vec{x}) + \Phi_\infty(\vec{x}) \tag{1}$$

Where ϕ is potential of perturbation velocity and Φ_∞ is undisturbed velocity potential. The total velocity potential Φ must satisfy Laplace's equation,

$$\nabla^2\Phi = 0 \tag{2}$$

And, the boundary conditions are:

1) Zero normal flow condition,

$$\frac{\partial\Phi}{\partial n} = 0 \quad \text{on body's surface} \tag{3}$$

where n is normal vector pointing outside fluid domain.

2) Kutta condition.

$$\Delta\Phi = \Phi^+ - \Phi^- = const. \quad \text{in wake.} \tag{4}$$

3) Linearized Neumann-Kelvin condition,

$$g\phi_z + U^2\phi_{xx} = 0 \text{ on } z = 0. \tag{5}$$

Using the Green's 3rd Identity, the perturbation velocity potential can be defined in distribution form of source (σ) and doublet (μ) over body surface and wake as:

$$\begin{aligned}\Phi(\vec{x}) = &-\frac{1}{4\pi}\iint_{S_B}\left[\sigma G(\vec{x},\vec{x}') - \mu\frac{\partial}{\partial n'}G(\vec{x},\vec{x}')\right]dS(\vec{x}') \\ &+\frac{1}{4\pi}\iint_{S_W}\left[\mu\frac{\partial}{\partial n'}G(\vec{x},\vec{x}')\right]dS(\vec{x}') + \Phi_\infty(\vec{x}')\end{aligned} \tag{6}$$

Where $G(\vec{x},\vec{x}')$ is Green's function that defines as:

$$G = g_0 + g_1$$

$$g_0 = \frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}} - \frac{1}{\sqrt{(x-x')^2+(y-y')^2+(z+z')^2}}$$

$$g_1 = -\frac{2}{\pi l}\Re\left(\int_0^{\pi/2} K\left[G_1(K\xi) + G_1(K\xi')\right]d\theta\right)$$

$K = \dfrac{1}{F^2\cos^2\theta}$, F is Froude number ($F = \dfrac{U}{\sqrt{gl}}$).

$$\xi = \frac{1}{l}\{z + z' + \mathrm{i}[(x-x')\cos\theta + (y-y')\sin\theta]\}$$

$$\xi = \frac{1}{l}\{z + z' + \mathrm{i}[(x-x')\cos\theta - (y-y')\sin\theta]\}$$

$$G_1(\chi) = \begin{cases}\exp(\chi)E_1(\chi) & \text{if } \Im(\chi) \ge 0 \\ \exp(\chi)[E_1(\chi) - \mathrm{i}2\pi] & \text{if } \Im(\chi) < 0\end{cases}$$

$E_1(\chi) = \displaystyle\int_\chi^\infty \frac{\exp(-t)}{t}dt$: 1st order complex exponential integral.

l is characteristic length.

From equation (3) and equation (6), the governing equation will be:

$$\begin{aligned}&-\frac{1}{4\pi}\iint_{S_B}\left[\sigma\frac{\partial G(\vec{x},\vec{x}')}{\partial n} - \mu\frac{\partial^2 G(\vec{x},\vec{x}')}{\partial n\partial n'}\right]dS(\vec{x}') \\ &+\frac{1}{4\pi}\iint_{S_W}\left[\mu\frac{\partial^2 G(\vec{x},\vec{x}')}{\partial n\partial n'}\right]dS(\vec{x}') + \frac{\partial}{\partial n}\Phi_\infty(\vec{x}') = 0\end{aligned} \tag{7}$$

or

$$\begin{aligned}\mathbf{U}_\infty\cdot\mathbf{n} = &\frac{1}{4\pi}\iint_{S_B}\left[\sigma\frac{\partial G(\vec{x},\vec{x}')}{\partial n} - \mu\frac{\partial^2 G(\vec{x},\vec{x}')}{\partial n\partial n'}\right]dS(\vec{x}') \\ &-\frac{1}{4\pi}\iint_{S_W}\left[\mu\frac{\partial^2 G(\vec{x},\vec{x}')}{\partial n\partial n'}\right]dS(\vec{x}')\end{aligned} \tag{8}$$

Where $\mathbf{U}_\infty$ is free stream velocity.

Surface of body is divided into N panels and wake surface is divided into N_W panels as shown in figure 1. Assume the difference of doublet's intensity is constant over each panel and define as Γ. The assumption of thin hydrofoil allows neglecting source effect ($\sigma = 0$). The equation (8) can be written in linear summation form as:

$$\sum_{k=1}^{N} \frac{\Gamma_k}{4\pi} \iint_{SB_k} \frac{\partial^2 G(\vec{x}, \vec{x}')}{\partial n \partial n'} dS(\vec{x}') + \sum_{l=1}^{N_W} \frac{\mu_l}{4\pi} \iint_{SW_l} \frac{\partial^2 G(\vec{x}, \vec{x}')}{\partial n \partial n'} dS(\vec{x}') = -\mathbf{U}_\infty \cdot \mathbf{n} \tag{10}$$

or

$$\sum_{k=1}^{N} \Gamma_k C_k + \sum_{l=1}^{N_w} \mu_l C_l = -4\pi(\mathbf{U}_\infty \cdot \mathbf{n}) \tag{11}$$

From Kutta condition, equation (4), the intensity of doublet in wake equals to the difference of doublet's intensity at trailing edge.

$$\mu_{wake} = \Gamma_{TE} \tag{12}$$

So, equation (11) can be reduced to:

$$\sum_{k=1}^{N} \Gamma_k A_k = -4\pi(\mathbf{Q}_\infty \cdot \mathbf{n}) \tag{13}$$

$$A_k = \iint_{SB_k} \frac{\partial^2 G(\vec{x}, \vec{x}')}{\partial n \partial n'} dS(\vec{x}') + \ddot{a}_{SB_k STE_l} \iint_{SW_l} \frac{\partial^2 G(\vec{x}, \vec{x}')}{\partial n \partial n'} dS(\vec{x}') \tag{14}$$

Where $\delta_{S_i S_j} = \begin{cases} 1, & S_i \equiv S_j \\ 0, & \text{otherwise} \end{cases}$

Writing equation (13) on centroid of all body's panels, then the system of linear equation will be obtained,

$$\sum_{k=1}^{N} \Gamma_k A_{jk} = -4\pi(\mathbf{Q}_\infty \cdot \mathbf{n}_j) \tag{15}$$

Or writing in matrix form,

$$[A]\{\Gamma\} = -4\pi\{\mathbf{Q}_\infty \cdot \mathbf{n}\} \tag{16}$$

Solve equation (16), now, the hydrodynamic force can be obtained from:

$$F = \int_{S_B} P \cdot \mathbf{n} dS \tag{17}$$

$$P = \frac{1}{2}\rho(\nabla\Phi)^2 \tag{18}$$

According to dynamic free surface boundary condition, the free surface geometry can be found from,

$$gz + U\phi_x + \frac{1}{2}(\nabla\phi)^2 = 0 \tag{19}$$

Since the elevation of wave is assumed to be small, the dynamic boundary conditions on the free surface may be linearlized to:

$$z = -\frac{1}{g} U\phi_x \tag{20}$$

3. Validation of numerical results

Firstly, The lift coefficients computed by present method are compared with experiment data of circular arc hydrofoil, which has been tested in towing tank at the University of Stellenbosch. Hydrofoil has rectangular form with aspect ratio of 5.11. The data were measured at Froude number of 4.3 based on chord length. The numerical results correspond with experiment data as shown in figure 2 where d is distance from mean position of free surface to trailing edge of hydrofoil and c is chord length.

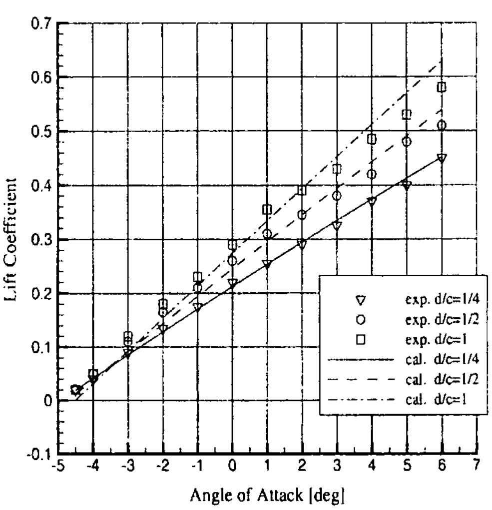

Figure 2. Lift coefficient of circular arc hydrofoil, AR=5.11, Fr=4.3

Secondly, the effect of Froude number and depth of submergence on finite span hydrofoil of several aspect ratios are computed. The present results are compared with the work of Thiart [10]. He used the vortex lattice method to calculate lift coefficient of rectangular flat plate hydrofoil. Figure 3, 4 and 5 show the comparison for the hydrofoil at angles of attack of 5 degrees with aspect ratio of 2, 5 and 10 respectively. It is found that two numerical results are quite similar. ($C_{L\infty}$ denotes the lift coefficient of hydrofoil at very far from free surface.)

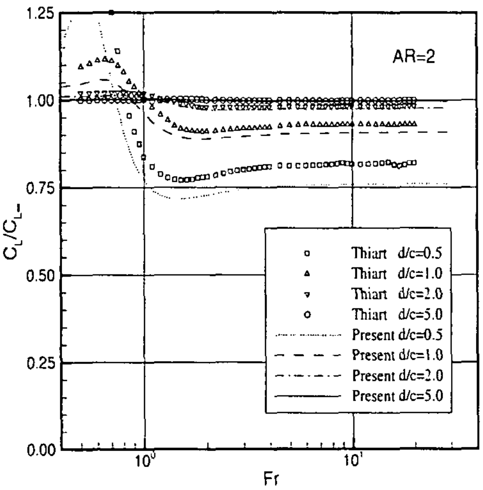

Figure 3. Effect of Froude number for flat plate hydrofoil, AR=2

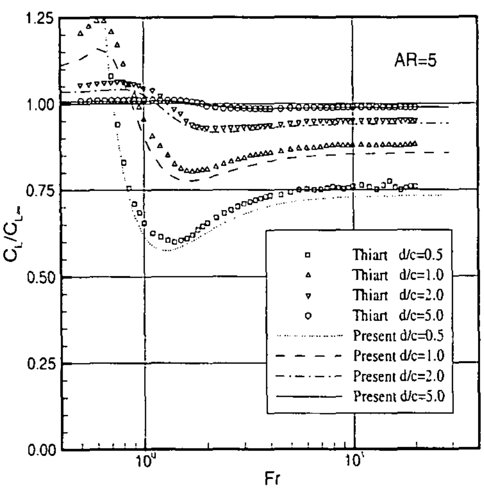

Figure 4. Effect of Froude number for flat plate hydrofoil, AR=5

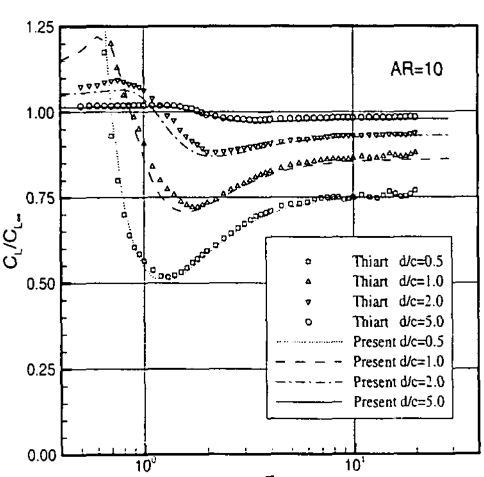

Figure 5. Effect of Froude number for flat plate hydrofoil, AR=10

4. Wave pattern

Figure 6-14 show waves generated by rectangular hydrofoil which aspect ratio 5 at position below undisturbed free surface 0.5 with respect to chord length (d/c=0.5). From observation of wave patterns, It is evidently found that wave pattern has some correlation with lift coefficient. The wave pattern varies with Froude number, it can be divided into 3 zones.

The first zone is about Froude number up to 0.4 . The results obtained are not quite clear because our Green function is not suitable for very low Froude number. In the second zone ($Fr \approx 0.4-1.0$), the lift coefficient rapidly changes with respect to Froude number. The wave pattern is characterized by transverse wave. In the last zone, both of transverse and diverging waves can be obtained which is similar to waves generated by ship hull. The wavelength is proportional to speed.

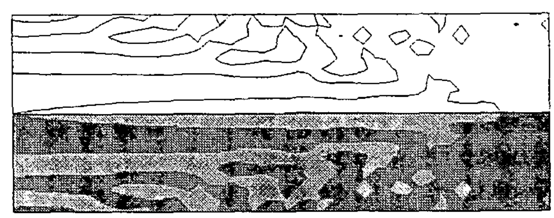

Figure 6. Wave pattern at Fr = 0.4

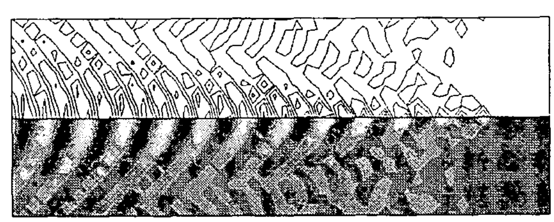

Figure 7. Wave pattern at Fr = 0.5

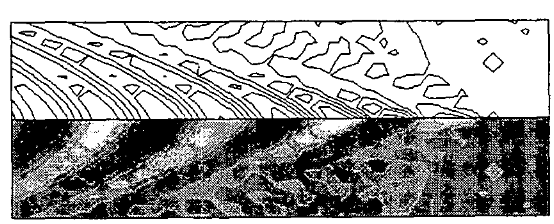

Figure 8. Wave pattern at Fr = 0.54

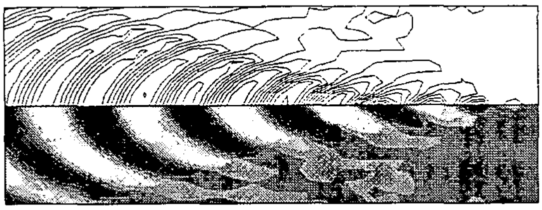

Figure 9. Wave pattern at Fr = 0.6

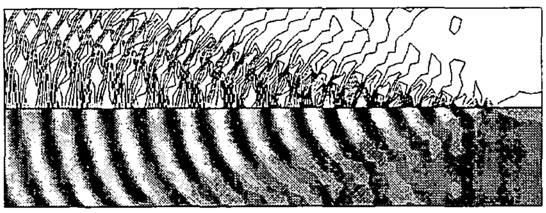

Figure 10. Wave pattern at Fr = 0.7

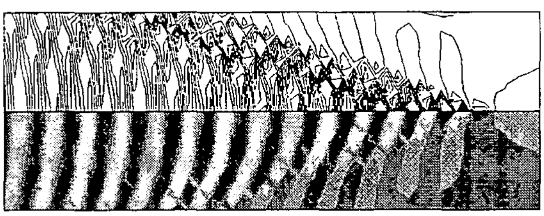

Figure 11. Wave pattern at Fr = 1.0

Figure 12. Wave pattern at Fr = 1.5

Figure 13. Wave pattern at Fr = 2.0

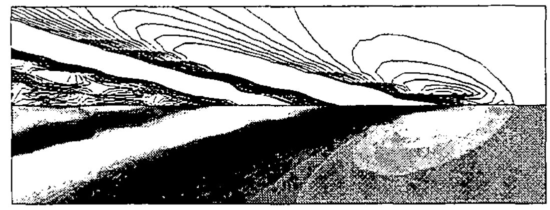

Figure 14. Wave pattern at Fr = 5.0

Considering carefully in the second zone, there are two forms of wave pattern, convex (Fig.7, 8) and concave (Fig.9, 10) form. The convex form is occurred in Froude number closing to critical point where highest lift is occurred however the concave form appears for the others. The wavelength of convex form is proportional to speed while the concave is inverse proportional.

5. Conclusion

The method of prediction hydrodynamic force and free surface geometry has been presented. By this study, we expect that the ship performance can be improved by installing lifting elements which proper form and position on ship hull. This installation is not for raising ship hull over free surface, but for creating waves to compensate waves generated by ship hull. That means the overall wave making resistance of ship will be reduced.

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