J. Marine. Sci. Appl. (2009) 8: 275-280
DOI: 10.1007/s11804-009-8060-x

Using the surface panel method to predict the steady performance of ducted propellers

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Abstract: A new numerical method was developed for predicting the steady hydrodynamic performance of ducted propellers. A potential based surface panel method was applied both to the duct and the propeller, and the interaction between them was solved by an induced velocity potential iterative method. Compared with the induced velocity iterative method, the method presented can save programming and calculating time. Numerical results for a JD simplified ducted propeller series showed that the method presented is effective for predicting the steady hydrodynamic performance of ducted propellers.
Keywords: surface panel method; ducted propeller; velocity potential iteration; steady hydrodynamic performance
CLC number: U661.3 **Document code:** A **Article ID:** 1671-9433(2009)04-0275-06

1 Introduction

Ducted propellers have higher efficiency in heavy load conditions compared with conventional propellers. So they have been widely used on various types of ships, such as towboats, push boats, fish boats and large scale vessels. It has been proven that the use of ducted propellers can increase efficiency and reduce vibration. However, ducted propellers also can reduce efficiency and create noise and vibration if the interaction of the duct and the propeller is not treated properly. Therefore, it is really important to be able to theoretically predict the hydrodynamic performance of ducted propellers.

Some numerical methods for ducted propellers, which consist of iterative method[1,2,5-9] and directly solving method[3,4,10], have been developed by many researchers[1-10]. And iterative method can be composed of "lifting surface theory & panel method theory[1,5-7]" and "panel method theory & panel method theory[2,8,9]". As to iterative method, both induced velocity method and induced velocity potential method can deal with the interaction between duct and propeller. As to lifting surface theory, only induced velocity method can be employed because of the characteristics of lifting surface theory. Also as to the surface panel method, most of researchers prefer to apply induced velocity method to deal with the interaction between duct and propeller.

In this paper, the induced velocity potential method is used to deal with the interaction. Compared with velocity, velocity potential is scalar, and it costs less space to store and less time to compute data. As to programming, the algorithmic language program of potential method is the same as the conventional propeller's self-induced potential calculating algorithm, and it does not need to make a new code. Therefore, the induced velocity potential method can save programming and calculating time.

2 Numerical methods

2.1 Numerical dispersion of equations and Panel division

Consider a ducted propeller working in an unbounded flow field. The fluid is assumed to be inviscid and incompressible. A Cartesian coordinate system fixed in space *O-xyz* is defined as shown in Fig.1. The *x*-axis coincides with the shaft axis of propeller and points downstream. The *z*-axis points vertically upwards, and the *y*-axis completes the right-handed system. The inflow $\boldsymbol{V}_0$ is along the *x*-axis. The propeller blades rotate around *x*-axis at a constant angular velocity Ω.

In this paper, a potential based panel method is employed both for the duct and the propeller. The potential problem can be solved by considering the duct and the propeller as a single surface and applying Green's formula in order to solve the potential ϕ on this surface as follows:

$$2\pi\phi(P) = \int_{S_B}\left[\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})} - \frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\frac{\partial\phi}{\partial n}\right]\mathrm{d}S + \int_{S_W}\left[\Delta\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\right]\mathrm{d}S \quad (1)$$

Received date: 2008-09-03.
Foundation item: Supported by the Open Research Foundation of State Key Laboratory of AUV, HEU under Grant No. 2007015.
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where, S_B and S_W are the combined duct/propeller surface and the combined wake surface respectively; $\boldsymbol{n}$ the outer unit normal vector on the body or wake surface; $r(\boldsymbol{P},\boldsymbol{Q})$ the distance between the field point P and the boundary point Q; $\Delta\varphi$ the jump in potential across the wake surface.

The $\frac{\partial\phi}{\partial n}$ term is equivalent to the perturbation velocity normal to the boundary surface S; therefore, it must satisfy the kinematic boundary condition that normal velocity is zero.

$$\frac{\partial\phi}{\partial n} = -\boldsymbol{V}_0 \cdot \boldsymbol{n} \tag{2}$$

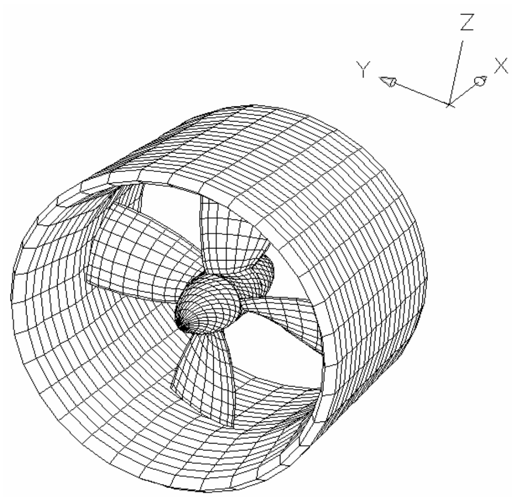

Fig.1 Coordinate system

Eq.(1) can now be broken down into the integrals over two separate body surfaces and two wake surfaces. In this manner the potential on each of these surfaces can be determined separately.

$$2\pi\phi = \int_{S_p}\left[\phi\frac{\partial}{\partial n}\frac{1}{r} - \frac{1}{r}\frac{\partial\phi}{\partial n}\right]\mathrm{d}S + \int_{S_{pw}}\left[\Delta\phi\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}S + \int_{S_d}\left[\phi\frac{\partial}{\partial n}\frac{1}{r} - \frac{1}{r}\frac{\partial\phi}{\partial n}\right]\mathrm{d}S + \int_{S_{dw}}\left[\Delta\phi\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}S \tag{3}$$

where, S_p and S_{pw} are the propeller surface and propeller wake surface respectively; S_d and S_{dw} are the duct surface and duct wake surface respectively.

When solving the potential at a point on the duct surface, the integrals over the propeller and propeller wake surfaces in this equation represent the perturbation potential induced by the propeller at that point multiplied by a factor of 4π corresponding to Green's formulation for the potential at a point in the field outside the surface. Therefore, the boundary value problem for the potential on the duct surface can be written as follows:

$$2\pi\phi(P) = \int_{S_d}\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \int_{S_d}(\boldsymbol{V}_0\cdot\boldsymbol{n})\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \int_{S_{dw}}\{\Delta\phi\}\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + 4\pi\phi_{dp} \tag{4}$$

where, ϕ_{dp} is the potential of point P on duct induced by the propeller.

$$\phi_{dp} = \frac{1}{4\pi}\int_{S_p}\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \frac{1}{4\pi}\int_{S_p}(\boldsymbol{V}_0\cdot\boldsymbol{n})\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \frac{1}{4\pi}\int_{S_{pw}}\{\Delta\phi\}\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S \tag{5}$$

The propeller induced potential ϕ_{dp} is steady only with respect to the rotating propeller coordinate system. Therefore, the duct potential should be solved by using the circumferential mean of the induced potential from the propeller. Then, the boundary value problem for the potential on the duct sruface can be expressed as

$$2\pi\phi(P) = \int_{S_d}\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \int_{S_d}(\boldsymbol{V}_0\cdot\boldsymbol{n})\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \int_{S_{dw}}\{\Delta\phi\}\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + 4\pi\overline{\phi}_{dp} \tag{6}$$

where, $\overline{\phi}_{dp}$ is the circumferential average of the potential induced on the duct surface by the propeller.

However, when solving the propeller potential problem, it is not necessary to use the circumferential average of the potential induced by the duct. The boundary value problem for the potential on the propeller surface can be written as follows:

$$2\pi\phi(P) = \int_{S_p}\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \int_{S_p}(\boldsymbol{V}_0\cdot\boldsymbol{n})\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \int_{S_{pw}}\{\Delta\phi\}\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + 4\pi\phi_{pd} \tag{7}$$

where, ϕ_{pd} is the potential of point P on propeller induced by the duct.

$$\phi_{pd} = \frac{1}{4\pi}\int_{S_d}\phi(Q)\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \frac{1}{4\pi}\int_{S_d}(\boldsymbol{V}_0\cdot\boldsymbol{n})\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S + \frac{1}{4\pi}\int_{S_{dw}}\{\Delta\phi\}\frac{\partial}{\partial n}\frac{1}{r(\boldsymbol{P},\boldsymbol{Q})}\mathrm{d}S \tag{8}$$

As formulas above described, the interaction of the propeller and duct is taken into account by an induced velocity potential iterative method. In calculating, the potential induced by duct ϕ_{pd} described in Eq.(8) is treated as the known quantity to add to the right-hand side of the propeller equations, i.e. Eq.(7); also, the circumferential average of the potential induced by propeller $\overline{\phi}_{dp}$ described in Eq.(5) is treated as the known quantity to add to the right-hand side of the duct equations, i.e. Eq.(6).

The blade part includes a blade, the wake generated from the blade and part of the hub and duct correspond to the blade. For the steady condition, each blade part performs the same; therefore, only one blade part is involved in the solving process.

The surface of the duct and the propeller together with hub are divided into small hyperboloidal quadrilateral panels. The divided numbers are N, Nd, of which the blade and part of the hub and duct correspond to the blade. The wake of propeller and duct is represented by an approximate model. The wake model of the propeller is considered for the convergence and the pitch change. The wake model of the duct is along the center line of the upside and downside surface angle first, and then along the flow direction. The number of wake panels is respectively $M\times N_W$, $Md\times N_W d$, where M, Md are the spanwise panel numbers of blade and duct respectively, N_W, $N_W d$ are the wake chordwise numbers of propeller and duct respectively. Fig.2 shows panel arrangement of the ducted propeller and its wake.

The control point is located at the center of each panel. The doublet and source with constant strength are distributed on each panel. As the strength of the latter is known, the boundary integral equations of doublet, i.e. Eq.(6) and Eq.(7) combined with Eq.(5) and Eq.(8) can be discretized into two sets of linear algebraic equations as follows:

$$\sum_{j=1}^{N}(\delta_{ij}-(C_{ij})_p)\varphi_{pj}-\sum_{j=1}^{N_W}(W_{ij})_p\Delta\varphi_{pj}=-\sum_{j=1}^{N}(B_{ij})_p(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jp})+ \{\sum_{j=1}^{Nd}(C_{ij})_{pd}\varphi_{dj}+\sum_{j=1}^{N_W d}(W_{ij})_{pd}\Delta\varphi_{dj}-\sum_{j=1}^{Nd}(B_{ij})_{pd}(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jd})\} \tag{9}$$

$$\sum_{j=1}^{Nd}(\delta_{ij}-(C_{ij})_d)\varphi_{dj}-\sum_{j=1}^{N_W d}(W_{ij})_d\Delta\varphi_{dj}=-\sum_{j=1}^{Nd}(B_{ij})_d(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jd})+ \{\sum_{j=1}^{N}(C_{ij})_{dp}\varphi_{pj}+\sum_{j=1}^{N_W}(W_{ij})_{dp}\Delta\varphi_{pj}-\sum_{j=1}^{N}(B_{ij})_{dp}(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jp})\} \tag{10}$$

where, δ_{ij} is the Kronecker function; φ, $\Delta\varphi$ are the strengths of the doublet on the propeller and duct and wake surface respectively; $\boldsymbol{V}_0$ the undisturbed inflow velocity; $\boldsymbol{n}$ the outer normal vector on the panel; C, W and B are the influence coefficients derived from the Morino method.

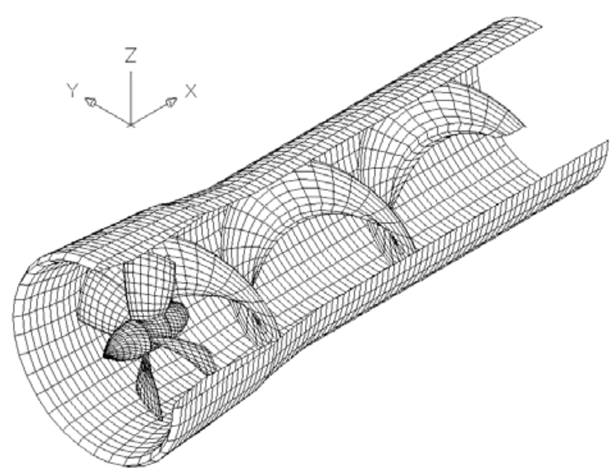

Fig.2 Panel arrangement and wake model

2.2 The implementation of the Kutta condition

The non-linear equal-pressure Kutta condition should be applied to the blade and duct trailing edge, i.e. the pressures of points on the upper and lower panels at the trailing edge of the propeller or duct are equal to each other. The equation is written as follows:

$$\Delta p_i = p_{TE}^{+} - p_{TE}^{-} = 0 \qquad i=1, 2, \cdots, M \tag{11}$$

$$\Delta p_j = p^{+} - p^{-} = 0 \qquad j=1, 2, \cdots, Md \tag{12}$$

In which, p_{TE}^{+} and p_{TE}^{-} are the pressures of the blade's back and face at the trailing edge respectively; p^{+} and p^{-} are the pressures of the inside and outside panels at the trailing edge respectively.

The equation sets Eqs.(9) and (10) are solved by the Newton-Raphson method, combined with the Eqs.(11) and (12). The initial value of $\Delta\phi$ is determined by the Morino Kutta condition.

2.3 Solving equations and calculating forces

Two sets of linear algebraic Eqs.(9) and (10) are solved iteratively. Specific steps are written as follows:

1) Ignore the interaction, i.e. ignoring $\overline{\phi}_{dp}$ and ϕ_{pd} in Eqs.(6) and (7), then, the Eqs.(9) and (10) are simplified as follows:

$$\sum_{j=1}^{N}(\delta_{ij}-(C_{ij})_p)\varphi_{pj}-\sum_{j=1}^{N_W}(W_{ij})_p\Delta\varphi_{pj}=-\sum_{j=1}^{N}(B_{ij})_p(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jp})+ \{\sum_{j=1}^{Nd}(C_{ij})_{pd}\varphi_{dj}+\sum_{j=1}^{N_W d}(W_{ij})_{pd}\Delta\varphi_{dj}-\sum_{j=1}^{Nd}(B_{ij})_{pd}(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jd})\} \tag{13}$$

$$\sum_{j=1}^{Nd}(\delta_{ij}-(C_{ij})_d)\varphi_{dj}-\sum_{j=1}^{N_W d}(W_{ij})_d\Delta\varphi_{dj}=-\sum_{j=1}^{Nd}(B_{ij})_d(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jd})+ \{\sum_{j=1}^{N}(C_{ij})_{dp}\varphi_{pj}+\sum_{j=1}^{N_W}(W_{ij})_{dp}\Delta\varphi_{pj}-\sum_{j=1}^{N}(B_{ij})_{dp}(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jp})\} \tag{14}$$

Solve Eqs.(13) and (14) respectively to obtain singularity strengths on the blade and the duct.

2) Calculate $\overline{\phi}_{dp}$ and ϕ_{pd} respectively, i.e. calculate terms of the second line described in the Eqs.(9) and (10). Specific descriptions of the terms are written as follows:

$$\sum_{j=1}^{N}(\delta_{ij}-(C_{ij})_p)\varphi_{pj}-\sum_{j=1}^{N_W}(W_{ij})_p\Delta\varphi_{pj}=-\sum_{j=1}^{N}(B_{ij})_p(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jp})+$$
$$\{\sum_{j=1}^{Nd}(C_{ij})_{pd}\varphi_{dj}+\sum_{j=1}^{N_Wd}(W_{ij})_{pd}\Delta\varphi_{dj}-\sum_{j=1}^{Nd}(B_{ij})_{pd}(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jd})\}$$

and

$$\sum_{j=1}^{Nd}(\delta_{ij}-(C_{ij})_d)\varphi_{dj}-\sum_{j=1}^{N_Wd}(W_{ij})_d\Delta\varphi_{dj}=-\sum_{j=1}^{Nd}(B_{ij})_d(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jd})+$$
$$\{\sum_{j=1}^{N}(C_{ij})_{dp}\varphi_{pj}+\sum_{j=1}^{N_W}(W_{ij})_{dp}\Delta\varphi_{pj}-\sum_{j=1}^{N}(B_{ij})_{dp}(\boldsymbol{V}_0\cdot\boldsymbol{n}_{jp})\}$$

3) Renew the right-hand sides of Eqs.(9) and (10) with terms which are obtained in step 2). Solve Eqs.(9) and (10) respectively to obtain singularity strengths on the blade and the duct.

4) Calculate the total thrust and torque coefficients of ducted propeller and the trust coefficient of duct and propeller.

Repeat steps 2), 3), 4) iteratively until both loads of duct and propeller calculated in step 4) converge.

Loads of duct and propeller cited in step ④ are expressed as follows:

$$K_T=\frac{T_p+T_d}{\rho n^2 D^4},\quad K_Q=\frac{Q_p}{\rho n^2 D^5},\quad K_{tn}=\frac{T_d}{\rho n^2 D^4} \qquad (15)$$

where T_p and T_d denote the thrust of propeller and duct respectively, Q_p is the torque of propeller, n and D are the rotating velocity and diameter of propeller respectively, ρ is the density of water. During calculating, T and Q can be obtained from integrating the pressure on the entire body surface. The pressure is obtained from the equation of Bernoulli, and the method presented by Yanagizawa is used to calculate the velocity on the body surface.

3 Numerical results

Based on the new method presented in this paper, numerical calculations are carried out for JD7704 simplified ducted propeller series[11]. In calculating, the propeller blade is divided into 20(chordwise) × 15(spanwise) in cosine form and the duct into 36(circumferentially) × 30(chordwise) in mean form.

Fig.3~7 display the comparison between the numerical and experimental results. And numerical calculation results following the induced velocity method[8] are also added in the comparison. In Fig.3~7, “potential” and “velocity” mean that the calculating results are obtained in the induced velocity potential method and in the induced velocity method respectively.

It can be seen from figures that the thrust and torque are in good agreement in a range of high advance coefficients. But for heavy loads and low advance coefficients, the calculating results are a slight lower than the experimental data. Both the induced velocity potential method and the induced velocity method can be accepted in calculating precision.

Table 1 shows the CPU time needed in both potential method and velocity method. Calculating case of Fig.3 is chosen to be an example. We used a personal computer with an Intel Core(TM)2 Duo 2.33 GHz CPU. We can see that the potential method takes less time and iterations to finish the calculating task and it is more efficient.

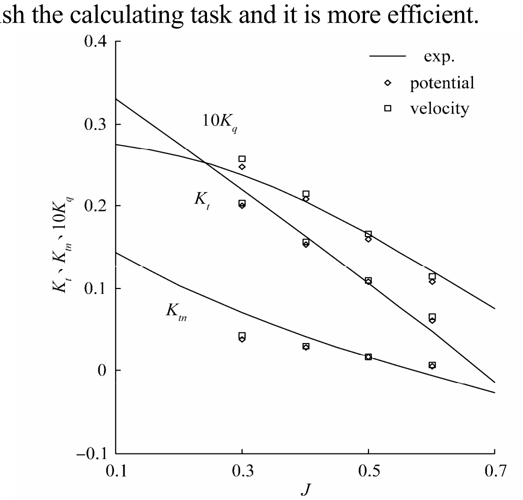

Fig.3 JD7704 duct + Ka4-55 propeller (*P/D*=0.8), open water steady performance

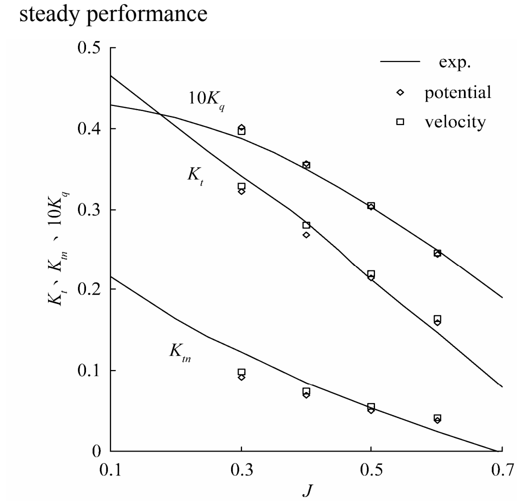

Fig.4 JD7704 duct + Ka4-55 propeller (*P/D*=1.0), open water steady performance

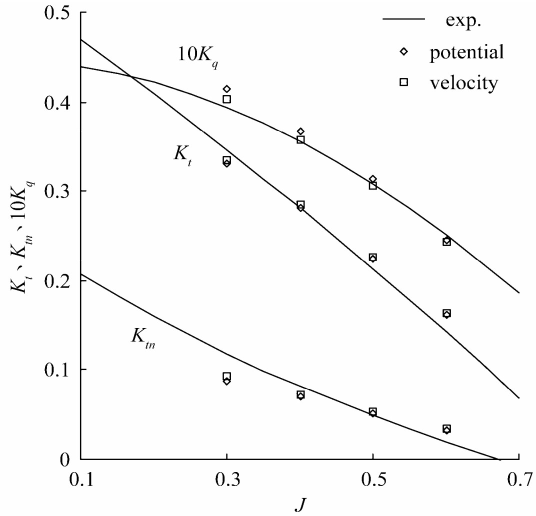

Fig.5 JD7704 duct + Ka4-70 propeller (*P/D*=1.0), open water steady performance

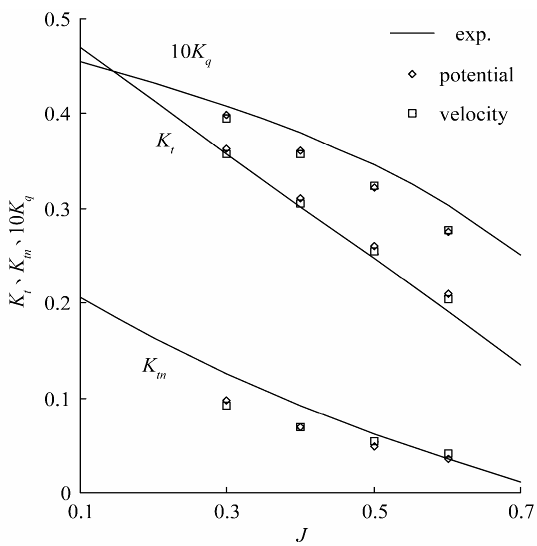

Fig.6 JD75 duct + Ka4-55 propeller (*P/D*=1.0), open water steady performance

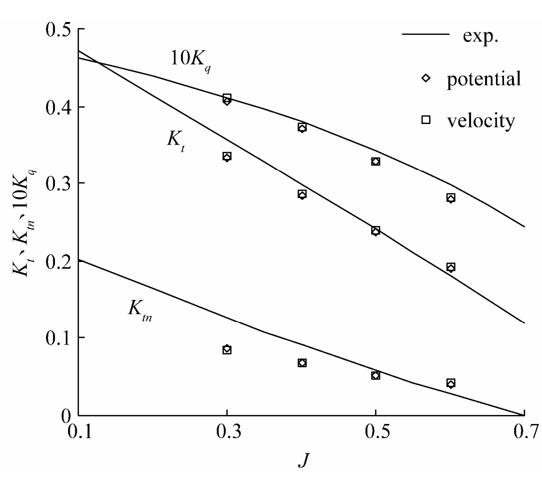

Fig.7 JD75 duct + Ka4-70 propeller (*P/D*=1.0), open water steady performance

Table 1 Comparison of CPU Time

	Potential method	Velocity method
CPU Time /s	105	612
Iterations	4	6

4 Conclusions

The interaction between propeller and duct is solved by a potential iterative method. Compared with the velocity iterative method, the presented method can save programming and calculating time and require less storing space. The numerical results have an acceptable precision and show that the presented method is effective for predicting the steady hydrodynamic performance of ducted propellers.

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面元法预估导管螺旋桨水动力性能的一种新方法

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摘　要：采用一种新的方法预估导管螺旋桨的水动力性能；导管和螺旋桨均采用基于速度势的面元法，它们间的影响通过相互的诱导速度势数值迭代来体现. 与诱导速度体现相互影响的方法相比，本文方法可节省编程及计算时间；对 JD 系列导管螺旋桨的计算与实验结果的比较表明，该方法可以有效地预估导管螺旋桨的水动力性能.

关键词：面元法；导管螺旋桨；速度势迭代；定常水动力性能