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A surface panel method for the analysis of hybrid contra-rotating shaft pod propulsor

Rui Wang*, Ying Xiong, Zhan-Zhi Wang

Department of Naval Architecture, Naval University of Engineering, Wuhan 430033, Hubei, China

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ABSTRACT

The present work is devoted to the hydrodynamic performance prediction of the hybrid contra-rotating shaft pod (HCRSP) propulsors. The HCRSP propulsor is divided into two parts, a single forward propeller and a podded propulsor. For the podded propulsor, an unsteady surface panel method is developed to analyze the open water performance; also the wake model is modified according to wake flow analysis. Then a podded propulsor in uniform flow is simulated by the unsteady surface panel method and the numerical results show a good agreement with experimental data. To improve the computational efficiency and simplify the analysis of HCRSP propulsor, we present a steady surface panel method that treats the propeller and pod unit as a single unit. Numerical results of the steady surface panel method also show good agreement with experimental data. Based on this study, an iterative steady surface panel method program for the HCRSP propulsor is presented and a model test is carried out in a cavitation tunnel to verify the numerical results.

1. Introduction

The hybrid contra-rotating shaft pod (HCRSP) propulsor has come into notice in recent years. It combines the advantages of a contra-rotating propeller and a podded propulsor, and it includes some improvements in system control and redundancy. Numerous experimental and numerical studies on the hydrodynamic performance of the HCRSP propulsor have carried out recently. A procedure for model tests of the HCRSP propulsor was presented by Sasaki et al. (2009); also, a design methodology was proposed and verified by a model test. An experiment performed by Black and Cusanelli (2009) analyzed the open water performance and cavitation inception. A model test (Shimamoto et al., 2010) conducted in National Maritime Research Institute showed that the HCRSP propulsor has relatively little electric conversion loss, and the pod propeller has high maneuverability at low speeds as a strong stern thruster. The basic characteristics of the HCRSP propulsor studied by Chang and Go (2011) indicate that in design point, the effect of a podded propulsor on the forward propeller is small. The EU project TRIPOD (Sanchez et al., 2013) presents a new propulsion concept for improving a ship's energy efficiency based on the combination of pod, CLT and CRP propulsion. The TRIPOD project includes methods for the extrapolation of model tests to full scale and the accurate estimation of effective wakes by CFD tools. Numerical computations (Zhang et al., 2013; Guo et al., 2013; Sheng and Xiong, 2012) performed on the HCRSP propulsor show that the gap between two propellers has little effect on the open water performance of the forward propeller.

Numerical approaches such as the RANS and surface-panel methods can be used to predict the hydrodynamic performance of the HCRSP propulsor. The surface panel method generally has greater computational efficiency than the RANS method, which is important in the design and optimization of an HCRSP propulsor. Unfortunately, little research has focused on the analysis of an HCRSP propulsor by the surface panel method. A reasonable explanation can be given by considering the treatment's complexity. When analyzing an HCRSP propulsor, the iterative surface panel method (Liu, 2009; Ye et al., 2009), which is often used in the analysis of a contra-rotating propeller or podded propulsor, can also be used. But an HCRSP propulsor consists of three parts-a forward propeller, an aft propeller, and a pod unit-and this will complicate the iterative process.

2. Unsteady surface panel method for podded propulsor

2.1. Governing equations for unsteady surface panel method

To simplify the iterative process, an HCRSP propulsor can be considered as two parts: a single forward propeller and a podded propulsor. The interaction between these two parts can be obtained by induced velocity iteration. In this method, the pod and aft propeller are treated as a unit, so the iterative surface panel method (Xiong et al.,

* Corresponding author.
E-mail address: wangshadows@163.com (R. Wang).

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2007) that treats the propeller and pod unit as two separated parts is ill-suited for this treatment. For a podded propulsion system, only the unsteady surface panel method can be used for the analysis of podded propulsion system if the pod unit and propeller are treated as a unit. In general, the unsteady surface panel method requires more computation time than the steady surface panel method, and this is not what we want in the preliminary design and optimization of a podded propulsor. Therefore, a steady surface panel method for the analysis of podded propulsion must be developed.

Firstly, an unsteady surface panel method is developed to analyze the podded propulsor. This process not only can help us understand the characteristics of podded propulsor open water performance; but also can obtain some validation data for the integral steady panel method. The low-order surface panel method based on velocity potential is employed in this paper. For single propeller under steady condition, only key blade needs to be solved due to the symmetrical inflow condition and propeller geometry. Both the blades and the hub are discretized with hyperboloidal panels carrying constant strength sources and dipoles in the analysis of propeller hydrodynamic performance, and the same to propeller vortex sheet. Based on Laplace equation and green theory, the velocity potential in each panel can be expressed in discrete form as shown in Eq. (1), which is presented in detail by Katz and Plotkin (1991).

$$\begin{aligned}\phi_i =& \sum_{k=1}^{Z}\sum_{j=1}^{N}\phi_j\frac{1}{2\pi}\oint_{S_{Bj}}\frac{\partial}{\partial n_{qj}}\left(\frac{1}{r(p_i,q_{jk})}\right)dS_{qj}\\ &+\sum_{k=1}^{Z}\sum_{j=1}^{N}\left(\frac{\partial\phi}{\partial n_q}\right)_j\left[-\frac{1}{2\pi}\oint_{S_{Bj}}\frac{\partial}{\partial n_{qj}}\left(\frac{1}{r(p_i,q_{jk})}\right)dS_{qj}\right]\\ &+\sum_{k=1}^{Z}\sum_{j=1}^{N_W}\Delta\phi_j\frac{1}{2\pi}\oint_{S_{Wj}}\frac{\partial}{\partial n_{qj}}\left(\frac{1}{r(p_i,q_{jk})}\right)dS_{qj}\quad i=1,2,\cdots N\end{aligned} \tag{1}$$

Where Z is the blade number; N is the total mesh number on propeller and hub surface, N_W is the total mesh number on wake surface; S_B is the surface of propeller, S_W is the surface of wake; p is field point and q is control point, r is the distance between point p and q; For a single traditional propeller, when k(represents the different blades) takes different values, the values of ϕ_j($(\partial\phi/\partial n_q)_j$ or $\Delta\phi_j$) are the same. But for a podded propulsor, when k takes different values, the values of $\phi_j((\partial\phi/\partial n_q)_j$ or $\Delta\phi_j)$ are also different. The item $(\partial\phi/\partial n_q)_j$ in Eq. (1) can be determined by boundary condition (Katz and Plotkin, 1991):

$$\left(\frac{\partial\phi}{\partial n_q}\right)_j = -\boldsymbol{U_{in}}(q_j)\cdot\boldsymbol{n_q} \tag{2}$$

Where $\boldsymbol{U_{in}}(q_j)$ is the inflow velocity ; $\boldsymbol{n_q}$ is the normal direction of the surface panel. In order to solve the velocity potential ϕ, the items $\partial\phi/\partial n$ and $\Delta\phi$ must be defined.

The value of $\Delta\phi$ can be obtained with Kutta condition, and the pressure at the upper and lower control points at trailing edge should be equal (Kerwin et al., 1987):

$$\Delta p_m = p_{mU} - p_{mL},\quad m = 1, 2, ..., m_b \tag{3}$$

Where m_b is the total radial panel on propeller trailing edge. A direct solution of Eqs. (1) and (3) is difficult due to the nonlinear of Eq. (3). Therefore an iterative Newton-Raphson method is employed, and if the k^{th} iteration $\Delta p_m^{(k)}$ is not equal to zero within desired tolerance, the $(k+1)^{th}$ iteration $\Delta\phi^{(k+1)}$ is determined as follow:

$$\Delta\phi^{(k+1)} = \Delta\phi^{(k)} - J^{-1}\Delta p^{(k)} \tag{4}$$

Where J^{-1} is the inverse of Jacobian matrix J and the elements of J is defined as

$$J_{ij} = \frac{\partial(\Delta p)_i}{\partial(\Delta\phi)_i},\quad i = 1, 2, ..., m_b;\quad j = 1, 2, ..., m_b \tag{5}$$

The initial guess of $\Delta\phi^{(0)}$ is determined by Morino Kutta condition as

$$\Delta\phi_m^{(0)} = \phi_{mU} - \phi_{mL} \tag{6}$$

Where ϕ_{mU} and ϕ_{mL} are the potentials of the upper and lower control points at the propeller trailing edge. The viscous effect is ignored by potential method. In order to obtain practically useful results, a viscous drag correction is needed, and the viscous coefficient C_D used by Tan (2003) is applied in this paper:

$$\begin{aligned}&C_D(P_i) = \tfrac{1}{2}\left(C_f + 0.04\left(1 - \tfrac{J}{P/D}\right)^2\right)\\ &C_f = \frac{0.05808\left(1+2.3\frac{t_{\max}}{c}\right)}{R_{ns}^{0.1458}}\\ &R_{ns} = \tfrac{V_I c}{\nu},\quad V_I = \sqrt{V_A^2 + (w\cdot r)^2}\end{aligned} \tag{7}$$

Where P_i represents different blade section, $t_{\max}$ is the P_i section max thickness, c is the P_i section chord length, V_A is the inflow velocity, w is the propeller rotating speed, r is the P_i section radial distance, ν is the kinematic coefficient of viscosity.

Based on Eq. (1), governing equations for podded propulsion system can be written as Eq. (8). And in uniform flow, the strut is considered as no lifting body (Yang et al., 2003) due to the influence of wake is small in terms of straight forward condition (the angle between propeller axial and inflow direction is zero).

$$\begin{aligned}\phi_i =& \underbrace{\sum_{k=1}^{Z}\sum_{j=1}^{N}\phi_j^k C_{ij}^k}_{1} + \underbrace{\sum_{k=1}^{Z}\sum_{j=1}^{N}\left(\frac{\partial\phi}{\partial n_q}\right)_j^k B_{ij}^k}_{2} + \underbrace{\sum_{k=1}^{Z}\sum_{j=1}^{N_W}\Delta\phi_j^k W_{ij}^k}_{3} + \underbrace{\sum_{l=1}^{M}\phi_l C_{il}}_{4}\\ &+\underbrace{\sum_{l=1}^{M}\left(\frac{\partial\phi}{\partial n_q}\right)_l B_{il}}_{5}\quad i = 1, 2, ..., Z\cdot N\cdot Z\cdot N+1, ..., Z\cdot N+M\end{aligned} \tag{8}$$

where items labeled 4 and 5 are the influences of the pod unit (consist of pod and strut) on field point; M is the total mesh number of pod unit; The influence coefficients C_{ij}^k,B_{ij}^k,W_{ij}^k,C_{il},B_{il} are defined as:

$$C_{ij}^k = \frac{1}{2\pi}\oint_{S_{Bj}}\frac{\partial}{\partial n_{qj}}\left(\frac{1}{r(p_i,q_{jk})}\right)dS_{qj},\quad C_{il} = \frac{1}{2\pi}\oint_{S_{Pl}}\frac{\partial}{\partial n_{ql}}\left(\frac{1}{r(p_i,q_l)}\right)dS_{ql}$$

$$B_{ij}^k = -\frac{1}{2\pi}\oint_{S_{Bj}}\left(\frac{1}{r(p_i,q_{jk})}\right)dS_{qj},\quad B_{il} = -\frac{1}{2\pi}\oint_{S_{Pl}}\left(\frac{1}{r(p_i,q_l)}\right)dS_{ql}$$

$$W_{ij}^k = \frac{1}{2\pi}\oint_{S_{Wj}}\frac{\partial}{\partial n_{qj}}\left(\frac{1}{r(p_i,q_{jk})}\right)dS_{qj}$$

where S_P is the surface of pod.

For the solving of Eq. (8), a time domain potential based on low order surface panel method (Kinnas and Hsin, 1992) is employed here, and the discrete form of Eq. (8) is:

$$\begin{aligned}&\sum_{j=1}^{N+M}(\delta_{ij} - C_{ij}^1(n_t))\phi_j^1(n_t) - \sum_{k=1}^{Z}\sum_{j=1}^{N_w}W_{i,j}^k(n_t)\Delta\phi_j^k(n_t)\\ &= \underbrace{\sum_{k=2}^{Z}\sum_{j=1}^{N}C_{ij}^k(n_t)\phi_j^k(n_t)}_{1} + \underbrace{\sum_{k=1}^{Z}\sum_{j=1}^{N}B_{ij}^k(n_t)\left(\frac{\partial\phi}{\partial n_q}\right)_j^k}_{2}\\ &+\underbrace{\sum_{k=2}^{Z}\sum_{j=1}^{N_W}\Delta\phi_j^k(n_t)W_{ij}^k(n_t)}_{3} + \underbrace{\sum_{l=1}^{M}\phi_l(n_t)C_{il}(n_t)}_{4}\\ &+\underbrace{\sum_{l=1}^{M}\left(\frac{\partial\phi}{\partial n_q}\right)_l B_{il}(n_t)}_{5}\quad i = 1, 2, \cdots N\cdot N+1, \cdots N+M\end{aligned} \tag{9}$$

where n_t is time step, and it's value is 60. For δ_{ij}, if $i = j$, $\delta_{ij} = 1$, else $\delta_{ij} = 0$. The superscript '1' represents key blade. The influence coefficient in Eq. (8) change with time step due to the relative position between propeller and strut is different.