A Potential Method for Steady and Unsteady Hydrodynamic Performance Computation of Podded Propulsors

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ABSTRACT

Based on potential flow theory, a numerical method is proposed in this paper for predicting the steady and unsteady hydrodynamic performance of podded propulsors. Podded propulsors can be divided into three types, which are pulling-, pushing-, and twin-screw type propulsors. As the first and third types are applied more often and the calculation method of the second type is similar with the first, the emphasis is put on introduction of calculation methods of pulling- and twin-screw type propulsors. The propeller blades are calculated with a vortex lattice method, while the pod including its strut with a boundary element method for non-lifting bodies. Hydrodynamic interactions between the propeller and the pod are treated via iterative calculations. For the propeller, the linear system of equation for solution of load distribution on the blades can be obtained by satisfaction of all object plane boundary conditions on all control points on the camber plane of blades. For the pod, the linear system of equation for solution of source sink intensity of each unit can also be obtained by satisfaction of all object plane boundary conditions on center of each unit (control point) on its surface. For the towed propeller and the pushing-type one, due to the different positions of these propellers, the influence of pod on the fore propeller vortex has to be considered for the towed one; for the pushing-type one, it is similar to that without pod. The other calculation and processing are the same. For the twin-screw podded propulsor, not only the influence of pod on the wake of fore propeller but also the mutual influences among the fore propeller, the pod and the aft propeller have been considered in the iterative calculation. Then a real case computation has been carried out and the results obtained agree well with those obtained from the experiments carried out in a cavitation tunnel.

INTRODUCTION

The more and more ripe permanent-magnet motor technology has made it possible to install a propulsion motor in an underwater case for direct drive of propeller and has therefore bright forth a rapid development of podded propulsor. As a result, the podded propulsor now represents the up-to-date development trend of propulsion technology of propellers in the world [1] . Such companies as SIEMENS, ALSTOM and KAMEWA etc. have been investing a lot on the R&D of Podded propulsor technology and put their own products successively into the market[2][3], but in China, no department is doing such kind of research, the hydrodynamic research base is particularly weak and new design and test methods etc. have to be found. This article has made a research on the theoretical method for predicting the steady hydrodynamic performances of Podded propulsor with the vortex lattice method and the surface element method in the lifting surface theory.

DEFINITION OF COORDINATE SYSTEM

First, consider the podded propulsor in the infinite flow field. Assume the fluid is ideal, can not be compressed and comes evenly along the axial line of propeller.

As shown in Figure 1, the computation of propeller is carried out in the rectangular coordinate system (o-xyz) rotating with the propeller blade and the cylindrical coordinate system (o-xrθ). The initial point o is set on the intersecting point between the reference line of blade and the axial line of propeller. Axis x overlaps with the axial line of propeller and directs to the tail of propeller. Axis y overlaps with the reference line of a blade and goes vertically up initially. Axis z is determined by the Right-hand Rule and directs horizontally to the starboard initially. The blade rotates in a negative direction around axis x. The cylindrical coordinates (r,θ) are defined to be in the plane o-yz. θ shall be calculated from axis y and the positive direction around axis x shall be positive in value.

The computation for the pod shall be carried out definitely in the rectangular coordinate system of pod o-$x'y'z'$. Initially, coordinate systems o-$x'y'z'$ and o-xyz overlap, but a phase difference will be established between two coordinate systems when the blade rotates.

For the twin-screw Podded propulsor, the calculation for the fore and aft propellers shall be carried out in the same coordinate system o-xyz. The initial point o is set on the intersecting point between the fore propeller's reference line and the propeller's shaft line. There are an axial spacing and a circumferential included angle between the fore and propellers' reference lines. This included angle is the phase difference between the blades of fore and aft propellers.

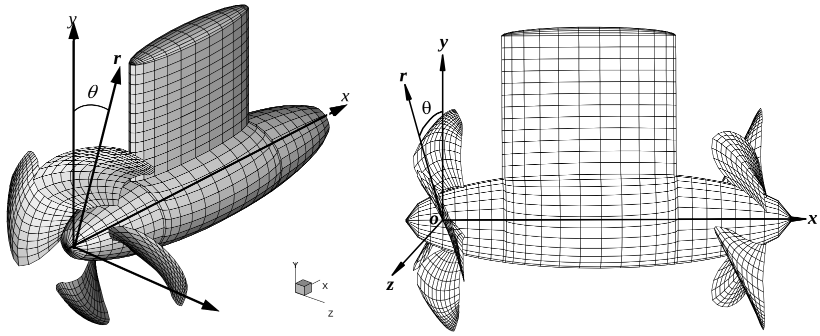

Fig.1 Definition of coordinate system

MATHEMATICAL EXPRESSION OF GEOMETRY OF BLADE

In the rectangular coordinate system *o-xyz* rotating with the blade, the skew angle $\theta_m(r)$ and the trim distance $x_m(r)$ of blade can be used to determine the blade's reference line and thus the relative positions of each section plane of blade. The leading edge and the trailing edge can be expressed as:

$$\left.\begin{aligned} x_{l,t}(r) &= x_m(r) \mp \frac{c(r)}{2}\sin\varphi(r) \\ \theta_{l,t}(r) &= \theta_m(r) \mp \frac{c(r)}{2}\cos\varphi(r) \\ y_{l,t}(r) &= r\cos\theta_{l,t}(r) \\ z_{l,t}(r) &= r\sin\theta_{l,t}(r) \end{aligned}\right\} \tag{1}$$

In it, subscripts *l* and *t* represent the leading edge and trailing edge respectively, and $c(r)$ and $\varphi(r)$ represent the chord length and the pitch angle at radius r. In this way, the profile of blade can be represented. Additionally, define the dimensionless chord length *s*, the leading edge's *s*=0 and the trailing edge's *s*=1. Use $f(r,s)$ to represent the camber distribution of blade's sectional plane at radius *r*. Then the camber plane of blade can be represented as:

$$\left.\begin{aligned}
x_c(r,s) &= x_m(r) + c(r)(s-\frac{1}{2})\sin\varphi(r) - f(r,s)\cos\varphi(r) \\
\theta_c(r,s) &= \theta_m(r) + c(r)(s-\frac{1}{2})\frac{\cos\varphi(r)}{r} + f(r,s)\frac{\sin\varphi(r)}{r} \\
y_c(r,s) &= r\cos\theta_c(r,s) \\
z_c(r,s) &= r\sin\theta_c(r,s)
\end{aligned}\right\} \quad (2)$$

In it, the subscript *c* represents the camber plane. Assume number of blades to be *Z*, then, for the *k*-th blade, its camber plane coordinates can be obtained so long as $2\pi(k-1)/Z$ is added onto $\theta_c(r,s)$ in equation 2.

LATTICING OF BLADES AND POD SURFACE

In accordance with the vortex lattice method in the lifting surface theory[4], the propeller can be substituted by the odd point system arranged on the camber plane and in the wake. In it, the adjacent vortex system and the free vortex system simulate the lifting force and the source-sink system simulates the influence of blade's thickness. In the numerical calculation, the odd point system is handled discretely to linear element; the adjacent vortex element is arranged radially along the blades and the strength is unknown; the free vortex element in the blade area and the wake area is arranged chordwise and its strength depends on the corresponding adjacent vortex strength; the strength of source-sink unit shall be determined by the sectional thickness distribution and the relative incoming flow velocity in accordance with the linearization theory. Arrange control points on the proper positions of vortex lattice in the blade area so as to establish a linear system of equation for the adjacent vortex strength by satisfying the object plane conditions. Solve the equation for the load distribution on blades so that the hydrodynamic force can be calculated. Therefore, spanwise (radial) and chordwise latticing on the camber plane of blades should be carried out in numerical calculation.

In this article, the refined latticing calculation is conducted near the blade tip based on the radial and chordwise latticing so as to adapt to the big changes of geometry and load in this area. The radial latticing shall be represented by the following formulas:

$$\left.\begin{aligned}
\Delta r &= \frac{0.98R - 1.05r_H}{M-6} \\
r_1 &= 1.05r_H \\
r_i &= r_{i-1} + \Delta r, \quad i = 2,3,\ldots,M-8 \\
r_i &= r_{i-1} + \Delta r/2, \quad i = M-7, M-6 \\
r_i &= r_{i-1} + \Delta r/3, \quad i = M-5,\ldots,M-3 \\
r_i &= r_{i-1} + \Delta r/4, \quad i = M-2,\ldots,M+1
\end{aligned}\right\} \quad (3)$$

The chordwise latticing can be represented as:

$$s_j = \frac{(j-3/4)}{N}, \quad j = 1,2,...,N \tag{4}$$

The control points are arranged on the center of each vortex lattice and their positions can be represented as:

$$\left.\begin{aligned} r_i^c &= (r_i + r_{i+1})/2, \quad i = 1,2,...,M \\ s_j^c &= (j-1/4)/N, \quad j = 1,2,...,N \end{aligned}\right\} \tag{5}$$

In it, R and r_H are the radius of blade tip and the radius of propeller hub respectively, M and N are the number of radial lattices and the number of chordwise lattices respectively, Δr is the space between the radial lattices, r_i is the radius of radial lattice and s_j is the positions of dimensionless chordwise lattices.

The pod surface is divided into several rectangular units with source and sink evenly distributed. Being a solid of revolutionary, the pod body can be axially divided into three sections, i.e., the fore section (from the fore end of pod body to the fore edge of its strut), the intermediate part (from the fore edge of strut to its aft edge) and the aft section (from the aft edge of strut to the aft end of pod body). The fore section and the aft section are axially and evenly latticed and the axially latticed position in the intermediate section and the chordwise latticing position on the strut are the same. Each section is evenly latticed circumferentially. The strut shape is similar to the rectangular aerofoil. For the sake of simplification, it has been regarded as an object without lifting force. Its section plane is regarded as an elliptical one or a flat plate with a limited thickness and semi-circular fore and aft edges. The strut is evenly latticed in a spanwise (vertical) direction, and is unevenly distributed in a chordwise direction according to the Cosine Rule. The places near the fore and aft edges are more intensively latticed. What's more, the curved surface on the top of shielded strut is a semi-elliptical one, its chordwise latticing position is the same to that on the strut surface and it is evenly latticed in the direction of thickness. The radius of propeller hub section on the fore and aft parts of strut changes axially, so it is necessary to calculate the cross line between the blade root and the propeller hub and carry out local adjustment of the positions of vortex lattices and control points in accordance with the cross line shape so as to guarantee the iso-spaced latticing near the blade root.

BOUNDARY CONDITIONS AND DISCRETE EQUATION

As discussed before, this article has not only respectively calculated the propeller and the pod but also calculated the mutual influence between the propeller and the pod with the iterative method. For the propeller, the linear system of equation for solution of load distribution on the blades can be obtained by satisfaction of all object plane boundary conditions on all control points on the blade's camber plane. Similarly, for the pod, the linear system of equation for solution of source sink intensity of each unit can also be obtained by satisfaction of all object plane boundary conditions on center of each unit (control point) on its surface. For the towed propeller and the pusher-type one, due to the different positions of these propellers, the influence of pod on the fore propeller vortex has to be considered for the towed one; for the pusher-type one, it is similar to that without pod (i.e., an open-water single-screw). The other calculation and processing are the same. For the twin-screw Podded propulsor, not only the influence of pod on the wake of fore propeller but also the mutual influence among the fore propeller, the pod and the aft propeller have been considered in the iterative calculation.

For the sake of being clear, the boundary condition equations for the fore propeller, the aft propeller and the pod are listed in accordance with the program for the twin-screw Podded propulsor.

1. Boundary conditions and discrete equations for fore propeller

On the control point of fore propeller, the boundary condition of an object surface the fluid can not pass through can be expressed as:

$$(\vec{V}_{GF} + \vec{V}_{QF} + \vec{V}_{PF} + \vec{V}_{AF} + \vec{V}_I) \cdot \vec{n}_F = 0 \qquad (6)$$

Where $\vec{n}_F$ is the normal vector of the camber plane of fore propeller's blade; $\vec{V}_I = \vec{V}_A + \vec{r} \times \vec{\omega}$ is the relative velocity of incoming flow on the control points. And $\vec{V}_A$ is the axial incoming flow velocity, positive in the direction of axis *x*; $\vec{\omega}$ is the velocity vector of rotation angle around axis *x*; $\vec{r}$ is the projection position vector of control point in *o-yz* plane; $\vec{V}_{GF}$ is the induced velocity of fore propeller's vortex system on the control point; $\vec{V}_{QF}$ is the induced velocity of source sink that simulates the influences of blade's thickness of fore propeller; $\vec{V}_{PF}$ is the induced velocity of pod to the fore propeller; and $\vec{V}_{AF}$ is the induced velocity of aft propeller to the fore propeller.

Discretize formula (6), and then the linear group of equation of adjacent vortex ring value Γ_{mn}^{sF} of fore propeller's blade can obtain as follows:

$$\sum_{m=1}^{M_F}\sum_{n=1}^{N_F}\left\{\sum_{k=1}^{Z_F}\left[K_{ijmnk}^{sF} + \sum_{l=n}^{N_F}(K_{ij(m+1)lk}^{cF} - K_{ijmlk}^{cF}) + \sum_{l=1}^{N_{wF}}(K_{ij(m+1)lk}^{wF} - K_{ijmlk}^{wF})\right]\right\}\Gamma_{mn}^{sF}$$
$$= -\left\{\vec{n}_F \cdot (\vec{V}_I + \vec{V}_{QF} + \vec{V}_{PF} + \vec{V}_{AF})\right\}_{ij}, \quad (i = 1, 2, ..., M_F;\ j = 1, 2, ..., N_F) \qquad (7)$$

Where M_F and N_F are respectively the spanwise and chordwise latticing numbers of fore propeller; Z_F is the blade quantity of fore propeller; N_{wF} is the lattice quantity of trailing vortex line of the fore propeller; K is the influence efficient, i.e., the normal component of induced velocity of vortex line unit in unit strength on the control point; the superscripts s, c *and* w respectively represent the spanwise vortex, the chordwise vortex and the trailing vortex; the superscript F represents the fore propeller, the subscripts i and j are respectively the number for spanwiseness and that for chordwiseness of control points, the subscripts m and n respectively represent the spanwise and the chordwise serial numbers of vortex line unit, and the subscript k is the serial number for propeller blade.

2. Boundary conditions and discrete equations for aft propeller

On the control point of aft propeller, the boundary condition of an object surface the fluid can not pass through can be expressed as:

$$(\vec{V}_{GA} + \vec{V}_{QA} + \vec{V}_{PA} + \vec{V}_{FA} + \vec{V}_I) \cdot \vec{n}_A = 0 \qquad (8)$$

Where, $\vec{n}_A$ is the normal vector of the camber plane of aft propeller's blade; $\vec{V}_I = \vec{V}_A + \vec{r} \times \vec{\omega}$ is the relative velocity of incoming flow on the control points. Among it, $\vec{V}_A$ is the axial incoming flow velocity, positive in the direction of axis x; $\vec{\omega}$ is the velocity vector of rotation angle around axis *x*; $\vec{r}$ is the projection position vector of control point in *o-yz* plane; $\vec{V}_{GA}$ is the induced velocity of aft propeller's vortex system on the control point; $\vec{V}_{QA}$ is the induced velocity of source sink that simulates the influences of blade's thickness of aft propeller; $\vec{V}_{PA}$ is the induced velocity of pod to the aft propeller; and $\vec{V}_{FA}$ is the induced velocity of fore propeller to the aft propeller.

Discretize formula (8), and then the linear group of equation of adjacent vortex ring value Γ_{mn}^{sA} of the blade of aft propeller can obtain as follows:

$$\sum_{m=1}^{M_A}\sum_{n=1}^{N_A}\left\{\sum_{k=1}^{Z_A}\left[K_{ijmnk}^{sA}+\sum_{l=n}^{N_A}(K_{ij(m+1)lk}^{cA}-K_{ijmlk}^{cA})+\sum_{l=1}^{N_{wA}}(K_{ij(m+1)lk}^{wA}-K_{ijmlk}^{wA})\right]\right\}\Gamma_{mn}^{sA}$$
$$=-\left\{\vec{n}_A\cdot(\vec{V}_I+\vec{V}_{QA}+\vec{V}_{PA}+\vec{V}_{FA})\right\}_{ij}\ ,\quad (i=1,2,...,M_A;\ j=1,2,...,N_A) \tag{9}$$

Where M_A and N_A are respectively the spanwise and chordwise lattice numbers of aft propeller; Z_A is the number of blades for aft propeller; N_{wA} is the number of lattices of trailing vortex line of the aft propeller; K is the influence efficient, i.e., the normal component of induced velocity of vortex line unit in unit strength on the control point; the superscripts s, c *and* w respectively represent the spanwise vortex, the chordwise vortex and the trailing vortex; the superscript *A* represents the aft propeller, the subscripts i and j are respectively the spanwise and chordwise serial numbers on control points, the subscripts m and n respectively represent the spanwise and chordwise serial numbers of the vortex line unit, and the subscript k is the serial number for propeller blade.

3. Boundary conditions and discrete equation for pod

The pod body and the strut can be dealt with as objects without lifting force and be calculated with Hess-Smith surface panel method. The propeller hub can be calculated as a part of pod, i.e., assume that it does not rotate with the blade. Since the propeller hub is a revolutionary body, and in this method it is considered only that the interaction between the propeller and the pod without calculation of the stress of pod, it is approximately rational, however, this processing has some shortcomings since it has not comprehensively considered the influence of propeller hub on the load of blade root.

The pod is in the potential flow field established by the evenly incoming flow, i.e., the induced velocity of propeller. The disturbing velocity potential of pod φ can be expressed as:

$$\varphi(p)=\oiint_S\frac{\sigma(q)}{R'(p,q)}dS \tag{10}$$

Where *S* is the object surface, i.e., the pod surface; *p* is the field point; *q* is the source point; $R'(p,q)$ is the distance between *p* and *q*; $\sigma(q)$ is the distribution density of source sink on the object surface. The boundary condition of an object surface the fluid can not pass through can be expressed as:

$$\frac{\partial\varphi}{\partial n_p}+\vec{n}_p\cdot(\vec{V}_A+\vec{V}_{FP}+\vec{V}_{AP})=0 \tag{11}$$

Note that $\vec{n}_A$ is the outward normal vector on outside pod surface; $\vec{V}_{FP}$ is the induced velocity of fore propeller on the pod; $\vec{V}_{AP}$ is the induced velocity of aft propeller to the fore propeller. Solve the normal partial derivative of eqn (10) at point *p* and substitute eqn (11) into eqn (12), then a second kind of Fredholm integral equation can be obtained as follows:

$$2\pi\sigma(p) - \oiint_S \frac{\partial}{\partial n_p(p)}\left(\frac{1}{R'(p,q)}\right)\sigma(q)dS = \vec{n}_p(p)\cdot[\vec{V}_A + \vec{V}_{FP}(p) + \vec{V}_{AP}(p)] \quad (12)$$

Numerically solve equation (12) and obtain the distribution of source-sink intensity σ on the object surface, then, calculate the velocity and pressure distribution on and around the object surface.

CALCULATION OF HYDRODYNAMIC FORCE OF PROPELLER

The hydrodynamic force applied on the propeller blade can be numerically calculated in the discrete mode. The hydrodynamic force is divided into the potential flow force and the viscous force which are respectively described below.

1. Kutta-Joukowsky force

The Kutta-Joukowsky force applied on the discrete spanwise and chordwise vortex units can be expressed as:

$$\delta\vec{F}^{K}_{nm} = \rho\Delta l_{nm}\vec{V}_{nm}\times\vec{\Gamma}_{nm} \quad (13)$$

In it, ρ is the fluid intensity, Δl_{nm} is the length of spanwise or chordwise vortex element, $\vec{V}_{nm}$ is the velocity of fluid on the center of vortex element, $\vec{\Gamma}_{nm}$ is the circulation strength and the subscripts m and n represent respectively the spanwiseness and chordwiseness.

2. Lagally force

Legally force acted on the discrete source-sink unit can be expressed as:

$$\delta\vec{F}^{L}_{nm} = -\rho\Delta l_{nm}Q_{nm}\vec{V}_{nm} \quad (14)$$

Where Q_{nm} and Δl_{nm} are respectively the line density and length of source-sink unit and $\vec{V}_{nm}$ is the velocity of fluid on the center of source-sink unit.

3. Viscous force

The viscous force that acts on a vortex lattice can be written as follows:

$$\delta\vec{F}^{F}_{nm} = \frac{1}{2}\rho c_f \Delta A_{nm}\left|\vec{V}_{nm}\right|\vec{V}_{nm} \quad (15)$$

In it, ΔA_{nm} is the area of vortex lattice; c_f is the viscous resistance coefficient of section plane of blade, which usually takes $c_f = 0.0084$ in accordance with experiences; $\vec{V}_{nm}$ is the velocity on the control point.

4. Increment of viscous force

Under undesigned operating conditions, the viscous resistance on the section plane of blade will increase. In this article it takes 1/3 suction force of leading edge under the same operating conditions. The suction force of leading edge can be obtained with the following formula:

$$\delta\vec{F}^{s}_{m} = \frac{1}{4}\pi\rho C_s^2\delta r_m \vec{S}_0 \quad (16)$$

In it, $\vec{S}_0$ represents the direction of chordwise element on fore edge of leading edge . The suction force coefficient of leading edge C_s can be expressed as:

$$C_s = \frac{\Gamma_{1m}}{2(\sqrt{S_{1m}} - \sqrt{S_{0m}})} \tag{17}$$

Where S_{0m} and S_{1m} are the chordwise position coordinates on the leading edge and Γ_{1m} is the strength of the first spanwise vortex element.

5. Additional force due to unsteady case

The additional force applied on the discrete spanwise and chordwise vortex units can be expressed as:

$$\delta \vec{F}^t_{mn} = \rho \vec{n}_{mn} \frac{\partial}{\partial t}\left[\sum_{l=1}^{n} \Gamma^s_{ml}\right] \Delta A_{mn} \tag{1.8}$$

Where $\vec{n}_{mn}$ is the outward normal vector on the discrete vortex outside, ΔA_{mn} is the area of vortex lattice.

6. Overall thrust and torque of propeller

In summary, the force applied on the directions of x, r, θ on the propeller blade can be expressed in a discrete mode as:

$$F_{x,r,\theta} = Z\sum_{m=1}^{M}\left[\sum_{n=1}^{N}(\delta\vec{F}^K_{nm} + \delta\vec{F}^L_{nm} + \delta\vec{F}^F_{nm} + \delta\vec{F}^t_{mn}) - \frac{1}{3}\delta\vec{F}^s_m\right]_{x,r,\theta} \tag{19}$$

The thrust of propeller T is:

$$T = Z\sum_{m=1}^{M}\left[\sum_{n=1}^{N}(\delta\vec{F}^K_{nm} + \delta\vec{F}^L_{nm} + \delta\vec{F}^F_{nm} + \delta\vec{F}^t_{mn}) - \frac{1}{3}\delta\vec{F}^s_m\right]_{x} \tag{20}$$

The torque Q is:

$$Q = Z\sum_{m=1}^{M}\left[\sum_{n=1}^{N}(\delta\vec{F}^K_{nm} + \delta\vec{F}^L_{nm} + \delta\vec{F}^F_{nm} + \delta\vec{F}^t_{mn})_\theta \cdot \vec{r}^c_{nm} - \frac{1}{3}(\delta\vec{F}^s_m)_\theta \cdot \vec{r}^c_{1m}\right] \tag{21}$$

Finally, the thrust coefficient K_T and the torque coefficient K_Q can be obtained as follows:

$$K_T = \frac{T}{\rho n^2 D^4},\ K_Q = \frac{Q}{\rho n^2 D^5} \tag{22}$$

Where n is the rotating speed of propeller and D is the diameter of propeller.

CALCULATION EXAMPLE

Calculations on the single-screw Podded propulsor has been conducted with the numerical method mentioned in this article. The main geometrical parameters of pod are listed in Table 1. The main calculation parameters are: the lattice quantity of blade $M_F = 15$, $N_F = 10$ and $c_{TE} = 0.65$; the axial lattice quantity of pod body $M_B = 29$; the circumferential lattice quantity $N_B = 24$, the lattice quantity in the vertical direction of strut $M_S = 12$, the circumferential lattice quantity of the section plane $N_S = 24$ and the whole pod surface is disretized into 1104 surface elements. The test was carried out in a cavity water tunnel in Shanghai Jiaotong University.

Table 1. Main geometrical parameters of pod

	Pod body			Strut			
	Length	Max. diameter	Shape	Height	Chord length	Max. thickness	Sectional plane shape
Computation model	1.667	0.417	Elliptical revolution body	0.792	0.75	0.15	Ellipse
Test model			Cylinder streamlined dome				Flat plate + semicircular bow and stern

Note: the numerical values are all the ratios with the diameter of propeller.

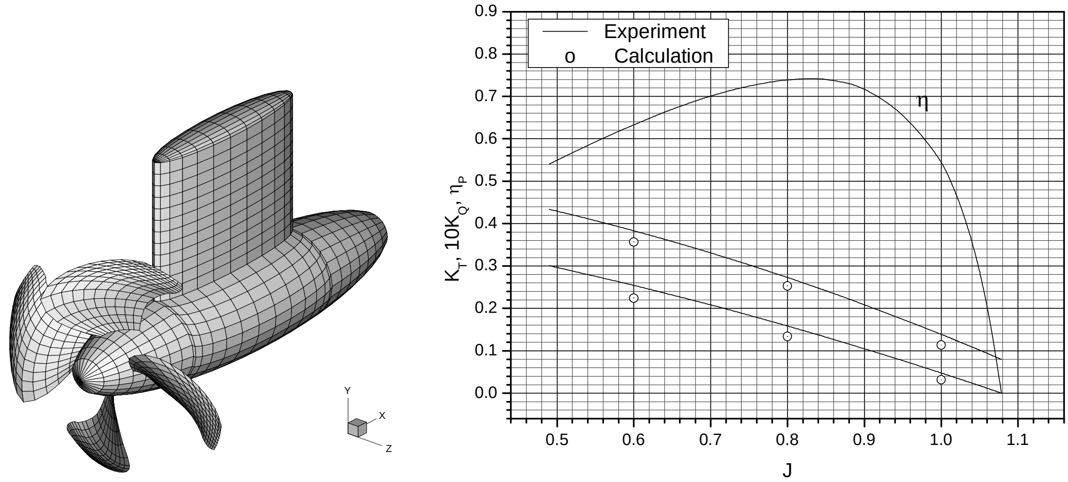

Fig. 3 Calculation lattice and comparison between the calculation results and the test results for the propeller performances of pulling- podded propulsor

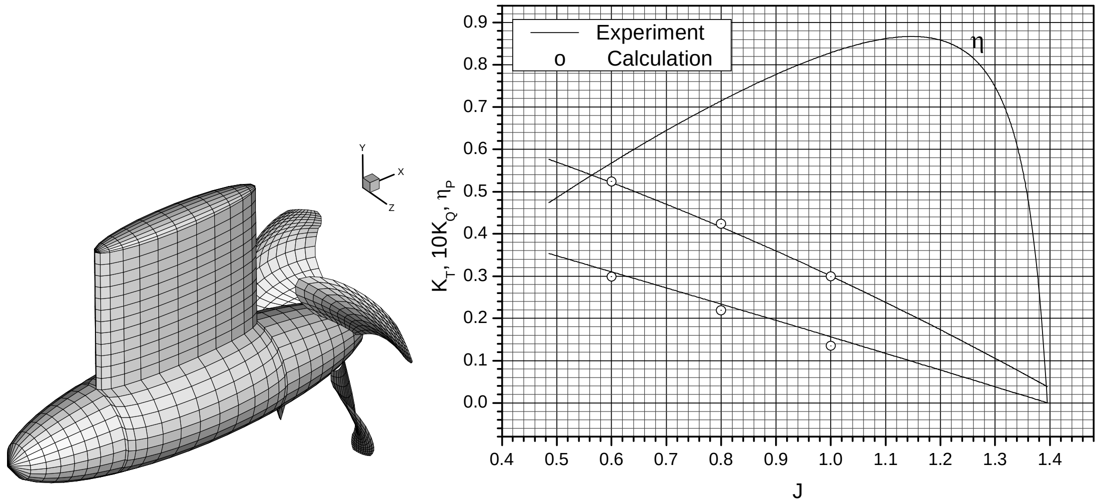

Fig.4 Calculation lattice and comparison between the calculation results and the test results for the propeller performances of pushed-podded propulsor

As shown in Table 1, there are only slight differences on the pod body and the sectional plane shape of strut in the main geometrical parameters obtained from the test model and the calculation model for the pod, but these differences have little effect on the calculation results of stress applied on the blade. Calculation of the force applied on the pod must use the test and calculation models with the same shape. The comparison between the calculation results and the test results are shown in Fig.3 and Fig.4. From the result, it can be seen that the calculated values of thrust and torque coefficients are slightly different compared with the test results. But generally speaking, they agree well.

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