Analysis of Hydrodynamic Performance of Ducted Paddle with Front Rectifying Guide Blade

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Abstract. The SST $k-\omega$ model is used to simulate the open water performance of the ducted propeller, and the hydrodynamic performance is compared with the experimental results. The SST $k-\omega$ model is validated to effectively predict the hydrodynamic performance of ducted propellers. Based on the analysis of the optimization of the ducted propeller, guide blades are installed in front of the blades to improve the performance of the ducted propellers. The performance of the ducted propellers on the ducted propellers is analyzed, and the influence laws are studied to provide a theoretical basis for the subsequent improvement of the ducted propellers.

1. Introduction

Ducted propeller with stator duct (sometimes called pump-jet propeller) is a special propeller with high propulsion efficiency and low radiation noise [1]. It has been widely used in newly designed underwater vehicles in many countries in the world [2]. However, due to the complicated geometric structure, the prediction of hydrodynamic performance of ducted propellers with stator is more difficult than that of conventional ducted propellers. Ducted propellers with stator are usually used on military ships, related researches are rarely seen in public journals. Some scholars have used experiments, potential flow theory, CFD and other methods to study the ducted propeller with stator. Suryanarayana et al. [3-4] used wind tunnel experiments to study the performance of underwater vehicles with pump-jet propellers and tested their cavitation performance in water tunnels. The experimental results provide a useful reference for the performance experiments and evaluation of high-speed underwater vehicles with rear-stator ducted propellers. Hughes et al. used the potential flow theory to calculate the open water performance of a front-stator ducted propeller[5]. The duct and propeller parts are solved by the surface element method, as well as the blade and stator parts are solved by the vortex lattice method. The calculation results show that the potential flow theory can obtain accurate prediction results when the forward speed is small.

With the continuous development of numerical computing capabilities of computers, the use of CFD technology to solve the hydrodynamic characteristics of the propellers has become a commonly used tool. Guo C. and Zhao W. [6-7] etc. numerically simulated the ducted propeller and front-stator ducted propeller using numerical simulation methods, and obtained valuable results in hydrodynamic performance. The research results indicate that the CFD method is reliable.
This paper uses the CFD method to predict the open water hydrodynamic performance of the front-stator ducted propeller and analyzes the influence of parameters such as the stator mounting angle and the number of stator blades on the performance of the propellers.

2. Computational methods

2.1. Control equation

The governing equations include continuous equations, momentum equations, and energy equations. When the flowing fluid is defined as a continuum, the governing equations are as follows.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0$$  \hspace{1cm} (1)

Momentum equation:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \mu \delta_{ij} \frac{\partial u_l}{\partial x_l}\right] + \frac{\partial}{\partial x_j} \left(-\rho \bar{u}_i^r u_j^r\right)$$  \hspace{1cm} (2)

Energy equation:

$$\frac{\partial (\rho C_p T)}{\partial t} + \frac{\partial (\rho C_p u_i T)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(K \frac{\partial T}{\partial x_j} - \rho C_p \bar{u}_i^r u_j^r\right)$$  \hspace{1cm} (3)

Where, $\rho$ is the density, $\mu_i$ is the eddy viscosity coefficient, $u, u'$ are the speed and pulsation speed; $C_p$ is the specific heat capacity, $K$ is the thermal conductivity, and $u_i^r u_j^r$ is the Reynolds stress tensor.

SST $k$-$\omega$ model is a hybrid model based on standard $k$-$\varepsilon$ model and $k$-$\omega$ model proposed by Menter [8]. The transport equation of the SST $k$-$\omega$ model is as follows.

$$\frac{\partial \rho_m k}{\partial t} + \nabla (\rho_m U k) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) \nabla k\right] + P_k - \beta' \rho_m k \omega$$  \hspace{1cm} (4)

$$\frac{\partial \rho_m \omega}{\partial t} + \nabla (\rho_m U \omega) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right) \nabla \omega k\right] + a \rho_m P_k - \beta' \rho_m \omega^2 + (1 - F_1) \frac{2 \rho \sigma \omega^2}{\omega} \nabla k \cdot \nabla \omega$$  \hspace{1cm} (5)

In the formula, $\rho_m$ is the mixing density, $k$ and $\omega$ are the turbulent kinetic energy and turbulent vortex frequency respectively; $\mu$ is the viscosity, $\mu_t$ is the turbulent viscosity, $P_k$ is the turbulent energy term, $\beta' = 0.09$, and $F_1$ is the mixing function.

3. Physical model and meshing

The model used in this article is JDC7704 duct and ka4-5512 blade. The parameters of blades and duct are shown in Table 1 and Table 2 [9].

When using Fluent to perform the rotating machine calculations, the flow field is divided into two parts, a small part of the rotating part and a large part of the stationary part. The interface between the two parts is set as interface to simplify the calculation. The inlet is set as velocity-inlet, and the outlet is set as outflow. The walls of the duct and propeller are set as non-slip solid walls.

| Table 1 Parameters of blades |
|-----------------------------|
| Parameters                  | Value     |
| Propeller diameter          | 0.12 m    |
| Disk ratio                  | 0.55      |
| Hub diameter ratio          | 0.167     |
| Pitch ratio                 | 1.0       |
Table 2 Parameters of duct

| Parameters                   | Value    |
|------------------------------|----------|
| Duct aspect ratio            | 0.6652   |
| Blade clearance diameter ratio | 0.02     |

4. Results and discussion

4.1. Analysis of hydrodynamic performance with different guide blade angles

As shown in Figure 3, the calculation results of the performance of the ducted propeller with different guide blade angles and different speeds. It can be observed from the figure that as the blade angle increases, the thrust coefficient of the blade increases significantly. Between the forward speeds of 0.1-0.7, as the forward speed increases, the resistance generated by the guide blade becomes larger, which is consistent with the increase in the thrust of the blades, which leads to an insignificant increase in the thrust of the ducted blades.
4.2. **Pressure cloud picture**

As shown in Figure 4, the pressure distribution of the blade after the guide blades are installed. The figure shows that with the installation of the guide blades, the pressure pulsation of the blades is smaller. The pulsation on the pressure surface is uniform. As the blade angle increases, the pulsation becomes smaller. On the suction surface, it is found that with the addition of the guide vane, the difference between the maximum pressure and the minimum pressure becomes significantly smaller. Delayed the beginning of cavitation, which is beneficial to improve the efficiency of the propeller. As the blade angle increases, the degree of delay improves significantly.

![Figure 4: Pressure surface](image)

![Figure 5: Suction surface](image)

5. **Conclusion**

The effects of the presence or absence of rectifying guide blades on the performance of ducted propellers were compared with the installation of front rectifying guide blades.

1. The thrust performance of ducted propellers with front rectifying guide blades has been significantly improved. The performance of ducted propellers can be optimized by the research of front rectification.

2. The front rectifying guide blades reduce the pressure pulsation in the blade section, delay the cavitation initiation, and effectively improve the noise performance.

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