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To cite this article: Juan Xu et al 2020 J. Phys.: Conf. Ser. 1570 012040

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Effect of pre-swirl stator on wake flow of an ducted propeller

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Abstract. Numerical simulations of wake flow field of ducted propellers with and without preswirl stator are carried out by means of k- ω model. Then the velocities and the pressure fluctuations of the wake flow at different positions from the propeller are analyzed. The result shows that both the near-propeller blade velocity and the overall averaged velocity are obviously increased by the pre-swirl stator. Moreover, the pre-swirl stator can improve the surface pressure distribution near the blade but at the same time can enhance the pressure pulsation in the wake flow, especially at the downstream region.

1. Introduction

Ducted propellers with pre-swirl stators have become vigorously developed propulsion systems due to the advantages of high efficiency, low noise and high critical speed. A ducted propeller is composed of a duct, a pre-swirl stator and a rotary propeller. The strong interaction between the parts makes it difficult to analyze the performance of a ducted propeller system with a pre-swirl stator using conventional techniques like lifting surface theory and surface panel method. Therefore, except for a few of experimental studies [1-3], many previous studies used computational fluid dynamics (CFD) to evaluate the design of a ducted propeller system. Rao et al. [4] analyzed the hydrodynamic performance of a ducted propeller with a pre-swirl stator using RNG k-E viscous model. The effects of geometrical parameters setting angle, section thickness and stator blade number on hydrodynamic performance were obtained. Motallebi-Nejadh et al. [5] applied another turbulent model, SST $k-\omega$ model, to a ducted propeller simulation. The presented results of thrust, torque and efficiency for the ducted propeller are compared with experimental data and shown to be in good agreement. Fang et al. [6] simulated the sheet cavitation shape of a ducted propeller with a pre-swirl stator using a hybrid mesh based on RANS solver coupled with Singhal cavitation model. The predicted sheet cavitation shapes and tip vortex cavitation inception were in good agreement with experimental observation, suggesting the suitability of this method to predicting sheet cavitation shape of the propeller and the vortex cavitation inception at the tip. Furthermore, Peng et al. [7] compared open-water performance, cavitation capability, and pressure fluctuation characteristics between the ducted propellers with a pre-swirl stator and a post-swirl stator respectively using CFD prediction.

The above studies mostly focused in internal flow of the ducted propellers and rarely involved wake flow. As the source and foundation of the ship design, the wake flow should be one of the important

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ICAACE 2020

Journal of Physics: Conference Series

objects of the ship's hydrodynamics. Although some effective works have been carried out in the numerical prediction of the ships wake flow, they are generally studied only for the axial speed, while the study on three dimensional flow filed of the wake flow is still lacking, especially for the ducted propellers [8]. To this end, the influence of the pre-swirl stator on the wake flow field of a ducted propeller is analyzed numerically in this paper.

2. The numerical method

2.1. The governing equation

The governing equation includes the continuity equation, the momentum equation and the energy equation. The specific expressions are as follows.

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

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial\rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j} \left(-\rho \overline{u'_l u'_j} \right)$$
(2)

$$\frac{\partial(\rho c_p T)}{\partial t} + \frac{\partial(\rho c_p u_i T)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[K \frac{\partial T}{\partial x_i} - \rho C_p \overline{u_i' T'} \right]$$
(3)

Where ρ is the density of the fluid, μ_t is the eddy viscosity coefficient, u is the velocity, u is pulse velocity, C_p is specific heat capacity, K is heat conductivity coefficient and $\overline{u_i u_j}$ is Reynolds stress tensor.

Based on standard $k - \varepsilon$ model and $k - \varepsilon$ model, Menter [9] proposed a hybrid model. And it called the SST $k - \omega$ model. The transport equation is as follows.

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

$$\frac{\partial \rho_m \omega}{\partial t} + \nabla (\rho_m U \omega) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \nabla \omega \right] + \alpha \rho_m P_k - \beta' \rho_m \omega 2 + (1 - F_1) \frac{2\rho_m \sigma_{\omega 2}}{\omega} \nabla k \times \nabla \omega$$
(5)

Where ρ_m is mixture density, k is the turbulent kinetic energy, ω is turbulent vortex frequency, μ is the viscosity, μ_t is the eddy viscosity, P_k is the turbulent energy, β' is 0.09 and F_1 is the blending function.

2.2. Geometric model

JDC7704 type duct and Ka4-5512 type propeller blade are adopted for the study in this paper. Parameters of the duct are shown in Table 1, and the parameters of the blade are shown in Table 2 [10]. The overall three-dimensional model of the ducted propeller and the pre-swirl stator are shown in Figure 1. It should be noted that the two snapshots of the ducted propeller (with or without pre-swirl stator) are in different view angles.

Table 1	L. Duct	parameters
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Parameter	Value	
Ratio of length to diameter	0.6652	
Ratio of tip clearance to diameter	0.02	

Parameter	Value (m)
Propeller diameter	0.12
Blade area ratio	0.55
Hub radial ratio	0.167
Pitch ratio	1.0





Figure 1. Geometric model and grid.

Fluent software was used to perform the numerical simulation. The computational domain is divided into two parts: the rotating part and the stationary part. The connection surface of the two parts is set as the interface in Fluent so as to couple the calculation of the two parts. The wall of the duct and the propeller were set as non-slip solid walls.

3. Results and analysis

3.1 Wake flow field

The velocity fields of the wake flow in the perpendicular cross-sections to the propeller's shaft are studied. Four different locations along the axis of the propeller's shaft away from the propeller plane, namely x/r=0, 0.1639, 0.3821and 0.6562 are selected. The corresponding velocity distributions are shown in Figure 2. It can be seen that the near-propeller blade velocity of the case with pre-swirl stator is obviously higher than that without the pre-swirl stator. Moreover, the overall averaged velocity with pre-swirl stator is also higher than that without the pre-swirl stator. In other words, the propeller blade can get more energy to push the water through the pre-swirl stator.



With pre-swirl stator (x/r=0.3921)



Figure 2. Velocity distribution at different locations in the wake flow

3.2 Pressure fluctuation

As shown in Figure 1, two monitoring points, P1 and P2, with different axis distance from propeller plane are set on inner surface of the duct. The coordinates of P1 and P2 are (0.07,0,0) and (0.1,0,0), respectively. The pressure histories at the two locations are shown in Figure 3 and Figure 4 below.



Figure 3. Pressure fluctuation of P1



It can be seen from the two figures, the pressure histories in the wake flow changes drastically when a pre-swirl stator is involved. Because P1 is closer to the propeller plane, the pre-swirl stator doesn't change the overall pressure very much but make the pressure fluctuate more violently (see Figure 3). For P2 which is downstream to P1, the pressure magnitude gets much higher when the pre-swirl stator is incorporated, meanwhile the fluctuation of the pressure seems more orderly and smoothly relative to P1. Specially, comparing with Figure 3, Figure 4 shows more pressure difference between the cases with and without pre-swirl stator. These behaviors of the pre-swirl stator indicate that the pre-swirl stator can improve the surface pressure distribution near the blade but at the same time can enhance the pressure pulsation in the wake flow, especially at the downstream region.

4. Conclusion

Numerical simulations of the wake flow for ducted propellers with and without pre-swirl stator are carried out by means of $k-\omega$ model. The result shows that both the near-propeller blade velocity and the overall averaged velocity are obviously increased by the pre-swirl stator. Moreover, the pre-swirl stator can improve the surface pressure distribution near the blade but at the same time can enhance the pressure pulsation in the wake flow, especially at the downstream region.

Acknowledgments

This work was financially supported by the National Key R&D Program of China (2016YFC1402306), Natural Science Foundation of Shandong (ZR2017MEE046), Shandong Key Research and Development Program (2019JZZY010819), Shandong Key Research and Development Program (2019GSF110009) and Shandong Key Research and Development Program (2019GGX104042), Shandong Key Research and Development Program (2018GGX103018).

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