The Pressure Pulsation and Spectrum Analysis of Ducted Propeller Based on SST k-ω model

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Abstract. The pressure pulsation and spectrum of the four-blade ducted propeller are numerical simulated by CFD method. The flow field inside and behind the propeller is analysed by using SST k-ω Model. On the basis of the flow field, an acoustic grid is built. By setting several monitoring points in the area behind the propeller, the pressure pulsation in these points are recorded. Time domain curves of pressure pulsation in different points show a similar changing circle. After Fast Fourier Transformation (FFT), the blade passing frequency is calculated. The pulsation value near the hub is smaller than that at the tip of the blade. The fundamental frequencies of the pressure pulsations of the wake field are the same at different axial positions. The rotation of the blade has a great influence on the pressure pulsation near the blade. The pressure pulsation amplitude is larger near the propeller, and the amplitude at a far distance is smaller.

1. Introduction
Propellers are important propulsion tools for ships and submarines. In order to get better performance, the ducted propeller is developed a propulsion device for heavy-duty ships, and is also an active control mechanism for underwater submersible navigation posture [1]. The presence of the duct affects the shape of the wake field. This change increases propulsion while increasing propulsion efficiency. Thus, the ducted propellers are used to reduce vibration and improve the stability of the ship while sailing in the wind and waves.

A lot of research has been done on the hydrodynamic properties of ducted propellers in recent years. The detailed design procedures is discussed by Koronowicz, and also present the comparative results of computation results for different ducts [2]. Celik calculated the propulsive characteristics of ducted propellers obtained from improved lifting line modal, and compared the CFD code and experimental results [3]. The hydrodynamic forces and moment on a duct propeller are numerical simulated and experimental tested by de Barros [4]. The relationship between strength of non-uniform and amplitude of periodic variation is discussed [5]. The open water performance of propellers are investigated by employing the panel method panMARE and the RANSE code ANSYS-CFX [6]. Numerical
investigation of non-cavitation noise of ducted propeller is applied and the results show that the only high order BPFs are influenced by the existence of the duct [7]. Seol analyzed the dominant noise source of the underwater propeller [8].

In this study, an acoustic grid is built to analyze the noise performance of ducted propellers. Acoustic characteristics are numerically simulated to obtain the amplitude of pulsating pressure. Power spectral density curve is calculated by FFT method.

2. Computational methods

2.1. Control Equations

2.1.1. Governing equation of fluid flow. The laws of mass and momentum are applied for compressible laminar and turbulence flow. All control equations are represented by a conservation law. The coordinate system used to describe the problem is the Cartesian coordinate system in the Euler description. When the flowing fluid is defined as a continuum, the governing equations used to solve are as follows.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0.$$  (1)

\(u\) is the instantaneous velocity in the \(j\) direction and \(\rho\) is the density of the fluid.

Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_j) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i.$$  (2)

\(P\) is the static pressure, \(\tau_{ij}\) is the viscous stress tensor and \(f_i\) is the volume force. \(\tau_{ij}\) can be expressed as:

$$\tau_{ij} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3} \mu \left(\frac{\partial u_m}{\partial x_m}\right) \delta_{ij}.$$  (3)

\(\mu\) is the hydrodynamic viscosity, \(\delta\) is the Kronecker function.

Bring (2) into (1) to get the Navier-Stokes equation:

$$\frac{\partial}{\partial t}(\rho u_j) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i + \frac{\partial}{\partial x_j}(\rho \nabla \cdot \mathbf{u}) - \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_m}{\partial x_m} \delta_{ij}\right).$$  (4)

2.1.2. SST \(k-\omega\) Model. SST \(k-\omega\) Model was proposed in 1993 by F.R. Menter [8]. As the Wilcox \(k-\omega\) model is accurate in the near wall region and the \(k-\varepsilon\) model is suitable for freestream, this model combines these advantages of the Wilcox \(k-\omega\) model and the \(k-\varepsilon\) model. The \(k-\varepsilon\) model is transformed into a \(k-\omega\) model. The two models are weighted averaged by function \(F1\) and then added to obtain the BSL \(k-\omega\) model. Based on the BSL \(k-\omega\) model, the SST \(k-\omega\) model modified the definition of the eddy-viscosity for adverse pressure gradient boundary-layer flows.

Original \(k-\omega\) model and transformed \(k-\varepsilon\) model are weighted and averaged to obtain the following model:

$$\frac{\partial}{\partial t}(\rho k) = \nabla \cdot \left(\tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta' \rho \omega k + \rho f_i \right) + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_m}{\partial x_m} \delta_{ij}\right)\right]$$  (5)

$$\frac{\partial}{\partial t}(\rho \omega) = \frac{\nu_t}{\nu} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta' \rho \omega^2 + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_m}{\partial x_m} \delta_{ij}\right)\right] + 2 \rho (1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_i}$$  (6)

Where,

$$\mu_t = \frac{\rho \alpha_k k}{\max(\alpha_{1\omega} F_2)}, \ \nu_t = \frac{\mu}{\rho} = \frac{\alpha_k k}{\max(\alpha_{1\omega} F_2)}, \ F_2 = \tan \gamma \omega^2, \ \arg_2 = \max\left(\frac{2 \kappa}{\beta' \omega^2}, \frac{500v^2}{\delta^2}\right), \ \arg_1 = \min\left[\max\left(\frac{2 \kappa}{\beta' \omega^2}, \frac{500v^2}{\delta^2}\right), 3 \rho \sigma_{\omega 2} k^2 \right], \ CD_{k\omega} = \max\left(2 \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_i}, \ 10^{-20}\right).$$

\(\beta', \beta, \gamma, \sigma_1, \sigma_2, \sigma_3, \text{ and } \alpha_1\) are empirical constants. For any constant \(\phi\), there is
The subscript 1 indicates the constant value in the inner layer, and the subscript 2 indicates the constant value in the outer layer.

2.2. Geometric model parameters and meshing

The parameters of the simulated ducted propeller are listed as blow.

| Table 1. Parameters of the simulated ducted propeller |
|------------------------------------------------------|
| Propeller Diameter | Propeller solidity ratio | Number of blades |
| $R_p = 120$[mm]     | $\Phi = 0.55$            | $N = 4$          |
| Inclination         | Inlet diameter           | Outlet diameter  |
| $\alpha = 0^\circ$  | $R_i = 150$[mm]          | $R_o = 150$[mm]  |

There are three methods for solving the problem of rotating motion commonly: dynamic grid, slip grid, and motion reference system settings. In this study, the method of motion reference system settings is chosen.

An unstructured tetrahedral mesh is used through the domain. The total nodes of channel 173413 and the total number of grids is 972572. The calculating grids are as shown in Fig. 1.

![Figure 1. Duct and propeller surface meshing.](image1)

2.3. Monitoring methods

An acoustic grid is established based on a ducted propeller model. Multiple monitoring points are set around the blade to monitor the pulsating pressure of the monitoring points in the flow field and acquire acoustic signals in different directions of the ducted propeller. The position of monitoring points are set as Fig. 2.

![Figure 2. Positions of monitoring points](image2)
3. Results and discussion
The time domain curve of the pulsating pressure at different monitoring points is shown in Fig. 3. The amplitudes of the pulsating pressure at different monitoring points are inconsistent, but periodic laws are similar. After FFT transformation, power spectral density curves of pulsating pressure at each point are shown in Fig. 4. As can be seen, the blade passing frequency is 30Hz, and the rotating speed is 50RPS. Other lobulation frequency values are small, so the first-order blade frequency is mainly studied.

By comparing the pulsation characteristics at the blade radial directions P1, P2, and P3, the pulsation carried by the tip of the blade is the largest, and the pulsation near the hub is small. This is related to the high speed of the propeller blade tip and the low speed near the hub. This indicates that the rotation of the blade has a great influence on the pressure pulsation near the blade.
Figure 5 shows the distribution of the pressure pulsation frequency of the wake field at different axial positions. It can be found that the fundamental frequency is still 200Hz, which is corresponding to the blade frequency. This indicates that the frequency domain characteristics of the wake field are the same as the blade frequency. Due to the influence of wake flow at different positions, the amplitudes are different. The amplitude near the propeller is larger, and is smaller at the position away from the propeller.

4. Conclusion

The acoustic field of wake flow of a ducted propeller was simulated by the CFD method. Several points were set in the area of wake flow to monitor the pressure pulsation. The pressure pulsation near the tip of the blade was larger than the pulsation near the hub, which was related to the differences of flow speed. The amplitude of pulsation near the propeller is larger than that at the position away from the propeller.

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