

A Study on Effects of Blade Pitch on the Hydrodynamic Performances of a Propeller by Using CFD

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Abstract: The main objective of this work is to use the CFD (Computational Fluid Dynamics) technique to study the effects of pitch ratio on the controllable pitch propeller's thrust characteristic. The propeller analyzed is at the following design condition: diameter of 3.65 m, speed of 200 rpm, blade number of 4, average pitch of 2.459 m, pitch ratio at 0.7 of 0.6737. The first stage involves the mesh generation and refinement on domain of the designed propeller. The second stage deals with the identification of initial and boundary conditions of the mesh-equipped module. In the final stage, various results are calculated and analyzed for pitch ratio affecting on the propeller's thrust characteristic. The achieved results are the basis design and improving efficiency of the controllable pitch propeller.

Key words: Controllable pitch propeller, propeller, blade pitch, ship, CFD, thrust.

1. Introduction

From a propulsion point of view CPP (controllable pitch propeller) has many advantages compared to FPP (fixed pitch propeller) for business ships as: higher propulsion efficiency than with a fixed pitch propeller, optimizing speed and bollard pull performances. More efficient use of the diesel engine: 100% engine power remains available at the propeller in every situation (cruising, trawling, maneuvering, etc.). Moreover, a CPP allows constant operation of the engine at its nominal speed, thereby reducing significantly the fuel consumption, maintenance cost, and clutch disc wear. Better maneuverability: passing from "ahead" to "reverse" occurs smoothly and without dead time, simply through propeller pitch inversion. The very short response time while maintaining full power ensures higher safety for the ship and crew, and considerably reduces the stopping distance of the vessel.

A current comparison of propulsion capability for open CPP, open FPP and ducted FPP reported by Lee,

S. K. (2008), indicated that CPP design not only is the best energy-saving propulsor among the designs but also has the capability to continuously generate enough thrusts for severe operating conditions even when the FPP designs are broken down [1]. In the last forty years, the controllable pitch propeller has grown in popularity from representing a small proportion of the propellers produced to its current position of having a very substantial market share. Currently the controllable pitch propeller has about a 35 per cent market share when compared to fixed pitch propulsion systems and it is the most favoured in the passenger ship and ferry, general cargo, tug and trawling markets [2, 3]. Therefore a systematic study of controllable pitch propellers and the effects of pitch ratio on controllable propeller characteristics is thus essential in order to seek crucial design guidance for enhancing the operational efficiency of the propeller. The most popular reports on controllable pitch propeller that had been published in recently years are researching on hydrodynamic characteristic of marine propeller and controllable pitch propeller of a ship by developing a numerical simulation method or using [4-8]. Others reported on the effects of blade pitch, shape, profile of

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blade and optimization of a blade pitch for the controllable pitch propeller [1, 2, 9, 10].

In this paper, the CFD method was used to investigate the effects of pitch ratio on characteristics of the controllable pitch propeller. The simulations were performed by using the commercial software ANSYS-FLUENT v. 14.0 to calculate thrust coefficient, torque coefficient and efficiency of the propeller at various pitch ratios. The results illustrate the relationship between pitch ratio and efficiency of propellers in operation. The results are used to highlight design guidance the controllable pitch propeller.

2. Numerical Methods and CFD

2.1 Governing Equations

The problem was investigated by using the finite volume method of ANSYS-FLUENT in which the fundamental equations are the continuity equation and the RANS (Reynolds-Averaged Navies-Stocker) equations in moving reference frame written as follows [1-12].

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}_r) = 0 \quad (1)$$

Conservation of momentum:

$$\begin{aligned} & \frac{\partial}{\partial t} (\rho \vec{v}_r) + \nabla \cdot (\rho \vec{v}_r \cdot \vec{v}_r) + \\ & \rho (2\vec{\omega} \times \vec{v}_r + \vec{\omega} \times \vec{\omega} \times \vec{r} + \vec{a} \times \vec{r} + \vec{a}) = \\ & -\nabla p + \nabla \cdot \bar{\bar{\tau}} + \vec{F} \end{aligned} \quad (2)$$

where, $\vec{a} = \frac{d\vec{\omega}}{dt}$ and $\vec{a} = \frac{d\vec{v}_t}{dt}$

The stress tensor $\bar{\bar{\tau}}$ is given by

$$\bar{\bar{\tau}} = \mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla \vec{v} I \right] \quad (3)$$

The momentum equation contains four additional acceleration terms. The first two terms are the Coriolis acceleration ($2\vec{\omega} \times \vec{v}_r$) and the centripetal ($\vec{\omega} \times \vec{\omega} \times \vec{r}$),

respectively. These terms appear for both steadily moving reference frames (that is, and are constant) and accelerating reference frames (that is, and/or are functions of time). The third and fourth terms are due to the unsteady change of the rotational speed and linear velocity, respectively. These terms vanish for constant translation and/or rotational speeds [1-12].

2.2 Computational Models

The analyzed propeller in this paper has these designed details as: speed of 200 rpm, propeller diameter 3.65 m, the number of blade propeller of 4, average pitch of 2.459 m, pitch ratio at 0.7 of 0.6737. The profile used to construct the geometry propeller is Naca 66 series with $a = 0.8$. In this work to investigate the effects of pitch ratio on the propeller's characteristic, attack angles of the propeller blades change from the -7 degrees to 7 degrees. Fig. 1 shows model of the propeller.

2.3 Computed Fluid Domain and Boundary Conditions

In this research, the computed fluid domains consist of two components, the first one is the dynamic domain, and the other is the static domain. The limited computation of fluid domain is 11 m of length and 12 m of diameter. The next stage in the simulation process is to mesh and refine on the domains. The number of mesh has the dramatically important role in the CFD calculation result, so a suitable mesh number should be determined [1-12]. In this work, seven models have the reasonable number of mesh in the range of 3.3 millions. Fig. 2 shows the computed domain and mesh.

For computation, the RNG k- ϵ two-equation model is chosen as the turbulent viscous model to close Reynolds averaged equations, velocity inlet is selected as inlet boundary condition. Pressure outlet is specified as the outlet boundary condition, and gauge pressure on the outlet is set to be 0 Pa. As to wall boundary condition, no slip condition is enforced on wall surface and standard wall function is also applied to adjacent region of the walls. MRF (moving reference frame) is

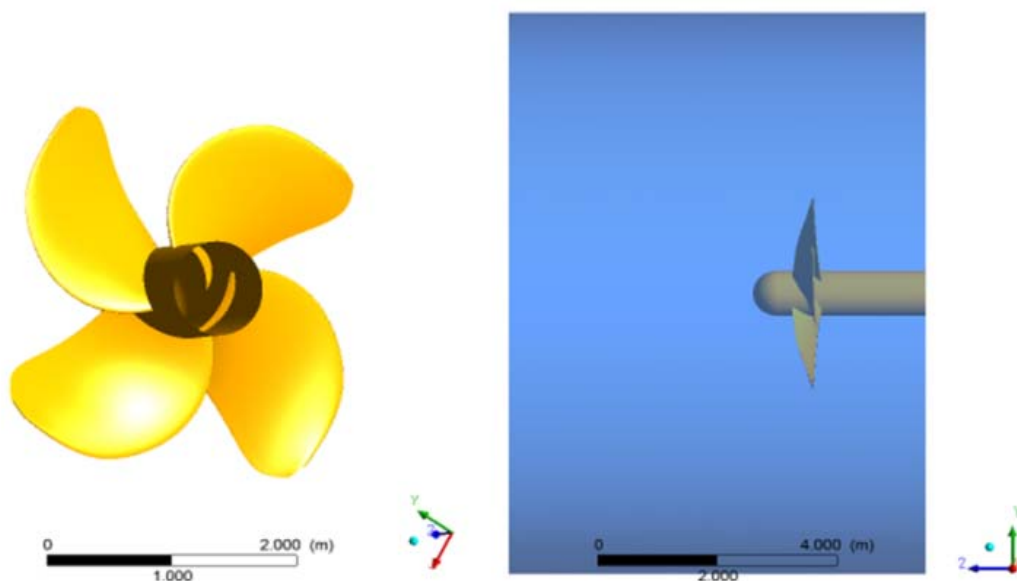


Fig. 1 Model of the propeller using for computation.

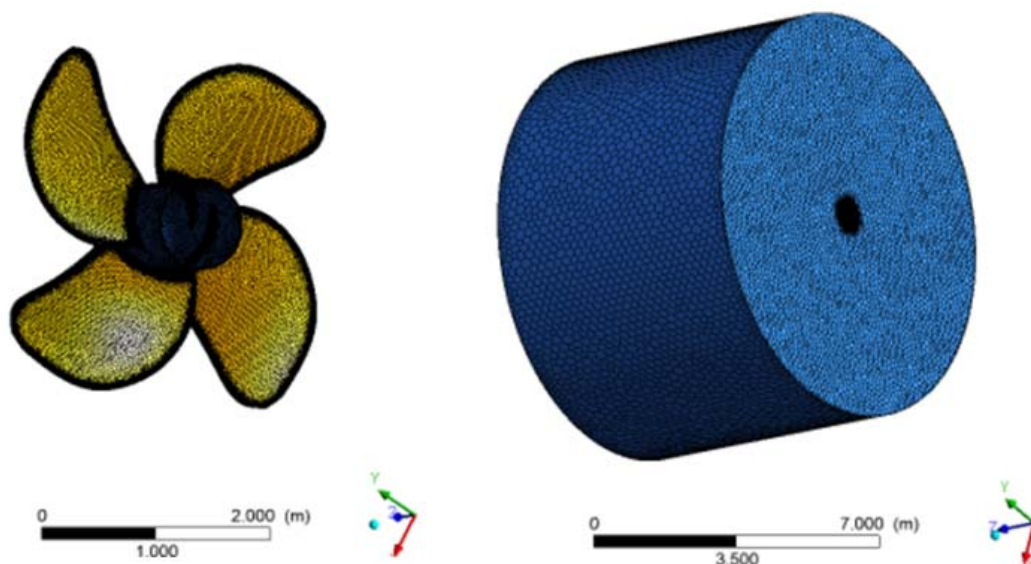


Fig. 2 Computed fluid domain and mesh.

used to establish the moving coordinate system rotating with the propeller synchronously and the stationary coordinate system fixing on static shaft of the propeller, respectively. The first order upwind scheme with numerical under-relaxation is applied for the discretization of the convection term and the central difference scheme is employed for the diffusion term. The pressure-velocity coupling is solved through the SIMPLE algorithm. Convergence precision of all residuals is under 0.0001 [9-12].

3. Results and Discussion

3.1 Effects of the Pitch Ratio on the Pressure Distribution

Fig. 3 shows the pressure distributions on the back and pressure face of the propeller at various attack angles. As can be seen, the pressure difference between the back face and pressure face is higher when the attack angle goes up in the indicated range when the velocity inlet is constant. As the results, the force and

torque of propeller also increase, and this is absolutely appropriate with the wing theory [8, 11]. This is especially meaningful when the ship operates in the heavy load conditions in which the thrust of the optimally designed propeller is not enough to overcome the resistance acting on the ship hull.

Fig. 4 shows velocity distribution on the axial plane with the different blade pitch angle. From the displayed results, we can see the change of velocity at the axial plane when the blade pitch angle alters.

3.2 Effects of the Pitch Ratio on Velocity Flow Distribution around Propeller

Fig. 5 shows the CFD results of velocity distribution around the propeller with a different pitch ratios. As can be seen from the figures, the streamline surrounding the propeller becomes more turbulent when the pitch ratio increases. As the consequence, the efficiency of the propeller goes down compared to the efficiency at the designed point corresponding the specific condition of the ship, although thrusts and

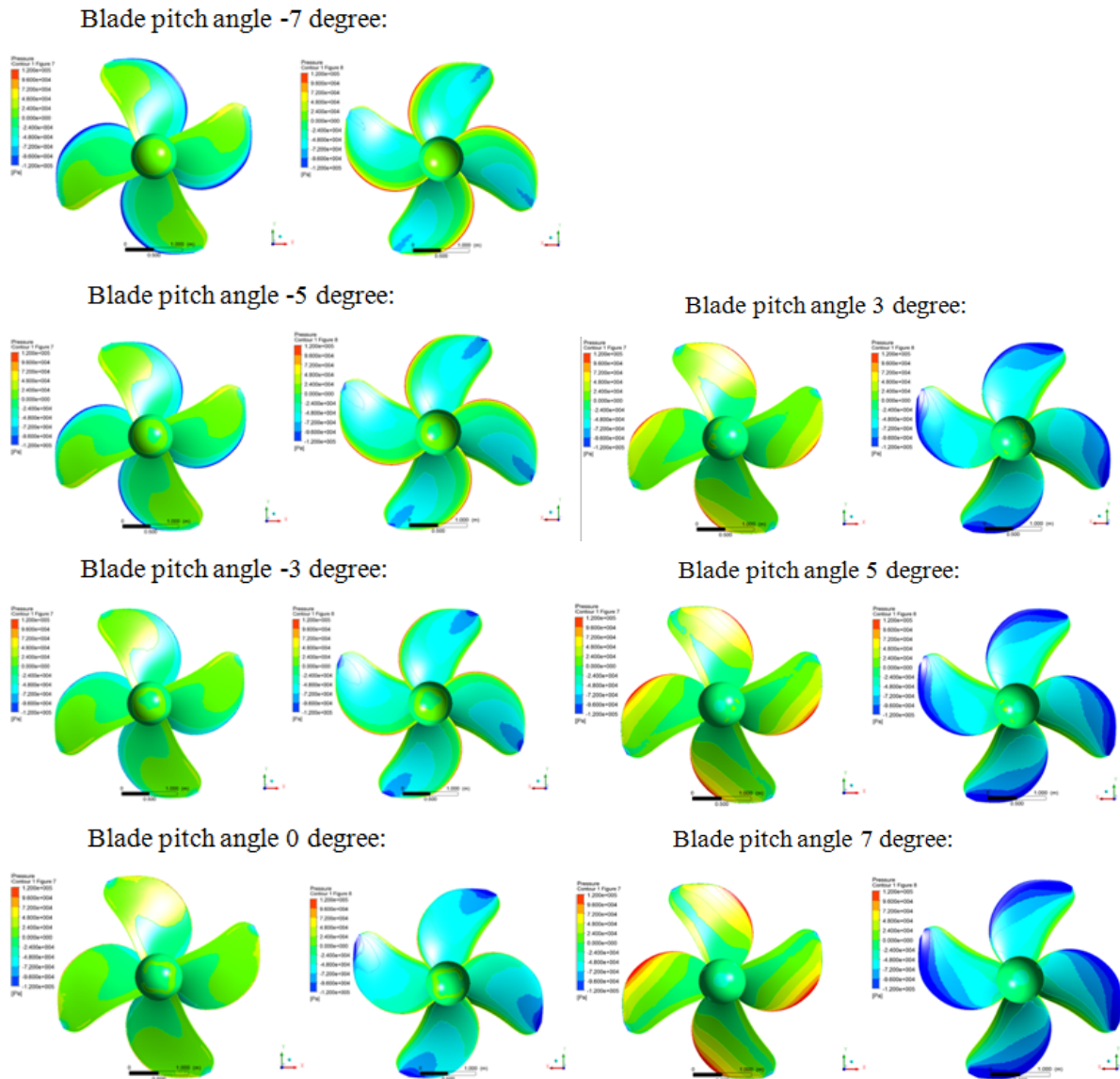


Fig. 3 Pressure distribution on blade surfaces of the propeller at various pitch ratios in the same condition, $\omega = 200$ rpm, $v = 6.08$ m/s, $J = 0.5$.

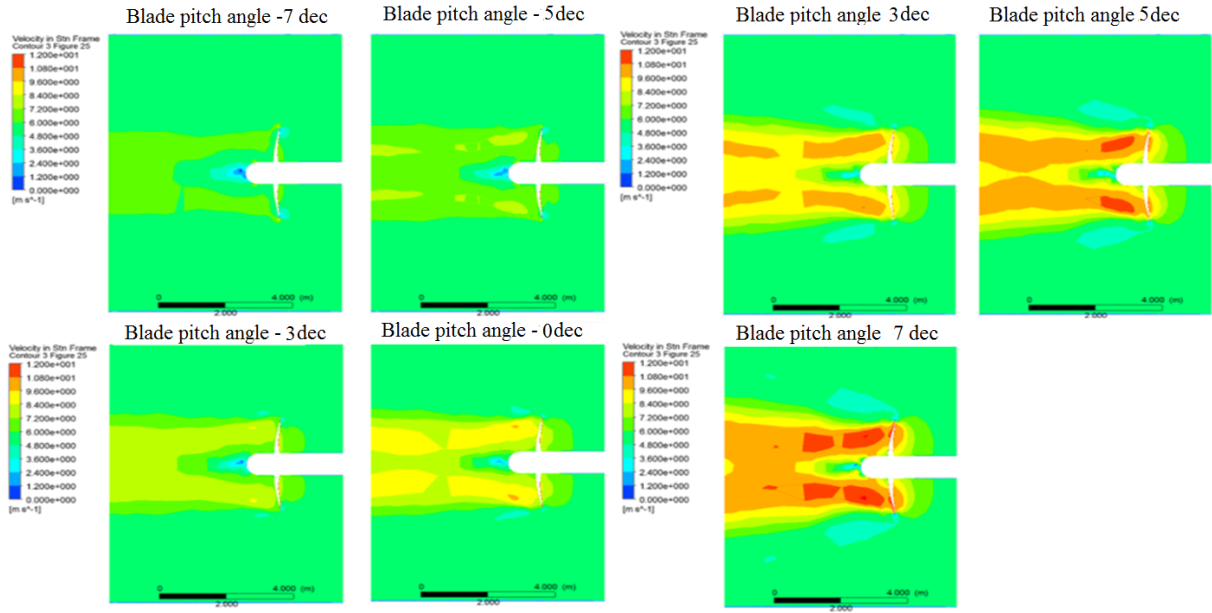


Fig. 4 Velocity distribution around propeller on the axial plane of computed domain.

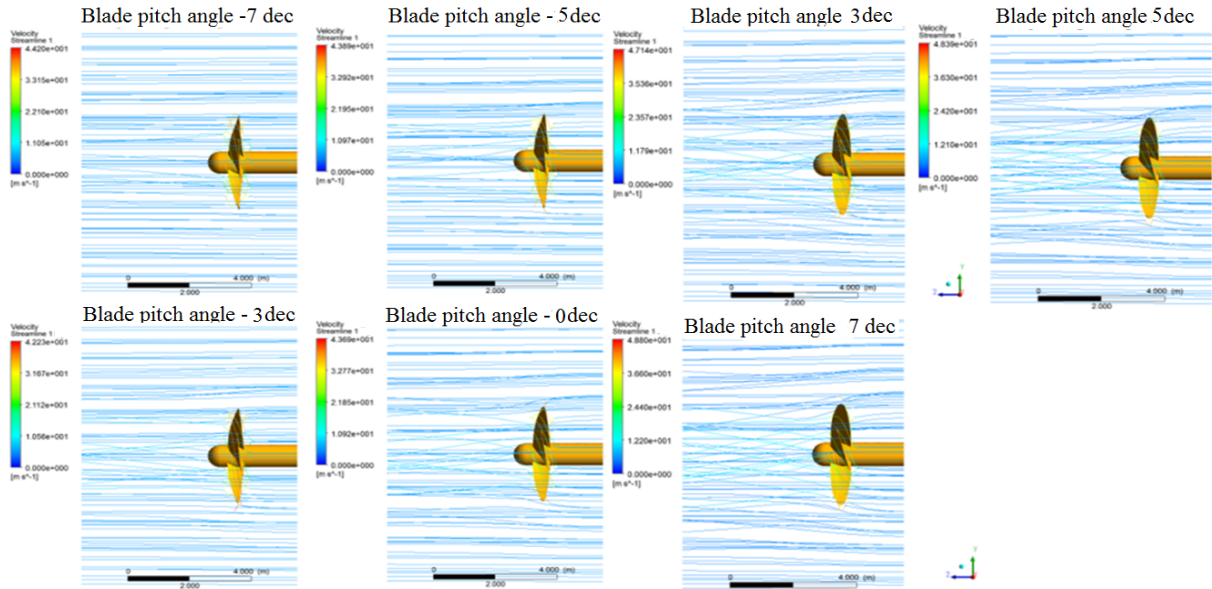


Fig. 5 Stream line surrounding propeller in various different pitch ratios, $\omega = 200$ rpm, $v = 6.08$ m/s, $J = 0.5$.

torques in the cases go up dramatically. This can be explained that when the attack angle of blade goes up, the flow field is more turbulent especially at the trailing edge of the propeller. This reduces the exchange energy ability of the propeller with the flow field, so the efficiency of the propeller decreases.

3.3 Effects of the Pitch Ratio on Thrust and Torque Coefficient

In this section, the effects of pitch ratios on thrust

and torque coefficients of the propeller are investigated by the CFD. In analyzing the impeller with the computation fluid dynamic method, thrust coefficient (K_T), torque coefficient (K_Q), propeller efficiency (η_0), and advance coefficient (J) of the propeller can be integrated as follows [8-10]:

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

$$J = \frac{V_a}{nD} \quad \eta_0 = \frac{K_T J}{K_Q \cdot 2\pi} \quad (4)$$

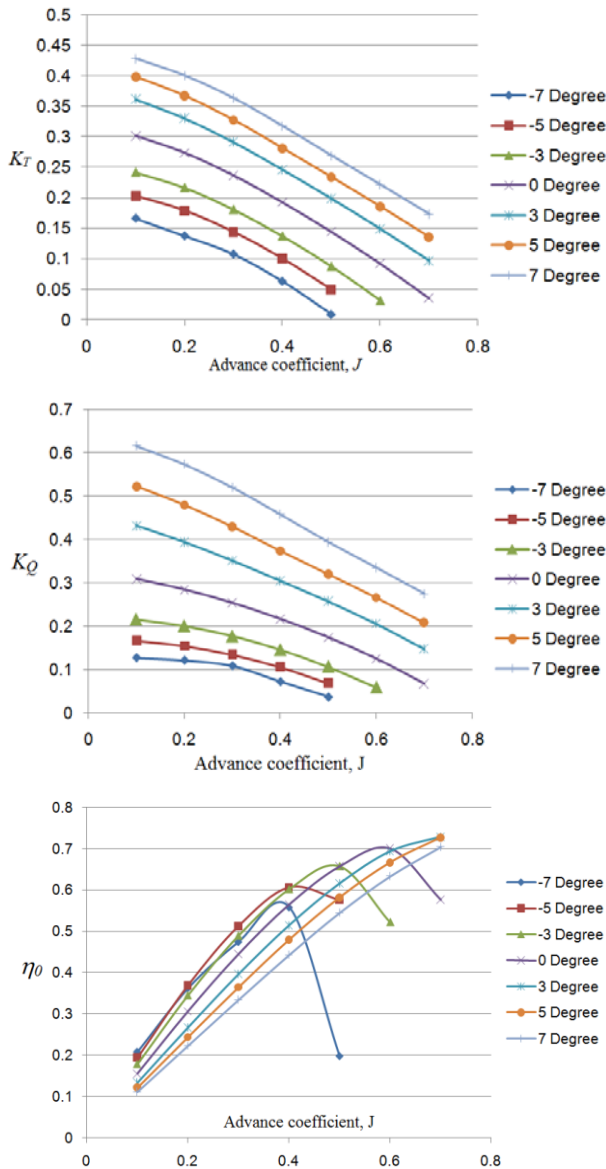


Fig. 6 Thrust, torque and power efficiency coefficients of the propeller.

where, T is thrust; Q is torque; D is propeller diameter; V_a is speed of advance; n is rotational speed and ρ is fluid density.

Fig. 6 shows the characteristics curves of the propeller at the various pitch ratios consisting of thrust coefficient curves, torque coefficient curves and the efficient curves.

The results given in Fig. 6 shows that when the pitch rises, the coefficient thrust and torque of the propeller also goes up. However the efficiency of the propeller changes on the principle of the axial turbo machinery,

the maximum efficiency of the propeller at the different pitch ratios is the function of the advance ratio J . When the pitch ratio increases, the maximum efficiency also rises to the optimized value of the designed propeller. With the controllable pitch propeller, the set of characteristic curves at the different pitch ratio are called the general characteristic curve. From Fig. 6, we can see that in operation, the ship equipped the controllable propeller can operate in the large range of advance velocity with high efficiency by changing the blade pitch of the propeller without altering the revolution of the engine shaft.

4. Conclusions

In this paper, by using CFD the effects of blade pitch angle on hydrodynamics performance of the propeller are investigated. These are conclusions of the paper:

- By using CFD for the steady flows around propeller at the different ratios of blades pitch, with unstructured grid based on RANS and applied the turbulence model. The hydrodynamic performances of the propeller have been investigated.
- The four-bladed skewed propeller of the real ship named the Tancang foundation is selected for simulation. The results show that K_T and K_Q are decreasing when pitch ratios change out the designed point and the CFD results are in good agreement with theory prediction.
- The computational results of propeller thrust increase dramatically when the pitch ratio goes up. This is extremely useful when the ship operates in the bad conditions in which the resistance on the ship hull that is significant larger than the initially designed condition.

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