Controllable Pitch Propeller Performance Comparison of Different Speed and Pitch Matches at non-cavitation condition

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Abstract. The paper took one controllable pitch propeller as study model. Open water performance at different pitches were calculated based on FLUENT. On this basis, rotational speeds that match P/D=1.5, 1.3, 1.15, 1.0 at 21kn were obtained according to characteristic curve of navigation. Propeller efficiency and pulsing pressure were carried out and compared at different matches. The result shows that pulsating pressure is both influenced by speed and pitch. It is non-linear relationship between pitch ratio and cavitation and efficiency and is inconsistent with the character of propulsion efficiency. Hence it brings adverse effect on pulsing pressure if the match of speed and pitch is selected only according to propulsion efficiency. The paper recommends comprehensive consideration about pulsing pressure and propulsion performance should be taken to choose match of speed and pitch at non-cavitation condition.

1. Introduction
The controllable pitch propeller is a kind of propeller that can make full use of the full power of main engine in any sailing state; it has good energy saving performance in comparison with fixed pitch propeller. Especially in today's energy shortage, reducing fuel consumption has become the unremitting pursuit of ship designers [1, 2], so the research on controllable pitch propeller is still a hot work.

There are many research directions of controllable pitch propellers, such as research on basic parameters of propellers [3,4], research on matching between ship and propellers [5,6], research on control system of controllable pitch propellers [7,8], and research on appendages of controllable pitch propeller [9], etc.

There are usually the following two goals for the research on matching the pitch and speed of the controllable pitch propeller [1-2]:

(1) When the output power of the main engine is constant and its speed is constant, the proper pitch is selected to make the ship can maintain the maximum speed under any load.
(2) When the speed is constant, the proper pitch and main engine speed are selected to minimize the fuel consumption of the ship.

However, the existence of ship vibration, cavitation, noise and other phenomena have immeasurable impact on the performances of the ship in the actual sailing process of the ship, especially for ships under special operation conditions or ships which carrying out special missions, simply considering the
fuel consumption to determine the pitch and speed matching of the controllable pitch propeller does not conform to actual needs.

2. Governing equations
Continuity equation is the concrete pattern of manifestation of mass conservation in the fluid.

\[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]

Reynolds-Average Navier-Stokes (URANS) equations are represented as follows:

\[ \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial}{\partial x_j} (\rho u_i u_j) + \rho f_i \]

Where \( \rho \) is the fluid density and \( p \) is the static pressure, \( f_i \) the mass force per unit mass, \( u_i \), \( u_j \) the velocity components, \( -\rho u_i u_j \) the Reynolds stress representing turbulence effect.

Nowadays, turbulence energy equations and turbulence dissipation equations are basic method to reflect the turbulence characteristic. Added equations are needed to connect the pulse value and the time average in order to solve the increased Reynolds stress in N-S equations, which is called turbulence model. This paper adopted the SST \( k-\omega \) turbulence model, which is developed from the standard \( k-\omega \) turbulence model. This model owns high precision in the fluent simulation because it takes the advantage of the standard \( k-\omega \) turbulence model, combines the cross-diffusion from equation \( \omega \), and takes the spread of turbulent shear stress into consideration.

3. Model and Mesh
The study model is a controllable pitch propeller with 5 blades. Propeller diameter D=240mm, disk ratio Ae/Ao=0.741, designed pitch ratio at 0.7R P/D=0.7R=1.0. Fig.1 is the shape of the propeller model. Calculation pitches include P/D=1.0, P/D=1.15, P/D=1.3 and P/D=1.5.

![Fig. 1 Shape of the propeller model](image)

An integral ship-propeller model without free surface is built for pulsating pressure calculation. As the computational model is symmetrical, only starboard is considered in modeling and simulating. The length of waterline is 7.92m and propeller diameter is 0.173m. Fig.2 is the layout of the stern.
In order to eliminate the influence of the computational boundary on the simulated flow, the boundary of the computational flow field is set at a distance long enough away from the computational model. The inflow boundary, at a distance of one total model length upstream from the bow of the model, is imposed with the velocity-inlet boundary condition. The outflow boundary, at a distance twice the total model length downstream from the stern of the model, is imposed with the undisturbed pressure-outlet boundary condition. The outer boundary, at a distance of one total model length from the central axes of the model, is imposed with the undisturbed velocity boundary condition. The surface of the model is set as in no-slip boundary condition.

According to the theory of MRF, the rotating area around propeller should be a separate block, transmitting information with mesh around it through interpolation. The rotating area includes 5,000,000 unstructured grids, while the other area includes 6,000,000 structured grids. Fig. 3 is the mesh of the model.

4. Parameter matching
Firstly, open-water performance at different pitches is calculated. The result is shown in table 1-4.

Tab. 1 Open water performance at P/D=1.5

| J  | Kt   | 10Kq  | η     |
|----|------|-------|-------|
| 0.4| 0.5567| 1.0917| 0.3246|
| 0.6| 0.4451| 0.9155| 0.4642|
| 0.8| 0.3348| 0.7405| 0.5756|
| 1  | 0.2298| 0.5641| 0.6484|
| 1.1| 0.1786| 0.4729| 0.6614|

Tab. 2 Open water performance at P/D=1.3

| J  | Kt   | 10Kq  | η     |
|----|------|-------|-------|
| 0.4| 0.4646| 0.8169| 0.3621|
| 0.8| 0.2466| 0.5196| 0.6044|
| 1  | 0.1411| 0.3553| 0.6321|
| 1.2| 0.0150| 0.1443| 0.1991|
Tab. 3 Open water performance at P/D=1.15

| J  | Kt   | 10Kq | η   |
|----|------|------|-----|
| 0.2| 0.4951 | 0.7609 | 0.2071 |
| 0.6| 0.2790 | 0.5141 | 0.5183 |
| 0.8| 0.1722 | 0.3739 | 0.5864 |
| 0.9| 0.1167 | 0.2947 | 0.5672 |
| 1  | 0.0540 | 0.2028 | 0.4234 |

Tab. 4 Open water performance at P/D=1.0

| J  | Kt   | 10Kq | η   |
|----|------|------|-----|
| 0.2| 0.4154 | 0.5865 | 0.2255 |
| 0.4| 0.3106 | 0.4849 | 0.4079 |
| 0.6| 0.2047 | 0.3703 | 0.5280 |
| 0.7| 0.1517 | 0.3072 | 0.5500 |
| 0.8| 0.0930 | 0.2346 | 0.5049 |
| 0.9| 0.0261 | 0.1499 | 0.2499 |

By comparing the open water efficiency under the four pitches, it can be found that for the controllable pitch propeller, as the pitch increases, the maximum efficiency increases, and the speed coefficient that reaches the maximum efficiency also increases. Under low speed coefficients, the smaller the pitch, the greater the efficiency.

Fig. 4 Comparison of open-water efficiency

Fig. 5 shows the method of obtaining the matches of different speeds and pitches at 18kn by the effective power. The speed matching P/D=1.5, 1.3, 1.15, 1.0 is 608.11rpm, 664.71rpm, 723.37rpm, 798.05rpm.

Fig. 5 Match of pitch and rotational speed
5. Pulsating pressure

Fig. 6 and Fig. 7 show the distribution of the monitor points of pulsating pressure. Distance between points is 0.25D and distance between points and blade tip is 0.3125D. Calculating time step is set as 3° each step. The pressure-velocity coupling equation is solved by the SIMPLE method. The convection term is discretized by a second order upwind scheme, the diffusion term is discretized by the central difference scheme, the temporal term is discretized by a second order implicit scheme, The discretized algebraic equations are solved by the Gauss-Seidel iteration method.

\[ P = \rho \frac{\partial u}{\partial x} \]

In the above formula, \( P \) is the pulsating pressure, and \( \rho \) is the water density, which is 998.2 kg/m³, \( n \) is the propeller speed, and \( D \) is the diameter of the propeller.

The pressure data of time domain signal is transferred to frequency domain signals by fast Fourier transform (FFT). The sampling frequency is consistent with the time step. The first-order pulsating pressure coefficients of all the monitor points and the frequency are shown in table 5. Selecting different matches according to actual needs is conducive to avoid some sensitive frequencies because the pulsating pressure frequency is modulated by propeller speed.

Figure 8 shows first-order pulsating pressure coefficients of different points at the four pitches. It tells that the variation trend of different pitches is consistent. Pulsating pressure directly above the propeller surface is the largest, the front side of the propeller is larger than the back side of the propeller, this is because the propeller axle tips down, which causes the front measuring point to be closer to the propeller, the pulsating pressure inside the hull is larger than that outside the hull, which is caused by the internal rotation of the propeller.
Tab. 5 First-order pulsating pressure coefficient of different pitches ($\times 10^3$)

| Pitch ratio | First-order frequency/Hz | P1  | P2  | P3  | P4  | P5  | P6  | P7  | P8  | P9  |
|-------------|--------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| P/D = 1.0   | 55.27                    | 3.85| 2.78| 2.03| 2.78| 1.44| 1.68| 1.59| 3.88| 2.66|
| P/D = 1.15  | 47.79                    | 2.41| 2.23| 1.17| 1.41| 0.45| 0.94| 1.21| 2.30| 2.09|
| P/D = 1.3   | 43.81                    | 3.08| 2.77| 1.31| 1.55| 0.62| 1.11| 1.62| 2.98| 2.69|
| P/D = 1.5   | 39.92                    | 3.51| 3.22| 1.69| 2.17| 1.11| 1.79| 2.02| 3.38| 3.13|

Fig. 8 First-order pulsating pressure coefficient of different pitches

According to the dimensionless formula of pulsating pressure, the first-order pulsating pressure coefficient is converted into pulsating pressure, as shown in Table 6. Fig. 9 shows that the change laws of first order pulsating pressure of each measuring point with the pitch are basically the same, when it is lower than the design pitch, the first order pulsating pressure decreases rapidly as the pitch increases; and when it is higher than the design pitch, the first order pulsating pressure increases slowly as the pitch increases. It shows that the pulsating pressure is the smallest near the design pitch. When the pitch increases, the pulsating pressure does not change much. When the pitch decreases, the pulsating pressure will increase significantly. The pitch near or higher than the design pitch is recommended to select.

Fig. 9 Pulsating pressure coefficient at the first order blade frequency

Tab. 6 First-order pulsating pressure of different pitches (Pa)

| P/D | First-order frequency/Hz | Point1 | Point2 | Point3 | Point4 | Point5 | Point6 | Point7 | Point8 | Point9 |
|-----|--------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1.0 | 55.27                    | 389.4  | 281.2  | 205.3  | 281.2  | 145.7  | 169.9  | 160.8  | 392.5  | 269.1  |
| 1.15| 47.79                    | 182.3  | 168.7  | 88.5   | 106.6  | 33.7   | 71.2   | 91.5   | 174.0  | 158.1  |
| 1.3 | 43.81                    | 195.8  | 176.1  | 83.3   | 98.5   | 39.6   | 70.6   | 103.0  | 189.4  | 171.0  |
| 1.5 | 39.92                    | 185.3  | 170.0  | 89.2   | 114.5  | 58.6   | 94.5   | 106.6  | 178.4  | 165.2  |
Fig.10 more intuitively compares the pulsating pressure at the first order blade frequency of measuring points of each pitch. It can be seen that the size of the pulsating pressure does not show a single linear law under the dual influence of the pitch and the speed. This is because the increase of the pitch or the speed can increase the angle of attack of the propeller blade, which strengthens the propeller's disturbance to the surrounding flow field, thereby increasing the pulsating pressure generated by the hull surface. When the pitch and speed of the controllable pitch propeller are matching, the pitch increases, and the speed must decrease. Therefore, when the pitch increases and the speed decreases, or the pitch decreases and the speed increases, the influence on the angle of attack of the blade inflow becomes complicated, and it makes the size of the pulsating pressure present the nonlinear law.

The pulsating pressure under P/D=1.0 pitch is much larger than the other three pitches, it shows that when the pitch ratio is less than 1.15, rotational speed plays a leading role in the influence of pulsating pressure, which greatly increases the pulsating pressure. When the pitch is greater than 1.15, the influence of the speed is weakened, under the dual influence of the pitch and the speed, there is no significant difference in the size of the pulsating pressure, and it tends to be stable.

The efficiency of propeller after ship respectively are 0.4956, 0.5178, 0.4911, 0.4554 at P/D=1.5, 1.3, 1.15, 1.0. Efficiency at P/D=1.3 is the highest, while efficiency at P/D=1.0 is much lower than at other pitches.

For this propeller, pitch ratio should be selected within the range of P/D=1.15-1.3 under non-cavitation condition, for it can not only provide higher efficiency, but also obtain lower pulsating pressure, which is of benefit to reduce vibration, noise and so on. In addition, a suitable pitch can be selected within this range according to actual needs to avoid sensitive frequencies and improve the concealment of the ship.

6. Conclusion
Taking a controllable pitch propeller as the research object, this paper conducted comparison and research on its pulsating pressure performance and propeller efficiency at four pitches under 18kn operating conditions.

Pulsating pressure is both influenced by speed and pitch at non-cavitation condition. It is non-linear relationship between pitch ratio and pulsating pressure and is inconsistent with the character of propulsion efficiency. Hence it brings adverse effect on pulsating pressure if the match of speed and pitch is selected only according to propulsion efficiency. The paper recommends comprehensive consideration about pulsating pressure and propulsion performance should be taken to select match of speed and pitch at non-cavitation condition, which is of benefit to reduce vibration, noise and so on. In addition, it is conducive to avoid some sensitive frequencies to change different matches according to actual needs because the pulsating pressure frequency is modulated by propeller speed.
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