Comparative analysis of the efficiency of manual adjustable pitch propeller and fixed pitch propeller based on dual-scale coupling

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Abstract. In order to solve the problem of ship, engine, and propeller mismatch between the first manufacturing of a new type of ship and the long-term service of the ship, the idea of dual-scale coupling simulation is used to establish the meso-scale and macro-scale mathematical model of a manually adjustable pitch propeller. The thrust coefficient and the torque coefficient are the coupling points. A comparison calculation between the manual adjustable pitch propeller and the fixed pitch propeller is carried out on a small ship as an example. The results show that the manual adjustable pitch propeller could compensate for the efficiency deviation caused by the fixed pitch propeller design; When the ship's resistance increases or the ship's main engine power decays, the measures of adjusting the pitch and turning angle of the blades could effectively improve the efficiency of the propeller and the ship's speed, which indicates that the manual adjustable propeller has better adaptability than the fixed pitch propeller.

1. Introduction
Fixed pitch propellers are the most widely used propellers in the shipbuilding industry. If they can operate at the design operating point, higher efficiency and economy can be ensured. However, the ship, engine, and propeller may not match after the new ship’s first system and ship repairs. At present, the methods adopted for fixed pitch propellers are mainly based on edge cutting [1]. This process often relies on experience and requires high skill levels of workers, which makes it difficult to achieve the best matching state of the ship, machine, and propeller. The controllable propeller relies on the hydraulic transmission device to change the blade angle to achieve the purpose of changing the thrust. This kind of propeller needs to be matched with the corresponding hydraulic device. The system composition is complex and the cost is high. It is mostly used in special types of ships, such as tugboats, fire boats, icebreakers, etc.

Compared with fixed pitch propeller and controllable propeller, a manually adjustable pitch propeller referred to as APP is proposed, which can be adjusted by the angle of APP blades after the ships repair and the first manufacturing of new ships. Changing the thrust of the propeller eliminates the need for trimming techniques that rely on worker experience, and its initial investment and complexity are much lower than that of a controllable propeller, which is of great significance for ship construction and maintenance.
2. The working principle of APP

The APP adopts a specially designed mechanical structure, and the propeller blade and the propeller hub are made separately. The blade is designed with the vortex theory method [2-3]. The propeller hub is designed in two halves. The screw and crank slider mechanism are used as the main adjustment mechanism. By rotating the threaded adjustment rod 1 that connected with the stern shaft at the end of the propeller hub, the guide frame 2 connected with the groove on the flange of the blade through the sliding block moves forward and backward, which drives the blade to rotate, thereby realizing the change of the pitch of the entire propeller. After the pitch is adjusted to the required value, a specially designed fixing block 3 is used to fix the adjusting rod and the propeller hub, so as to realize the fixation of the APP. The structure of the APP hub is shown in Figure 1.

![Figure 1. The structure of the APP hub diagram](image)

3. Two-scale coupled mathematical model

3.1. Meso-scale mathematical model

The lattice Boltzmann method is adopted in meso-scale, and the simulation object is fluid particles, which are sufficiently large in microscopic and sufficiently small macroscopically. The specific form is as follows [4]:

\[ f_i(r + c_i \Delta t, t + \Delta t) = f_i(r, t) + \Omega_i \tag{1} \]

Where, \( f_i \) is the particle velocity distribution function along the i direction; \( c_i \) is the local particle velocity; \( \Omega_i \) is the collision operator, which represents the rate of change of \( f_i \) after the collision. Introducing the BGK collision operator model, this collision operator can be linearly expressed as:

\[ \Omega_i = \frac{1}{\tau} (f_i^{eq} - f_i) \tag{2} \]

Where, \( f_i^{eq} \) is the balanced distribution function, and \( \tau \) is the relaxation time. The lattice model adopts the lattice arrangement of the three-dimensional problem, namely the D3Q19 model, and its equilibrium distribution function is [5-7]:

\[ f_i^{eq} = \omega_i \rho \left( 1 + \frac{3c_i u}{c_s^2} + \frac{9(c_i u)^2}{c_s^4} - \frac{3u^2}{2c_s^2} \right) \tag{3} \]

Where, \( \omega_i \) is the weight coefficient, \( \rho \) is the fluid density, \( u \) is the fluid velocity, and \( c_s \) is the sound velocity in the fluid.
The calculation is carried out using XFLOW software based on the lattice Boltzmann method to calculate the thrust and torque of the APP. The calculation time of this method is about 1/7 of the macro CFD method, which can save a lot of computer calculation time. The relative error percentage calculated by Boltzmann method and macro CFD method is not much different [8].

3.2. Macro-scale mathematical model
When the ship is sailing under steady-state conditions, the effective thrust has the following relationship with the hull resistance [9]:

\[ T_e = R \]  
\[ (4) \]

Where, \( T_e \) is the effective thrust and \( R \) is the hull resistance. The ship resistance \( R \) can be described by the following formula [10]:

\[ R = \frac{1}{2} \rho S V_s^2 \]  
\[ (5) \]

\[ c = c_f \cdot k + \Delta c_f + c_e + c_w \]  
\[ (6) \]

Where, \( \rho \) is the seawater density, \( S \) is the immersed area of the ship, \( V_s \) is the ship speed, \( c_f \) is the frictional resistance coefficient, \( k \) is the correction coefficient introduced by the hull surface curvature, \( \Delta c_f \) is the hull surface roughness coefficient, \( c_e \) is the vortex resistance coefficient, and \( c_w \) is the wave resistance coefficient.

For the propeller's advance speed coefficient \( J \), thrust \( T \), torque \( Q \), open water efficiency \( \eta_P \) and thrust power \( P_T \), which can be described by the following formula:

\[ J = \frac{V_s}{nD} \]  
\[ (7) \]

\[ T = K_T \rho n^2 D^4 \]  
\[ (8) \]

\[ Q = K_Q \rho n^2 D^5 \]  
\[ (9) \]

\[ \eta_P = \frac{K_T}{K_Q} \frac{L}{2\pi} \]  
\[ (10) \]

\[ P_T = P_e \cdot \eta_c \cdot \eta_r \cdot \eta_P \]  
\[ (11) \]

Where, \( K_T \) is the propeller thrust coefficient, \( K_Q \) is the propeller torque coefficient, \( n \) is the propeller speed, \( D \) is the propeller diameter, \( P_e \) is the effective power of the main engine, \( \eta_c \) is the shaft transmission efficiency, \( \eta_r \) is the relative rotation efficiency, and \( \eta_P \) is the open water of the propeller effectiveness.

The effective power and resistance power of the hull are described by the following formulas:

\[ P_E = P_T \cdot \eta_s \]  
\[ (12) \]

\[ P_r = R \cdot V_S \]  
\[ (13) \]

Where, \( \eta_s \) is the hull efficiency, \( \eta_s = (1 - t)/(1 - \omega) \), \( t \) is the thrust derating coefficient, and \( \omega \) is the wake coefficient.
4. The calculation examples

4.1. Main parameters of ship, machine and propeller

The parameters of ship, engine and APP involved in the calculation in this paper were shown in Table 1-3.

**Table 1. Main parameters of the hull**

| Name                   | Value  | Name                  | Value  |
|------------------------|--------|-----------------------|--------|
| Total length $L_{oa}$/m | 17.85  | Boat depth $D$/m       | 2.62   |
| Boat length $L_{H}$/m   | 17.38  | Draught $d$/m         | 1.02   |
| Waterline length $L_{W}$/m | 15.96 | Displacement $\Delta/t$ | 29.7   |
| Boat width $B$/m        | 4.80   | Speed $V$/kn          | 20     |
| Diamond coefficient     | 0.751  | Square factor         | 0.432  |

**Table 2. Main parameters of engine and transmission equipment**

| Name                        | Value  |
|-----------------------------|--------|
| Engine power/hp              | 600*2  |
| Engine rated speed /rpm      | 3000   |
| Gearbox reduction ratio      | 2.208:1|

**Table 3. Main parameters of the APP**

| Name                        | Value  |
|-----------------------------|--------|
| Diameter $D$/mm              | 700    |
| Initial design pitch ratio $P/D$ | 1.1029 |
| Hub diameter ratio $d_{h}/D$ | 0.3071 |
| Number of blades $Z$         | 4      |
| Blade angle ($^\circ$)       | 4.21   |

In this example, the APP required normal adjustment under the operation of a worker. A 0.5-meter wrench could generate a torque of about 250NM, and the corresponding manual adjustable propeller power was about 1000KW. Therefore, in this example the APP was suitable for ships with engine power within 1000KW.

4.2. Coupling calculation method

The calculation idea of two-scale coupling was adopted [11], and the XFLOW software was used that based on the lattice Boltzmann method to calculate the thrust and torque of the APP under different velocity coefficient, and the thrust and torque characteristic curves were drawn as shown in the figure 2 and Figure 3, the thrust coefficient $K_T$ and the torque coefficient $K_Q$ were used as coupling points and then the macro-scale mathematical model was used for calculation. The calculation steps were: assuming that the initial speed was small enough, we calculated the propeller advance speed coefficient, and the open water efficiency $\eta_P$ of the APP with the $K_T$ and $K_Q$ curve fitting interpolation, and then calculated the effective power $P_E$ of the hull; In addition, we also calculated the resistance $R$ and resistance power $P_r$ of the hull according to the hull parameters and ship speed. When the relative error delta between the effective power and the resistance power of the hull was less than 0.1%, the ship was considered to be sailing in a steady state and the calculation was ended; otherwise, the speed was increased by $\Delta V$, and the calculation was repeated until the ship's steady-state speed $V_s$, advance speed $J$, effective hull power $P_E$, open water efficiency $\eta_P$ of the APP were obtained. The calculation process was shown in Figure 4.
5. Comparison and analysis of calculation results of adjustable pitch propeller and fixed pitch propeller

5.1. Operating conditions of blades with different pitch angles

The ship speed and propeller efficiency that could be achieved with different blade pitch angles under the rated power and speed of the engine were shown in Table 4.

| Pitch angle (°) | Ship speed (Kn) | Propeller efficiency (%) |
|----------------|-----------------|--------------------------|
| -8             | 20.8009         | 47.89                    |
| -4             | 23.8900         | 71.22                    |
| Fixed pitch propeller | 22.4417       | 59.54                    |
| 4              | 22.4125         | 59.31                    |
| 8              | 20.3927         | 45.26                    |

The calculation results in Table 4 showed that, the ship speed deviation was small within the adjustment range of the pitch angle of the APP under the rated conditions, but the propeller efficiency deviation was large. The ship’s speed and the propeller efficiency under rated conditions were reduced by 6.1% and 16.4% respectively if fixed-pitch propellers were used compared with the APP, which indicated that the APP could compensate for the efficiency deviation caused by fixed pitch propeller design, and the APP had a higher economy.
5.2. Working conditions of increased ship resistance
Table 5 showed the speed and propeller efficiency that the ship could achieve under the conditions of 4 degrees, fixed pitch propeller, 4 degrees blade pitch, and 2 to 5 times ship resistance with different engine speeds.
Table 5. Ship speed and propeller efficiency under different resistance, different speed, and different pitch angle conditions

| Pitch angle (°) | Resistanc.e multiple | 1350rpm Ship speed (Kn) | 1800rpm Propeller efficiency (%) | 1800rpm Ship speed (Kn) | 2250rpm Propeller efficiency (%) | 2250rpm Ship speed (Kn) | 2700rpm Propeller efficiency (%) | 2700rpm Ship speed (Kn) | 3000rpm Propeller efficiency (%) | 3000rpm Ship speed (Kn) |
|----------------|----------------------|-------------------------|----------------------------------|-------------------------|----------------------------------|-------------------------|----------------------------------|-------------------------|----------------------------------|-------------------------|
| -4             | 2                    | 7.818                   | 59.72                            | 10.303                  | 59.49                            | 13.079                  | 60.23                            | 15.892                  | 60.83                            | 17.781                  | 61.16                            |
|                | 3                    | 6.335                   | 50.17                            | 8.4098                  | 49.97                            | 10.686                  | 50.71                            | 12.993                  | 51.31                            | 14.547                  | 51.65                            |
|                | 4                    | 5.460                   | 43.81                            | 7.4456                  | 44.73                            | 9.2166                  | 44.32                            | 11.213                  | 44.89                            | 12.554                  | 45.21                            |
| 0              | 5                    | 5.160                   | 40.54                            | 6.6291                  | 40.13                            | 8.2057                  | 39.77                            | 9.9844                  | 40.29                            | 11.182                  | 40.59                            |
|                | 6                    | 4.994                   | 44.36                            | 9.2827                  | 44.18                            | 11.796                  | 44.84                            | 14.342                  | 45.37                            | 16.055                  | 45.67                            |
|                | 7                    | 5.608                   | 36.54                            | 7.7119                  | 37.24                            | 9.5665                  | 36.97                            | 11.638                  | 37.45                            | 13.032                  | 37.73                            |
| Fixed pitch propeller | 8 | 5.201                   | 33.03                            | 6.6446                  | 32.33                            | 8.2251                  | 32.03                            | 10.009                  | 32.46                            | 11.211                  | 32.71                            |
|                | 4                    | 4.713                   | 32.02                            | 5.9040                  | 28.85                            | 7.5097                  | 29.34                            | 8.8958                  | 28.97                            | 9.9650                  | 29.20                            |
|                | 5                    | 6.759                   | 40.24                            | 8.9697                  | 40.05                            | 11.407                  | 40.74                            | 13.878                  | 41.29                            | 15.542                  | 41.61                            |
|                | 6                    | 5.435                   | 32.43                            | 7.4184                  | 33.19                            | 9.1796                  | 32.86                            | 11.172                  | 33.32                            | 12.513                  | 33.59                            |
|                | 7                    | 5.300                   | 31.74                            | 6.3530                  | 28.45                            | 7.8635                  | 28.17                            | 9.5723                  | 28.58                            | 10.723                  | 28.81                            |
| 4              | 8                    | 5.112                   | 30.62                            | 5.6337                  | 25.24                            | 7.1695                  | 25.70                            | 8.4895                  | 25.36                            | 9.5121                  | 25.57                            |

The calculation results in Table 5 showed that as the ship's resistance increased, the propeller efficiency and ship speed would gradually decrease. When the APP was adopted, because of the pitch angle was adjustable, it could get higher working efficiency than the fixed pitch propeller. In this example, when the ship's resistance increased by 2 times, -4° of the APP is adjusted, its efficiency could be increased by 15.49% compared with fixed pitch propeller, and the efficiency could be increased by 13.92% when the resistance was increased to 3 times. It could be seen that when the ship resistance increased, the efficiency of the propeller could be improved by reducing the pitch angle of the APP. In addition, the ship resistance increased would cause the ship's speed to drop, but by adjusting the pitch angle of the APP, a higher speed than the fixed propeller could be obtained. In this example, when the ship's resistance was increased by twice, the APP is adjusted to -4°, and the speed could be increased by 9.71%. When the resistance was increased to 3 times, the speed could be increased by 10.41%, which indicated that when the resistance of the ship increased, the speed could be increased by reducing the pitch angle of the APP.

5.3. Engine power attenuation conditions

Table 6 showed the speed and propeller efficiency that the ship could achieve under the conditions of -4 degrees, fixed pitch propeller, 4 degrees blade pitch, and 5%-20% attenuation of the engine power with different engine speeds.
Table 6. Ship speed and propeller efficiency under different power attenuation, different speeds, and different blade pitch angles

| Pitch angle (°) | Engine power attenuation percentage (%) | 1350rpm | 1800rpm | 2250rpm | 2700rpm | 3000rpm |
|---------------|----------------------------------------|---------|---------|---------|---------|---------|
|               | Ship speed (Kn) | Propeller efficiency (%) | Ship speed (Kn) | Propeller efficiency (%) | Ship speed (Kn) | Propeller efficiency (%) | Ship speed (Kn) | Propeller efficiency (%) |
| Fixed pitch propeller | 4° | 5 | 10.126 | 70.62 | 13.717 | 0 | 70.93 | 17.348 | 4 | 71.09 | 21.010 | 9 | 71.18 | 23.466 | 2 | 71.21 |
|               | 10 | 9.9086 | 70.08 | 13.431 | 2 | 70.50 | 16.996 | 6 | 70.77 | 20.592 | 9 | 70.94 | 23.005 | 4 | 71.02 |
|               | 15 | 9.6773 | 69.36 | 13.126 | 0 | 69.89 | 16.617 | 2 | 70.25 | 20.141 | 9 | 70.50 | 22.507 | 8 | 70.63 |
|               | 20 | 9.4304 | 68.44 | 12.797 | 4 | 69.08 | 16.209 | 2 | 69.52 | 19.655 | 9 | 69.84 | 21.969 | 5 | 70.02 |
|               | 5 | 9.3682 | 56.55 | 12.733 | 3 | 57.34 | 16.148 | 9 | 57.93 | 19.605 | 4 | 58.39 | 21.928 | 5 | 58.65 |
|               | 10 | 9.1310 | 55.49 | 12.414 | 5 | 56.30 | 15.748 | 4 | 56.91 | 19.123 | 3 | 57.39 | 21.390 | 0 | 57.66 |
|               | 15 | 8.8841 | 54.33 | 12.082 | 0 | 55.17 | 15.330 | 5 | 55.80 | 18.619 | 8 | 56.30 | 20.830 | 1 | 56.58 |
|               | 20 | 8.6275 | 53.09 | 11.736 | 0 | 53.94 | 14.895 | 0 | 54.59 | 18.093 | 0 | 55.10 | 20.243 | 0 | 55.39 |
|               | 5 | 9.2574 | 54.67 | 12.614 | 7 | 55.82 | 16.030 | 3 | 56.71 | 19.490 | 7 | 57.42 | 21.821 | 5 | 57.84 |
|               | 10 | 8.9969 | 53.20 | 12.260 | 9 | 54.33 | 15.581 | 3 | 55.19 | 18.948 | 3 | 55.90 | 21.213 | 1 | 56.30 |
|               | 15 | 8.7286 | 51.67 | 11.895 | 4 | 52.77 | 15.120 | 5 | 53.63 | 18.388 | 4 | 54.32 | 20.587 | 1 | 54.71 |
|               | 20 | 8.4526 | 50.08 | 11.520 | 2 | 51.16 | 14.644 | 3 | 52.00 | 17.811 | 0 | 52.68 | 19.941 | 7 | 53.06 |

The calculation results in Table 6 showed that as the engine power decayed, the propeller efficiency and ship speed would gradually decrease. When using the APP, due to the adjustable pitch of the blades, higher working efficiency could be obtained than fixed pitch propellers. In this example, the APP had an optimal efficiency range, and the pitch angle of this range was −5°~+5°, the efficiency was 56.97%~71.22%, and the efficiency of the APP dropped significantly beyond this interval. In addition, the engine power attenuation would cause the ship’s speed to drop, but by adjusting the pitch angle of the APP, a higher speed than the fixed pitch propeller could be obtained. For example, when the engine power was attenuated by 10%, adjusted the APP to −4°, the speed could be increased by 7.02%, and the speed could be increased by 7.86% when the power of the engine was attenuated by 20% also, which indicated that the speed could be increased by reducing the pitch angle of the APP when the power of the engine was attenuated.

6. Conclusion
The calculation and analysis of the APP and fixed pitch propeller for small ships were carried out through the method of coupling meso-scale and macro-scale models. The results show that the APP could compensate for the efficiency deviation brought by fixed pitch propeller design in ship applications. Compared with the fixed pitch propeller, and when the resistance of the ship increased or the power of the ship’s engine decays, the APP is used to adjust the pitch angle to small, which could effectively improve the ship’s speed and propeller efficiency. Therefore, it is effective to apply the APP to small ships. The APP has better adaptability than fixed pitch propeller.

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References
[1] Xiao-ming Sun, Hong-bo Zhang, Gui-bin Liu. Study on Propeller Cutting Edge Process[J]. China Ship Repair. 2014, 27(1): 39-44.
[2] Yi Hou. Theoretical Design and performance Prediction Method Study of marine propeller[D]. Wu han, Huazhong University of Science Technology, 2014.
[3] Yu-min Su, Sheng Huang. Ship propeller theory[M]. Harbin. Harbin Engineering University Press, 2013.
[4] Zhao-li Guo, Chu-guang Zheng, Qing Li, Neng-Chao Wang. Lattice Boltzmann method for fluid dynamics[M]. Hubei Science and Technology Press, 2002.
[5] MCNAMARA G R, ZANETTI G. Use of the Boltzmann Equation to Simulate Lattice Gas Automata[J]. Physical Review Letters, 1988, 61(20): 2332.
[6] HIGUERA F J, JIMÉNEZ J. Boltzmann Approach to Lattice Gas Simulations[J]. Europhysics Letters, 1989, 9(7): 663.
[7] A.A. Mohamad. Lattice Boltzmann Method Fundamentals and Engineering Applications with Computer Codes[M]. Publishing House of Electronics Industry. 2015.06.
[8] DING Yiwen, WU Jiaming, MA Zhiqian. Analysis of Thrust Characteristics of Ducted Propeller based on lattice boltzmann method[J]. Ship engineering. 2018, 40(s1): 104-109.
[9] Jin-ming Lu. Principle and Design of Ship Power Plant[M]. National Defense Industry Press, 2014.
[10] Liang Zan tong. The Optimal Matching of the Engine-Propeller for Controllable Pitch Propeller Ship[D]. Da Lian. Dalian Maritime university, 2009.
[11] MA Xu, Yang Chen, Zhang Yu-Ying. Phenomena based modeling methodology research of complex system[J]. Journal of Chongqing University, 2008, 31 (1): 61-66.