Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 3, No. 1, 2022

Modeling and Simulation of Marine Electric Propulsion System

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Abstract: The propeller is an important load of the ship. The propeller can overcome the resistance of the ship through the control of the propulsion motor to control the speed and direction of the ship. The relationship between the interaction between propeller and ship and the resistance suffered by ship during navigation is very complex, and many factors will affect the movement of propeller, so it is very important to select a suitable mathematical model of propeller. In this paper, the modeling of propeller is simplified properly, and the calculation speed of the model is improved on the basis of ensuring the simulation accuracy.

Keywords: Ship electric propulsion, Modeling and simulation, Vector control, Propeller characteristics.

1. Introduction

The traditional propulsion mode is to use diesel engines to drive propellers to propel ships forward [1]. However, this conventional propulsion system has limitations in exhaust emissions, overall efficiency, flexibility of ship handling and many other aspects. The noise and pollution are relatively large. Therefore, it is the trend of the development of the current propulsion mode to find new energy sources and power devices, while electric propulsion has become the development direction of the ship propulsion mode with its many advantages. With the development of power electronics technology, some shortcomings of ship electric propulsion have changed fundamentally, and the advantages and advantages have been further developed [2]. The modeling and simulation of marine electric propulsion system can be used for reference in the development and application of electric propulsion technology. In this paper, the composition, characteristics and working principle of the electric propulsion system are analyzed. Matlab software is used to simulate and analyze the mathematical model of the system, focusing on modeling and simulation of current hysteresis vector control system, and analyzing the static and dynamic performance of the model by changing the load and speed. In order to simulate the propeller load characteristics realistically, this paper takes the propeller as a whole, builds the ship engine propeller mathematical model based on the Chebyshev polynomial fitting of the four quadrant propeller load characteristics map with an analytical method[3], and analyzes the speed and torque characteristics of the ship under typical working conditions such as forward start and reverse after start, The simulation results have a very good guiding significance to reveal the inherent laws of the system and the scientific and reasonable operation of the ship.

2. System Simulation

2.1. Working Characteristic Curve of Propeller

During the actual navigation of the ship, the propeller and water flow interact, and the propulsion motor drives the propeller to rotate to generate thrust, which pushes the ship forward[4]. The current acts on the propeller and produces resistance to it. Its torque is expressed in M, and the unit is N.m. The thrust generated by the propeller to overcome the resistance of water to make the ship move forward is expressed in P, and the unit is N. P and M are calculated as follows:

$$\begin{cases} P = K_P \rho n^2 D^4 \\ M = K_M \rho n^2 D^5 \end{cases} \tag{1}$$

In order to simplify the calculation, the ratio of propeller progress and diameter is used to express the speed ratio, which is expressed by J, so the expression is as follows:

$$J = \frac{h_P}{D} = \frac{v_P}{nD} \tag{2}$$

By introducing J into the simplification, it can be obtained that K_P and K_M are all functions about J.The function curve of K_P and K_M about J is called the open water characteristic curve of the propeller. The curve does not consider the influence of water flow on the ship, and the propeller is in a uniform water flow. The characteristic curve is shown in the following figure 1[5]. It can be seen thatK_P ,K_M and J are inversely proportional and decrease with the increase of J.

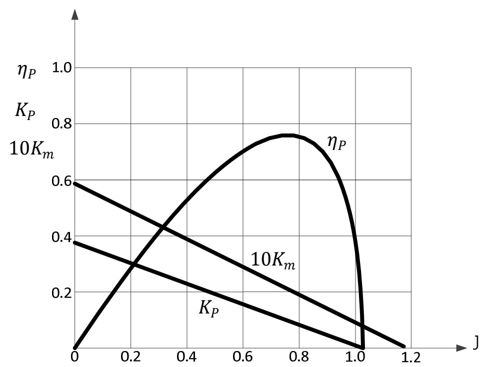
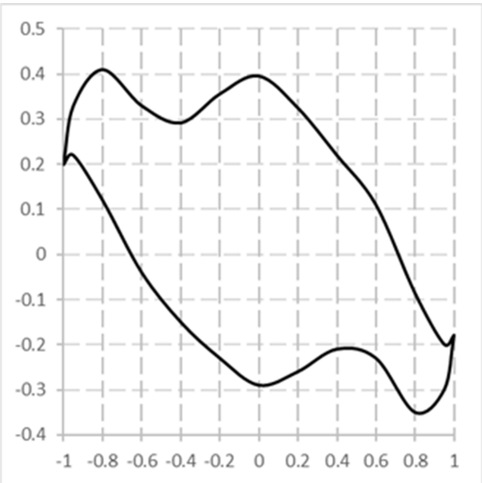


Figure 1. Working characteristic curve of propeller

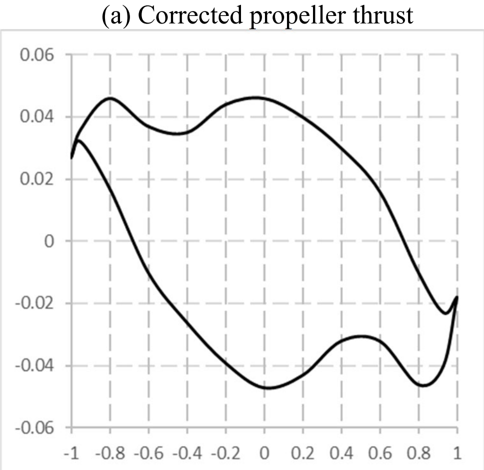
The above characteristic curve is located in the first quadrant and can only represent the forward rotation of the propeller and the forward motion of the ship. When simulating and analyzing the propeller, the influence of water flow on the ship must be taken into account[6]. The transformation of v_P and n will be very violent and will not keep synchronized, resulting in different thrust P and torque M. At this time, the change of J will exceed the range described in the above figure. For example, when the ship is in emergency braking, the propeller has stopped rotating and the speed is zero[7], but due to the huge inertial effect, the ship will continue to move forward. Based on this, the simulation results are infinite. The working characteristic curve obtained from the open water experiment in the above figure is no longer applicable, and K_P and K_M need to be modified as necessary. The modified equation is as follows:

$$\begin{cases} K_p' = \frac{P}{\rho D^2(v_p^2+n^2D^2)} = \frac{K_P}{1+J^2} = K_P(1-J'^2) \\ K_M' = \frac{M}{\rho D^3(v_p^2+n^2D^2)} = \frac{K_M}{1+J^2} = K_M(1-J'^2) \end{cases} \quad (3)$$

The modified propeller thrust and torque characteristic curve is shown in Figure 2. The relationship between the modified advance ratio J' and J is as follows, mapping from $J \in (-\infty, +\infty)$ to $J' \in (-1, +1)$.



(a) Corrected propeller thrust



(b) Corrected propeller torque

Figure 2. Corrected characteristic curve

$$J' = \begin{cases} 1 & n = 0, v_P > 0 \\ \frac{J}{\sqrt{1+J^2}} & n > 0 \\ -\frac{J}{\sqrt{1+J^2}} & n < 0 \\ -1 & n = 0, v_P < 0 \end{cases} \quad (4)$$

It can be seen from Equation 4 that the improved K_p', K_M' are functions of J', and the modified expressions of thrust and resistance can be obtained as follows:

$$\begin{cases} P = K_p'\rho D^2(v_p^2 + n^2D^2) \\ M = K_M'\rho D^3(v_p^2 + n^2D^2) \end{cases} \quad (5)$$

2.2. Interaction Between Propeller and Hull

Compared with the open water experiment, during the actual navigation of the ship, the propeller and the ship interact. Due to the navigation of the ship, the water velocity around the propeller is very different from that during the open water experiment, and the propeller will produce additional resistance to the ship's navigation, which is mainly reflected in the following two aspects[8]:

(1) The relationship between the ship's actual speed v_S and the propeller's actual speed v_P during the ship's voyage is:

$$v_P = v_s(1-\omega) \quad (6)$$

(2) The influence of propeller rotation on the ship: In the actual navigation of the ship, the propeller rotation will have a damping effect on the ship. Assuming that the total thrust of the propeller is F, where the resistance of the ship itself is F_1, and the additional resistance generated by the propeller is F_2, the following formula can be obtained:

$$F = F_1 + F_2 \quad (7)$$

Many factors will affect the movement of a ship in the course of driving. The resistance mainly comes from wind, water, the ship's own structure, speed, etc., but the current has the greatest impact on it and is the main source of the resistance suffered by the ship. The calculation of resistance mainly includes atlas calculation method, regression formula method, estimation method, etc. In the simulation analysis, it is generally assumed that the ship's resistance is proportional to the square of the sailing speed, as shown in the following formula:

$$R = Kv_s^k \quad (8)$$

2.3. Solution of Propeller Characteristic Curve

Although the modified characteristic curve can reflect the movement of propeller, it is not convenient to directly simulate and analyze it. In actual simulation analysis, interpolation method and graph fitting method are often used to solve the function of the curve. The interpolation method mainly uses the coordinates of finite points on the function interval to find out the functional relationship represented by these specific points, and then uses this function to calculate the data of other points on this interval. By dividing the curve space, It is solved step by step to reflect the overall characteristics. The interpolation method is complex and requires a large amount of calculation, so in engineering practice, the fitting method is often used to solve the functional relationship of complex curves. The fitting method obtains the approximate expression with the original function by solving the coordinate data of finite points and smoothing them. In solving the torque coefficient and inference coefficient of the propeller, the fitting method can more accurately reflect its characteristic curve equation. Direct fitting with ordinary polynomials will produce large errors. Although the error can be reduced by increasing the order, it will lead to increased calculation and affect the fitting accuracy. The least square method can effectively solve the shortage of ordinary polynomial fitting. It only needs to collect the coordinates of key points that can reflect the data curve. The fitting error is small, which can greatly simplify the calculation and meet the accuracy requirements.

Chebyshev[9] polynomials are used to approximately describe functions with continuous derivatives on (-1,1). When fitting, the mean square deviation is the minimum. The expression is as follows:

$$f_{(x)} \approx \frac{1}{2}a_0T_0(x) + a_1T_1(x) + a_2T_2(x) + \cdots + a_nT_n(x) \quad (9)$$

$$T_0(x) = 1$$

$$T_1(x) = \mathrm{x}$$

$$T_2(x) = 2x^2 - 1$$

$$T_3(x) = 4x^3 - 3\mathrm{x}$$

$T_\mathrm{k}(x)$ is orthogonal to each other. By expanding it, we can get a general polynomial. Assuming its coefficient is b_k, through the above analysis, we can get the expressions of propeller thrust coefficient and torque coefficient as follows:

$$K_P'(J') = \frac{1}{2}a_{0p}T_0(J') + a_{1p}T_1(J') + a_{2p}T_2(J') + \cdots + a_{np}T_n(J') \quad (10)$$

$$K_M'(J') = \frac{1}{2}a_{0M}T_0(J') + a_{1M}T_1(J') + a_{2M}T_2(J') + \cdots + a_{nM}T_n(J')$$

2.4. Mathematical Model of Marine Propeller

Through the above analysis, the torque M and thrust P of the propeller during operation can be obtained as follows:

$$P = K_p'\rho D^2\left(v_p^2 + n^2D^2\right) = K_p'\rho D^3 v_p^2/J'^2 \quad (11)$$

$$M = K_M'\rho D^3\left(v_p^2 + n^2D^2\right) = K_p'\rho D^2 v_p^2/J'^2$$

The motion model of the ship's propeller is obtained as shown in the figure 3.

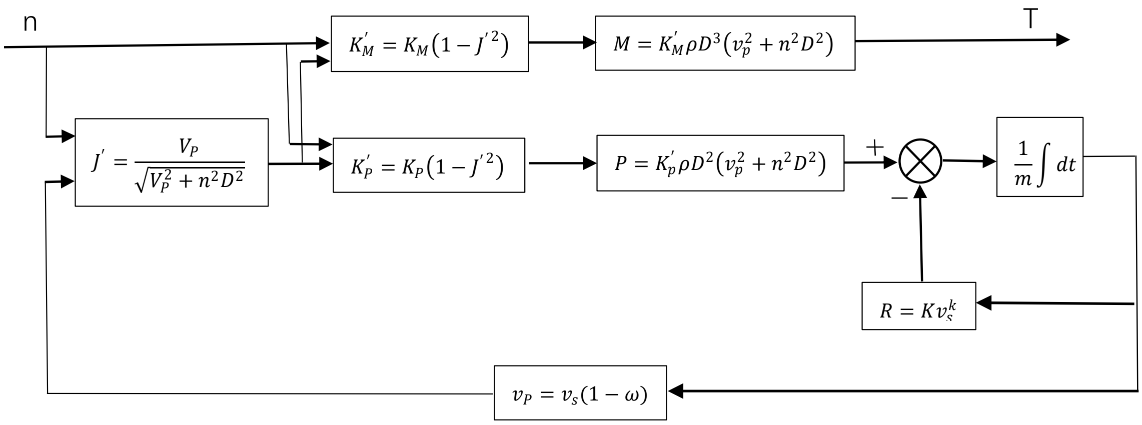


Figure 3. Propeller motion model

3. Simulation Analysis of Typical Working Conditions

In order to verify the correctness of the simulation system, the propeller model is simulated in MATLAB/Simulink. Its input is the rotation speed of the propeller, and its output is speed, propeller thrust F and torque M. The typical working conditions are simulated, such as the direct starting of the ship ahead, step starting, emergency stop, step stopping, etc. The characteristics of propeller speed, ship speed, torque, etc. are obtained, and the dynamic and static characteristics of the model are analyzed.

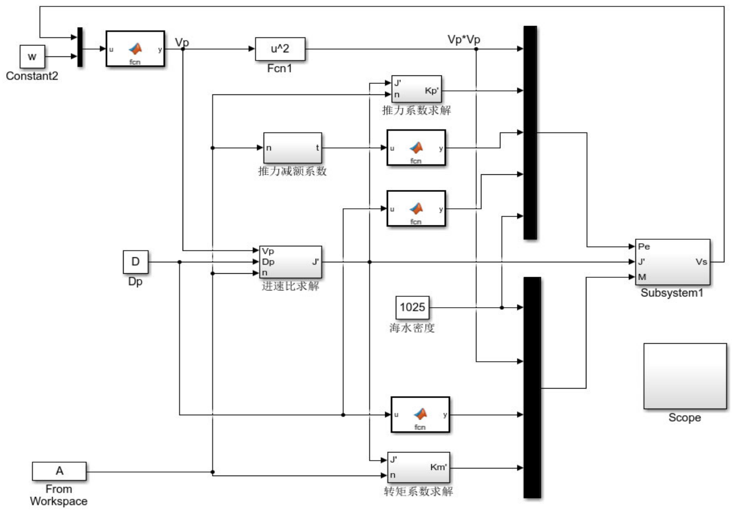
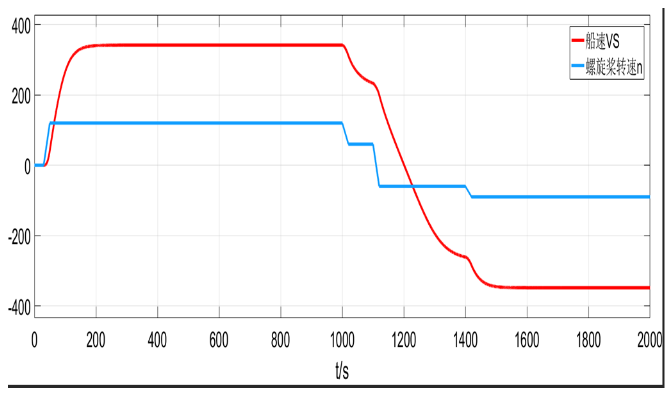


Figure 4. The ship engine propeller simulation model built

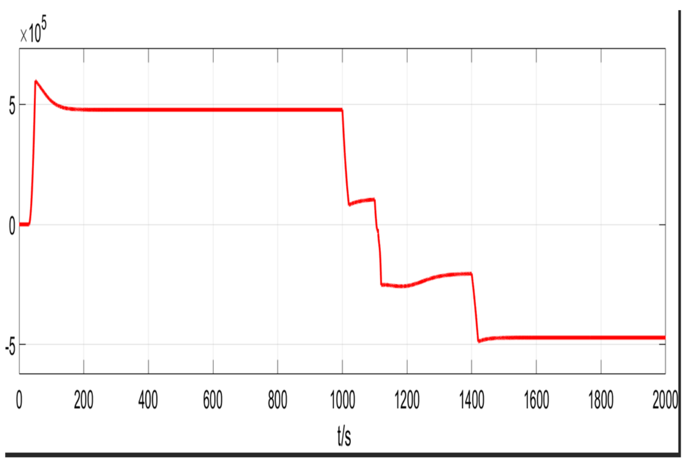
In the simulation analysis, the steady state characteristics only reflect the steady state tracking of the built model, which cannot really reflect the changes of the load on the propeller shaft, which is not conducive to the mobility design and analysis of the system. However, the dynamic simulation can solve this problem. The following simulation analysis is carried out for several typical working conditions to verify the correctness of the built model.

(1) Working conditions of ship direct starting and staged reversing

In this paper, the motor is set to start after 30 seconds of warm-up. After 20 seconds, the speed reaches 120r/min and is maintained. After 1000 seconds, the secondary deceleration is carried out. After 20 seconds, the speed of the propulsion motor is reduced to 60r/min and maintained at this low speed. After 1100 seconds, the propulsion motor starts to transition from forward rotation to reverse rotation. After 20 seconds, the speed reaches - 60r/min and operates stably at this reverse speed. After 1400 seconds, the propulsion motor accelerates in reverse direction. After 20 seconds, it reverses at full speed of - 90r/min. The changes of propeller speed, ship speed and propeller torque are shown in Figure 5.



(a) Propeller speed and ship speed



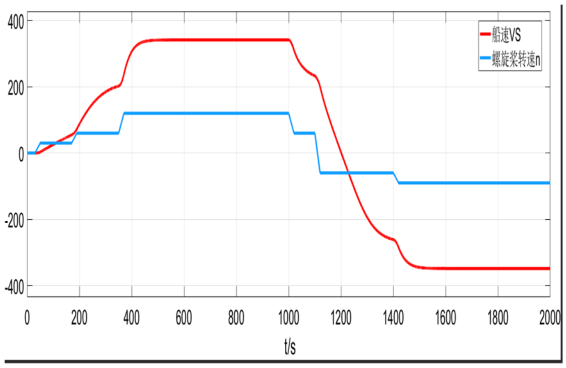
(b) Propeller torque

Figure 5. Working conditions of ship direct starting and staged reversing

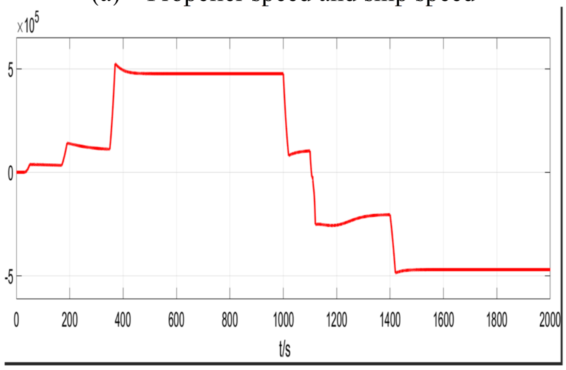
It can be seen from Figure 5 that the ship speed and propeller speed are both 0 when the ship is not ordered to sail. During 30-50s, the torque increases to the maximum value of 594.8kN m. After that, the propeller stabilized at 120r/min, the ship began to accelerate, and became stable after 275s. The speed reached the maximum, about 341m/min, and the propeller torque stabilized at 476.5kNm after reaching the maximum. After receiving the reverse signal for 1000s, the ship starts to decelerate. After secondary deceleration, the ship sails at a slow speed. At 1110s, the propeller speed changes from positive to negative. Due to the inertial effect of the ship, the ship's speed does not decrease to negative until about 1200s, and the ship starts to reverse; The propeller torque becomes negative at 1104s. With the reverse acceleration of the propeller, the ship's speed gradually increases. At about 1600s, the maximum reverse speed is stabilized at -348.5r/min, and the propeller torque is kept at 470.7kN.m.

(2) Grading startup and reversing of ships

In the above direct forward starting, the propeller will be overloaded seriously in the 20s acceleration process, and the equipment loss will be great. Therefore, the staged starting is generally adopted to make the speed gradually reach the rated speed. As shown in Figure 6, start slowly during 30-50s, and operate stably when the speed reaches 30r/min; conduct two-stage acceleration in 170-190s, and operate stably at 60r/min; conduct three-stage acceleration in 3350-370s, so as to stabilize the speed at the maximum speed of 90r/min, and operate stably when reversing in stages.



(a) Propeller speed and ship speed

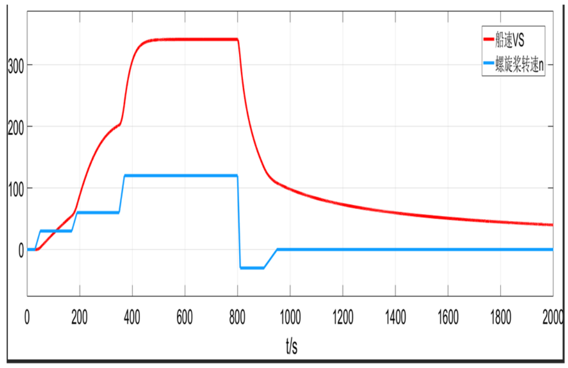


(b) Propeller torque

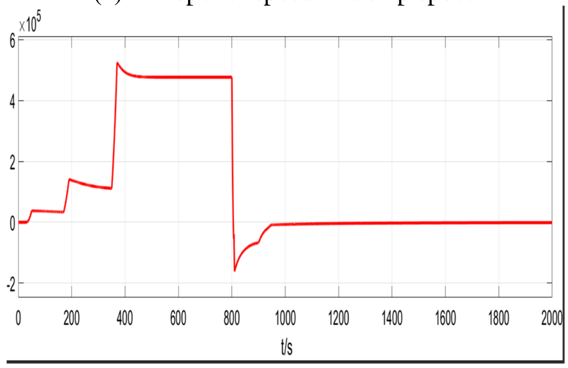
Figure 6. Grading startup and reversing of ships

(3) Emergency shutdown condition after starting of ship ahead

Emergency shutdown is generally a measure taken when a ship encounters an emergency during forward navigation. It mainly simulates the propulsion motor. In this paper, after the ship's staged starting speed reaches 90r/min, it suddenly drops to the reverse size of 30r/min at 800s, and finally stops. The variation of ship speed, propeller torque and speed is shown in Figure 7.



(a) Propeller speed and ship speed



(b) Propeller torque

Figure 7. Emergency shutdown condition after starting of ship ahead

4. Conclusion

This paper analyzes the working characteristics of propeller load, and analyzes the ship and propeller as a whole. In the simulation analysis, the interaction between ship and propeller and the resistance of ship engine propeller are considered. Through the correction of K_P and K_M, the working characteristics of the propeller in four quadrants are obtained, which is convenient for simulation analysis. The 8-order Chebyshev polynomial is used to fit the curve, and the model structure of the marine engine propeller is obtained. The marine engine propeller model is built in MATLAB/Simulink, and its thrust and torque performance are analyzed. Simulation analysis is made for its typical working conditions, and the dynamic and static characteristics of the model are studied.

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