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Analysis and Control for Propulsion System of Wind-Assisted Ship

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Abstract: This study aims to analyze and control the propulsion system of wind-assisted ship. Three control methods are given to control propulsion system with no change in cruise speed. The methods are as follows, adjusting pitch, adjusting revolution speed, adjusting the speed and pitch coordinately. By analysis and comparison, the third method can obtain the highest propulsion efficiency as well as make navigational speed following predefined speed under different conditions of wind. Finally, simulation results are given to verify the validity and effectiveness of the methods.

Key words: Speed control system, coordinated control, propulsion efficiency, wind-assisted ship

INTRODUCTION

Wind energy being ample, pollution-free and renewable, its applications on large ocean ship can significantly reduce the consumption of traditional fossil fuel energy and the carbon emission, hence wind energy has a broad application prospect.

The dynamic of propulsion system is complex and nonlinear. It is made up of several components such as engine and thrusters. As a prime mover, the diesel engine drives the propeller's rotation. And the propeller which is currently the most widely used as marine thrusters (Rolland and Clark, 2010), provides propulsion thrust for ship. And the controllable pitch propeller, being used to make system get higher efficiency by changing the screw pitch, plays more and more important role in the area of marine engineering.

Currently, some research on cooperatively controlling the main engine and propeller is proposed. Neural network method is used to control ship propulsion system (Shi *et al*., 2009). The characteristics of propulsion system are analyzed (Hu *et al*., 2010). Also the factors affecting main engine and propeller are presented. Fuzzy PID controller is designed to control propulsion system which has four propellers and four engines (Wang *et al*., 2011). A kind of calculating method is used to derive parameters of main engine, such as power, rotational speed and efficiency (Tamura *et al*., 1990).

The propulsion system of wind sail assisted ship mainly consists of main engine, controllable pitch propeller and sail. Coordinating the engine and sail decides whether the propulsion system work in high efficiency or not. As the auxiliary thrust provided by sail is changing constantly with wind conditions, the working conditions of propeller should change constantly. In order to prevent the propeller working in low efficiency, the pitch or the rotational speed of diesel engine can be adjusted. Moreover, the main engine and propeller must be controlled coordinately to make them work in high efficiency and low fuel consumption area.

PROPULSION SYSTEM OF WIND-ASSISTED SHIP

Propulsion system of wind-assisted ship is as shown in Fig. 1 (Izadi-Zamanabadi and Blanke, 1999).

Ship propulsion system includes the following components:

Host governor: Control the throttle opening of main engine which can use PI controller.

Main engine: Output torque, the drive shaft rotates at a constant speed.

Propeller: Provide thrust for sailing and torque.

Ship driven by sailing auxiliary propulsion, the propeller thrust, ship resistance and other external forces:

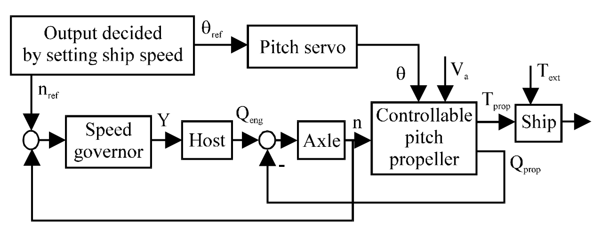

Fig. 1: Ship propulsion system

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Coordinated controller: Determine the main engine speed, propeller pitch and sail angle.

The dynamic equations of high-power, low speed, two stroke diesel engine are as follows:

$$n(s) = \frac{1}{I_m s}[Q_m(s) - Q(s)]$$

$$\frac{Q_m}{Y}(s) = \frac{K_y}{1 + T_y s} e^{-\tau s}$$

where, n denotes the shaft speed (rad sec^{-1}), I_m denotes the moment of inertia (kg×m^2), Q is propeller torque (N_m), Q_m is the output torque of main engine.

The equations of the sail thrust T_{ext} is as follow (Chen *et al*., 2010):

$$T_{ext} = C_T \frac{1}{2} \rho_{air} V^2 A_{sail}$$

where, C_T denotes thrust coefficient, when apparent wind direction angle changes within 40-180°, $C_T \in [0.2 \sim 2.2]$. The ρ_{air} is the air density under a standard atmospheric pressure and ρ_{air} = 1.1691 kg m^{-3}. The V denotes apparent wind speed, when wind force is within 1-8 scale, $V \in [1, 18]$ m sec^{-1}. The sail area, A_{sail} = 2160 m^2. In order to keep the schedule speed and cycle, the sailing auxiliary propulsion is restrained less than 722.134 KN by controlling the angle of sail. The sail thrust $T_{ext} \in [0.25, 720]$ KN could be got by calculations.

SPEED CONTROL METHODS OF SHIP PROPULSION SYSTEM

Most merchant ships are set up with low-speed diesel engines, the diesel engines drive propeller to push ship advance. To design a safe and reliable control system is very important. Considering structure, propulsion control system can be divided into two sections, bottom layer and top layer. Bottom layer is composed by the main engine speed controller, the propeller pitch control and the ship itself. Top layer provides the coordinated control strategy for bottom layer and control commands for the propulsion system. The details of system components are shown in Fig. 2.

The coordinated controller is used to define n_{ref} and θ_{ref} to make ship cruise in predefined speed U_{ref}. The ship speed control methods of wind-assisted ship are analyzed as follows.

Method 1: Fixing shaft speed n, changing the pitch θ.

The principle diagram of method 1 shown in Fig. 3. Once the ship speed U is given, the governor will regulate

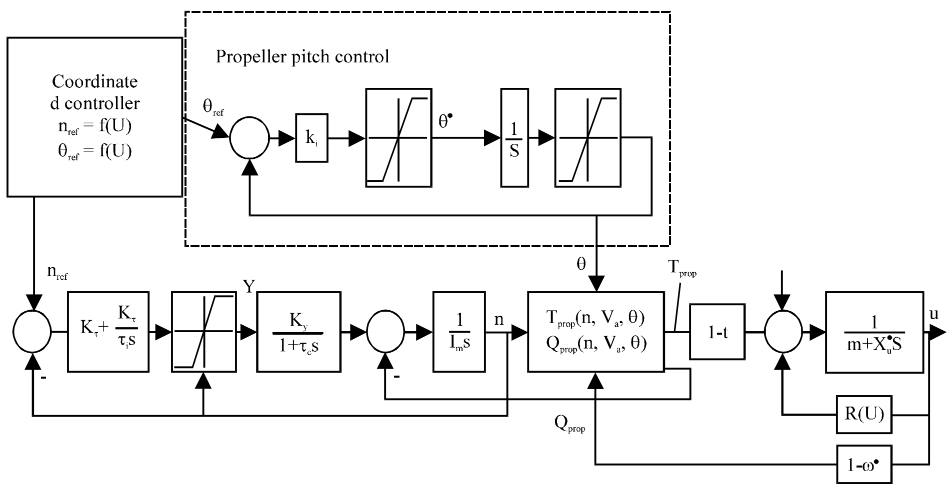

Fig. 2: System components

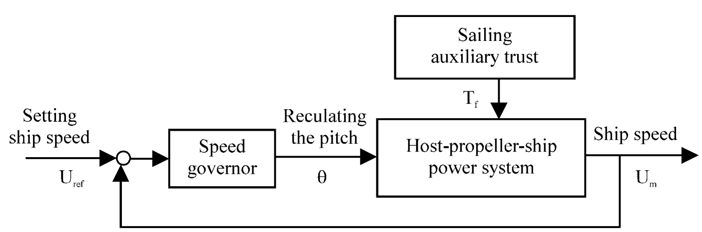

Fig. 3: Principle diagram of method 1

the pitch θ correspondingly based on the error between predefined and real ship speed under certain sailing auxiliary thrust T_f.

The input variables of the governor, ship speed U_{ref} and rotational speed n.

The output variable, the actual speed of ship U_m.

The control variable, the pitch θ.

Disturbance, auxiliary thrust T_f provided by wind sail.

Controller, PI controller, K_p and K_I.

Method 2: Fixing pitch, changing the rotational speed.

Method 2 is similar to method 1 as shown in Fig. 4. While the input and control variables are different.

In method 2, the input variables, ship speed U_{ref} and pitch θ. The control variable is the rotational speed n.

Method 3: Changing the speed and pitch coordinately, aiming at the optimal efficiency.

In Fig. 5, the best match between the pitch θ_i and the speed of main engine n_i which is calculated by the optimal efficiency controller, can make the propulsion system maintain high efficiency. The feedback variables of the optimal efficiency controller are actual rotational speed n of main engine, actual pitch θ and actual ship speed U_m. Then it is easy to find that the third method has the least fuel consumption at a certain ship speed.

The objective function is:

$$\max_{n,\theta}\{\eta_B\} = \max_{n,\theta}\left\{\frac{T(n,\theta)U_{ref}}{Q(n,\theta)n}\right\} = \max_{n,\theta}\left\{\frac{D\alpha_1 n^2\theta U_{ref} + (1-\omega)\alpha_2 U_{ref}^2}{D^2\beta_1 n^2\theta + D\beta_2(1-\omega)n\theta U_{ref}}\right\}$$

Also the following constraints should be hold:

$$T(1\text{-}t)+T_f = R(U_{ref})$$

$$n_{min} \le n \le n_{max}$$

$$0 < \theta \le \theta_{max}$$

$$P_e = \frac{TV_a}{\eta_p} < P_{max}$$

Here, n_{min} = 0.7 r sec^{-1}, n_{max} = 1.925 r sec^{-1}, θ_{min} = 0, θ_{max} = 1.

The specific steps of method 3 are as follows:

- Setting the speed of ship U_{ref} and finding out the corresponding resistance R in the ship-resistance curve. According to the auxiliary thrust T_f provided by sail, it is easy to calculate the propeller thrust R and forward speed V_a:

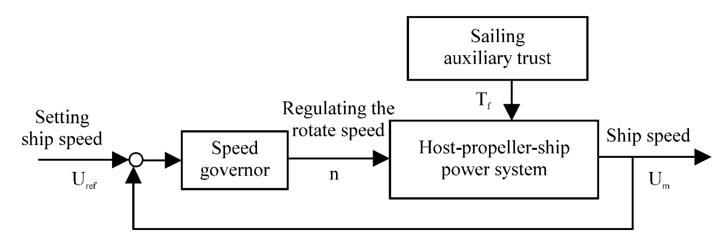

Fig. 4: Principle diagram of method 2

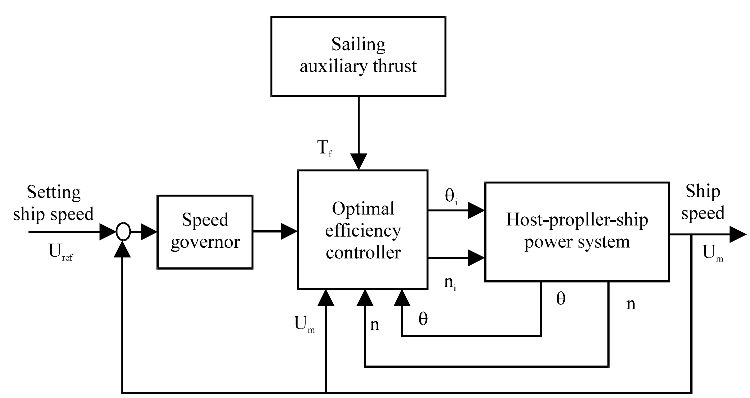

Fig. 5: Principle diagram of method 3

$$T = \frac{R - T_f}{1 - t}$$

$$V_a = (1\text{-}\omega)U_{ref}$$

- Selecting several rotational speed n, the corresponding advance ratio of propeller J can be obtained through the equation:

$$J = \frac{V_a}{nD}$$

- Calculating the corresponding thrust coefficient K_T with each rotational speed by equation:

$$K_T = \frac{T}{\rho n^2 D^4}$$

- According to the J and K_T, the pitch θ and efficiency η_B can be obtained
- Computing the output power P_e and torque Q of main engine. The P_e must be less than the maximum power provided by main engine. That is:

$$P_e = \frac{TU}{\eta_B} < P_{max}$$

According to the above steps, the rotational speed n and the pitch θ of the best match can be got which can keep the ship speed U_{ref} under the effect of the auxiliary thrust T_f.

SIMULATION RESULTS AND COMPARATIVE ANALYSIS

Here, is a case study to verify the methods in Panamax Bulk Carrier wind-assisted ship. The simulation results of these three methods are as follows.

Method 1: Fixing speed, changing the pitch.

Let ship speed be U_{ref} = 10 m sec^{-1}, rotational speed n = 1.75 r sec^{-1} and the parameters of PI controller are K_p = 0.02, K_I = 0.005.

Figure 6a-d show response curve of each variable in the control system. The predefined ship speed U_{ref} is given as U_{ref} = 10 m sec^{-1} as time goes by, shown in Fig. 6a. The auxiliary thrusts are shown under two kinds of wind conditions. The thrust has a jump from 360-720 KN on the time of 1000 sec. The curves for the thrusts are shown in Fig. 6b. The response curve of pitch and ship speed are shown in Fig. 6c-d, respectively.

Remark 1: According to the simulation results, it is easy to find that the controller can automatically adjust pitch to keep ship speed in different wind conditions. This method is simple to control and the real-time performance is great. But the propulsive efficiency is not considered.

Method 2: Fixing pitch, changing the rotational speed of main engine. Let ship speed be U_{ref} = 10 m sec^{-1}, fixed pitch be 0.652. Also the controller is designed as PI controller with parameters K_p = 1.8, K_I = 0.02. Figure 7a-d

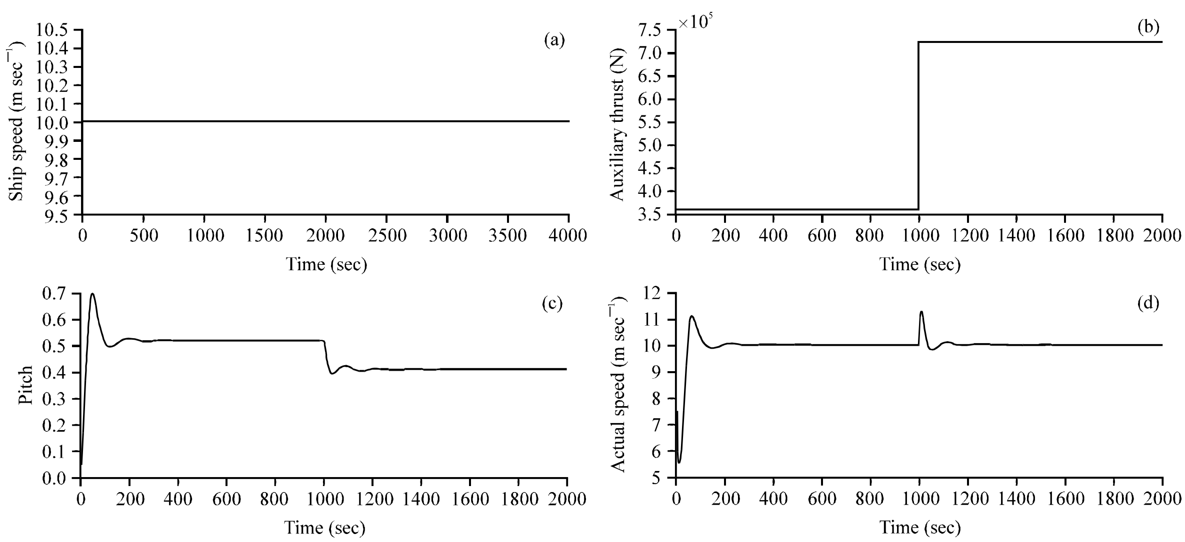

Fig. 6(a-d): Curve for (a) Predefined ship speed U_{ref}, (b) Auxiliary thrust in two kinds of wind conditions, (c) Response curve of pitch and (d) Real ship speed

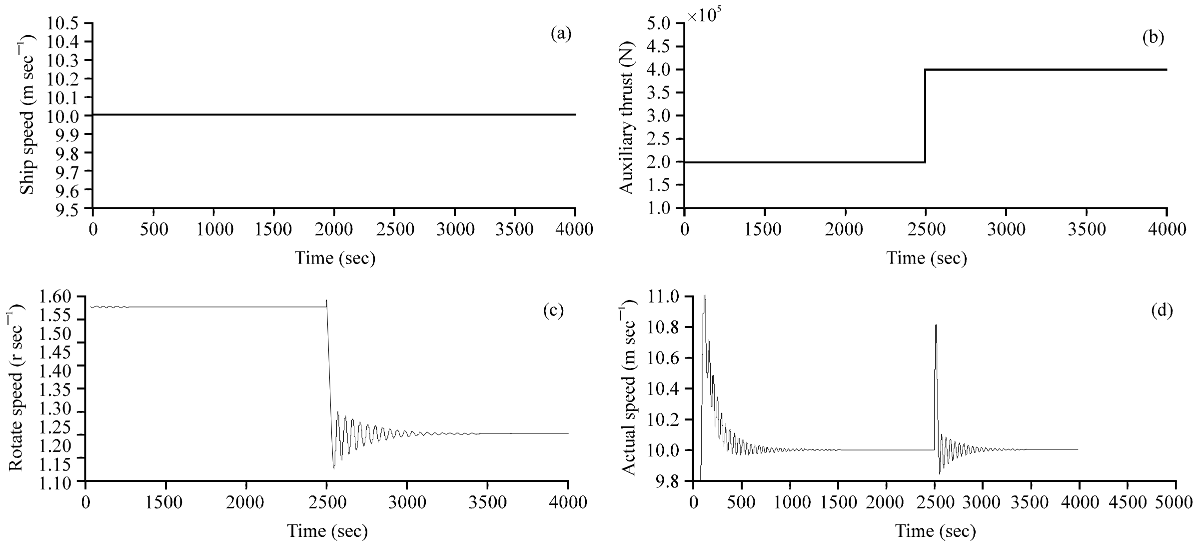

Fig. 7(a-d): (a) Given ship speed, (b) Auxiliary thrust in two kinds of wind conditions, (c) Response curve of main engine speed and (d) Real ship speed

show response curve of each variable in the control system. The predefined ship speed U_{ref} is given U_{ref} = 10 m sec^{-1}, shown in Fig. 7a. The auxiliary thrusts are shown under two kinds of wind conditions. The thrust has a jump from 200-400 KN on the time of 2000 sec. The curves for the thrusts are shown in Fig. 7b. The response curve of main engine speed and ship speed are shown in Fig. 7c-d, respectively.

Remark 2: Simulation results show that this method can achieve the purpose of maintaining speed but also the propulsion efficiency is not considered.

Method 3: Changing the speed and pitch coordinately, aiming at the optimal efficiency. The steps are as follows:

- Assume ship speed, U_{ref} = 10 m sec^{-1}, the thrust provided by wind-sail T_f = 400000 N. Then the ship resistance can be calculated $R = A_R U^2_{ref} = 6250\times10^2$ = 625000 N. Furthermore:

$$T = \frac{R - T_f}{1-t} = \frac{625000-400000}{1-0.1985} = 280723.6 \text{ N}$$

$$V_a = (1-\omega)U_{ref} = (1-0.1213)\times10 = 8.787 \text{ m sec}^{-1}$$

- By selecting several rotational speed, n = 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, the corresponding advance ratio of propeller J and the corresponding thrust coefficient K_T are achieved, the pitch θ and efficiency η_B are also obtained. The calculated results are list in the Table 1

Table 1: Calculated results

n (r sec^{-1})	J	K_T	K_Q	θ	η_p	P_e kw
0.7	0.306574	0.309292	0.0323	0.9421	0.531987	4637
0.8	0.268252	0.236802	0.0289	0.8414	0.398319	6193
0.9	0.238446	0.187103	0.0265	0.7724	0.305088	8085
1.0	0.214602	0.151553	0.0248	0.7230	0.237654	10379
1.1	0.195093	0.125250	0.0236	0.6865	0.187632	13147
1.2	0.178835	0.105245	0.0226	0.6587	0.150919	16345
1.3	0.165078	0.089676	0.0219	0.6371	0.122496	20137
1.4	0.153287	0.077323	0.0213	0.6199	0.100840	24462
1.5	0.143068	0.067357	0.0208	0.6052	0.083958	29380
1.6	0.134126	0.059200	0.0220	0.5619	0.065405	37714
1.7	0.126236	0.052441	0.0228	0.5243	0.052616	46881
1.8	0.119223	0.046776	0.0232	0.4913	0.043561	56627

As shown in the Table 1, when the rotational speed n exceeds 1 r sec^{-1}, the output effective power of the engine P_e has exceeded the allowed maximum power 8833 kw. By compare, it is easy to determine the rotational speed n = 0.7 and the pitch θ = 0.9421 which can ensure the minimum fuel consumption.

In the same way, when the sail thrust T_f = 200000 N, it is easy to get the optimal rotational speed and pitch n = 0.95, θ = 0.953.

According to the above steps, optimal control signals under different thrust at a certain speed achieved, these signals can be connected to the system at a speed of optimal control curve. Similarly, the optimal curve of the other speed is easy to get. So, after setting ship to run at a certain speed, the control curve which can keep ship work at the optimal propulsion efficiency is obtained by detecting the thrust.

Figure 8a-f show response curve of kinds of variables in the control system. The predefined ship speed U_{ref} is given as U_{ref} = 10 m sec^{-1}, shown in Fig. 8a. The auxiliary

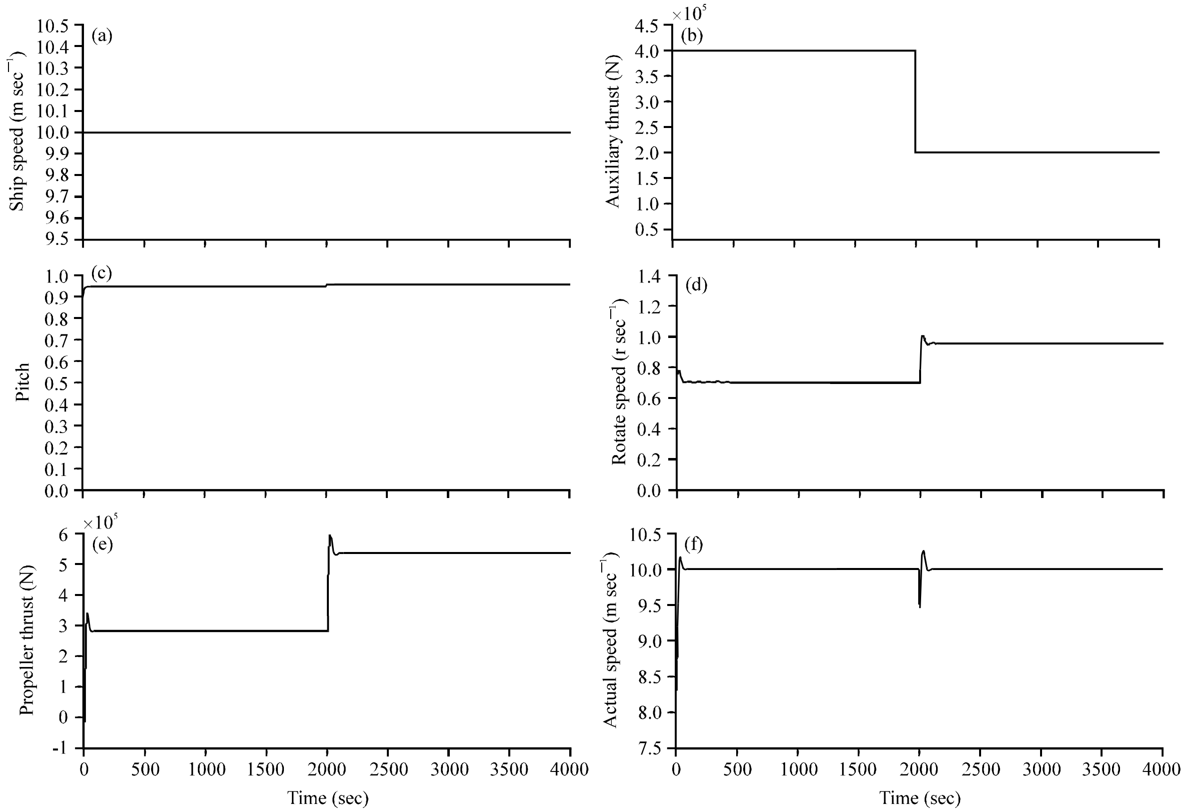

Fig. 8(a-f): (a) Curve for given ship speed, (b) Auxiliary thrust in two kinds of wind conditions, (c) Response curve of pitch, (d) Response curve of main engine speed, (e) Propeller thrust and (f) Curve for real ship speed

thrusts are shown under two kinds of wind conditions. The thrust has a jump from 400-200 KN on the time of 2000 sec. The curves for the thrusts are shown in Fig. 8b. The response curve of pitch, ship speed, propeller thrust and real ship speed are shown in Fig. 8c-f, respectively.

Remark 3: As is shown in the Fig 8a-f, the auxiliary thrust T_f changes at t = 2000 sec, speed control system regulates the rotational speed and the pitch to keep ship sailing at the predetermined speed. This method changes the speed and the pitch coordinately and obtains the optimal parameter allocation which guarantees the propulsion systems to work at the highest efficiency.

CONCLUSION

This study focuses on the analysis and modelling of the propulsion control system of wind-assisted ship. Through modeling of the propulsion system, three coordinated control methods for marine propulsion systems are designed which can keep ship sailing at the predetermined speed under different auxiliary thrust in different circumstances. By analyzing the simulation results, the advantages and disadvantages of the three methods are summarized. Finally, it is founded that cooperating the shaft speed of engine and pitch of propeller coordinately can obtain the highest efficiency and the specific steps and example of this method are given.

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