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Energy Efficiency Operating Indicator Forecasting and Speed Design Optimization for Polar Ice Class Merchant Vessels

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Abstract: In order to accurately forecast the main engine fuel consumption and reduce the Energy Efficiency Operational Indicator (EEOI) of merchant ships in polar ice areas, the energy transfer relationship between ship-machine-propeller is studied by analyzing the complex force situation during ship navigation and building a MATLAB/Simulink simulation platform based on multi-environmental resistance, propeller efficiency, main engine power, fuel consumption, fuel consumption rate and EEOI calculation module. Considering the environmental factors of wind, wave and ice, the route is divided into sections, the calculation of main engine power, main engine fuel consumption and EEOI for each section is completed, and the speed design is optimized based on the simulation model for each section. Under the requirements of the voyage plan, the optimization results show that the energy efficiency operation index of the whole route is reduced by 3.114% and the fuel consumption is reduced by 9.17 t.

Key words: Energy Efficiency Operational Indicator; ice-class ships; segment division; design optimization
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0 Introduction

The International Maritime Organization (IMO) officially implemented the Ship Energy Efficiency Operational Indicator (EEOI) in 2011, which has promoted the development of green shipping. From the perspective of ship operation, the main engine speed is directly related to the ship's speed, which is closely linked to energy efficiency indicators such as resistance during navigation and fuel consumption. Therefore, finding the optimal speed for a given route is an important way to reduce the EEOI and achieve energy savings and emissions reduction.

A considerable amount of analysis and research has already been conducted on the energy efficiency of ships operating in conventional waterways. Liu^[1] established an interference model of navigational environment, and derived the relationship between EEOI and sea state conditions, characteristic wave height, loading rate, cargo capacity, main engine speed, etc. Fan^[2] utilized the ship-engine-propeller relationship to

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establish the main engine energy consumption model based on Simulink, and compared the main engine energy efficiency with that of the ship's actual voyage through the real ship algorithm. Ni^[3] analyzed the EEOI and made a sensitivity analysis of the ship EEOI with the sailing speed, berthing time, full load rate factor, ship type factor, etc.. Huo^[4] studied the energy saving of the ship during sailing by optimizing the ship's section and subsection speeds in order to determine the lowest total fuel consumption. Most of the researches have focused on the energy efficiency of ships operating in conventional waters, but not much work has been done on the energy efficiency of ships navigating in ice. Finland-Sweden proposed a formula in the ice-class specification guidelines to calculate the minimum power for ice-class ships^[5], with this formula additionally defining a minimum speed for Finnish-Swedish ice-class ships in specific channel ice conditions. By comparing the empirical formula method for forecasting the minimum main engine power of ice-class vessels in the Finnish-Swedish ice-class specification guidelines, Ni et al^[6] proposed the discrete element method to calculate the ice resistance and establish the resistance-velocity curve, through which the main engine power forecasting method for ice-class vessels was established. Hou et al^[7] applied uncertainty analysis and optimization theory to solve the minimum speed optimization model, using the main engine speed of ice-class ships as the design variable, validating the EEOI as an effective reference index for energy efficiency optimization in ice-class ships.

Simulink is used in this paper to establish a prediction model for the main engine EEOI of low-ice-class ships. Considering environmental factors, the route is divided into several segments, with fixed distance ranges for each segment. The average speed is used to predict the main engine fuel consumption and optimize the overall route, aiming to obtain the optimal speed profile. This approach minimizes the EEOI while ensuring fuel consumption not to increase.

1 EEOI model construction

The energy efficiency model of ice-class ships is constructed by analyzing the force during sailing and the energy transfer relationship between ship, engine and propeller. The resistance of a ship is calculated through the speed and sea state information, and the energy efficiency of the ship is finally obtained by matching the open water characteristics of the propeller and the characteristics of the main engine.

1.1 EEOI calculation

The energy efficiency of ship operations is used to describe the relationship between a ship's CO₂ emissions and the amount of cargo it carries. According to the Guidelines for Voluntary Use of the Ship EEOI^[8], if a single voyage is segmented, the overall EEOI can be obtained from the EEOI on the different segments. The energy efficiency operational indicator is defined as:

$$EEOI = \left(\sum_i FC_i \times C_{Fi} \right) / (m_{\text{cargo}} \times D) = \left(\sum_j \sum_i FC_{ji} \times C_{Fi} \right) / \left(\sum_j m_{\text{cargo},j} \times D_j \right) \quad (1)$$

where i is the fuel type; FC_i is the fuel consumption of the ship during the voyage; C_{Fi} is the CO₂ emission factor, i.e., CO₂ emissions per ton of fuel consumed; m_{cargo} is the ship's cargo mass; and D is the voyage distance. The CO₂ emission factors for commonly used marine fuels are shown in Tab. 1.

Tab.1 CO₂ emission factors

Marine fuel types	MDO	LFO	HFO
$C_{\text{carbon}}\%$	456	0.86	0.85
C_{Fi}	789	3.151 04	3.114 40

1.2 Environmental resistance calculation

The resistance components of ice-class 1A ships sailing through sea ice are more complex than those of ordinary merchant ships. In addition to hydrostatic resistance, wave resistance, and wind resistance, ice resistance in the sea ice area must also be considered. Based on empirical formulas, a resistance calculation model is developed using Simulink.

1.2.1 Hydrostatic resistance

The hydrostatic resistance to which a ship is subjected while sailing consists of the frictional resistance R_f , the residual resistance R_r and the attached resistance R_{ap} as shown in Eq. (2). Frictional resistance is related to hull surface roughness, wet surface area and speed.

$$R_0 = R_f(1 + K) + R_r + R_{ap} = (C_f + \Delta C_f)\rho V^2 S(1 + K)/2 + R_r + R_{ap} \quad (2)$$

where C_f is the frictional drag coefficient, ΔC_f is the roughness compensation factor, V is the speed, S is the wet surface area of the ship, and ρ is the seawater density.

The frictional resistance coefficient is calculated using the method proposed by ITTC. According to the assumption, the relationship between frictional resistance coefficient and the residual resistance of the ship are shown in Eq. (3):

$$R_r = C_r \rho v^2 S / 2 = (25.02 F_n^3 - 7.752 F_n^2 + 1.246 F_n + 0.2568) C_f \rho v^2 S / 2 \quad (3)$$

The appendage resistance can be calculated as $R_{ap} = K_A (R_f + R_r)$, in which K_A is a percentage of the appendage resistance in the hull resistance.

1.2.2 Wave resistance

The ship's wave resistance is calculated as per the formula proposed by Daidola et al^[11] to solve the axial average wave force, the formula^[9] is as follows:

$$\begin{aligned} R_{xw} &= (\rho g L \cos \chi \sum_{i=1}^n h_i^2 C_{xi}) / 2, C_{xi} = 0.05 - 0.2(\lambda/L) + 0.75(\lambda/L)^2 - 0.51(\lambda/L)^3 \\ R_{yw} &= (\rho g L \sin \chi \sum_{i=1}^n h_i^2 C_{yi}) / 2, C_{yi} = 0.46 - 6.83(\lambda/L) + 15.65(\lambda/L)^2 - 8.44(\lambda/L)^3 \\ N_w &= (\rho g L \sin \chi \sum_{i=1}^n h_i^2 C_{Ni}) / 2, C_{Ni} = -0.11 + 0.68(\lambda/L) - 0.79(\lambda/L)^2 + 0.21(\lambda/L)^3 \end{aligned} \quad (4)$$

where ρ represents the density of seawater, g is the gravitational acceleration, L denotes the ship length, h signifies the wave height, and χ indicates the wave direction angle. The coefficients C_{xi} and C_{yi} correspond to the wave-induced resistance coefficients in the axial and transverse directions, respectively, while C_{Ni} represents the wave-induced moment coefficient, and λ is the wavelength.

1.2.3 Wind resistance

The part of hull above the waterline, and the superstructure as well, will be affected by the sea wind. Isherwood^[12], through the waterline on the hull of the lateral projection area, the length of the ship, and other parameters for variables of the multivariate linear regression, got the wind load coefficient and the wind moment coefficient of the numerical expression for the wind calculation as shown in the following formula^[10]:

$$\begin{aligned} X_w &= C_x \rho v_w^2 A_T / 2, C_x = a_0 + 2a_1 A_L / L_{OA}^2 + 2a_2 A_T / B^2 + a_3 L_{OA} / B + a_4 S / L_{OA} + a_5 C / L_{OA} + a_6 M \\ Y_w &= C_y \rho v_w^2 A_L / 2, C_y = b_0 + 2b_1 A_L / L_{OA}^2 + 2b_2 A_T / B^2 + b_3 L_{OA} / B + b_4 S / L_{OA} + b_5 C / L_{OA} + b_6 A_{SS} / A_L \\ N_w &= C_N \rho v_w^2 A_L L_{OA} / 2, C_N = c_0 + 2c_1 A_L / L_{OA}^2 + 2c_2 A_T / B^2 + c_3 L_{OA} / B + c_4 S / L_{OA} + c_5 C / L_{OA} \end{aligned} \quad (5)$$

where C_x , C_y , C_N denote the wind load coefficients in each axial direction of the ship; v_w is the relative wind speed; A_T is the forward projected area of the ship hull above the waterline; A_L is the side projected area of the ship hull above the waterline; L_{OA} is the ship's length, B is the ship's breadth; S is the perimeter of the hull's

side projection area above the waterline; C is the distance of the side projection surface's centroid from the ship's bow; M is the number of pillars on the side projection centerline surface; A_{SS} is the superstructure's side projection area; a_0 - a_6 , b_0 - b_6 and c_0 - c_6 are regression coefficients.

1.2.4 Ice resistance

The empirical estimation method, based on extensive experimental data, has become a widely-used approach for predicting ice resistance. This method relies on continuous refinement and the generalized ice-floating resistance formula derived by Huang et al^[13] from experimental data of KCS, JCS, AIV, and Araon:

$$R_{ice} = (A\rho_{ice}hDv^2B)/(L_{pp}C^{1.5}Fr^{-0.8}) \tag{6}$$

where ρ_{ice} is the density of broken ice taken as 900 kg/m³, h is the thickness of sea ice, D is the diameter of the upper surface of sea ice, v is the speed of navigation, C is the density of ice, and Fr is the Froude number.

1.3 Boat-machine-propeller transfer model

Ship propulsion system is an energy conversion system composed of hull, host and propeller. The effective thrust generated by the propeller overcomes the drag force on the ship. The propulsion system and the relationship between the different efficiencies and powers of the ship propulsion system are shown in Figs. 1-2, where η_g , η_s , η_R , η_0 , η_H are the gearbox efficiency, shaft efficiency, relative rotational efficiency, propeller efficiency and hull efficiency, respectively, and P_B , P_S , P_D , P_T , P_E are the braking power, shaft power, transmission power, propulsive power and effective power, respectively.

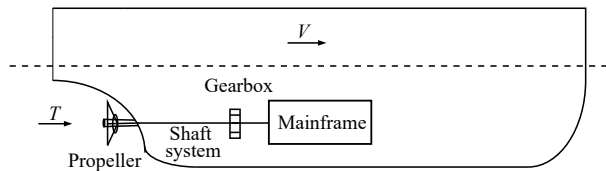


Fig.1 Schematic of propulsion system

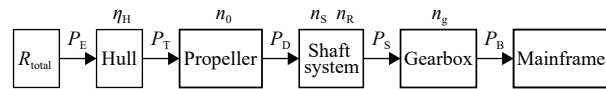


Fig.2 Efficiencies and powers in the system

For an ordinary single-propeller seagoing vessel, the Taylor's formula is used to calculate the wake fraction $\omega = 0.5C_B - 0.05$, the Hankschel's formula is used to calculate the thrust deduction fraction $t = 0.5C_P - 0.12$, $\eta_s = 0.96$, the hull efficiency $\eta_H = (1-t)/(1-\omega)$, and the relative rotational efficiency $\eta_R = 0.9922 + 0.07427 \times (C_P - 0.0225l_{cb}) - 0.05908A_0$. The joint speed coefficient and thrust coefficient eliminate the rotational speed N to get Eq. (7). From Eq. (7), a linear relationship exists between the ratio of the thrust coefficient to the square of the advance coefficient and the ratio of the ship's drag to the square of the speed. By drawing the relationship curve between K_T/J^2 and J , the output power of the main engine is ultimately obtained by Eq (8) and the fuel consumption of the main engine is calculated:

$$K_T/J^2 = (T/\rho N^2 D^4)/(V_a/ND) = T/(\rho D^2 V_a^2) = R/[\rho(1-t)(1-\omega)^2 v^2 D^2] = AR/v^2 \tag{7}$$

$$P_B = P_s = (R_{total}V)/(\eta_H\eta_0\eta_R\eta_s), w = g_e P_s t \tag{8}$$

where J is the advance coefficient, K_T is the thrust coefficient, V_a is the propeller advance speed, $V_a = (1 - \omega)v$, N is the main engine speed, D is the propeller diameter, T is the propeller thrust, ρ is the seawater density, A is a constant, ω is the wake fraction, v is ship speed, g_e is the main engine fuel consumption rate, P_s is the main engine output power, and t is the sailing time.

The fuel consumption rate can be obtained through the fuel consumption rate curve of the main engine. The model sets speed limits between 30% and 108% of the maximum continuous speed, with power limits ranging from 10% to 25% of maximum continuous power. The maximum power limit for the target ship's main engine is defined as shown in Eq. (9). The integrated model of the simulation optimization system comprises three main components: navigational meteorological data, resistance model and propulsion system^[15]. The Simulink simulation model is shown in Fig. 3.

$$P = [C + C_1 \times (N/N_{MCR}) + C_2 \times (N/N_{MCR})^2] \times MCR \tag{9}$$

where N_{MCR} represents the maximum continuous speed, MCR denotes the maximum continuous power, and C , C_1 , and C_2 are the relevant coefficients^[16].

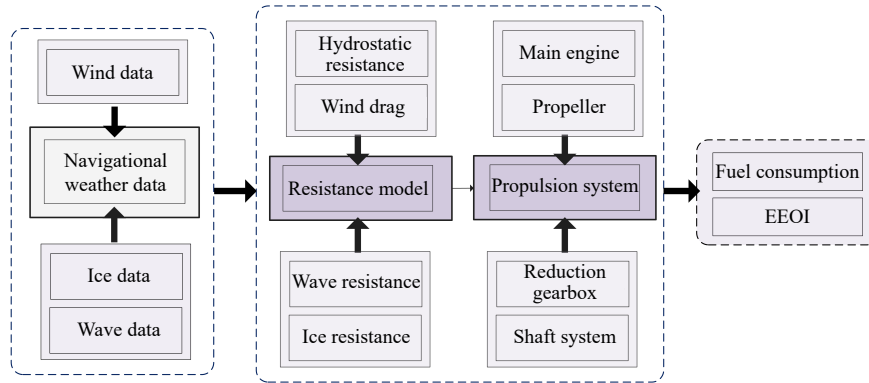


Fig.3 Simulink model

2 EEOI forecast and speed optimization results

2.1 EEOI forecast

Ice-class ships operate in ice-covered areas, making it essential to assess their performance under high ice resistance. A Finnish-Swedish 1A ice-class ship (shown in Fig. 4) embarked from Lianyungang, navigating through the Yellow Sea, Korea Strait, Sea of Japan, Soya Strait, and the Sea of Okhotsk before entering the Arctic Ocean via the Bering Strait. The route (shown in Fig. 5) continued through the Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea, Barents Sea, and Norwegian Sea. Covering a total distance of 8,096 n mile, the voyage included 713 n mile in ice channels and 7,383 n mile in open water, with no port calls en route. Equipped with low-speed diesel engine produced by Hudong Heavy Machinery Co. Ltd., the main parameters of the vessel and its main engine are shown in Tab. 2. and Tab. 3.

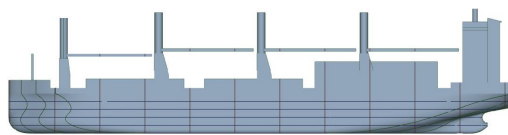


Fig.4 1A ice class target vessel

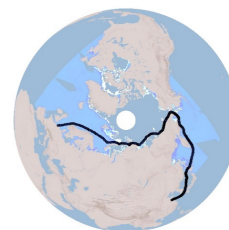


Fig.5 Target ship route

Tab.2 Main parameters of the target vessel

L_{pp}/m	B/m	Draft/m	D/m	Design speed/($m \cdot s^{-1}$)
186.4	28.5	15.8	11	14.8

Tab.3 Main engine parameters

Type	Number	Power _{max}	r/min _{max}
RT-flex50D	1	10 470	124

According to K_T/J^2-J curve obtained from propeller open water characteristic curve^[6], ship's mainframe generally run in 75%–95% power range for a long time, and the mainframe fuel consumption rate can be determined by the corresponding curve between the power and the fuel consumption rate, as shown in Fig. 6.

The rated power and rotational speed of the target ship under the service speed was 6806.0 kW × 107.4 r/min. The simulation model speed was set to 14.8 kn, the draught was 11 m, the water temperature was

5 °C, then the model forecast value obtained was 6540.9 kW × 106.6 r/min. The wind condition data of the target route is shown in Tab. 4 and percentage of wave and the sea state in the ice area is shown in Tab. 5.

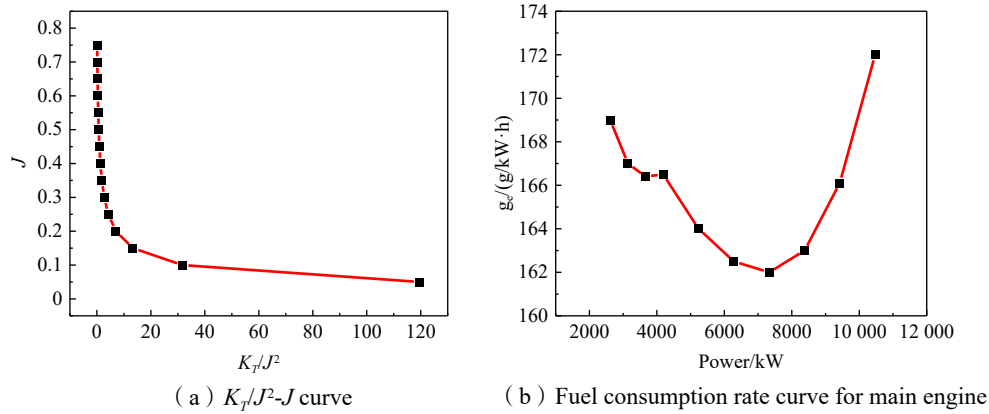


Fig.6 Target vessel K_T/J^2 - J curve and main engine's fuel consumption rate curve

Tab.4 Wind information in routes

Scale	2	2	3	3	4	4
Direction	Smooth wind	Top wind	Top wind	Smooth wind	Top wind	Smooth wind
Distance/n mile	85	261	676	1597	1188	1627
Scale	4	5	5	5	6	6
Direction	Cross wind	Top wind	Smooth wind	Cross wind	Top wind	Cross wind
Distance/n mile	515	242	641	222	426	626

Tab.5 Wave information and ice information in routes

H_{wave}/m	2.27	2	3.34	4	6.35	5	H_{ice}/m	0.3	0.5	0.7	1
T_{wave}/s	2	2.2	3	3	5.4	6	$C_{ice}(\%)$	10%	50%	30%	40%
Weight (%)	14.7	19.7	25.2	10.4	18.2	11.5	Distance/n mile	85	300	228	100

The speed of the target vessel was maintained at around 13 kn most of the time, and accelerated slightly to around 14 kn in good sea conditions with a fair wind and waves. When entering the ice area, the ship sailed in the water with about 30% ice. The speed was less than 8 kn in the sea with an ice thickness of 0.8–1.5 m^[14]. Based on the sea state data, the route was divided into 5 sections of top wind and wave area, 3 sections of cross wind and wave area, 3 sections of smooth wind and wave area and 4 sections of ice area, as shown in Tab. 6.

Tab.6 Segmented route data

Section No.	Navigation area	Sea conditions	Voyage/n mile	Speed/kn
1	Top wind and wave zone	Wind class 2	261	13
2		Wind class 3	576	13.5
3		Wind class 4	1088	12.2
4		Wind class 5	242	11.2
5		Wind class 6	416	11.6
6	Cross wind zone	Wind class 4	387	11.8
7		Wind class 5	222	13.5
8		Wind class 6	626	13.2

Tab.6 (Continued)

Section No.	Navigation area	Sea conditions	Voyage/n mile	Speed/kn
9	Smooth wind and wave zone	Wind class 3	1397	14.3
10		Wind class 4	1627	14.3
11		Wind class 5	541	14.3
12	Ice zone	H_{ice} 0.3 m, C_{ice} 10%, Wind class 2, top wind	85	11
13		H_{ice} 0.5 m, C_{ice} 50%, Wind class 2, top wind	300	8
14		H_{ice} 0.7 m, C_{ice} 30%, Wind class 4, top wind	228	8.5
15		H_{ice} 1 m, C_{ice} 40%, Wind class 5, smooth wind	100	6

The mathematical simulation model based on Simulink was used to forecast the rotational speed, power, fuel consumption, fuel consumption rate, and ship energy efficiency operational indicator at different constant speeds for each cruise section. The results in the top wind and top wave area are shown in Fig. 7 and those in the cross wind area are shown in Fig. 8.

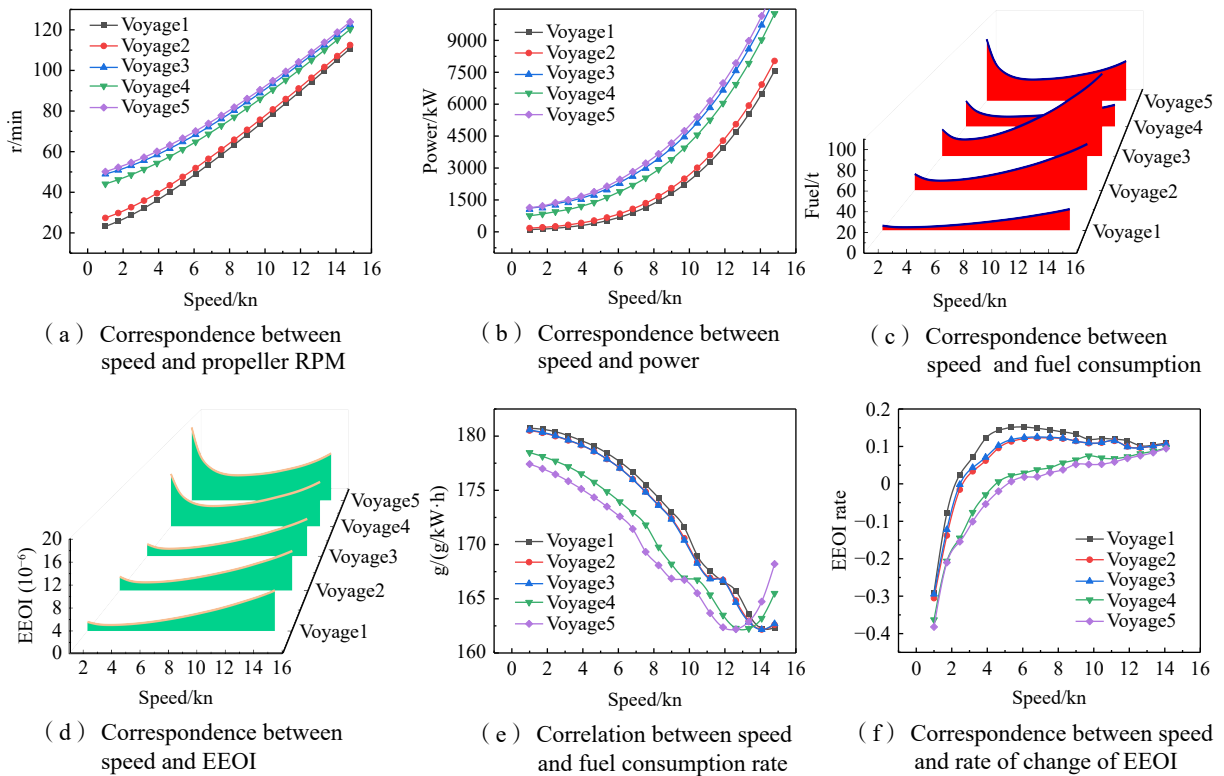
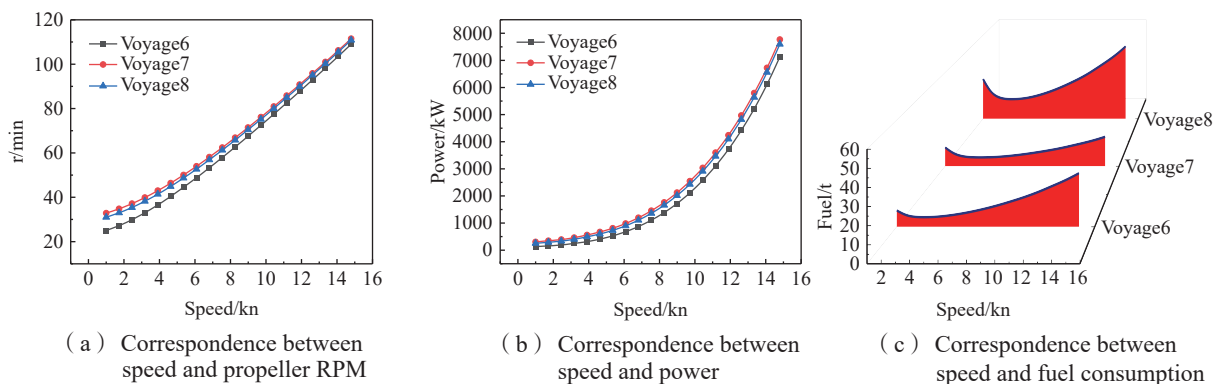


Fig.7 Relationship between ship's speed and energy efficiency in top wind and wave region



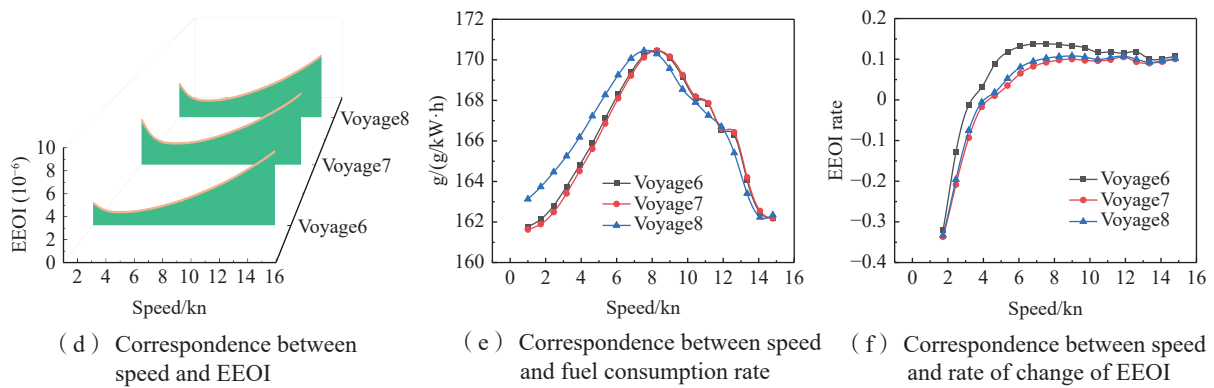


Fig.8 Relationship between ship's speed and energy efficiency in cross wind and wave region

The forecast results for each section in the smooth wind and smooth wave areas are shown in Fig. 9 and those for each section of the ice area are shown in Fig. 10.

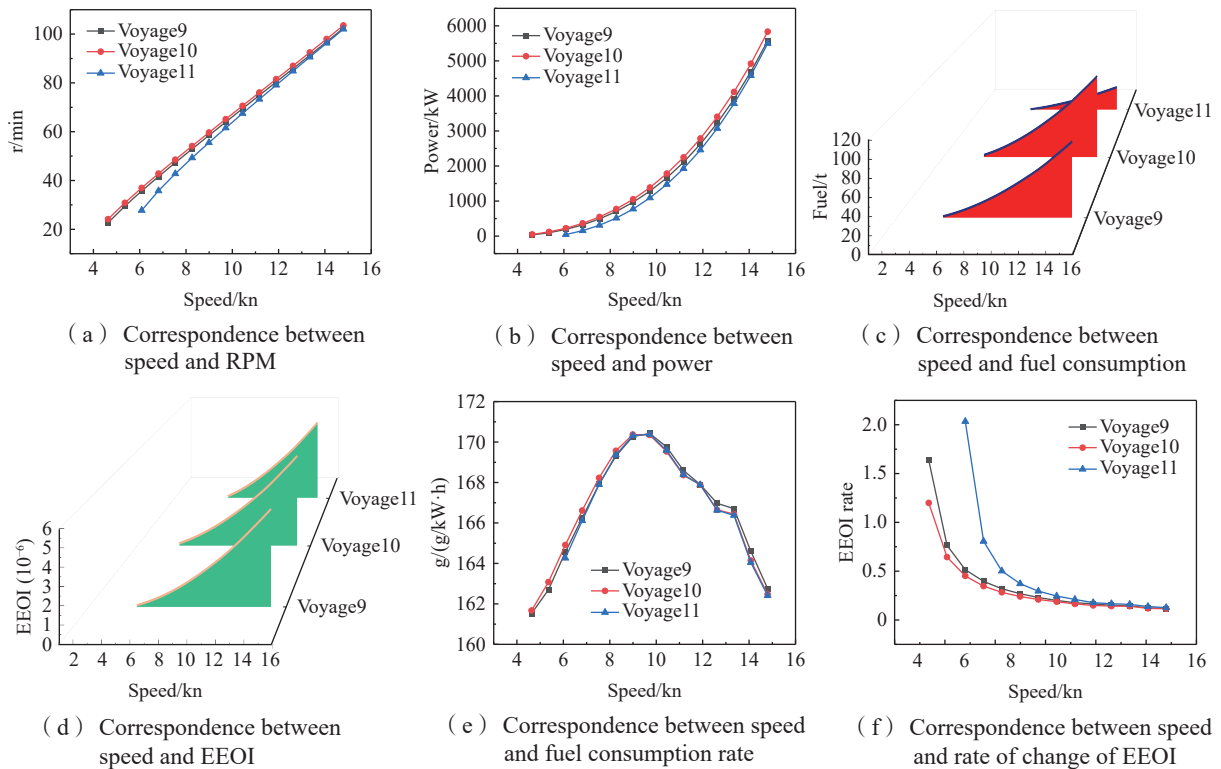
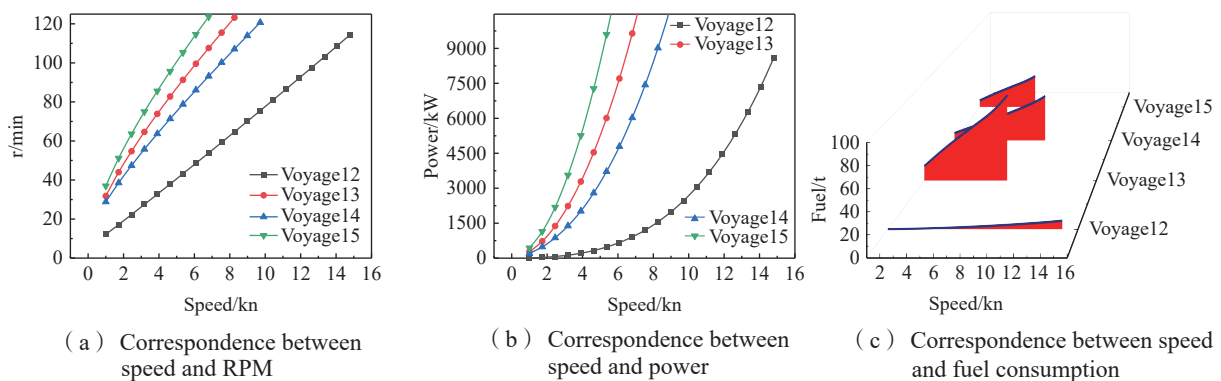


Fig.9 Relationship between ship's speed and energy efficiency in smooth wind and wave region



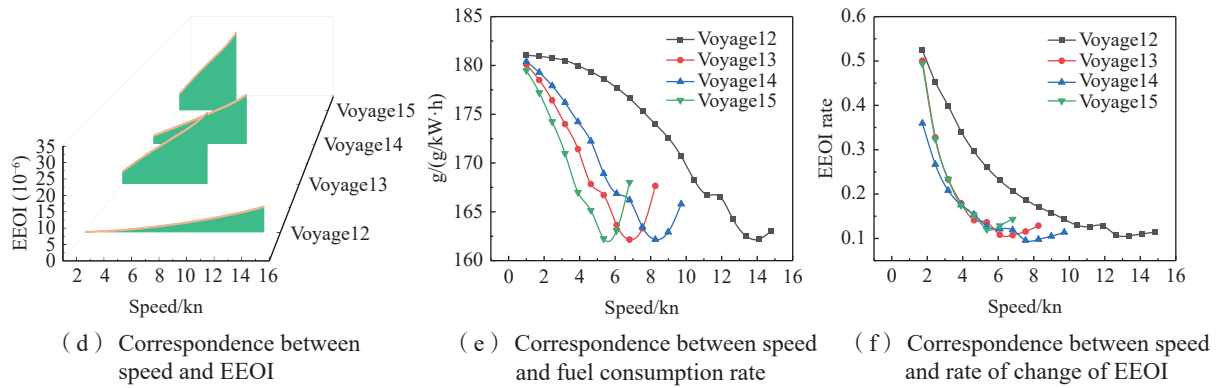


Fig.10 Relationship between ship's speed and energy efficiency in ice region

2.2 Speed optimization results

The performance analysis of the target ship along a complete route aims to reduce the total voyage EEOI without increasing fuel consumption or altering the total voyage time.

$$\begin{aligned}
 \text{Min } EEOI &= \text{Min}(\sum f_i(v_i)) \\
 \sum_{i=1}^{15} T_i &= \sum_{i=1}^{15} \frac{S_i}{v_{si}} = T, \sum_{i=1}^{15} S_i = S, \sum_{i=1}^{15} Fuel_i \leq Fuel_{total}, RPM_i \leq RPM_{max}, Power_i \leq Power_{max}, T \leq T_0
 \end{aligned} \tag{10}$$

where S is the voyage distance, T is the sailing time, and T_0 is the voyage period. By keeping limits on maximum sustained power and rotational speed while meeting navigation plan requirements, the safety of the ship and the main engine's own condition setting constraints are considered. The goal is to determine the optimal speeds for each voyage section, aiming for minimum EEOI for the voyage.

Due to varying sea conditions across different sections, the mapping relationship between speed and the energy efficiency operational indicator (EEOI) differs in each section. Therefore, the speeds are coordinated and optimized using the T-search algorithm for directed optimization. A fast convergence rate is exhibited, as shown in Fig. 11. The results of engine speed and RPM for each segment are shown in Fig. 12. The comparisons of fuel consumption and EEOI before and after optimization are illustrated in Figs. 13 and 14, respectively. The results show that the fuel consumption of the main engine of the target ship is reduced by 9.17 t, and the EEOI of the whole route is reduced by 3.114%.

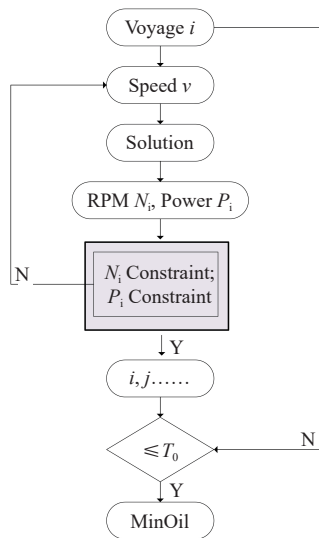


Fig.11 Optimized EEOI flowchart

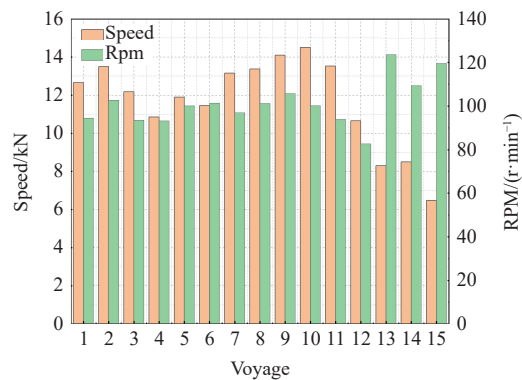


Fig.12 Optimization results for speed and corresponding propeller RPM

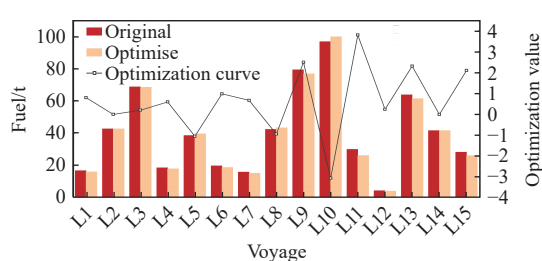


Fig.13 Comparison of fuel consumption before and after optimization

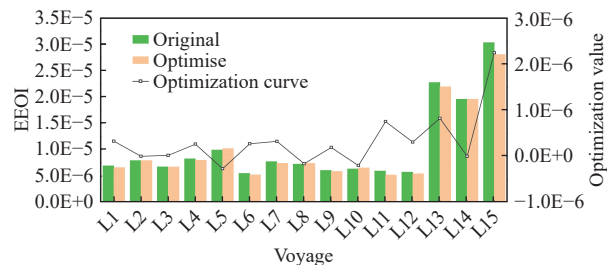


Fig.14 EEOI comparison before and after optimization

3 Conclusions

Adopting empirical formulas to build the simulation model can clearly reflect the relationship between each part of resistance, main engine power, rotational speed and fuel consumption, which is helpful to analyze the trend of fuel consumption and EEOI at a constant speed. The main conclusions of this paper are as follows.

(1) In head wind and head wave conditions, rotational speed and power increase linearly with speed, with minimum fuel consumption at 12–14.8 kn. Below 6 kn, speed changes significantly affect EEOI. In cross wind conditions, fuel consumption peaks around 8 kn, with minimal EEOI fluctuations at higher speeds. Following wind and waves can provide thrust, with significant EEOI variability at speeds below 10 kn.

(2) When the ship is navigating in the ice area, the target ship can easily reach the maximum sustained power and the maximum sustained RPM due to the high ice resistance generated by the floating broken ice. Ice thickness and ice density have a significant effect on the fuel consumption and EEOI of the target ship, and different ice segments have their own minimum fuel consumption rate and EEOI variation rate.

(3) Adjusting speeds for open water and ice segments reduces fuel consumption by 9.17 t and EEOI by 3.114%. Higher speeds in open water and lower speeds in ice improve efficiency. There are open water and ice areas in the target ship route, and the EEOI of the target ship in the ice area is of a higher magnitude than that in the open water area, and the ice area segments have a greater impact on the overall EEOI.

The final results show that in order to reduce the EEOI of the total voyage, adopting segmented speed strategies that maximize speed in open waters while ensuring safety and time margins in ice areas reduces overall EEOI. This approach is vital for green navigation and economic operations of low ice-class vessels.

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冰级商船营运能效指数预报及航速优化研究

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摘要: 为准确预报冰区商船的主机油耗以及降低营运能效指数(Energy Efficiency Operational Indicator, EEOI), 通过分析航行过程中的受力情况、船-机-桨的能量传递关系, 采用 Simulink 构建多环境阻力、螺旋桨效率、主机功率、油耗、燃油消耗率和 EEOI 计算模块。考虑风、浪、冰的影响对航线进行航段划分, 完成各航段主机功率、油耗和 EEOI 计算并进行航速设计优化。优化结果表明, 在满足航行计划的要求下, 船舶能效运营指数可降低 3.114%, 油耗减少 9.17 吨。

关键词: 能效运营指数; 冰级船; 航段划分; 优化设计

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