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## Research on intelligent ship energy efficiency management technology

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**WORLD MARITIME UNIVERSITY**

Dalian, China

**RESEARCH ON INTELLIGENT SHIP ENERGY  
EFFICIENCY MANAGEMENT TECHNOLOGY**

By

**MA RANQI**

**The People's Republic of China**

A dissertation submitted to the World Maritime University in partial  
Fulfillment of the requirements for the award of the degree of

**MASTER OF SCIENCE  
IN  
(MARITIME SAFETY AND ENVIRONMENTAL  
MANAGEMENT)**

2020

## DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature): \_\_\_\_\_

(Date): June 27, 2020

Supervised by: Professor Zhang Xianku

Supervisor's affiliation: Dalian Maritime University

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## ABSTRACT

Title of Dissertation: **Research on intelligent ship energy efficiency management technology**

Degree: **Master of Science**

Due to the stringent requirements and strict regulations, energy-saving and emission reduction have drawn wide attention in the shipping industry. Ship energy efficiency optimization can effectively reduce energy consumption and the CO<sub>2</sub> emissions. At present, there is an increasingly urgent need to improve ship energy efficiency optimization management technology. Given the complexity of ship operation mode, equipment performance and the navigation environment, research on ship energy efficiency optimization management technology can be conducted from various aspects. In this thesis, three methods are put forward in compliance with the requirements of international conventions and on the basis of the data collection technology of ship energy efficiency, namely, ship energy efficiency evaluation and analysis, ship trim optimization and ship energy efficiency optimization. The validity of these methods is verified by data analysis, model building, simulation optimization and real ship case. The results show that the use of these 3 methods can effectively improve the energy efficiency of operating ships. So, the research on intelligent ship energy efficiency management technology can promote the development of greener and more intelligent shipping industry.

**KEY WORDS:** Energy-saving emission reduction, Energy efficiency evaluation, Trim optimization, Speed and route optimization

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## LIST OF ABBREVIATIONS

NP	Nondeterministic Polynomial
EU	European Union
LFO	Light Fuel Oil
HFO	Heavy Fuel Oil
EHP	Effective Horse Power
LPG	Liquefied Petroleum Gas
LNG	Liquefied Natural Gas
MRV	Monitoring, Reporting and Verification
IMO	International Maritime Organization
GHG	Green House Gas
CCS	China Classification Society
ABS	American Bureau of Shipping
VOF	Volume of Fluid
PSO	Particle Swarm Optimization
BDN	Bunker Delivery Note
EEOI	Energy Efficiency Operation Index
EEDI	Energy Efficiency Design Index
SEEMP	Ship Energy Efficiency Management Plan
ECMWF	European Centre for Medium-Range Weather Forecasts
MARPOL	International Convention for the Prevention of Pollution from Ships
PRESTO	Pressure Staggering Option
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations

## Chapter I Introduction

### 1.1 Background

Waterway transportation plays an important role in the global economic development. About 90% of the world's trade transportation is completed by ships (UNCTAD, 2016). In the past few years, the annual growth rate of global seaborne trade has exceeded 3%, reaching a total of 10.837 billion tons (Clarksons., 2015). In recent years, with the introduction of a series of national strategies such as "Maritime Power", "One Belt and One Road" and "Yangtze river economic belt", new opportunities have emerged for the further development of the shipping industry. Figure 1-1 indicates that China's ship transport turnover has been increasing year by year (Yang H., Ma X. & Xing Y., 2017).

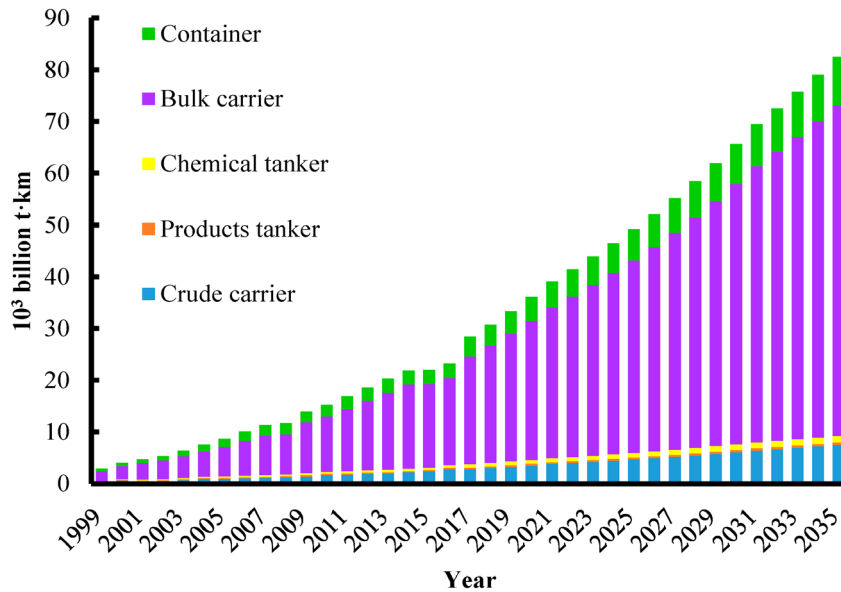


Fig. 1-1 Shipping turnover

However, despite the rapid development of waterway transportation, it also faces some problems and challenges, such as enormous energy consumption and greenhouse gas emissions. Figure 1-2 shows that the fuel consumed by ship transportation has also been growing continuously over years. (Vergara J., Mckesson C. & Walczak M., 2012).

In addition, global ship CO<sub>2</sub> emissions in 2007 totaled about 1.046 billion tons, accounting for about 3.3% of global CO<sub>2</sub> emissions. If no restriction measures are adopted, by 2050, the total carbon dioxide emissions of the shipping industry will reach up to 12%~18% of the total allowable carbon dioxide emissions globally (MEPC, 2009).

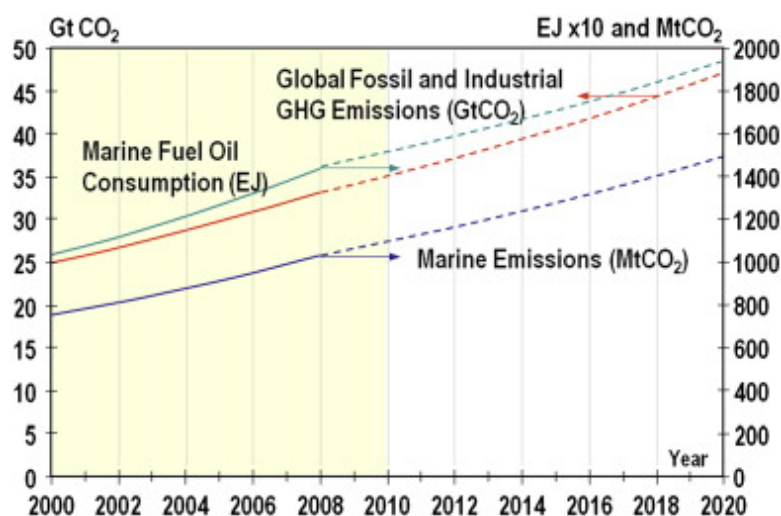


Fig. 1-2 Ship transport fuel consumption and CO<sub>2</sub> emissions

In recent years, the shipping industry has paid more and more attention to the emission of pollution gas from ships. The international convention for the prevention of pollution from ships (MARPOL) annex VI amendment sets forth clear provisions for controlling greenhouse gas emissions from ships, and introduces two mandatory energy efficiency management mechanisms, namely the energy efficiency design index (EEDI) of new ships and a ship energy efficiency management plan (SEEMP) carried aboard.. If this are well implemented, CO<sub>2</sub> emissions can be significantly reduced (Hannjohn., 2011). In addition, aiming at a large number of operating vessels, IMO also proposes to use the energy efficiency operation index (EEOI) as a monitoring tool for vessel operating efficiency (MEPC., 2011).

Meanwhile, our government also attaches great importance to the shipping industry's

energy consumption and pollution gas emissions. The work plan for controlling greenhouse gas emissions during the 13th five-year plan period (2016-2020) clearly proposes measures and implementation plans for ship energy conservation and emission reduction, and sets the target that "by 2020, the CO<sub>2</sub> emission level of operating ships will be 7% lower than that of 2015". On top of that, the ministry of transport released the implementation plan on emission control zones for vessels in the Pearl river delta, Yangtze river delta and Bohai sea rim at the beginning of 2016. The establishment of air pollution emission control zone is to promote the development of energy conservation and green shipping.

For the global shipping industry, CO<sub>2</sub> emissions from ships have reached a high level. The Third IMO GHG Study 2014 released by THE International Maritime Organization (IMO) published the emissions of Marine greenhouse gases (mainly CO<sub>2</sub>) from 2007 to 2012. According to the data, the CO<sub>2</sub> emissions of international ships in 2012 were about 796 million tons, 89 million tons less than the 885 million tons in 2007. Emissions from international ships accounted for 2.2% of global CO<sub>2</sub> emissions in 2012, 0.6 percentage points down from 2.8% in 2007. According to the prediction of the relevant carbon emission situation of the international shipping industry from 2012 to 2050, firstly, if the energy saving and emission reduction work of the shipping industry is not improved, its CO<sub>2</sub> emission will increase by 50% to 250% by 2050. Secondly, improving energy efficiency is an effective way to reduce carbon emissions. By contrast, the use of clean energy in the shipping industry will be less effective, and fossil fuels will remain dominant. Thirdly, the use of greenhouse gases other than carbon will increase, but NO<sub>x</sub> and SO<sub>x</sub> will remain low. Although ships account for merely approximately 3% of global carbon emissions, without effective regulation and action, this will rise to 18% by 2050.

### **International Maritime Organization Energy Efficiency Regulation**

After solving the problem of SO<sub>x</sub> and NO<sub>x</sub> emission, the International Maritime

Organization (IMO) has shifted its focus to greenhouse gas emission reduction. In July 2011, the 62nd Session of environmental Protection Society formally incorporated ship energy efficiency rules into MARPOL Annex VI, bringing technical emission reduction measures (EEDI) and operational emission reduction measures (SEEMP) as mandatory requirements into the Convention for the first time. Since then, every session of environmental protection committee has covered ship energy efficiency and related data collection mechanism. The 65th Session of the environmental protection committee proposed to set up a new and old ship energy efficiency standard. It achieved the purpose of emission control through the establishment of energy efficiency standards. At the same time, it also believed that the implementation should be carried out through MRV. The 66th session proposed the establishment of a global shipping emissions/energy efficiency data collection system similar to the EU MRV, and the establishment of a framework, identification mechanism and other key elements. The 67th session submitted the work report of the data collection system, including the core elements of the identification system, forming an overall framework of the data collection mechanism: data collection, the role of flag state and central database. The 69th session of IMO Data Collection Mechanism Working Group was held in September 2015, during which discussions were held on data content to be reported, data confidentiality and relevant guidelines. After discussion, it was agreed that Designed DWT would be used as a substitute parameter for the actual cargo capacity. In 2016, the 69th session of IMO MEPC finally approved the global vessel fuel consumption data collection mechanism to be officially adopted at the 70th MEPC Conference.

### **The transformation of "Internet +" energy efficiency management model**

According to the strategic concept of "E-navigation" put forward by IALA, the management direction of ships operating in the future will be clearer. "E-navigation"

will integrate existing ship-borne, shore-based navigation and navigation aids to realize a process of coordination, collection, aggregation, exchange and display of maritime and ship-related information. "E-navigation" will fully realize the interaction of navigation and navigation aid information, enhance ships' full-voyage navigation capability, enhance corresponding maritime services, safety and security capabilities and marine environmental protection capabilities, so as to further improve the navigation safety of ships and the management efficiency between ship and shore. From the perspective of implementation, "E-navigation" at the ship side needs to build a comprehensive information integration platform that can integrate existing and future ship-related systems. Ship energy efficiency in the whole life cycle of ships has been transformed gradually to intelligence information, and its characteristic is to format a variety of data acquisition, storage, and correlation analysis. The ship shore integrated intelligent information service system is built on the basis of large data, with prediction technology as the core, through the network of the fusion of information and the entity, thus achieving the ship shore information sharing, breaking the information asymmetry problem, create new value for the shipping companies through the implementation of intelligent decision making based on big data.

## **1.2 Significance of the Research**

In recent years, the increasing fuel costs and increasingly strict pollution gas emission regulations have brought about many challenges to the operation and optimal management of ships. The optimal management and operation of vessels need to achieve sustainable development in harmony with the environment while reducing costs and increasing efficiency. Fuel consumption is not only the main cost of vessel operation, but also the main source of pollution gas emissions. Research on optimization methods and technologies of vessel energy efficiency is an effective way



to reduce vessel fuel consumption. Therefore, it is of great significance to study and apply the key technologies of ship energy efficiency optimization, both from the perspective of energy conservation and environmental protection and from the perspective of improving enterprise economic benefits.

Shipping companies usually operate several ships with different economic and technical parameters. Due to the differences in technical and economic parameters, the energy efficiency management of ships is particularly complex, resulting in the frequent occurrence of energy waste, low operating efficiency, environmental pollution and other problems. At present, the optimization management of vessel operation energy efficiency is mainly embodied in the optimization management of vessel, the optimization of vessel navigation and the optimization management and control of key energy-consuming equipment. In terms of ship optimization management, the traditional ship management methods are no longer applicable to the demand of the shipping industry development. The ship operation management needs to gradually optimize the ship management program by taking into account the changes in the market demand and factors such as ship status parameters, navigation environment and service efficiency. With regard to ship speed optimization, the seafarers usually make decisions based on their rich navigation experience and certain economic analysis. However, under the influence of uncertain factors such as different navigation environments, different loading conditions and different arrival rate requirements, it becomes more and more difficult to analyze the optimal sailing speed of ships through experience. Therefore, it is a problem worthy of discussion to apply the model and method of optimal ship speed decision taking into account navigation environment and other factors affecting the optimal management of ship energy efficiency. In terms of equipment optimization management and control, it is difficult for the optimal control of traditional single equipment to achieve the goal of optimal system energy efficiency. In addition, the choice and distribution of goods, the optimal

decision of ship navigation and the optimal control of equipment are mutually related and affected. Therefore, in the new situation, the traditional ship operation management mode can hardly meet the needs of the shipping industry.

With the introduction and effective implementation of GHG emission reduction strategy, IMO sulfur limit standard, IMO nitrogen limit standard and greenhouse gas emission target, the whole shipping pattern governed by increasingly strict environment protection requirements and low emission target is progressing in a green direction. Meanwhile, in the context of artificial intelligence, big data and Internet of Things, intelligent ships have become the focus and development trend of the international shipping industry.

In 2018, the Ministry of Industry and Information Technology, the Ministry of Transport and the State Administration of Science, Technology and Industry for National Defense jointly formulated the Smart Ship Development Action Plan (2019-2021) to promote high-quality development of China's shipbuilding industry. In terms of regulation formulation, the China Classification Society (CCS) issued the Green Ship Code in 2012 with environmental protection, green and sustainable development as the core content, advocating the development and application of green technologies. In addition, with the continuous development of big data, artificial intelligence, machine learning and other technologies, as well as the implementation of "E-navigation" strategy, the research and application of intelligent energy efficiency management technology for intelligent ships will be an irresistible trend. CCS published the Smart Ship Specifications in 2015, regarding the realization of smart energy efficiency management as one of the six core functional modules for the development of smart ships in the future. It can be seen that in the context of the development of intelligent ships, the study of intelligent energy efficiency management methods will be an important part of the intelligent ship's development and also one of the effective ways to realize the goal of green ships.

## **Chapter II Research status of ship energy efficiency management technology**

### **2.1 Research on ship energy efficiency monitoring system**

With the rapid development of information sensing, wireless communication and other technologies, the development of remote online monitoring technology for ship energy efficiency has been promoted. The impact of draught and other factors on ship fuel efficiency was analyzed and on the basis of which eco-Assistant software was launched to enable crew members to monitor the fuel consumption of main and auxiliary engines in real time (Heikki H. Malte F., 2010). Jeppesen Marine, an American company, has launched the "Navigation and Ship Optimization System" software, which can calculate CO<sub>2</sub> emission reduction and greatly reduce ship fuel consumption by optimizing routes and choosing appropriate speeds. The energy efficiency monitoring system developed by Marorka can monitor the ship's performance parameters and form an optimal route, speed and trim scheme based on the voyage data and in combination with the results of voyage planning, route characteristics, fuel consumption assessment and voyage cost analysis, so as to reduce the vessel's navigation resistance and energy consumption. The energy efficiency optimization module developed by NAPA company can plan the optimal route and speed according to updated wind, wave and flow information, and provide the optimal loading scheme. In addition, SeaTechnik's Ship Energy Efficiency Monitoring system monitors ship performance and navigation data in real time, analyzes key performance indicators and trends online, and optimizes ship performance in real time for effective navigation in a variety of navigation environments. Besides, ABB, Kyma and other companies have also developed the corresponding integrated monitoring system for ship energy efficiency to achieve the monitoring and optimization of ship energy efficiency.

Current research on integrated management of energy efficiency control system was still in the stage of design, there is no uniform standard on the ship data on-line monitoring and energy efficiency data storage rules, data communication transmission

cost being higher, and the data parsing process is complex. There is no mature products and application of technology considering the low data utilization rate.

## **2.2 Application of Data Mining and intelligent algorithm to ship energy efficiency optimization**

In recent years, big data technology has become a hot research and application field in science and technology because of its advantages such as revealing objective laws fully and accurately, and not relying on accurate mathematical models. Big data technology is a technology to obtain more potential knowledge through the analysis and mining of a large number of various types of data to assist information acquisition and decision-making (Xie H. He Y. & Xie X., 2017). Big data processing technologies mainly include big data collection, big data storage, big data analysis and mining, and big data display and visualization technologies (Wren, & Kathy., 2014). The Platform for Action to Promote the Development of Big Data and the National Big Data Strategy issued by the Chinese government will further promote the development of big data and its application in various fields. Big data-based analysis methods and auxiliary decision-making will play an important role in future research and industrial applications (Kwon, O. , Lee, N. , & Shin, B., 2014). With the development of big data technology, its application in the shipping industry has become possible. In recent years, people in the industry have been actively studying shipping management optimization methods based on big data analysis technology. In July 2014, Japan Ship Technology Research Association began to carry out the work of "big data roadmap" for ships. Through collecting a large number of data related to ship navigation and operation, it aims to make applications available in energy efficiency optimization, ship design, system remote maintenance and other aspects. In addition, American Bureau of Shipping, Ningbo Port and Navigation Administration, Ministry of

Transportation and Maritime Administration and other organizations try to apply big data analysis technology in classification service, market transaction and safety emergency management. In addition, Maersk Line, as a representative of the application of big data technology in the industry, introduced a new service model and management concept based on the large amount of data obtained through information technology analysis, thus greatly enhancing its core market competitiveness.

The application prospect and development trend of big data analysis was discussed, including the current and future hardware development trend as well as application-oriented software technology and development trend (A, K. K., et al., 2014). The broad prospect of ocean big data and its management was expounded, the key methods and models of ocean big data, introduced the management architecture based on engineering examples, and analyzed the problems and challenges faced by ocean big data was summarized (Huang, D., et al., 2015). In addition, the challenges and opportunities faced by the application of big data technology in shipping was analyzed, and proposed that big data analysis could be used for ship decision support, ship performance analysis and ship optimization management (Rodseth O. J., Perera L. P., Mo B., 2016). In addition, Perera et al. focused on optimizing ship energy efficiency by using machine intelligence, including big data pretreatment and post-processing technologies (Perera, L. P., & Mo, B., 2016).

Intelligent energy efficiency management, as an important part of the intelligent ship specification system, aims to realize real-time monitoring, intelligent assessment and optimization of ship energy efficiency, and realize intelligent decision-making of ship energy efficiency through big data analysis and intelligent algorithm development, so as to improve the level of ship energy efficiency. Among them, intelligent algorithm based on data analysis is the core of intelligent energy efficiency management. In recent years, machine learning algorithms represented by neural networks have been applied in intelligent assessment and decision-making of ship energy efficiency. An artificial neural network model for evaluating the energy efficiency of ships by using

the energy efficiency data collected by real ships was established, and the model verification based on the measured data was carried out (Yan, X., Sun, X., & Yin, Q., 2015). Aiming at an oil tanker, a model and system for energy efficiency prediction and decision making based on artificial neural network using multiple daily report data was established (Besikci, E. B., et al., 2016). The support vector product method was adopted to achieve the evaluation of the ship operating energy efficiency, and the effectiveness of the method through an example was verified (Pagoropoulos A, Møller A H, McAlloone T C., 2017). In addition, swarm intelligence algorithms, such as genetic algorithm and particle swarm optimization algorithm, have also been applied in the optimization of ship energy efficiency (Ma R. Q., et al., 2018). The multi-objective particle swarm optimization algorithm was adopted to solve the established multi-objective optimization problem of ship energy consumption and service level, and achieved good results (Lee, H., et al, 2018).

Though, the relevant scholars have explored the application of intelligent algorithm on intelligent decision of ships' energy efficiency, there is still need to further improve the calculation accuracy and real-time performance of the algorithm, ensure to achieve the dynamic optimization in the process of Marine shipping, at the same time, more in-depth study of intelligent algorithm in the actual engineering application validation effect is needed, in the process of design verification plan to ensure the accuracy of intelligent algorithm. In addition, big data theory needs to be further used to refine the relationship between ship energy efficiency data. Through data standardization and correlation analysis, energy efficiency indicators conducive to shipping enterprise management are proposed to provide data support for operational decisions aimed at improving ship energy efficiency and promote the development of intelligent ship energy efficiency management.

### **2.3 Research on model and Method of Ship energy efficiency optimization**

At present, the modeling method of energy efficiency in ship operation is mainly to establish the relationship between ship speed and fuel consumption by theoretical formula according to the matching relationship between ship, machine and propeller,

and further verify and optimize the model by combining the test data of ship diesel engine or the measured data in actual operation. A general ship energy system model was established, the interaction mechanism between ship speed, fuel consumption and energy efficiency was analyzed and applied to ship energy consumption assessment and operation characteristics analysis (Tillig, F., et al., 2017). The energy efficiency evaluation model of ship power plant based on EEOI and the law of conservation of energy was established, taking VLSMT as the research object (Osses, J. R. P., Bucknall R. W. G., 2014). In addition, navigable environmental factors such as wind, wave and current, as well as ship navigation state and other factors can affect the energy consumption of ships. Therefore, comprehensive consideration of the influence of all factors is crucial to improve the accuracy and practicability of ship energy efficiency model. The impact of navigation environment factors on ship fuel consumption by using the three-dimensional modified iso-current-time line method was analyzed, and the ship speed optimization method was studied (Lin, Y. H., Fang, M. C., & Yeung, R. W., 2013). An easy-to-use semi-empirical ship performance prediction model was proposed, which can predict the ship operating state under different drafts, speeds and course conditions, thus effectively helping ship operators to analyze the relationship between ship fuel consumption and various navigation environments and course conditions (Lu, R., et al., 2015).

In terms of speed optimization, the impact of speed optimization on operating costs and pollutant emissions of various ships was analyzed (Lindstad, H., Asbjørnslett, B. E., & Strømman, A. H., 2011). It verifies the huge potential of energy saving and emission reduction brought by speed optimization in the shipping industry, which can reduce the emission of pollution gas by about 19% without increasing the operation cost. A series of ship speed optimization models was discussed, which take ship speed as decision variable and improve ship energy efficiency and then reduce CO<sub>2</sub> emissions by optimizing ship speed (Psaraftis H. N., Kontovas C. A., 2013). The fuel consumption and corresponding CO<sub>2</sub> emissions of different ship types was also studied (Chang, C. C., & Chang, C. H., 2013). The results show that the CO<sub>2</sub> emission can be reduced by 19%, 36% and 51% respectively when the speed is reduced by 10%, 20%

and 27.1%.

Route optimization is under the premise of ensuring the safety of the ship, to improve the economic efficiency of ship operation by comprehensively considering the ship's navigation performance, navigation safety, operating state, navigation requirements and other factors, and the optimal route of the ship is planned according to the navigation environment and other information of the ship's navigation area (Gershanik, V. I., 2011). A route optimization model based on Dijkstra algorithm on the basis of mechanism analysis was proposed, and the effectiveness of the algorithm and model through experiments was verified (Debabrata, Sen, Chinmaya, P., & Padhy., 2015). A new dynamic programming method for meteorological alignment to minimize the fuel consumption of ships was proposed (Shao, W., Zhou, P., & Thong, S. K., 2012). Compared with the traditional method, this method not only optimizes the ship's course, but also optimizes the ship's power. The results show that this method can reduce ship fuel consumption by 3.1% and also the sailing time can be reduced. The shipborne meteorological alignment system was studied, and the ship response model adopted taking into account the influence of various navigation environments to obtain optimized ship routes under different circumstances. With the development of related technologies, joint optimization of flight speed and route will achieve better optimization results (Vettor, R., & Guedes Soares, C., 2016).

Although scholars at home and abroad have done related research on optimizing ship speed and route, the priority is still given to theoretical analysis and mechanism study. For intelligent ships, speed and routes optimization should be achieved by combining a ship voyage plan, employing the prototype monitoring parameters, and the practical situation of ship operators. To establish a more perfect optimization model, more consideration should be given to shipping actual control principle, the integration of optimization results into ship navigation control, to further improve the level of intelligence.

To sum up, ship energy efficiency is the result of the comprehensive action of various information factors, while the knowledge about the influence of different information factors on ships is scattered. Moreover, due to the complexity of the mechanism, the



system of various influential information factors on ships is absent. In addition, in order to reasonably and comprehensively analyze the impact of various information elements on ship energy efficiency, it is necessary to deeply dig and analyze various information elements, but there is still a lack of reasonable theories and methods. On the other hand, the research and application of energy efficiency management and control system is an effective way to comprehensively improve the energy efficiency of ships, while mature technical products and their popularization and application have not yet been formed in China. In addition, with the continuous development of big data, artificial intelligence, machine learning and other technologies, as well as the implementation of "E- navigation" strategy, the research and application of intelligent energy efficiency management technology for intelligent ships will be an irresistible trend. Intelligent optimization of ship energy efficiency should be based on a variety of information and real-time dynamic optimization model to realize automatically decision; therefore, ship energy efficiency of intelligent optimization algorithm research needs to be conducted.

#### **2.4 Optimization management method for ship energy efficiency**

Ship energy efficiency management refers to measures and activities related to the management and optimization of ship energy consumption, energy use efficiency and carbon dioxide emissions. It usually includes formulating energy efficiency policies, targets, energy efficiency planning, energy efficiency control and energy efficiency improvement, etc. The key is how to develop the evaluation index of ship energy efficiency, explore the basic methods and technologies for the improvement of ship energy efficiency, and establish a comprehensive energy efficiency management system, so as to further improve its energy efficiency and reduce emissions, and to achieve the ultimate goal of ship energy conservation and emission reduction. In recent years, the study of exploring ship energy efficiency management measures in the shipping industry has gained great popularity. IMO has been actively promoting and

adopting technical and operational measures to reduce greenhouse gas emissions from ships, actively exploring vessel energy efficiency evaluation indicators and energy efficiency management methods, and taking measures from technical and operational management aspects to control vessel pollution gas emissions.

As an index to measure the energy efficiency of new ships, EEDI lays a foundation for the analysis and optimization of energy efficiency of ships. Based on the analysis of EEDI calculation formula, in order to meet the constantly improving energy efficiency requirements, the future ship type will bear the characteristics of low resistance, new energy utilization and clean energy power propulsion system. (Rehmatulla, N., Calleya, J., & Smith, T., 2017). The ship drags reduction method, design and application technology of new energy saving device involved are effective ways to reduce fuel consumption of ships and improve energy efficiency of ships.

According to the analysis of EEOI, reducing CO<sub>2</sub> emission level of ships is mainly to reduce fuel consumption per unit distance of ships (Geertsma, R. D., et al., 2017). The energy consumption of the main engine is directly related to the operating efficiency of the propulsion system and the ship's resistance, while the energy consumption of the auxiliary engine is closely related to the operating state of the equipment (Schiller, R. A., et al., 2017). Therefore, the application of the optimization design and control technology of the main propulsion system, as well as the comprehensive management and control of the key energy consumption equipment of the ship are the key to the improvement of the energy efficiency of the ship operation (Zhao, F., et al., 2016. Jun, H., Jing, S., & Hofmann, H. F., 2017). The combined application of multiple measures, such as joint optimization of airspeed routes, can effectively improve ship energy efficiency (Ballou, P., Chen, H., & Horner, J. D., 2008). In the specific implementation process, energy efficiency improvement measures and methods often encounter certain problems and obstacles (Rehmatulla, N., & Smith, T., 2015). Therefore, how to choose appropriate energy efficiency improvement methods and formulate reasonable energy

efficiency management plans for ships are the key to improving energy efficiency of ships (Armstrong, Victor, N., Banks, & Charlotte., 2015. Bouman, E. A., et al., 2017). The Guidelines for The Development of SEEMP formulated by IMO provides technical support for the design of systematic ship energy efficiency management plan. It aims to improve ship energy efficiency through four steps: planning, implementation, monitoring and self-assessment. In the planning and implementation stage, the technical measures and operational measures for improving the ship's energy efficiency should be fully considered. In the monitoring phase, if EEDI is used, calculation and verification shall be conducted according to IMO requirements or the requirements of the competent authority. Before ships are put into use, their energy efficiency and carbon dioxide emission targets should be effectively reviewed and validated. If using EEOI, collect and calculate fuel type and quantity, sailing distance, cargo type and other information according to relevant documents required by IMO; In the stage of self-assessment, factors affecting ship energy efficiency should be reasonably analyzed and measures should be taken to improve the energy efficiency. In conclusion, the core of the ship energy efficiency management system lies in formulating scientific and reasonable energy efficiency management plan, clarifying energy efficiency targets and indicators, establishing effective monitoring and supervision mechanism, and taking measures to continuously improve the ship energy efficiency. By establishing the energy efficiency management system and adopting the corresponding monitoring tools, the ship energy efficiency can be optimized step by step, thus promoting the energy conservation and emission reduction in the shipping industry.

## **Chapter III Research foundation and methodology**

### **3.1 Foundation of research**

#### **3.1.1 Collection scope of energy efficiency data**

a) Data to be collected under THE MRV regulations of the EU, including departure and arrival time and port name, consumption and emission coefficient of each fuel, sailing distance, sailing time, cargo load, applicable ship ice class and ice area navigation information, etc., among which:

(1) Port of call. Only refers to the port for loading and unloading of goods or passengers from the ship during stay in port, not including those for refueling, only getting supplies, the crew shifts, entering the dry dock, or for the repair of ship and/or repair the equipment

(2) Fuel and emission factor. Generally, Marine fuel is divided into heavy oil, light oil and diesel oil. For the sake of convenient management, shipping companies generally only have two kinds of fuel oil on board at present, namely high-sulfur heavy oil used in non-emission-control area and low-sulfur light fuel used in emission control area.

(3) The sailing distance can be the most direct route distance or the actual sailing distance between the port of departure and the port of arrival. If the nearest straight-line distance between the port of departure and the port of arrival is used, conservative correction coefficient should be considered to ensure that the sailing distance, in nautical miles, will not be seriously underestimated. The algorithm of sailing distance in this study USES the great circle distance of 2 GPS coordinate points, which is calculated automatically every 10 minutes, and automatically accumulates the sailing distance per hour, the sailing distance per day, and the voyage distance of the section in turn. If the ship moves with the tide during anchoring, the ship will also generate

displacement, but this displacement is not included in distance statistics, that is, the speed is less than 2 knots, and the distance is not calculated.

(4) Voyage time, generally refers to the voyage time of the ship.

(5) Cargo capacity, which is the weight of the cargo carried by the ship, is expressed in metric tons or standard cubic meters. The measurement units used by different types of ships in the trade are different, and usually metric tons are used to indicate cargo capacity.

b) International Maritime Organization requirements for energy efficiency data collection. The Voluntary Guidelines for the Use of Vessel Energy Efficiency Operating Index (EEOI) formulated by the International Maritime Organization (IMO) specify the collection scope of energy efficiency data, such as fuel consumption, cargo load and voyage distance, which are based on voyage or day, and are currently adopted by shipping companies. Data collection mechanism of environmental protection will determine the class of 69, need for annual cycle of measurement data include fuel consumption, distance and time main information, such as other ship regular parameters such as IMO number, gross tonnage, net tons, deadweight tons, the main auxiliary power, energy efficiency design index and ice information etc., but does not include the actual shipment information.

### **3.1.2 Method of data collection**

Whether it is the MRV regulation of the EU or the IMO, the core content of energy efficiency data collection is fuel consumption data, so the key research should be done.

#### ***3.1.2.1 Fuel metering method of EU MRV regulations***

There are four methods, including fuel supply order (BDN) and tank regular measurement, onboard tank monitoring, flowmeter monitoring of combustion process,

and direct measurement (CO<sub>2</sub>) emission.

(1) Fuel supply order (BDN) and tank regular measurement

Calculation method of fuel consumption:

$$FC = \sum (FC_{1j} - FC_{2j} + FC_{3j} - FC_{4j}) \quad (3-1)$$

Where,

- FC refers to fuel and fuel consumption in the metering period;
- FC<sub>1j</sub> is the fuel storage of the JTH fuel at the beginning of the metering cycle;
- FC<sub>2j</sub> is the fuel storage of the JTH fuel at the end of the metering cycle;
- FC<sub>3j</sub> is the JTH fuel filling amount in the metering cycle;
- FC<sub>4j</sub> is the JTH fuel in the metering cycle.

The measurement period includes the time between two ports of call or in-port time (i.e., sailing time plus in-port time). The BDN is mandatory under current MARPOL annex VI, and the rules require that records be kept on board for three years after refueling and available at any time.

(2) Onboard tank monitoring

$$FC = \sum (FC_{d1j} + FC_{d2j} + FC_{d3j} + FC_{d4j} + \dots) \quad (3-2)$$

Where,

FC<sub>d1j</sub> is the sum of the tank reading difference between the first day and the second day of the JTH fuel in the metering cycle;

FC<sub>d2j</sub> is the sum of the tank reading difference between the second and the third day of the JTH fuel in the metering cycle;

...

This method is based on all tank readings on board. When the ship is at sea, the tank readings shall be recorded every day. It is necessary to specially record the tank

readings related to refueling or refueling.

(3) Flow meter monitoring of combustion process

$$FC = \sum (FC_{mj} + FC_{aj} + FC_{bj} + \dots) \quad (3-3)$$

Where,

- $FC_{mj}$  is the JTH fuel consumption of the main engine;
- $FC_{aj}$  is the JTH fuel consumption;
- $FC_{bj}$  is the JTH fuel consumption of boiler.

This method USES fuel flow meter to measure fuel consumption of energy consumption equipment on board. The energy consumption data of all flowmeters are combined to determine the total fuel consumption over a specific period (metering cycle).

(4) Direct measurement of (CO<sub>2</sub>) emissions

CO<sub>2</sub> emissions are calculated by measuring exhaust flow and concentration. To adopt this method, it is necessary to install the measuring equipment of waste gas flow and CO<sub>2</sub> concentration in waste gas in the waste gas discharge channel of energy consumption equipment. The measuring period can be determined according to the demand, and it can be measured according to the time interval such as voyage, port, voyage and voyage section.

The following formula can be used to calculate CO<sub>2</sub> emissions:

$$E = \sum (F_x \times C_x) \quad (3-4)$$

Where,

E is the total CO<sub>2</sub> emission (unit: ton/hour, depending on the unit setting of the measuring instrument);

$F_x$  is the exhaust emission flow of energy-consuming equipment X (unit: m<sup>3</sup>/h, depending on the unit setting of the measuring instrument);

$C_x$  refers to the CO<sub>2</sub> concentration in the waste gas emitted by energy-consuming

equipment X (unit: T /m<sup>3</sup>, depending on the unit setting of the measuring instrument); X is energy dissipation equipment, such as main engine, auxiliary engine, boiler, etc. Using this method, it is necessary to measure the CO<sub>2</sub> concentration and exhaust flow in the waste gas emitted by energy-consuming equipment simultaneously, so as to accurately calculate the CO<sub>2</sub> emission at the monitoring time. Moreover, continuous and continuous measurement is required. The higher the frequency of data collection and the shorter the interval, the more accurate the calculated CO<sub>2</sub> emissions will be. This method can be used to calculate fuel consumption by dividing CO<sub>2</sub> emission by the corresponding fuel emission factor.

### ***3.1.2.2 IMO requirements for energy efficiency data collection***

The IMO has no clear requirements on energy efficiency data collection methods, and only recommends using existing ship records such as engine log and ship log, in order not to increase the burden on the crew. The analysis and study of the existing sources of Marine turbine and logbook data are basically consistent with the methods mentioned in the EU regulations (excluding the direct measurement of CO<sub>2</sub> method).

### ***3.1.2.3 Fuel consumption measurement method selection***

Considering the requirements of real-time monitoring and energy efficiency assessment, this study adopts the flowmeter monitoring method of combustion process. At the same time, considering the needs of the company, the data entry module is provided, which is applicable to the company's demand for recording the results obtained from the fuel supply bill (BDN) and periodic tank measurement as well as the onboard oil measurement.



### **3.1.3 Energy efficiency evaluation index**

For the operation ships, energy efficiency evaluation index applied in the industry include consumption and emission per unit transport function, energy consumption and emission per unit distance, energy consumption per unit cargo capacity, energy intensity, kilogram standard coal per thousand tons nautical miles and other indicators. Different indicators have different evaluation purposes.

### **3.1.4 Carbon emission factor**

Both THE EU MRV regulation and THE EEOI recommended by IMO involve the CO<sub>2</sub> conversion factor, that is, the emission factor. Different emission factor values have been proposed by intergovernmental Panel on Climate Change (IPCC), IMO and domestic and foreign research institutions, which can be classified into three types: IPCC emission factor (recommended by THE MRV regulations of the European Union), IMO emission factor and dynamic factor based on installed ship capacity (HEREINAFTER referred to as dynamic factor). Different sources of the three emission factors lead to different quantitative results.

#### ***3.1.4.1 IPCC emission factors***

IPCC emission factors include carbon content per unit calorific value and carbon oxidation rate factor. In order to facilitate the calculation, IPCC established the Emission Factor Database (EFDB), which is widely used in the field of greenhouse gas calculation and is the emission factor adopted by the European Union Carbon Emission Trading System (EU-ETS). At present, this factor is widely used in carbon emission accounting of chemical industry and steel industry in China, but it has not been used by water transport enterprises in China. It should be noted that when using

the calorific value of fuel oil, it is necessary to pay attention to whether it is industrial fuel oil or ship fuel oil. Calorific value of fuel oil is shown in Table 3-1.

Tab. 3-1 Default values of fuel oil related parameters

Fuel type	The measuring unit	Low calorific value	Carbon per calorific value	Fuel carbon oxidation rate	
Liquid fuels	Fuel oil (water transport)	Ton	40190 kJ/kg	20.1 t-C/TJ	0.98
	Fuel oil (industrial)	Ton	41816 kJ/kg	21.1 t-C/TJ	0.98

#### 3.1.4.2 IMO recommended emission factor

Different types of fuel emission factors are not in same, as shown in Table 3-2:

Tab. 3-2 Conversion coefficient between fuel volume and CO<sub>2</sub> volume (Source: IMO MEPC.1/ CIRC.684)

Fuel type	Reference	Carbon content	Cf (T-CO <sub>2</sub> / T-fuel)
Diesel/gasoline	ISO8217 DMC to DMX	0.875	3.206000
LFO	ISO8217 RMA to RMD	0.86	3.151040
HFO	ISO8217 RME to RMK	0.85	3.114400
LPG	Propane and butane	0.819 0.827	3.000000 3.030000
LNG		0.75	2.750000

#### 3.1.4.3 Suggestion of carbon emission quantification method

Through the calculation and analysis of IPCC factors and IMO factors, it can be found that:

(1) Based on the IPCC emission factor of carbon emissions quantification method, it is not only the fuel consumption, and the quality of the fuel (fuel of low calorific value) that is to be considered, but also the carbon fuel oxidation rate value (0.98), this method has more scientific quantitative process, more reasonable quantitative results and less quantitative values.

(2) Based on IMO carbon emission factor of quantitative method, only the fuel consumption and emission factors are considered, and the quantitative method is simple, the cost of enterprise statistical quantification is low, but without attention to two or more things governing fuel quality and fuel oxidation rate, the quantitative result is larger, the measuring accuracy is not high; this method applies to emission results statistical simple and with low cost.

## **3.2 Methodology**

### **3.2.1 Analysis and evaluation of ship energy efficiency**

The state of energy efficiency of a ship is to describe the efficiency of energy utilization shown by the ship and its equipment in the process of completing its functions. The energy consumption equipment of a ship mainly includes the main engine, auxiliary engine and boiler. The energy efficiency status of the main engine and auxiliary engine can use fuel consumption rate (g/kW.h) as a parameter to represent their energy efficiency status, while the boiler can use fuel consumption rate (g/h) as a parameter to represent its energy efficiency status. Figure 3-1 shows the navigation data chart of a complete voyage of a ship.

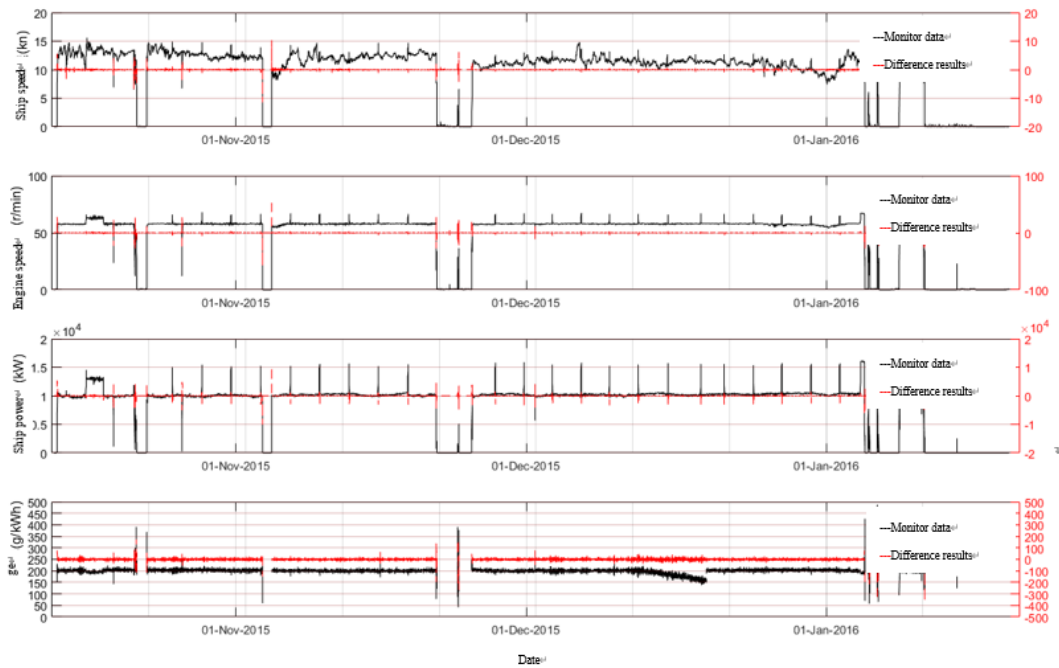


Fig. 3-1 Overview of navigation data

It can be seen from Figure 3-1 that the fuel consumption rate of the main engine is significantly affected by the navigation status of the ship during navigation: when the ship is in the process of maneuvering or acceleration and deceleration, the rotation speed fluctuation of the main engine increases, leading to a significant increase in the fuel consumption rate of the main engine. The fuel consumption rate of the main engine monitored in such cases does not reflect its level of energy efficiency and should therefore be eliminated through navigational state judgment.

The performance of diesel engine in working process is the focus of energy efficiency analysis. Figure 3-2 shows the scatter diagram of fuel consumption rate and host power. As can be seen from Figure 3-2, the data of fuel consumption rate fluctuates greatly in the range of 0~8000kW and is distributed in the range of 0~500g/kW.h. Within this power range, the ship is generally in the state of maneuvering navigation and the host machine is unstable, so the fuel consumption rate also fluctuates greatly. When the power of the main engine exceeds 8000kW, the ship is in the state of constant speed

sailing. At this time, the fuel consumption rate is more stable and converges within a certain range.

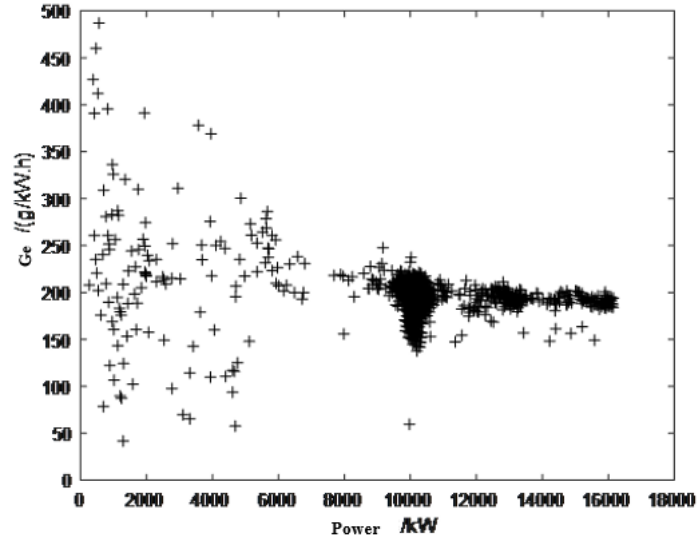


Fig. 3-2 Scatter distribution of fuel consumption rate

The target data sets are grouped into 3 categories, which correspond to the normal sailing state ( $n_e=58$  r/min), the state of increasing speed ( $n_e=63$  r/min) at the beginning of the voyage (near 2015-10-17), and the accelerated state of regular washing ( $n_e=66$  r/min). The clustering centers of each working condition point are shown in Table 3-3:

Tab. 3-3 Cluster centers of each working condition point

Working condition	Ship speed (kn)	Main engine speed (r/min)	Main Engine power (kW)	Fuel consumption rate of main engine (g/kW.h)
1	11.7	58	10156	199.8
2	13.4	63	15468	194.0
3	13.0	66	12895	189.6

In the existing method of using fuel consumption and power correspondence as the baseline to evaluate the diesel engine status, quadratic polynomials are generally used to fit the monitoring data. However, this fitting requires at least three kinds of monitoring data of the normal operating conditions of the host to be able to carry out.

By further analyzing the monitoring data of energy consumption equipment of other similar ships, it is found that it is common for ships to use only one main engine for constant speed navigation in the whole voyage, which makes it impossible to use the existing baseline method, that is, to establish a baseline through the corresponding relationship between fuel consumption rate and power and further describe the energy efficiency status of diesel engines. Therefore, it is necessary to unify the fuel consumption rate of diesel engine in different working conditions to the same working condition.

### **3.2.2 Ship trim optimization**

Best trim is recommended by the international maritime organization (IMO) ship energy conservation and emissions reduction technology, and its basic principle is: all the factors such as the ship sailing speed, water resistance of displacement, the influence of the draft and trim angle, by adjusting the float state of structure, the change of ship sailing underwater shape, then the wave, ship wet surface area, the ship stem to flow, the stern to flow, have influence on resistance of ship sailing, so choose a good voyage floating state can effectively reduce the hull resistance, reduce the host power demand.

Ship best trim technology at home and abroad based on the full analysis on the basis of research and product, the numerical simulation calculation and experimental test resistance prediction technology, the whole life cycle of building covering ship operating trim map, and designed a kind of relatively effective adaptive optimization algorithm, in order to quickly calculate the float state any conditions optimum trim, to form operation best trim decision-making system of the ship. The green shipping solution provided to shipowners can effectively reduce the power demand of the main engine, save fuel consumption and reduce carbon emissions by reasonably changing

the ship's operating habits, so as to realize the green intelligent decision support and refined management of the ship's operation in the whole life cycle of the ship's operation.

### **3.2.3 Optimization of ship energy efficiency**

Ships usually select circular navigation lines during the oceangoing voyages to shorten the navigation distance and sailing time. However, this method may not be the most fuel-efficient way for the ship navigation due to the influence of meteorological conditions on the fuel consumption. The ship energy consumption is influenced by the meteorological and marine environmental factors. Therefore, it is possible to find the optimal sailing route corresponding to the lowest fuel consumption by considering the real-time environmental factors. On the other hand, the fuel consumption is influenced largely by the speed of the ship under different environmental conditions. The energy efficiency has an approximate quadratic relationship with the sailing speed of the ship. Therefore, it is also necessary to determine the optimal sailing speed under different navigational conditions to ensure the optimal energy efficiency level under different operational conditions. The optimization degree of a single optimization method is limited and the joint optimization of sailing route and speed can further improve the ship's energy efficiency level. Therefore, a joint optimization method of sailing route and speed considering the real-time marine meteorological conditions is proposed, in order to achieve better optimization result of ship energy efficiency. The illustration of the proposed joint optimization method is shown in Fig. 3-3.

The data acquisition is an important part for the joint optimization of sailing route and speed. The energy efficiency data of the ship is obtained by the sensors installed on the ship. Among others, the fuel consumption data is obtained by the fuel flow meter, the voyage data is obtained by the odometer, the shaft power data is obtained by the

shaft power meter and the longitude and latitude data is obtained by the installed GPS instrument. At the same time, the real-time meteorological information, including wind speed and wind direction as well as the wave height, is obtained from the European Centre for Medium-Range Weather Forecasts. Subsequently, a fuel consumption model considering environmental factors can be established based on the obtained data. Then, the ship navigation area is meshed according to the longitude and latitude values, and the real-time marine meteorological information for different grid positions can be obtained. After that, a joint optimization model of sailing route and speed is established. The optimization model aims to determine the optimal grid position and the corresponding sailing speed within the time limit of the ship's schedule. In this way, the joint optimization of the speed and route can be realized through the intelligent optimization algorithm. Finally, the proposed joint optimization method can be validated by a case study.

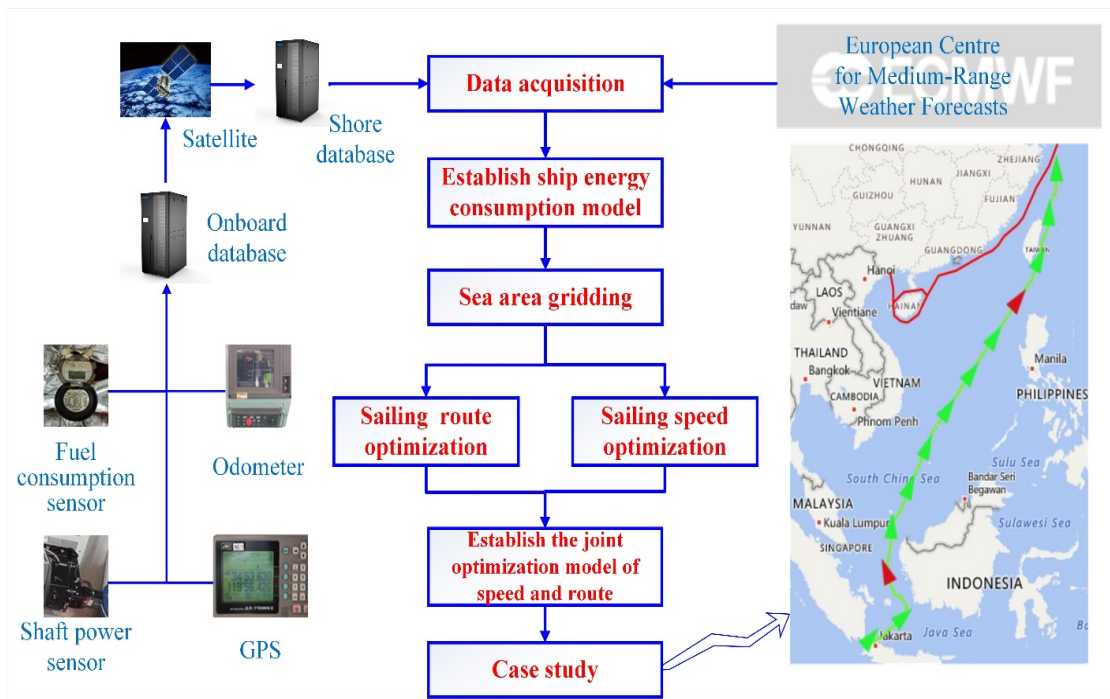


Fig. 3-3 Illustration of the joint optimization method

The joint optimization processes are illustrated in Fig.3-4. When the voyage area is



divided into  $M$  parts in the latitude direction, the decisions of the sailing route and efficient speeds will include  $2M-3$  dimensions of optimization variables. These variables include  $M-2$  dimensions of the optimal sailing speed between the two adjacent grids and  $M-1$  dimensions of the sailing positions of these grids. The constraints include the sailing time, position and sailing speed of the ship. The sailing time and fuel consumption are the nonlinear function of the variables of sailing speed and sailing positions of the grids. Therefore, the joint optimization of sailing route and speed is a multi-constraints and variables nonlinear optimization problem.

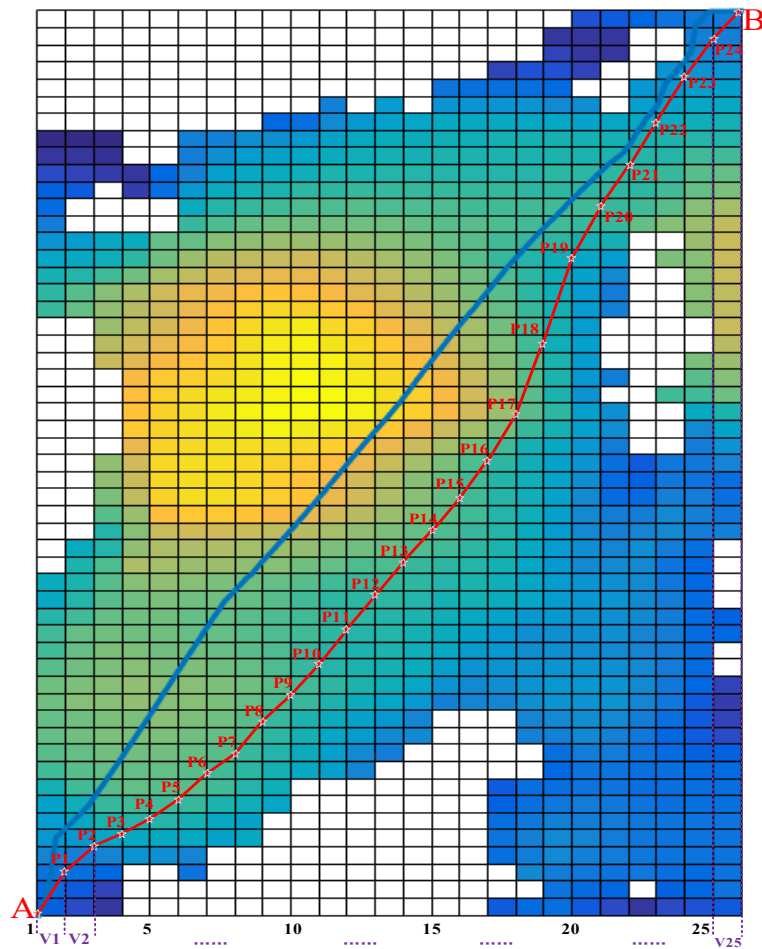


Fig. 3-4 Schematic diagram of joint optimization processes

In recent years, scholars have proposed a variety of intelligent optimization algorithms to solve the complex nonlinear optimization problems, such as ant colony algorithm,

simulated annealing algorithm and particle swarm optimization (PSO) algorithm. Among others, PSO algorithm is a new intelligent optimization technology, which is suitable for solving dynamic and multi-objective optimization problem. Compared to other optimization algorithms, PSO algorithm has the advantage of faster calculation speed and better global search ability. Therefore, the PSO algorithm is adopted to solve the joint optimization model of sailing route and speed in this thesis.

### 3.3 Data content

Data in this study include ship and equipment parameters, operation monitoring data and user manual input data. The information used in the study is shown in Table 3-4-Table 3-6.

Tab. 3-4 Ship and equipment parameters

No.	Parameter	Unit	No.	Parameter	Unit
1	Line length	m	13	Number of cylinders	
2	perpendiculars	m	14	stroke	mm
3	The beam	m	15	Propeller blade number	
4	Type deep	m	16	Blade diameter	m
5	The design draft	m	17	Pitch ratio	
6	Square coefficient		18	Area ratio	
7	Service speed	kn	19	The moment of inertia	kg · m <sup>2</sup>
8	Designed deadweight ton	t	20	The weight of the	kg
9	The host model		21	Maximum sustained power	kW
10	stroke		22	The cylinder diameter	mm
11	Maximum output	kW	23	Density of sea water	kg / m <sup>3</sup>

12	Orthographic area of ship	m <sup>2</sup>	24	Air density	kg / m <sup>3</sup>
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Tab. 3-5 Operational monitoring parameters

No.	Item	Unit	No.	Item	Unit
1	Ground speed	kn	7	Wind speed	m / s
2	The water speed	kn	8	Wind direction	°
3	Ship's course	°	9	Engine fuel flow	m <sup>3</sup>
4	The host power	kW	10	time	
5	The host torque	N · m	11	Ship's longitude	°
6	Main engine rate of revolution	r / min	12	Ship's latitude	°

Tab. 3-6 User input data

No.	Item	Unit	No.	Item	Unit
1	The wind speed	m/s	7	Wave height	m
2	The direction of the wind	°	8	Wave direction	°
3	The velocity	m/s	9	voyage	n mile
4	flow	°	10	Sailing schedule	
5	Departure port		11	longitude	
6	Arrival port		12	latitude	

Among them, ship and equipment parameters are derived from ship data such as instructions and used in the establishment of corresponding models; The operation monitoring parameters are derived from the monitoring data in the online intelligent management system for ship energy efficiency, which transmits and stores the data recorded by each sensor to the database, and extracts and processes the data from the corresponding database for use during the research. User input data is in the navigation forecast of speed optimization, which requires the user to input segmental information and forecast meteorological information according to the navigation plan. Since a ship's voyage is as short as 20 days and as long as one or two months, the long-term accuracy of meteorological information cannot be guaranteed. Therefore,

meteorological information needs to be updated gradually to make the input of speed optimization as close to the actual situation as possible.

## Chapter IV Analysis and evaluation of ship energy efficiency

### 4.1 Research on navigational state judgment methods

In the course of a voyage, the sailing state of a ship includes berthing, maneuvering and constant speed sailing. In the berthing state, the value of ship speed, host speed and host power should be 0, wherein the speed can be directly used to determine whether the ship is in the berthing state. For the actual collected data, sometimes the data drift is not equal to 0, but a value close to 0. Therefore, the threshold T1 is set as the standard to judge whether the ship is in berth.

For constant speed navigation and maneuvering navigation, the biggest difference lies in the constant speed navigation, the main engine speed keeps stable, while the motor speed fluctuation range is large when maneuvering navigation. Therefore, the different results of each parameter are made in Figure 3-1. It can be seen from the difference in the power of the main engine that the difference distribution of the constant speed sailing is around 0. When the ship is cleaning the turbocharger and maneuverable sailing, the power changes greatly. It can be seen from the difference of the main engine speed that when the ship sails at a constant speed, the difference of the speed is distributed around 0. When the ship is in the state of collision, although the difference of the main engine speed increases, it is obviously less than the difference value of the ship during the maneuvering. Therefore, threshold T2 can be used to judge whether the ship is in the maneuvering navigation.

When the actual statistical thresholds T1 and T2 are calculated, the data will be normalized first to make the results universal. For normalized data, T1=0.02 and T2=0.05 are generally taken.

## 4.2 Research on diesel engine fuel consumption correction method

### 4.2.1 Fuel density correction

Currently, the fuel flow meters installed in operating ships are generally volumetric flow meters, so the density modification is required according to the fuel temperature. The correction method is as follows:

$$\rho_{t_f}^4 = \rho_{t_f}^{20} - \alpha_f (t_f - 20) \quad (4-1)$$

Where,  $t_f$  is fuel temperature;  $\rho_{t_f}^4$  is the density of fuel oil at  $t_f$  °C relative to 4 °C pure water;  $\rho_{t_f}^{20}$  is the density of fuel oil at 20°C relative to 4 °C pure water;  $\alpha_f$  is the temperature correction coefficient, which can be inquired through Table 4-1.

Tab. 4-1 Fuel density temperature correction factor table

Relative density $\rho_4^{20}$	Temperature correction factor $10^4 \times \alpha, \text{ } ^\circ\text{C}^{-1}$	Relative density $\rho_4^{20}$	Temperature correction factor $10^4 \times \alpha, \text{ } ^\circ\text{C}^{-1}$
0.85~0.86	6.99	0.96~0.97	5.54
0.86~0.87	6.86	0.97~0.98	5.41
0.87~0.88	6.73	0.98~0.99	5.28
0.88~0.89	6.60	0.99~1.00	5.15
0.89~0.90	6.47	1.00~1.01	5.02
0.90~0.91	6.33	1.01~1.02	4.89
0.91~0.92	6.20	1.02~1.03	4.76
0.92~0.93	6.07	1.03~1.04	4.63
0.93~0.94	5.94	1.04~1.05	4.50
0.94~0.95	5.91	1.05~1.06	4.37
0.95~0.96	5.67	1.06~1.07	4.27

#### 4.2.2 Environmental modification of fuel consumption rate and methods for obtaining environmental parameters

Environmental corrections for diesel fuel consumption and power are made according to the method described in ISO3046:2002:

$$\begin{aligned}
 k &= \left( \frac{p_x}{p_{ra}} \right)^m \left( \frac{T_{ra}}{T_x} \right)^n \left( \frac{T_{cra}}{T_{cx}} \right)^s \\
 \alpha &= k - 0.7(1-k) \left( \frac{1}{\eta_m} - 1 \right) \\
 \beta &= \frac{k}{\alpha} \\
 P_x &= \alpha P_r \\
 b_x &= \beta b_r
 \end{aligned} \tag{4-2}$$

Where,  $p_x$ ,  $T_x$  and  $T_{cx}$  are the atmospheric pressure, air temperature and sea water temperature of the ship's position;  $p_{ra}$ ,  $T_{ra}$ ,  $T_{cra}$  is the atmospheric pressure, air temperature and sea water temperature in the standard state, whose values are  $1 \times 10^5$  Pa,  $25^\circ\text{C}$  and  $25^\circ\text{C}$  respectively; m, n and s are obtained according to main engine type, fuel type, etc.  $P_r$  and  $P_x$  are respectively the diesel engine power before and after modification;  $b_r$  and  $b_x$  are respectively the diesel fuel consumption rate before and after modification.

#### 4.2.3 Modification of fuel consumption rate

Based on the test data of diesel engine, according to the scatter relationship between fuel consumption rate and diesel engine power, the quadratic polynomial was used to fit the curve. Based on the fuel consumption rate at 75% power, the fuel consumption

correction coefficient due to power change is determined by using the proportional relationship between the power difference and the fuel consumption difference in the test results. The fuel consumption rate is corrected to the same working condition by using the coefficient.

### 4.3 Methods and analysis of meteorological data acquisition

In ISO3046-1:2002 environmental corrections for power and fuel consumption rates, atmospheric pressure, atmospheric temperature and sea water temperature are input parameters to the revised formula. At present, there are two methods to obtain meteorological parameters of ships: one is real-time collection by sensors on board ships and the other is marine environmental data obtained from meteorological information service agencies. It is found that some ship monitoring system databases do not contain sea state data. In such cases, external meteorological data can be used to complete the ship's sea condition data. Exogenous Weather Forecasts of the present study were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) 's Era-Interim Reanalysis Data Set. The data set covers the period from 1979 to the present and includes meteorological data for the atmosphere, ocean waves and land surface. The parameters in this data set that can be used to complete the ship's sea state data are shown in Table4-2.

Tab. 4-2 Exogenous meteorological parameters and their explanations

Parameters	Abbreviations	Unit	Instructions
Sea surface temperature	sst	K	Describe the surface temperature of seawater
Sea level atmospheric pressure	msl	Pa	Describe the ambient atmospheric pressure
Wind field component in the direction of longitude at 10m sea level	u10	m/s	Used to analyze ship wind load
The wind field component in the latitude direction at 10m from sea level	v10	m/s	Used to analyze ship wind load
Air temperature 2m above sea level	t2m	K	Describe ambient air temperature



Combined wave and swell characteristic wave height	swh	m	Used for analyzing ship's wave load
Mean wave direction	mwd	°	Used for analyzing ship's wave load
Mean wave period	mwp	s	Used for analyzing ship's wave load

These meteorological data are stored as geographic units in the same latitude and longitude grid points and the shape of the data grid points is approximately trapezoid. In the actual research, the ship's position is not exactly on the grid point, so it is necessary to interpolate the grid point data on the basis of the ship's actual position. As shown in figure 4-1, a certain period of time provided by the ECMWF local Marine meteorological data distribution as an example, the  $O(x_0, y_0, t)$  on behalf of  $t$  time coordinates  $(x_0, y_0)$  point of physical quantities,  $O_{i,j}$ ,  $O_{i+1,j}$ ,  $O_{i,j+1}$ ,  $O_{i+1,j+1}$  ( $x_0, y_0$ ) lattice point is the four corners of physical quantities, is  $O(x_0, y_0, t)$  according to the current coordinates to the four corners of the relative position and quantity is obtained by three-dimensional linear interpolation.

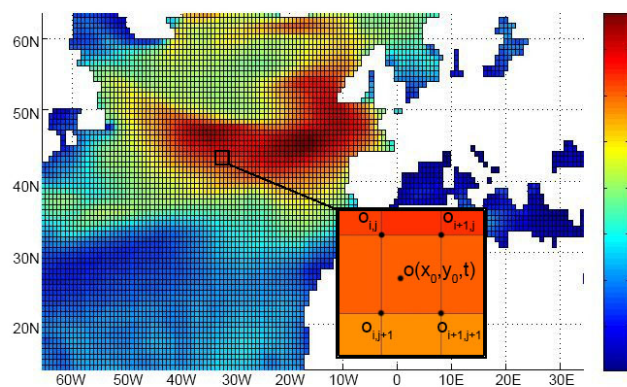


Fig. 4-1 Schematic diagram of meteorological data extraction

In the analytical data set, the frequency of meteorological data is four times per day (0, 6, 12 and 18 points). The data at each time point is taken as the average of meteorological parameters within 15 minutes before and after the corresponding time.

Since the time of meteorological data is discrete, interpolation in time is needed on the basis of spatial interpolation. The specific method is that after obtaining the spatial interpolation results using the method shown in Figure 6, time interpolation is carried out at the same position according to the current time.

The wave usually refers to the phenomenon of intra - water propagation caused by periodic vibration of seawater particles in the ocean by the action of wind, including waves, surges and near-shore waves. Wind wave is a state of sea surface fluctuation under the direct action of the wind. A swell is a wave left over the surface of the sea when the surface of the sea is moved from another part of the sea or when the local wind is reduced, calmed or changed. Inshore waves are waves that are transmitted from the sea to the coast and are affected by the topography.

In the current wave load studies, the wave characteristics are generally described by random wave spectrum and its influence on ship motion is described by amplitude response factor. In the wave spectrum, wave period and characteristic wave height are generally taken as inputs, which are modified into relative wave spectrum through wave direction and ship's relative motion.

#### **4.4 Research on generating methods of energy efficiency evaluation criteria for main engine based on box diagrams**

Figure 4-2 shows the box chart statistical method. In this method, Q1 is the upper quartile, which is the value at 25% when the data is arranged in increasing order. Q3 is the value of the data quantity at 75%.  $QR = Q3 - Q1$ , the quarter-space; Outliers are values less than  $Q1 - 1.5IQR$  (interquartile) or greater than  $Q3 + 1.5IQR$ . This method does not need to assume that the data is subject to a specific distribution form in advance, does not make any restriction on the data, and is based on the above lower quartile and quartile distance, and has good resistance to outliers.

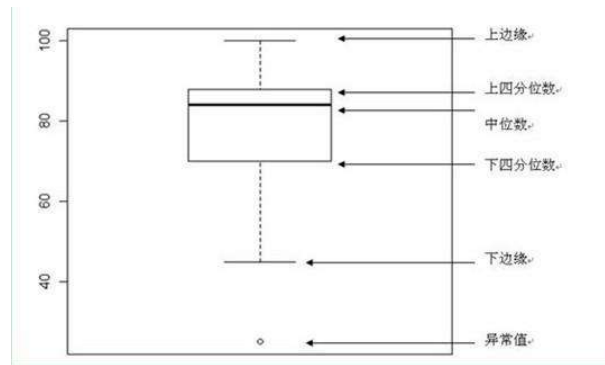


Fig. 4-2 Schematic diagram of box diagram

According to the principle of box graph, four boundary values and five intervals are formed. The first interval is from the upper quartile to the lower quartile, representing the range of 50% data distribution near the median of the overall data. In the energy efficiency status assessment, it is defined as the normal state of energy consumption when the real-time fuel consumption rate of ship equipment is within the interval. The second interval is from the upper edge to the upper quartile, which is defined as high energy consumption state and energy efficiency state deviation. The third interval is from the lower quartile to the lower edge, which is defined as low energy consumption state and good energy efficiency state. Greater than the upper edge or less than the lower edge are abnormally high and abnormally low energy consumption. A statistical method based on box diagram principle is used to generate a quantitative index of energy efficiency evaluation, which is not only the boundary of real-time energy efficiency evaluation, but also the result of post-evaluation of equipment energy efficiency. At the same time, the statistical boundary of the box diagram is used to form the energy efficiency evaluation interval to evaluate the energy efficiency of the equipment. The specific demarcation method is shown in Table 4-3.

Tab. 4-3 Energy efficiency evaluation of main engine

The state of energy efficiency	Status flag	Judgment method
--------------------------------	-------------	-----------------

Abnormal high -	ANH	Is greater than the upper bound
high	H.	Upper bound - Upper quartile
normal	N	Upper quartile - Lower quartile
low	L	Lower quartile - Lower bound
Abnormal low -	ANL	Less than the lower bound

According to this method, the revised fuel consumption rate is used as the data basis to generate the flight energy efficiency status assessment results when analyzing the status of each flight host and side function. When analyzing the energy efficiency state of each voyage boiler, the data of fuel consumption rate is directly used for statistics to obtain the result of energy efficiency evaluation.

## **Chapter V Ship trim optimization technology**

### **5.1 Forecast of navigation resistance of multi-floating vessels**

The core of ship trim optimization lies in the establishment of various ship float resistance and power databases covering common operating conditions and the correct optimization algorithm. Therefore, the accuracy of the resistance prediction will directly determine trim optimization, and the accurate optimization algorithm will give the optimal trim value under the current float state. In constructing trim resistance database in this thesis, numerical simulation and test, combined with CFD numerical simulation, is used to study from the mechanism analysis for hull trim change flow field, streamline distribution, wave, hull pressure distribution, the influence of such factors as tank test in CFD resistance prediction calculation comparison at the same time, as a result, more can guarantee the accuracy of the forecast results of resistance.

#### **5.1.1 Resistance prediction based on CFD numerical calculation**

Ship resistance is generally divided into two independent parts, namely, viscous resistance and wave-making resistance. The former is caused by the viscosity of water, while the latter is caused by the presence of a free surface and the action of gravity. Viscous flows and free surface calculations are considered separately for a long time, that is, the potential flow theory is used to deal with the free surface, and in addition, the viscous boundary layer of a ship hull is calculated by solving the RANS equation. In this separation method, the influence of freedom on viscosity is ignored. This is because the existence of a free surface makes flow calculation is very difficult: on the one hand, a free surface is a necessary condition for the solution; on the other hand, its shape and position are not predicted in advance and are given as part of the solution process. With the development of computer performance and computational fluid

dynamics, numerical simulation has become a powerful research method in the field of ship engineering, and the way to simulate the viscous flow field around the free surface of a ship has also become a research direction with important theoretical value and practical significance in the field of ship fluid mechanics.

The whole process of numerical computation includes the establishment of computational model, the discretization of computational domain, the setting of boundary conditions, the iteration of computation and the analysis of results.

### **1) Model establishment**

First, the ship body value data is converted into 3D coordinates, and coordinate points are input in CATIA. The input of batch data can be read in the text form supported by the software. Then, spline curves are used to smooth the connection to obtain three-dimensional contour lines and construct the basic framework, as shown in Figure 5-1.

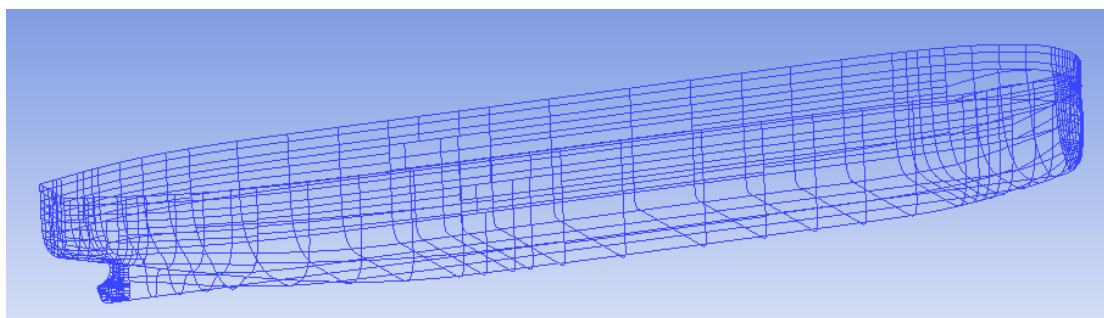


Fig. 5-1 Three-dimensional diagram of hull

Finally, several surfaces are generated by 3D profile, and the surfaces are combined into surface groups to obtain the whole hull surface model. To obtain a solid model, the hull model can be synthesized into a closed surface and materialized, as shown in Fig 5-2.

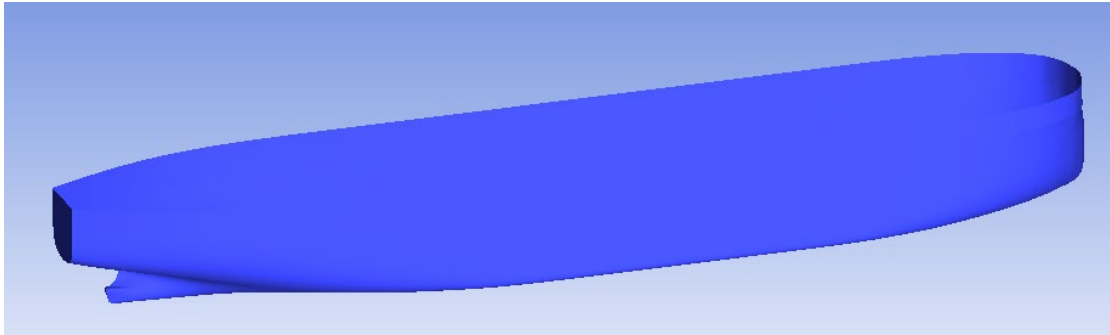


Fig. 5-2 Hull solid model

The computational domain model is divided into two parts: water domain and air domain. The interface between the two is the waterplane of the hull model, with the air domain above the waterplane, and the water domain below it. The method of calculation is a symmetric model with the midship section of the model as the plane of symmetry. The whole numerical simulation area is approximately 4 times the length. The inlet of air and water is at  $L$  upstream of the bow (1 time the length), and the outlet is at  $2L$  downstream of the tail. The side of the calculation area is beyond the surface of the ship, and the bottom is at  $L/2$  away from the bottom of the ship. The computational domain model is shown in Figure 5-3.

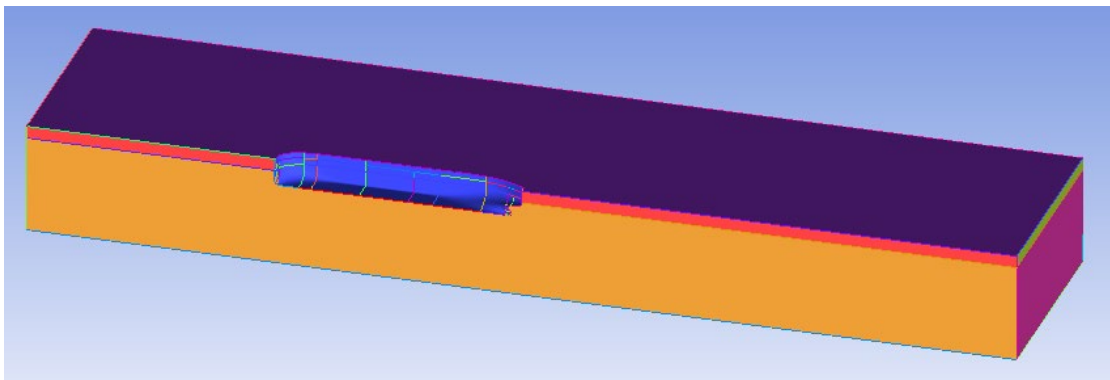


Fig. 5-3 Model of calculation domain

## 2) Discretization of calculation domain

The discretization of the computational domain is completed by the ICEM meshing

tool. All hexahedral meshes were used, h-shaped meshes were used globally, and C-shaped meshes were used near the hull. Hull surface curve change is bigger, need to hull into multiple block for meshing, while the middle part of hull lines being quite gentle, need to be divided into several big block to form high quality hexahedral grid, and fore and aft curve change being bigger, need to be divided into multiple small block to form hexahedral grid. This way, distortion rate of the grid will not appear to be very obvious.

The grid division is shown in Figure 5-4 and Figure 5-5.

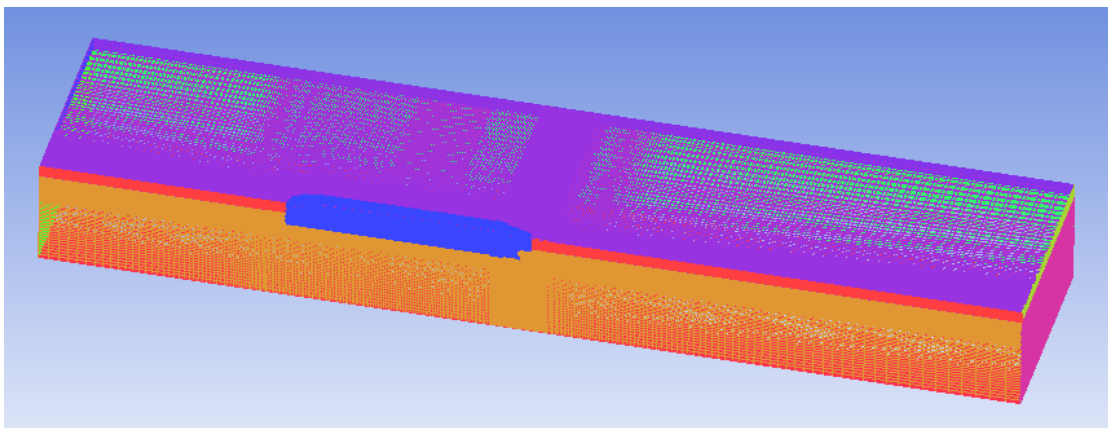


Fig. 5-4 Grid of calculation domain

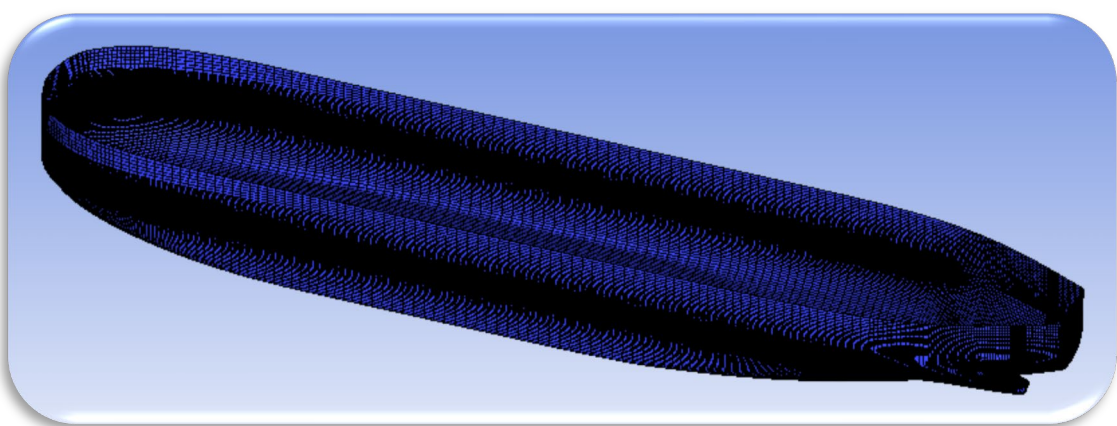


Fig. 5-5 Hull surface mesh

In the grid generation process, the distribution should be sparse and reasonable. The



free surface needs to capture waveform, the mesh near the free surface is dense, and the mesh at the bottom of the flow field is sparse. The parameter variation gradient near the object surface is large and the error is large if the mesh is too thin. Far away from the object, the parameter change is small, and the grid is too dense, which will waste the calculation time. In the middle of the hull, the curve is gentle, and the structure grid can be distributed evenly without being too dense. The bow and stern curves of the hull vary greatly, so the mesh should be dense. Grid lines should be orthogonal and smooth, consistent with the flow direction. In all meshes, no negative volume is allowed, and the quality of meshes should meet the computational requirements.

### **3) Setting of boundary conditions**

Boundary conditions are set to: turbulence intensity was 0.1%, the turbulent viscosity ratio is 1, the entrance of the water for speed entrance, turbulence intensity was 1%, the turbulent viscosity ratio is 1, in order to avoid the flow at the exit, given the same as the entrance to the boundary conditions, the calculation area of the above is the same as the air inlet conditions, set the bottom and sides as wall boundary conditions of hull surface for wall boundary condition, the middle plane of symmetry given conditions, the flow velocity, density, viscosity and model test conditions are the same.

### **4) Solution method setting**

Euler's implicit VOF method is used to solve free surface, which can be used for steady and unsteady computation. Since the concern is the final free surface condition, Fluent suggests that the steady Euler implicit VOF method can be used for the calculation of a ship's free surface. However, due to the problem of mesh quality, the convergent solution cannot be obtained by steady-state solution, so unsteady solution is adopted, and the time step is used as pseudo-time step to approach steady-state solution step by step. In order to achieve better convergence, the time step was 0.001s at the beginning, and 0.005 at the end of convergence, with 20 iterations within each time step. For

different meshes and different turbulence models, stable residual convergence curve could be obtained after about 100s. The interpolation method for pressure uses PRESTO!( PREssure STaggering Option); other items were discretized with a second-order wind format, including volume fraction and a relatively accurate geometric reconstruction of the free surface. The coupling method of velocity pressure is SIMPLE (Semi-implicit Method for pressure-linked Equations) Method. In order to speed up the convergence of the algorithm, fluent software adopts the multi-grid technology to accelerate the convergence, that is, to divide the grid thickness to eliminate the error of high-frequency pulsation first, and then eliminate the error of low-frequency pulsation until convergence.

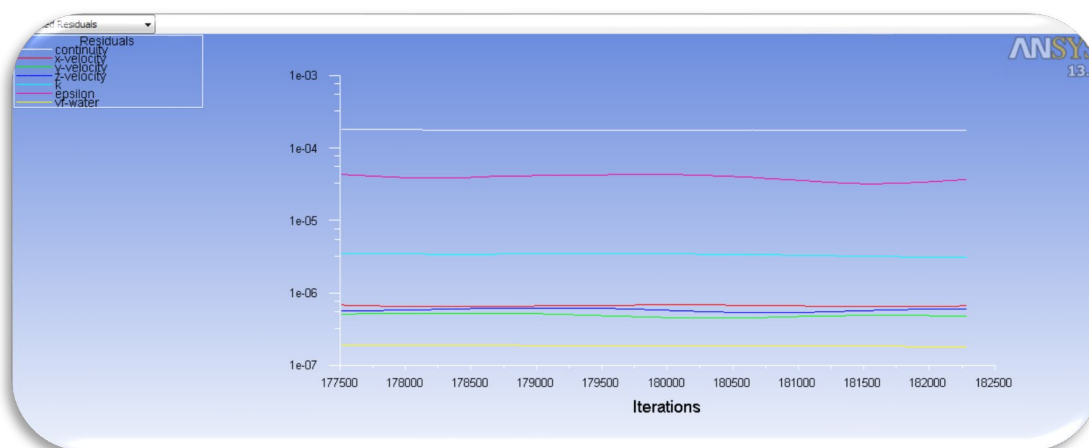


Fig. 5-6 Convergence curve of calculated residual error

## 5.1.2 Results and analysis of CFD numerical calculation

### 1) Calculation results of the resistance of each ship type at different draft and dip Angle

Table 5-1 and Table 5-2 list the CFD resistance calculation results of each ship at different inclinations respectively under the conditions of design draft and light load draft. The resistance results at each inclination are expressed as the relative percentage

of the levelling resistance or the resistance at a certain inclination angle.

Tab. 5-1 CFD resistance calculation results under different inclinations in design  
draft state (relative percentage)

57000DWT (draft=11.3)					
Trim (m)	-2.0	-1.0	0	1.5	3.0
Vs=14.2kn					
Error(%)	3.00	<b>-1.22</b>	0.0	<b>-1.70</b>	<b>-3.05</b>
Vs=12.0kn					
Error(%)	0.65	<b>-1.68</b>	0.0	<b>-2.70</b>	<b>-3.58</b>
82000DWT (draft=12.2)					
Trim (m)	-2.0	-1.0	0	1.5	3.0
Vs=14.1kn					
Error(%)	4.92	1.53	0.0	<b>-0.52</b>	<b>-1.04</b>
Vs=12.0kn					
Error(%)	5.77	2.14	0.0	<b>-0.45</b>	<b>-2.40</b>
180000DWT (draft=16.5)					
Trim (m)	-3.0	-1.5	0	1.5	3.0
Vs=15.0 kn					
Error(%)	2.93	<b>-0.08</b>	0.0	<b>-4.67</b>	<b>-3.97</b>
400000DWT (draft=22.0)					
Trim (m)	-2.0	-1.0	0	1.5	3.0
Vs=14.8kn					
Error(%)	<b>-2.584</b>	<b>-1.499</b>	0.0	2.760	1.404
Vs=12.0kn					
Error(%)	<b>-1.730</b>	<b>-3.484</b>	0.0	2.397	2.125

Tab. 5-2 CFD resistance calculation results under different dip angles in light load draft state (relative percentage)

57000DWT (draft=6.24)					
Trim (m)	0.121	1.171	2.221	3.273	4.001
Vs=14.2kn					
Error(%)	0	<b>-1.95</b>	<b>-0.98</b>	<b>-4.29</b>	<b>-7.53</b>
Vs=12.0kn					
Error(%)	0	<b>-0.93</b>	<b>-1.58</b>	<b>-4.55</b>	<b>-7.91</b>
82000DWT (draft=6.443)					
Trim (m)	0.914	1.800	2.592	3.200	4.000
Vs=14.1kn					
Error(%)	0	<b>-0.49</b>	<b>-1.01</b>	<b>-1.89</b>	<b>-1.67</b>
Vs=12.0kn					
Error(%)	0	<b>-0.56</b>	<b>-0.97</b>	<b>-2.58</b>	<b>-2.35</b>
400000DWT (draft=13.0)					
Trim (m)	-2.0	-1.0	0	1.5	3.0
Vs=14.8kn					
Error(%)	<b>-1.727</b>	2.113	0.0	<b>-2.884</b>	<b>-3.514</b>
Vs=12.0kn					
Error(%)	1.360	3.069	0.0	<b>-3.322</b>	<b>-2.974</b>

Fig. 5-7 to Fig. 5-10 shows the relative percentage curve of CFD trim resistance under different trim states in the design draft state.

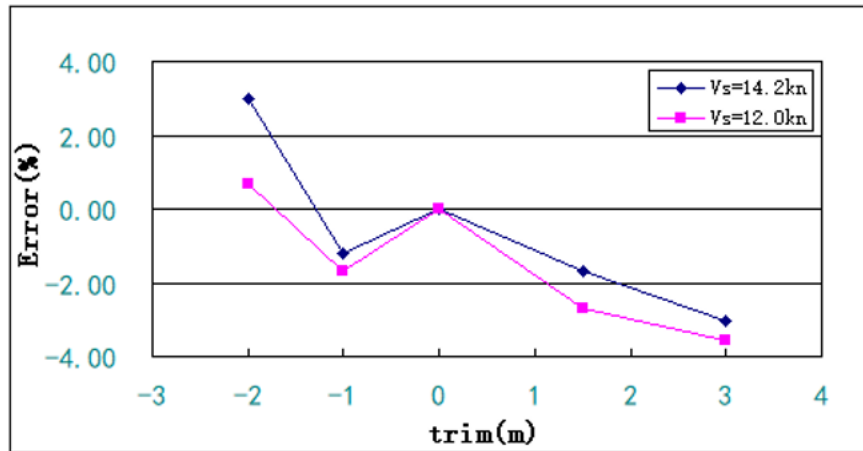


Fig. 5-7 Resistance percentage curve at different dip angles  
(draft=11.3m,57000DWT)

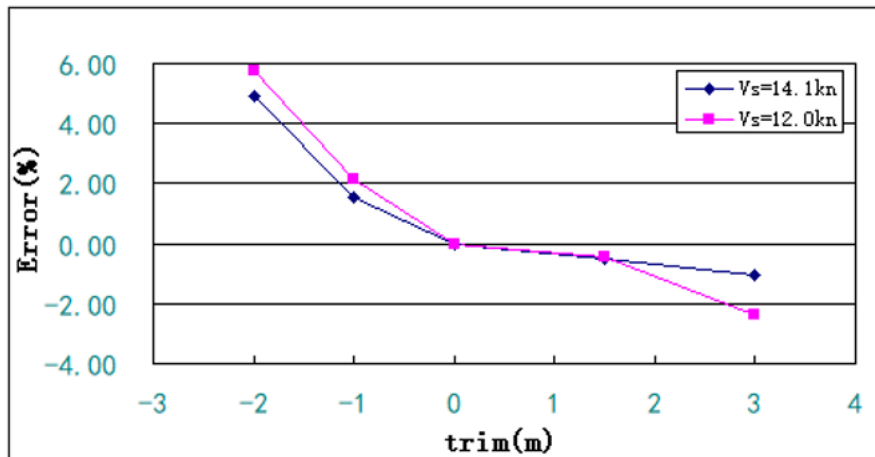


Fig. 5-8 Resistance percentage curve at different dip angles  
(draft=12.2m,82000DWT)

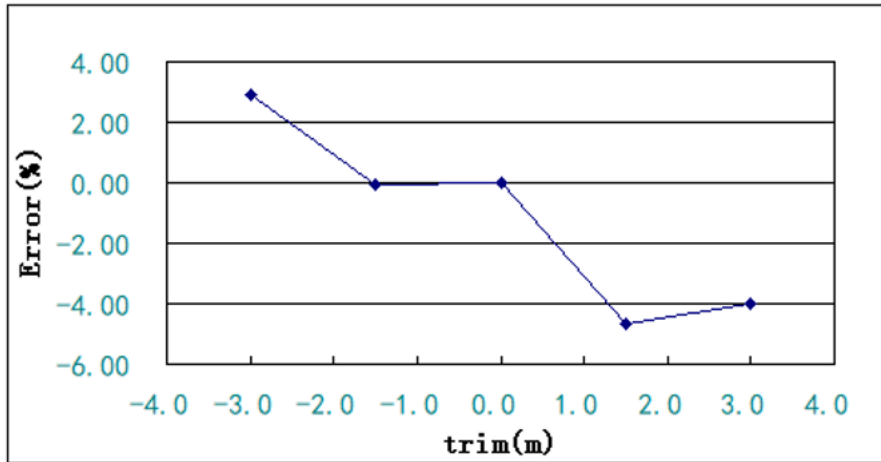


Fig. 5-9 Resistance percentage curve at different dip angles  
(draft=16.5m,180000DWT)

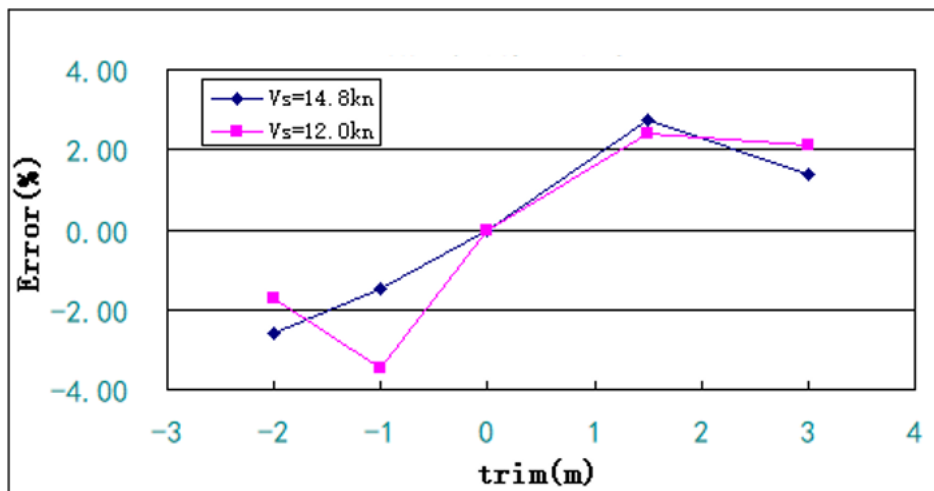


Fig. 5-10 Resistance percentage curve at different dip angles  
(draft=22.0m,400000DWT)

Fig. 5-11 to Fig.5-13 shows the relative percentage curve of CFD trim resistance under different trim states under light load draft.

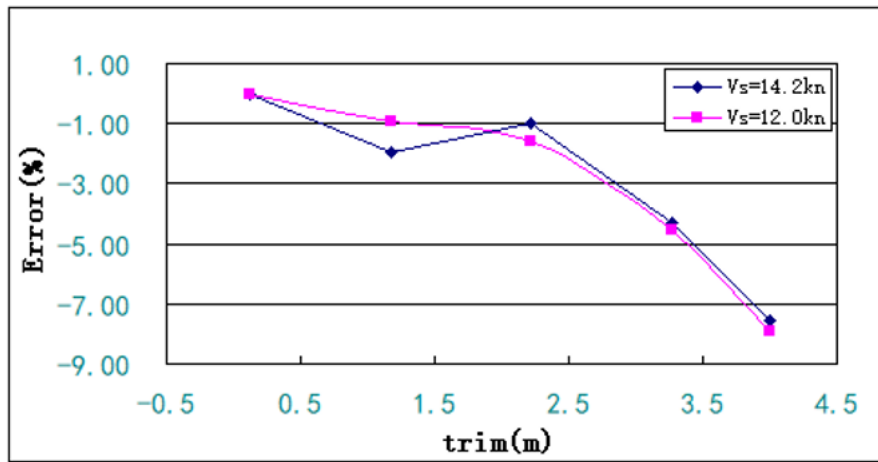


Fig. 5-11 Resistance percentage curve at different dip angles  
(draft=6.24m,57000DWT)

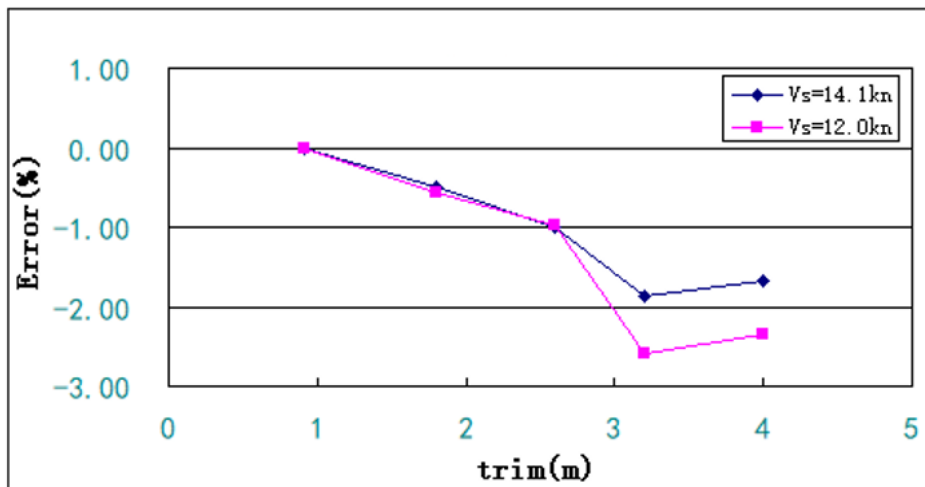


Fig. 5-12 Resistance percentage curve at different dip angles  
(draft=6.443m,82000DWT)

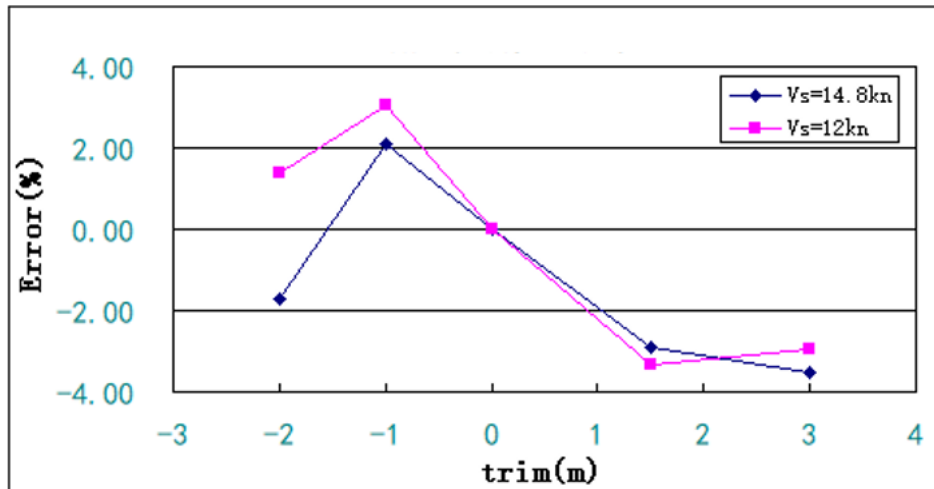


Fig. 5-13 Resistance percentage curve at different dip angles  
(draft=13.0m,400000DWT)

It can be seen from the calculation results that the drag performance of bulk carrier series with different tonnage varies significantly under the same draft, same speed and different trim state. In the design of draft state, except for the 400000DWT ship type, the drag performance is better when tilting forward, the other three tonnage ship types all have better drag performance when tilting aft. Under the condition of light load draft, the drag performance of the three tonnages calculated is better when the ship tilts aft.

## 2) Dynamic pressure distribution on hull surface at each dip Angle (taking 400000DWT as an example)

Fig 5-14 to Fig. 5-16 shows the distribution diagram of dynamic pressure on the hull surface at all angles when Draft=22.0m and design speed  $V_s= 14.8\text{kN}$ . It can be seen from the figure that the dynamic pressure distribution on the hull surface is the largest and non-uniform when the tail-tilt is  $0.2435^\circ$ .



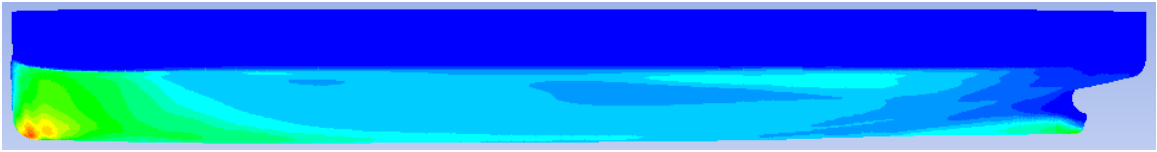


Fig. 5-14 Distribution of dynamic pressure on hull surface at head tilt of  $0.3246^\circ$



Fig. 5-15 Distribution of dynamic pressure on hull surface during levitation

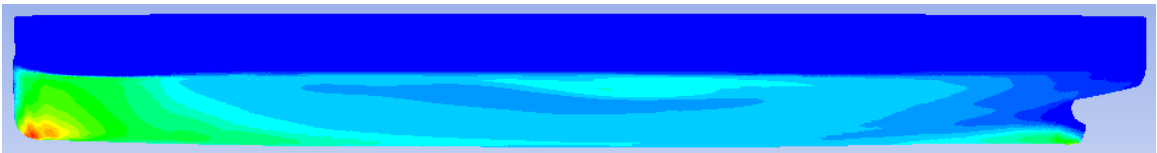


Fig. 5-16 Distribution of dynamic pressure on hull surface at tail-tilt of  $0.2435^\circ$

Fig. 5-17 to Fig. 5-19 shows the cloud map of dynamic pressure distribution on the hull surface at various angles when Draft=13.0m and speed  $V_s=12\text{kN}$  under light load.



Fig. 5-17 Distribution of dynamic pressure on hull surface at head tilt of  $0.1623^\circ$

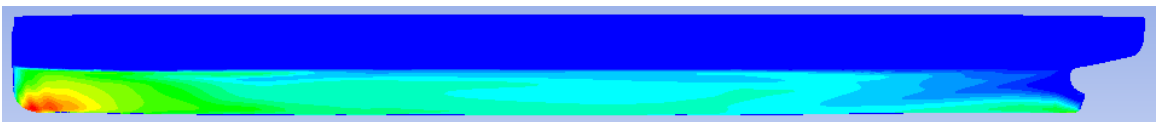


Fig. 5-18 Distribution of dynamic pressure on hull surface during levitation



Fig. 5-19 Distribution of dynamic pressure on hull surface at tail-tilt of  $0.2435^\circ$

## 5.2 Trim map database and optimal trim optimization

The model for trim optimization can be directly described as the following three optimization models;

Model 1: determine the speed, displacement, and calculate the trim under the optimal host power. At fixed speed, the minimum power output is directly manifested as smaller power consumption of the main engine;

Model 2: Determine power output, displacement, and calculate the optimal trim; under fixed power output, to obtain the fastest speed, directly manifested as the faster sailing speed;

Model 3, only gives the trim range and seeks the optimal power and trim of within a certain range. The space optimization problem aims at the smallest Power and the fastest Vkn under the largest Disp, which is directly manifested as: loading more goods, consuming less Power of the main engine, and achieving the fastest sailing speed;

Since the experimental and computational data are discrete data, a continuous map should be constructed. After research and calculation, the Lagrangian interpolation method is adopted in this thesis, which has been verified to be accurate enough for the application of real ship engineering.

### Mapping of trim profile

Assuming that ship speed and displacement are fixed during a voyage (ignoring some factors), this thesis firstly discusses and studies the drawing method of THREE-DIMENSIONAL Trim map based on the changes of Trim, Power and Vkn, and takes Trim resistance data of a certain 4250Teu as an example to illustrate.

Draft=11m, speed Vkn= 15kN, and corresponding data are shown in Table 5-3.

Tab. 5-3 Trim data

Draft=11	-3.0	-2.0	-1	0	1.0	2.4	4.0
Vs(kn)	EHP(kw)	EHP(kw)	EHP(kw)	EHP(kw)	EHP(kw)	EHP(kw)	EHP(kw)
10	1579.3	1544.5	1523.7	1610.6	1607.1	1739.3	1648.9
12	2711.6	2686.5	2502.9	2686.5	2807.5	2916.0	3320.9
14	4213.2	4076.8	3960.0	4403.0	4510.2	4846.1	5381.7
16	6152.0	6118.6	5957.2	6291.1	6502.5	7120.2	7865.8
18	8827.3	8389.1	8645.7	8745.9	9396.9	9891.5	11087.1
20	12279.3	12042.8	12244.5	12397.5	12821.8	13670.4	15151.9
22	16732.0	16257.6	16387.7	16915.6	16831.5	18254.5	20611.1
23.5	20920.8	21076.0	20839.0	20405.9	21337.6	22637.0	24974.4

Figure 5-20 shows the trim effective horse-power diagram under the current design draft.

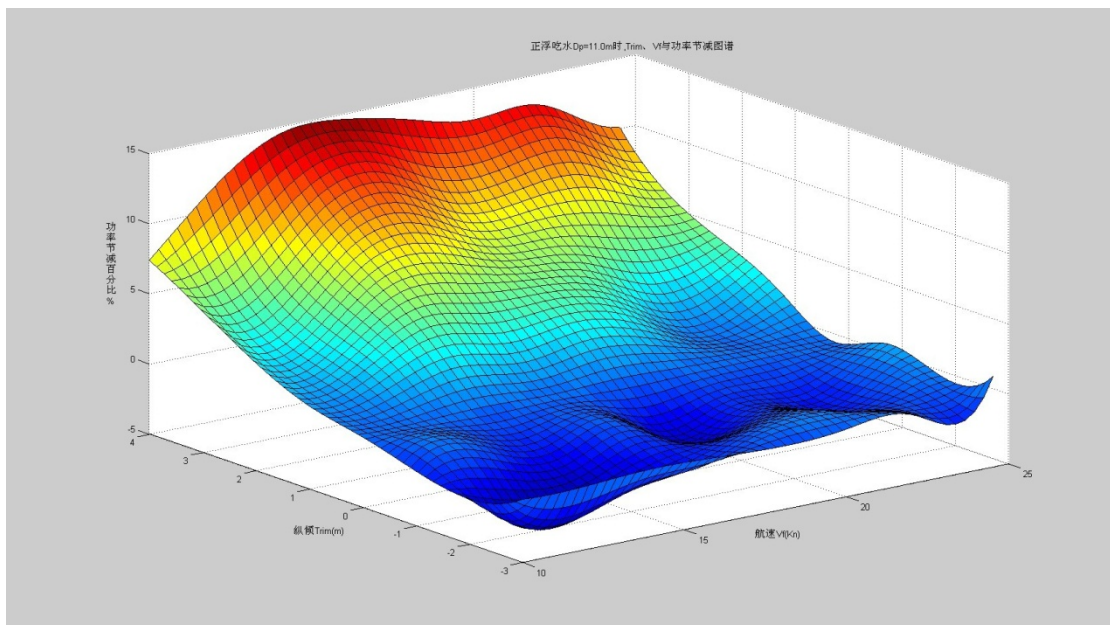


Fig. 5-20 An example of a trim diagram

If we want to find the change curve of the effective horsepower of the main engine at any speed along with the trim, you can get the figure just by intersecting the plane perpendicular to the  $V_{kn}$  axis with the surface.

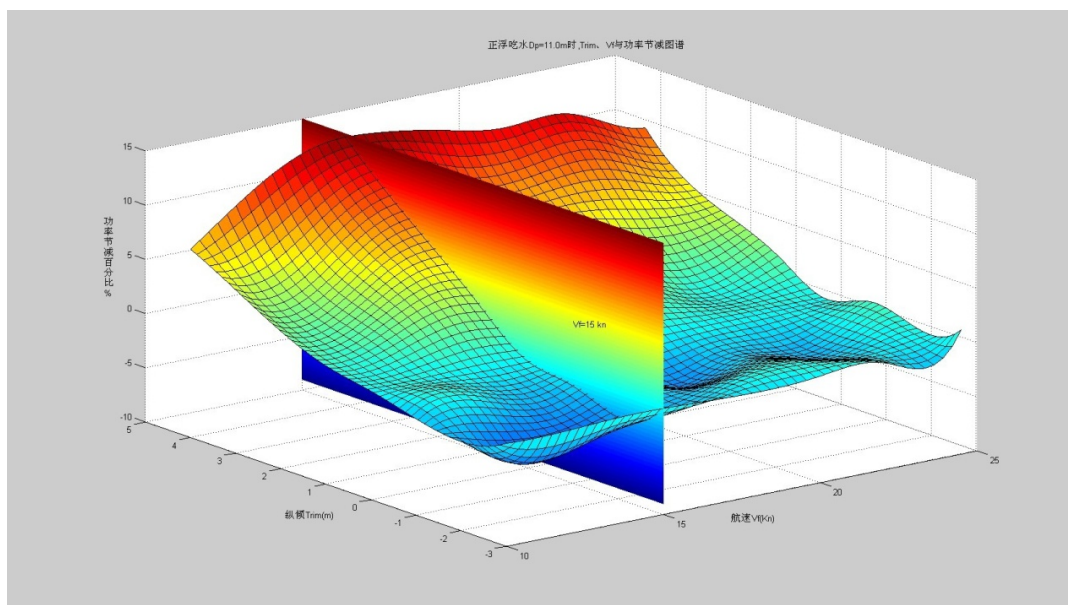


Fig. 5-21 Curve of trim calculation

The simple assumption is made that sailing ship's displacement in the process of constant does not tally with the actual situation. This is because in the process of the navigation, oil and water consumption, and constantly adjusting ballast water, the displacement of the ship is variable. This thesis also discusses the research based on the Trim, Power, Draft three-dimensional map drawing method.

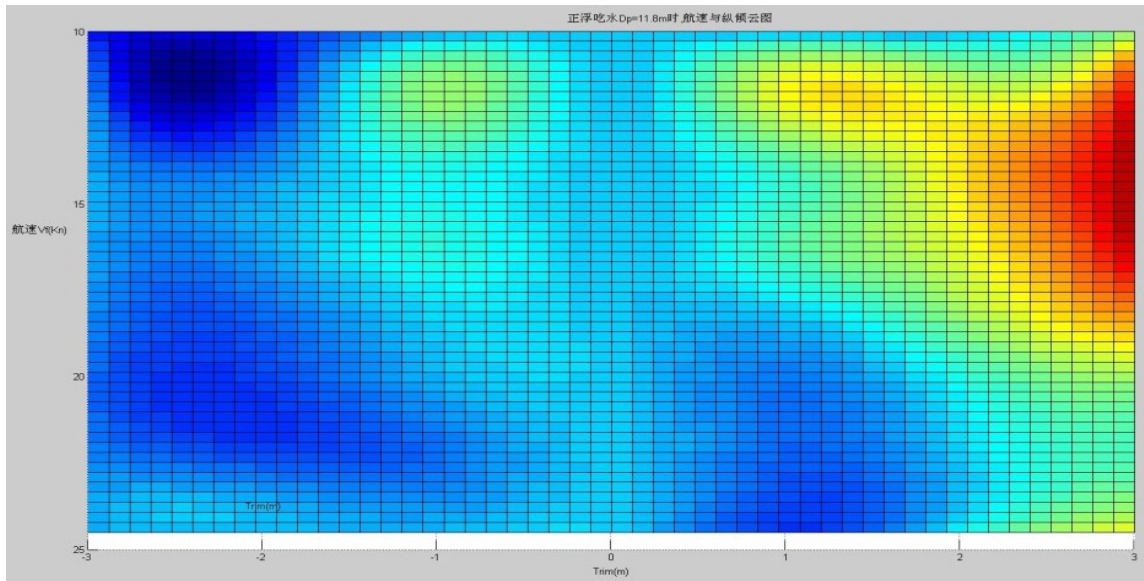


Fig. 5-22 Trim power consumption distribution cloud map

In addition, it can be seen from the cloud map distribution of trim diagram that the optimal area distribution of trim adjustment can help grasp the trim adjustment of the current ship working condition, as is shown in Fig. 5-22. The red area indicates large power consumption, while the dark blue area indicates small power consumption under current trim.

## Chapter VI Techniques for ship energy efficiency optimizing

### 6.1 Joint optimization model of sailing route and speed

#### 6.1.1 Ship energy consumption model considering environmental conditions

When a ship sails at sea, it should be provided with continuous power by the main engine to overcome the resistance. The power from the marine diesel engine is transmitted to the propeller through the shaft and then to the ship hull to overcome the sailing resistance of a ship. At a certain speed, the different environmental conditions would result in different sailing resistance and thus leading to different propeller thrust and energy consumption. The relationship among the propeller thrust and resistance as well as propeller revolution speed can be shown as Eq. (6-1).

$$T_{prop} = \frac{T_{eff}}{(1-t) \cdot k} = \frac{R_{ship}}{(1-t) \cdot k} = K_T \times \rho n^2 D^4 \quad (6-1)$$

where,  $T_{prop}$  is propeller thrust;  $T_{eff}$  is the effective thrust of the propeller, which is equal to the resistance exerted on the hull;  $t$  is thrust deduction coefficient;  $k$  is the number of propellers;  $R_{ship}$  denotes the total ship resistance;  $K_T$  is the thrust coefficient of propeller;  $\rho$  is the density of the water;  $n$  is the propeller speed;  $D$  is diameter of the propeller.

A ship sailing on the sea would face two main kinds of resistance. Above the waterline, it will face the wind resistance when going through the air. In addition, water resistance under the waterline of the ship is unavoidable. The water resistance can further be divided into the static resistance and the added resistance caused by waves. Therefore, the total resistance of the ship includes the static resistance, wind resistance and wave added resistance. Among others, the static resistance of the ship is shown in Eq. (6-2) (Holtrop and Mennen, 1982).

$$R_T = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad (6-2)$$

where,  $R_T$  represents the total resistance in still water;  $R_F$  represents the friction

resistance;  $R_{APP}$  represents the appendages' resistance;  $R_W$  represents the wave making and breaking resistance;  $R_B$  represents the additional resistance in bulbous bow;  $R_{TR}$  represents the additional resistance in stern immersion;  $R_A$  represents the relevant resistance in model ship;  $k_l$  represents the viscous resistance factor in ship type.

In addition, the wind resistance can be obtained by Eq. (6-3) (Kwon, 2008).

$$R_{wind} = C_a \frac{1}{2} \rho_a v_a^2 A_s \quad (6-3)$$

where  $C_a$  represents air resistance coefficient;  $\rho_a$  represents air density;  $v_a$  represents wind speed;  $A_s$  represents the area of positive projection above the waterline of the ship.

Moreover, the wave adding resistance can be expressed by Eq. (6-4) (ISO, 2015).

$$R_{wave} = 2 \int_{-\pi}^{\pi} G(\alpha - \chi) \left[ \int_0^{\infty} S(f) \frac{\Delta(f, \alpha)}{\zeta_A^2} df \right] d\alpha \quad (6-4)$$

where,  $G$  is the direction distribution of incident wave;  $\alpha$  is the initial direction of incident wave;  $\chi$  is the incident angle of wave;  $S(f)$  is the frequency distribution of incident wave,  $\Delta(f, \alpha) / \zeta_A^2$  is the corresponding function of increasing resistance in regular wave;  $\zeta_A$  is the characteristic wave height. When the characteristic wave height is 1.5-2 m, the wave adding resistance can be calculated by Eq. (6-5) (ITTC, 2005).

$$R_{wave} = 0.64 \zeta_A^2 B^2 C_b \rho g / L \quad (6-5)$$

where  $B$  is the ship width;  $C_b$  is the square coefficient;  $L$  is the ship length.

Above all, the total resistance of the ship can be expressed by Eq. (6-6).

$$R_{ship} = R_T + R_{wind} + R_{wave} \quad (6-6)$$

where  $R_{ship}$  is the total resistance of the ship;  $R_T$  is the static resistance of the ship;  $R_{wind}$  is the wind resistance;  $R_{wave}$  is the wave resistance.

When the ship resistance is known, the output power of the main engine of the ship can be obtained by Eq. (6-7).

$$P_B = \frac{R_{ship} \cdot V_s}{k_0 \cdot \eta_s \cdot \eta_G \cdot \eta_O \cdot \eta_H \cdot \eta_R} \quad (6-7)$$

where,  $k_0$  refers to the number of propellers;  $\eta_S$  refers to the transmission efficiency of shafting;  $\eta_G$  refers to the transmission efficiency of gearbox;  $\eta_O$  refers to the open water efficiency of propeller,  $\eta_O = (K_T \cdot J) / (K_Q \cdot 2\pi)$ ;  $\eta_H$  is the hull efficiency,  $\eta_H = (1-t) / (1-w)$ , where  $t$  is the thrust deduction coefficient and  $w$  is the wake coefficient;  $\eta_R$  is the relative rotation efficiency of propeller.

To sum up, the output power of the main engine can be expressed as Eq. (6-8).

$$P_B = \frac{R_{ship} \cdot V_s \cdot K_Q \cdot 2\pi \cdot (1-w)}{k_0 \cdot \eta_S \cdot \eta_G \cdot \eta_R \cdot K_T \cdot J \cdot (1-t)} \quad (6-8)$$

where  $J$  is the propeller advance coefficient;  $K_T$  is the propeller thrust coefficient;  $K_Q$  is the propeller torque coefficient;  $K_T$  and  $K_Q$  can be expressed by the following equations.

$$K_T = f_{K_T}(J) = a_t \cdot J^2 + b_t \cdot J + c_t \quad (6-9)$$

$$K_Q = f_{K_Q}(J) = a_q \cdot J^2 + b_q \cdot J + c_q \quad (6-10)$$

In addition, the propeller advance coefficient can be expressed by Eq. (6-11).

$$J = \frac{V_s \times (1-w)}{n \times D} \quad (6-11)$$

where  $D$  is the diameter of the propeller.

At a given speed, the speed of the main engine and the advance coefficient of the propeller can be obtained by combining Eq. (6-1), Eq. (6-9) and Eq. (6-11). Then, the power of the main engine at different sailing speed can be obtained by the following Eq. (6-12).

$$P_B = \frac{R_{ship} \cdot V_s \cdot K_Q \cdot 2\pi \cdot (1-w)}{k_0 \cdot \eta_S \cdot \eta_G \cdot \eta_R \cdot K_T \cdot J \cdot (1-t)} \quad (6-12)$$

To sum up, the fuel consumption per unit distance of the main engine of the ship can be expressed by Eq. (6-13).

$$q = \frac{k_0 \cdot P_B \cdot g_{main}}{V_s} \quad (6-13)$$

where,  $q$  is the fuel consumption per unit distance of the main engine;  $V_s$  is the sailing speed of the ship;  $g_{main}$  is the fuel consumption rate of the main engine.

From the above-established fuel consumption model, it can be concluded that the fuel



consumption of the main engine per unit of distance varies with the resistance of the ship. The resistance of the ship depends on the sailing speed, wind speed and wave height. Therefore, determining the optimal sailing route with the navigational environment corresponding to the lowest fuel consumption and the optimal sailing speed at different segments on the route is the key to improving the ship energy efficiency. The energy consumption and CO<sub>2</sub> emissions of the ship can be reduced by adopting a joint optimization decision-making method of sailing route and sailing speed.

### 6.1.2 Joint optimization model

For a voyage from position  $A$  to position  $B$ , the sailing distance of each segment can be obtained by Eq. (6-14).

$$S_{i,i+1} = R \cdot 2 \cdot a \sin\left(\sqrt{(\sin(a/2))^2 + \cos(x_i \cdot \pi/180) \cdot \cos(x_{i+1} \cdot \pi/180) \cdot \sin(b/2)^2}\right) \quad (6-14)$$

where,  $S_{i,i+1}$  denotes the sailing distance between position  $P_i(x_i, y_i)$  and  $P_{i+1}(x_{i+1}, y_{i+1})$ ,  $x$  means the latitude and  $y$  means the longitude among others;  $R$  means the radius of the earth;  $a$  and  $b$  can be obtained by Eqs. (6-15) and (6-16) respectively.

$$a = x_i \cdot \pi/180 - x_{i+1} \cdot \pi/180 \quad (6-15)$$

$$b = y_i \cdot \pi/180 - y_{i+1} \cdot \pi/180 \quad (6-16)$$

Then, the total fuel consumption between position  $A$  and  $B$  can be obtained by Eq. (6-17).

$$Q_{total} = \sum_{i=0}^m (q_{i,i+1} \cdot S_{i,i+1}) \quad (6-17)$$

where,  $Q_{total}$  denotes the total fuel consumption between position  $A$  and  $B$ ;  $q_{i,i+1}$  denotes the fuel consumption per unit distance between position  $P_i(x_i, y_i)$  and  $P_{i+1}(x_{i+1}, y_{i+1})$ . It is the function of the sailing speed  $V_{i,i+1}$  and the environmental factors between position  $P_i(x_i, y_i)$  and  $P_{i+1}(x_{i+1}, y_{i+1})$ .

In addition, the total sailing time can be obtained by adding the time spent on each sections between position  $P_i(x_i, y_i)$  and  $P_{i+1}(x_{i+1}, y_{i+1})$ , as shown in Eq. (6-18).

$$T_{total} = \sum_{i=0}^m T_{i, i+1} = \sum_{i=0}^m (S_{i, i+1} / V_{i, i+1}) \quad (6-18)$$

where,  $T_{total}$  denotes the total time between position A and B;  $T_{i, i+1}$  denotes the sailing time between position  $P_i (x_i, y_i)$  and  $P_{i+1} (x_{i+1}, y_{i+1})$ ;  $V_{i, i+1}$  denotes the sailing speed between position  $P_i (x_i, y_i)$  and  $P_{i+1} (x_{i+1}, y_{i+1})$ .

Above all, the total fuel consumption and sailing time corresponding to the different sailing routes and speeds under different environmental conditions can be calculated based on the established energy consumption model considering multiple environmental factors. For the joint optimization of sailing route and speed, it is a nonlinear optimization model. The optimization target and constraints of the optimization model can be expressed in the following equations.

$$\min Q_{total} = \sum_{i=0}^m (q_{i, i+1} \cdot S_{i, i+1}) \quad (6-19)$$

$$\sum_{i=0}^m (S_{i, i+1} / V_{i, i+1}) < T_{limit} \quad (6-20)$$

$$N_{min} < f_{engine\_speed} (V_{i, i+1}) < N_{max} \quad (6-21)$$

$$V_{min} < V_{i, i+1} < V_{max} \quad (6-22)$$

where,  $T_{limit}$  denotes the sailing time limitation between position A and B;  $N_{min}$  denotes the minimal engine speed and  $N_{max}$  denotes the maximal engine speed;  $f_{engine\_speed} (V_{i, i+1})$  means the engine speed between position  $P_i (x_i, y_i)$  and  $P_{i+1} (x_{i+1}, y_{i+1})$ .

Eq. (6-19) is the optimization objective function, in which the sailing speeds and positions of each segment are the optimization variables. The first constraint in Eq. (6-20) ensures that the ship can finish the whole voyage within the required time. The second and third ones in Eqs. (6-21) and (6-22) are the physical limitations corresponding to the engine speed and the sailing speed respectively, which can avoid overload.

### 6.1.3 Solution method of the joint optimization model

The PSO algorithm is adopted to solve the established nonlinear joint optimization model, as is shown in Fig. 6-1. The specific implementation processes are as follows:

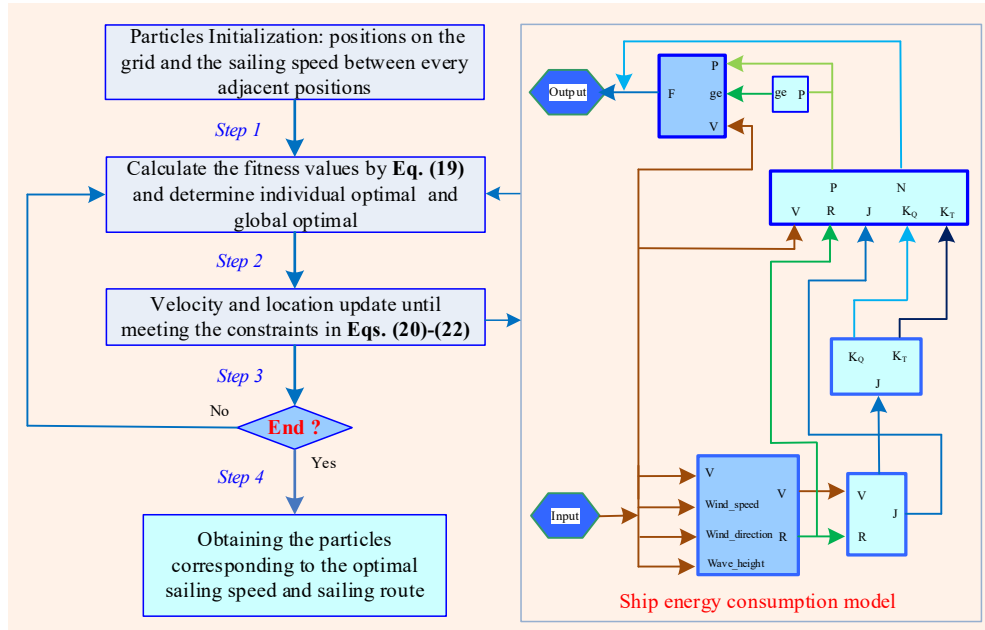


Fig. 6-1 Solution method based on the PSO algorithm

*Step 1:* Initialization. Generate a population of particles with  $M$  dimensions representing the positions on the grid and  $M-1$  dimensions expressing the sailing speeds between every adjacent positions. Allocate a velocity to each particle randomly.

*Step 2:* Evaluation. Compute the optimization fitness function, namely the total fuel consumption of the voyage, according to Eq. (6-19), and update the best locations of the particles by selecting the optimal values.

*Step 3:* Velocity and location update. The location of each particle is changed by updating its velocity, and the velocity of the particle is dynamically changed by Eqs. (6-23) and (6-24). The updates of velocity and location of each particle would be continuously conducted until meeting the constraints in Eqs. (6-20)-(6-22).

$$V^{k+1} = w \cdot V^k + c_1 \cdot r_1 (p_{\text{best}}^k - X^k) + c_2 \cdot r_2 (g_{\text{best}}^k - X^k) \quad (6-23)$$

$$X^{k+1} = X^k + V^{k+1} \quad (6-24)$$

where,  $k$  denotes the number of iterations of the current;  $w$  denotes the inertia weight;  $p_{\text{best}}$  denotes the previous best;  $g_{\text{best}}$  denotes the global best;  $X$  denotes the location of the particle;  $V$  denotes the velocity of the particle;  $c_1$  and  $c_2$  denote the learning factors;

and  $r_1$  and  $r_2$  denote the random numbers between 0 and 1.

In order to improve the accuracy of the algorithm, the dynamic method of inertia weight is adopted, as shown in Eq. (6-25). In this way, the larger inertia weight can ensure the strong global search ability of the algorithm at the beginning of iteration, and in later iterations, the lower inertia weight can guarantee the accurate local search of the algorithm (Wang et al., 2017).

$$w = w_{max} - (w_{max} - w_{min}) \cdot it_{current} / it_{max} \quad (6-25)$$

where,  $w_{max}$  denotes the maximum inertia factor;  $w_{min}$  denotes the minimum inertia factor;  $it_{current}$  denotes the current iteration times; and  $it_{max}$  denotes the maximum iteration times.

*Step 4:* Iteration and termination. Go to *Step 2* and continue the algorithm until meeting the stopping criterion of the algorithm.

## 6.2 Case study

### 6.2.1 Study case description

This thesis takes a VLOC named “YU ZHONG HAI” from a China shipping company as the research target, as shown in Fig. 6-2. The target ship transports ore from Brazil to China. In this thesis, the section from Indonesia Sunda Strait (105° E, 6° S) to Zhoushan, Zhejiang Province, China (123° E, 28° N) is selected as the research object, because of the relatively complex hydrometeorology, as is shown in Fig. 6-3.



Fig. 6-2 The vessel “YU ZHONG HAI”



Fig. 6-3 The navigational area of the target ship

In addition, the basic information of the target ship is shown in Table 6-1.



Tab. 6-1 Basic information of the target ship


Item	Parameter	Item	Parameter
Length	327 m	Design speed	14.5 kn
Depth	29 m	Number of blades	5
Width	55 m	Diameter of propeller	9.7 m
Deadweight	297959 t	Engine rated power	19000 kW
Draft	21.4 m	Engine rated speed	73 rpm

### 6.2.2 Data acquisition and preprocessing

The acquisition of energy efficiency data is realized by the onboard installed sensors, as shown in Table 6-2. The fuel consumption is calculated by the difference of fuel flow meter per unit time. The shaft power is measured and recorded by the shaft power sensor. The real-time position information is obtained by the GPS. In addition, the voyage mileage of the ship is recorded through the odometer. All the energy efficiency data obtained by these sensors are stored in the energy efficiency system and they can be queried and downloaded by ship managers at any time. Part of the obtained data is shown in Table 6-3.

Tab. 6-2 Data acquisition form of the ship energy efficiency

Sensor	Schematic diagram	Parameter	Remark
GPS receiving device		Ship navigation speed (kn), Longitude and Latitude (°)	Mounted on the upper deck. Acquiring ship speed to ground and the position of the ship.
Shaft power sensor		Shaft speed (r/min) and shaft power (kW)	Mounted on the shaft. Collecting real-time speed and power of the shaft.

Fuel consumption sensor		Real-time fuel consumption (m <sup>3</sup> )	Mounted on the main oil pipe. Gathering the real-time fuel consumption
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Tab. 6-3 Part of the obtained ship energy efficiency data

Date	Longitude/(°)	Latitude/(°)	Main engine speed/(r/min)	Shaft power/(kW)	Sailing speed/(kn)	Fuel consumption/(g/m)
2015-12-31 00:30	113.8757 E	12.3798 N	56	10520	9.5	126.3499
2015-12-31 00:40	113.8920 E	12.4022 N	56	10420	9.4	127.6940
2015-12-31 00:50	113.9077 E	12.4233 N	56	10420	9.4	124.4198
2015-12-31 01:00	113.9237 E	12.4438 N	56	10280	9.3	129.0671
2015-12-31 01:10	113.9412 E	12.4646 N	56	10410	9.3	129.0671
2015-12-31 01:20	113.9580 E	12.4842 N	57	10420	9.3	125.7577
2015-12-31 01:30	113.9748 E	12.5039 N	57	10230	9.3	135.6859
...	...	...	...	...	...	...

The considered meteorological factors include wave height, wind speed and wind direction, which are obtained from the European Centre for Medium-Range Weather Forecasts ([www.ecmwf.int](http://www.ecmwf.int)). The frequency of the meteorological data acquisition is four times per day and once per 0.125° in the space dimension. In this way, totally 991692 pieces of data have been obtained. In order to ensure the validity of the obtained data and the practicability of the model application, the following data pre-processing procedures are conducted.

Firstly, the abnormal data is detected and processed;

Secondly, the dynamic real-time meteorological data at different positions and different time are obtained by the three-dimensional linear interpolation method because the time interval and location information between the acquired meteorological data and the data collected by the real ship are not united.

Finally, Vector operation on the wind field components in latitude and longitude are conducted to obtain the final wind speed and direction data.

Effective data have been obtained through the above preprocessing steps, and part of the energy efficiency and meteorological data is shown in Table 6-4.

Tab. 6-4 Part of the obtained effective data

Date	Longitude (°)	Latitude (°)	Shaft power (kW)	Sailing speed (kn)	Fuel consumption (g/m)	Wind speed (m/s)	Wind direction (°)	Wave height (m)
2015-12-31 00:30	113.8757 E	12.3798 N	10520	9.5	126.3499	11.90152	216.0341	3.0859
2015-12-31 00:40	113.8920 E	12.4022 N	10420	9.4	127.6940	11.84837	216.0324	3.0856
2015-12-31 00:50	113.9077 E	12.4233 N	10420	9.4	124.4198	11.79555	216.0432	3.0850
2015-12-31 01:00	113.9237 E	12.4438 N	10280	9.3	129.0671	11.74245	216.0612	3.0840
2015-12-31 01:10	113.9412 E	12.4646 N	10410	9.3	129.0671	11.68833	216.0858	3.0824
2015-12-31 01:20	113.9580 E	12.4842 N	10420	9.3	125.7577	11.63465	216.1213	3.0806
2015-12-31 01:30	113.9748 E	12.5039 N	10230	9.3	135.6859	11.58149	216.1635	3.0789
...	...	...	...	...	...	...	...	...

### 6.2.3 Mesh generation of the navigational area

In this thesis, the navigational area of the ship is meshed according to the dimensions of the longitude and latitude. In this way, the optimization problem can be transformed



into determining the best grid positions and the optimal speeds between adjacent positions, in order to reduce the fuel consumption and CO<sub>2</sub> emissions of the whole voyage within the given navigational time. The accuracy of the generated mesh should be determined by considering the actual operation and situation of the ship as well as the calculation speed comprehensively. Too large grid would lead to a fast calculation speed but reduce the accuracy of the optimization method. Nevertheless, extremely small grid would improve the accuracy of the optimization results but it would prolong the calculation time and make the ship change the speed and route very frequently. Above all, the generated mesh of the navigational area after multiple simulations is shown in Fig. 6-4.

As is seen from Fig. 6-4, the navigational area is divided into 34 grids and 72 grids in the dimension of the latitude and longitude direction respectively. Therefore, there are total 67 variables to be determined, including 34 variables about the sailing speed and 33 variables on the sailing position. To sum up, the joint optimization method proposed in this thesis are adopted to realize the decisions of these variables in case study, in order to validate the effectiveness of the proposed method.

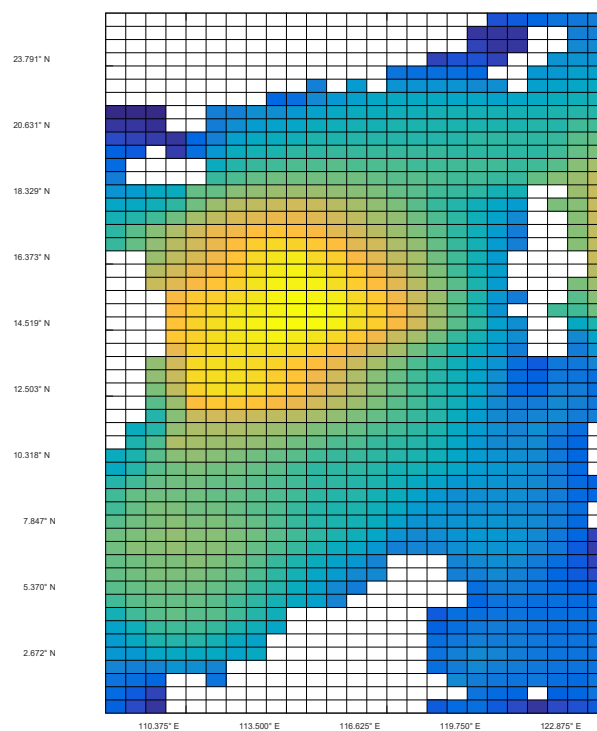


Fig. 6-4 Illustration of the generated mesh of the navigational area

### 6.2.4 Optimization results and analysis

In this case study, the time constraint is 179.67 hours, and the other required parameters for the PSO algorithm are shown in Table 6-5. The optimization results including the optimal sailing positions and the optimal sailing speeds between adjacent positions based on the above-established model and algorithm are obtained. The original and optimal sailing positions along the whole route are shown in Fig. 6-5. Besides, the original and optimal sailing speeds between adjacent positions along the whole voyage are shown in Fig 6-6.

Tab. 6-5 Required parameters for the PSO algorithm

Parameters	$c_1$	$c_2$	$w_{\max}$	$w_{\min}$	$iter_{\max}$
Values	2	2	0.9	0.4	100

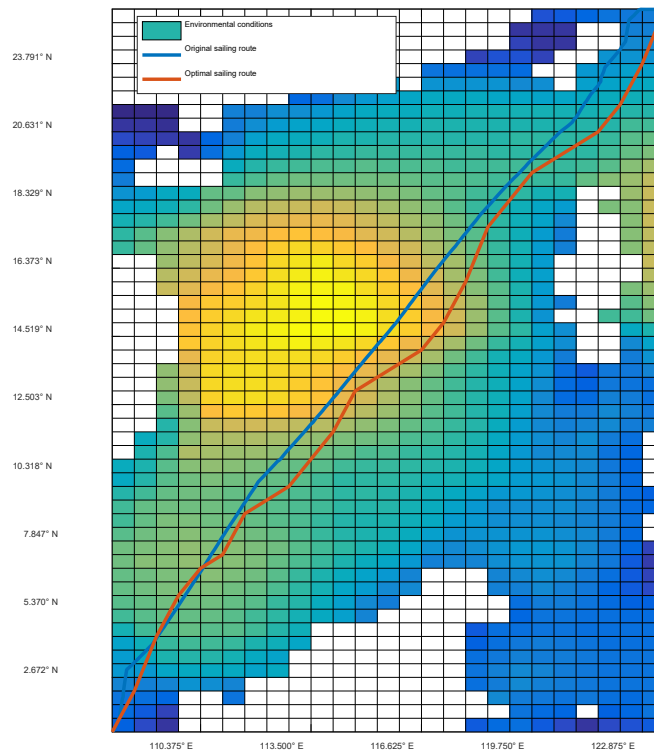


Fig. 6-5 The original and optimal sailing positions along the whole route

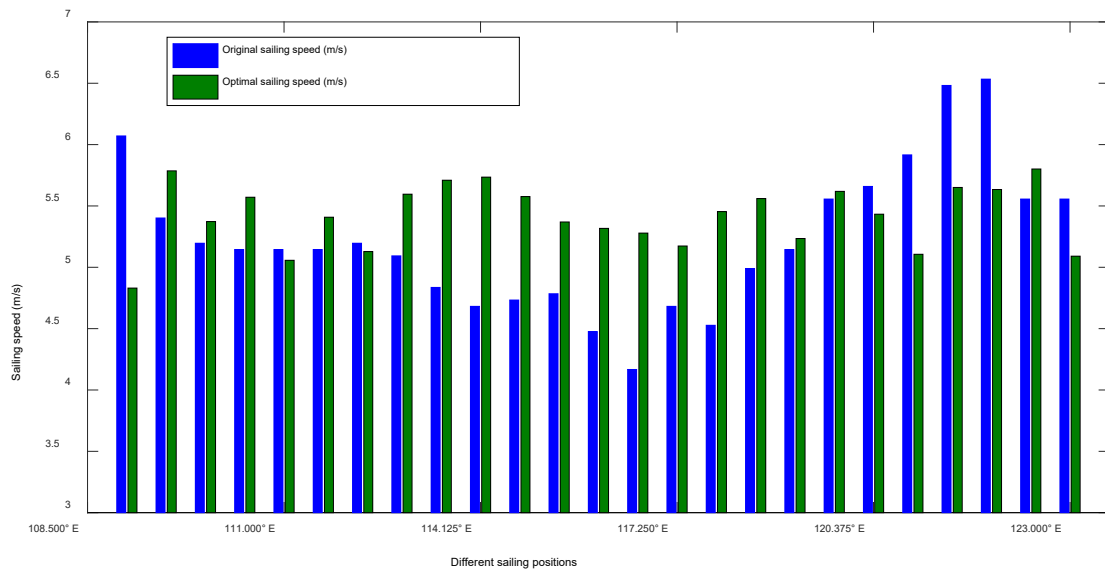


Fig. 6-6 The original and optimal sailing speeds between each adjacent position

The optimization results reveal that the optimal sailing route and speed can be jointly determined. This joint optimization method can not only optimize the sailing route considering the navigational environment, but also optimize the sailing speed of ships in different positions along the whole route. This method can help the ship to automatically avoid the bad weather conditions that would lead to more energy consumption although the sailing distance will be extended.

The original and optimal fuel consumption are shown in Fig. 6-7. In addition, the CO<sub>2</sub> emissions under the original operational mode (the pre-given sailing route and sailing speed that do not consider the environmental factors) and the proposed joint optimization method are illustrated in Fig. 6-8. The CO<sub>2</sub> emission is calculated through the fuel consumption multiplied by its CO<sub>2</sub> conversion rate. For the HFO, the CO<sub>2</sub> conversion rate is 3.114 (Baumler et al., 2014).

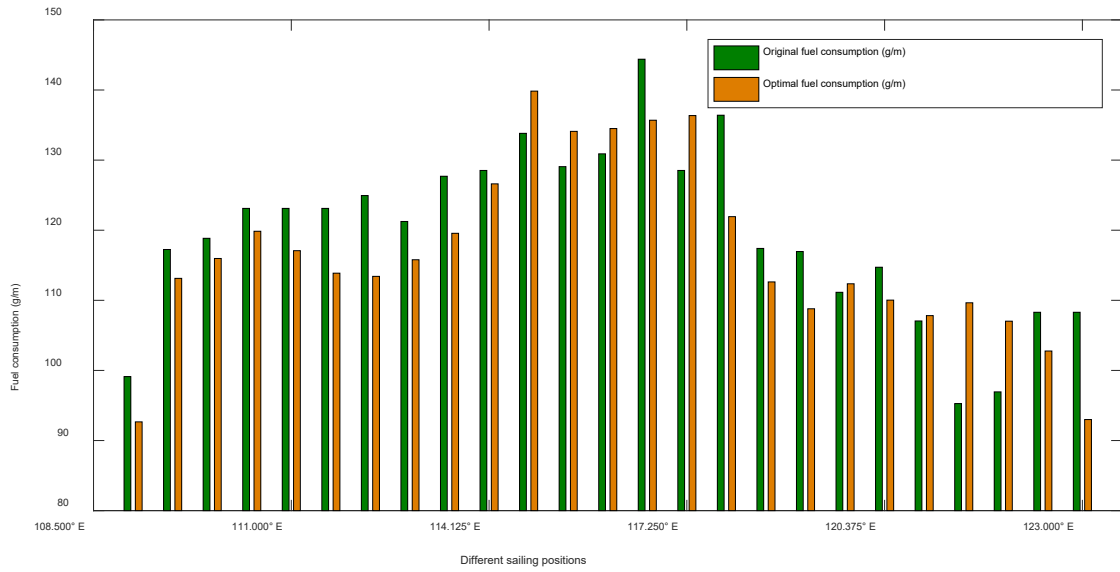


Fig. 6-7 The original and optimal fuel consumption at different positions

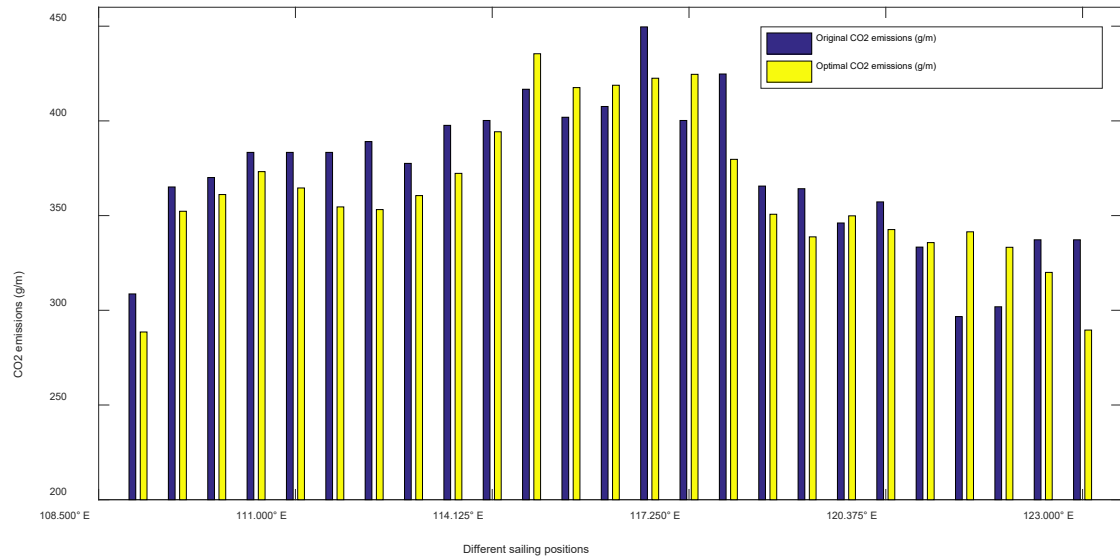


Fig. 6-8 The original and optimal CO<sub>2</sub> emissions at different positions

As is shown in Figure 6-7 and Figure 6-8, the fuel consumption and CO<sub>2</sub> emissions under different environmental conditions and sailing speeds are different. That is also the main concept of improving the ship energy efficiency by optimizing the sailing route and speed considering the navigational conditions.

In order to show the effectiveness of the joint optimization method, a comparative analysis on the fuel consumption and CO<sub>2</sub> emissions is conducted. The total fuel consumption and CO<sub>2</sub> emissions along the whole route under the original operational mode and the proposed method are shown in Table 6-6 respectively. According to the information from this table, utilizing the proposed method can reduce ship's fuel consumption and CO<sub>2</sub> emission by 4.13% compared with the original operational mode, which means saving approximately 17 tons of fuel for a voyage. Therefore, this can be pivotal for the shipping companies to improve the market competitiveness. In addition, it can also reduce 54.4 tons of CO<sub>2</sub> emissions of the ship under the conditions of the same sailing time. It should be noted that more energy could be saved if the environmental conditions of the original sailing route is worse for the fuel consumption.

Tab. 6-6 Comparative analysis on the fuel consumption and CO<sub>2</sub> emissions

Items	Fuel consumption (t)	CO <sub>2</sub> emission (t)
Original operational mode	410.80	1317.02
Joint optimization method	393.33	1262.68
Optimized percent (%)	4.13	4.13

## Chapter VII Conclusion

In this thesis, the study is focused on ship equipment energy consumption state of energy efficiency evaluation method based on the current operating state parameters of energy efficiency of marine equipment, monitoring data, aiming at the problems existing in the actual assessment process. The ship sailing condition judgment method, environment and working condition of revision of diesel engine fuel consumption rate and sea state environmental data acquisition method and the energy consumption of equipment state quantitative evaluation method of energy efficiency are also investigated in depth respectively. These methods are the key technologies to realize the real-time and post-assessment of the energy efficiency status of the main energy consumption equipment of ships in operation, the analysis and early warning of the abnormal energy efficiency status, and the horizontal comparison of the energy efficiency status of the same energy consumption equipment among different ships of the same type.

Due to there is no polynomial function relationship between horse power, trim, draft (speed) and so on, under any speed condition, the best trim optimization problem is a NP (nondeterministic polynomial)-hard problem for any working conditions. In this study, a relatively effective adaptive optimization algorithm was designed to effectively solve the problems mentioned above, and better timeliness and rapidity were obtained. The core idea is an adaptive algorithm for continuous space optimization problem, a new heuristic allocation algorithm based on the value of the objective function, and a screening method for the optimal solution in the search process. The path search behavior is adjusted according to the objective function, so that the algorithm can find the global optimal solution quickly.

To comply with the requirements of reducing energy consumption and CO<sub>2</sub> emissions in the shipping industry, it is significant to improve the ship energy efficiency. The

sailing route and speed optimization are effective ways to improve the energy efficiency of ships in service. In this thesis, a joint optimization method of sailing route and speed is proposed for the purpose of fully realizing the potential of energy saving and emission reduction. An energy consumption model considering environmental factors is established by analyzing the ship resistance, propeller propulsion characteristics and fuel consumption characteristics of the main engine. On this basis, the nonlinear joint optimization model of sailing route and speed is constructed. The corresponding optimal sailing route and speeds along the route are obtained by PSO algorithm with the goal of minimizing fuel consumption and CO<sub>2</sub> emissions. The case study shows that the proposed method could reduce the fuel consumption by 4.1%, compared to the original operational mode. That is meaningful to improve the market competitiveness of the shipping company. In addition, it can reduce CO<sub>2</sub> emissions of the ship by 4.1% under the same sailing time, compared to the original operational mode. Therefore, the proposed method is of great significance for promoting energy conservation and emission reduction in the shipping industry.

The proposed joint optimization method can also be used for other kinds of sea-going ships because it improves ship energy efficiency based purely on the sailing optimization. The joint optimization method for a fleet would bring more benefits for the shipping company. Therefore, the joint optimization method focusing on the fleet energy efficiency considering multiple dynamic influencing factors would be the focus of future study. Due to the urgent requirement and strict regulations of energy saving and emission reduction, it is significant to explore more effective novel energy efficiency optimization method. The proposed method can provide the shipping companies with a new way to reduce fuel consumption and CO<sub>2</sub> emissions.

## Reference

- A, K. K., B, G. K., C, V. K., & A, A. G. (2014). Trends in big data analytics. *Journal of Parallel and Distributed Computing*, 74(7), 2561-2573.
- Armstrong, Victor, N., Banks, & Charlotte. (2015). Integrated approach to vessel energy efficiency. *Ocean Engineering*.
- Ballou P, Chen H, Horner J D. (2008). Advanced methods of optimizing ship operations to reduce emissions detrimental to climate change. *Oceans*, 1-12.
- Besikci, E. B., Arslan, O., Turan, O., & Olcer, A. I. (2016). An artificial neural network-based decision support system for energy efficient ship operations. *Computers & operations research*, 66(FEB.), 393-401.
- Bouman, E. A., Lindstad, E., Rialland, A. I., & Stromman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing ghg emissions from shipping - a review. *Transportation Research*, 52D (PT. A), 408-421.
- Chang, C. C., & Chang, C. H.. (2013). Energy conservation for international dry bulk carriers via vessel speed reduction. *Energy Policy*, 59, 710-715.
- Clarksons Research. (2015). August 2015 Seaborne Trade Monitor. Clarksons Research: London, UK
- Debabrata, Sen, Chinmaya, P., & Padhy. (2015). An approach for development of a ship routing algorithm for application in the north indian ocean region. *Applied Ocean Research*.
- Geertsma, R. D., Negenborn, R. R., Visser, K., & Hopman, J. J. (2017). Design and control of hybrid power and propulsion systems for smart ships: a review of developments. *Applied Energy*, 194, 30-54.
- Gershanik, V. I. (2011). Weather routing optimisation - challenges and rewards. *Proceedings of the Institute of Marine Engineering, ence and Technology*, 10(3), p.29-40.
- Hannjohn. (2011). IMO: CO<sub>2</sub> emissions from shipping projected to continue increasing, despite new regulation. NOVEMBER. [https://energyefficientshipping.wordpress.com/2011/11/15/CO<sub>2</sub>-emissions-from-shipping-projected-to-almost-double-by-2050-despite-new-imo-regulation/](https://energyefficientshipping.wordpress.com/2011/11/15/CO2-emissions-from-shipping-projected-to-almost-double-by-2050-despite-new-imo-regulation/)
- Heikki H. Malte F. (2010). Assistance Tools for Operational Fuel Efficiency. *COMPIT'10 Conference Proceedings*.
- Huang, D., Zhao, D., Wei, L., Wang, Z., & Du, Y. (2015). Modeling and analysis in marine big data: advances and challenges. *Mathematical Problems in Engineering*, 2015(pt.11), 384742.1-384742.13.
- International Organization for Standardization (ISO). (2015). Ships and marine technology-guidelines for the assessment of speed and power performance by analysis of speed trial data: ISO 15016: 2015 [S/OL]. <https://www.iso.org/standard/61902.html>
- International Towing Tank Conference (ITTC). (2005). Full scale measurements speed



- and power trials analysis of speed/power trial data. Kgs. Lyngby, Denmark: International Towing Tank Conference (ITTC), 2005.
- Jun, Hou, Jing, Sun, Heath, & F. (2017). Mitigating power fluctuations in electric ship propulsion with hybrid energy storage system: design and analysis. *IEEE Journal of Oceanic Engineering*.
- Kwon, O., Lee, N., & Shin, B.. (2014). Data quality management, data usage experience and acquisition intention of big data analytics. *International Journal of Information Management*, 34(3), 387-394.
- Kwon Y. J., (2008). Speed loss due to added resistance in wind and waves. *The naval architect* 3, 14-16.
- Lee, H., Aydin, N., Choi, Y., Lekhavat, S., & Irani, Z.. (2018). A decision support system for vessel speed decision in maritime logistics using weather archive big data. *Computers & operations research*, 98(OCT.), 330-342.
- Lin, Y. H., Fang, M. C., & Yeung, R. W.. (2013). The optimization of ship weather-routing algorithm based on the composite influence of multi-dynamic elements. *Applied Ocean Research*, 43(Complete), 184-194.
- Lindstad, H., Asbjørnslett, B. E., & Strømman, A. H.. (2011). Reductions in greenhouse gas emissions and cost by shipping at lower speeds. *Energy Policy*, 39(6), 3456-3464.
- Lu, R., Turan, O., Boulougouris, E., Banks, C., & Incecik, A.. (2015). A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping. *Ocean Engineering*, 110, 18-28.
- Ma, R. Q., Huang, L. Z., Wei, M. S., Liu, T., Liu, Y. F. & Wang, H. Y.. (2018). Research on intelligent speed optimization for given route ship based on ship monitoring data. *Journal of Dalian Maritime University*, 044(001), 31-35.
- Marine Environment Protection Committee. (2009). Prevention of air pollution from ships (Second IMO GHG Study 2009). London: Marine Environment Protection Committee.
- Marine Environment Protection Committee. (2011). Report of the Marine Environment Protection Committee on Its Sixty-Second Session. London: Marine Environment Protection Committee.
- Osses J R P, Bucknall R W G. (2014). A marine engineering plant model to evaluate the efficiency and CO<sub>2</sub> emissions from crude oil carriers. *Shipping in Changing Climates: Provisioning The Future Convergence*.
- Pagoropoulos A, Møller A H, McAlone T C. (2017). Applying Multi-Class Support Vector Machines for performance assessment of shipping operations: The case of tanker vessels. *Ocean Engineering*, 140: 1-6.
- Perera, L. P., & Mo, B.. (2016). Machine Intelligence for Energy Efficient Ships: A Big Data Solution. *International Conference on Maritime Technology & Engineering*.
- Psarafitis H. N., Kontovas C. A. (2013). Speed models for energy-efficient maritime

- transportation: a taxonomy and survey. *Transportation Research Part C: Emerging Technologies*, 26: 331-351.
- Rehmatulla, N., Calleya, J., & Smith, T.. (2017). The implementation of technical energy efficiency and CO<sub>2</sub> emission reduction measures in shipping. *Ocean Engineering*, 139(jul.15), 184-197.
- Rehmatulla, N., & Smith, T.. (2015). Barriers to energy efficient and low carbon shipping. *Ocean Engineering*, 110, 102-112.
- Rodseth O J, Perera L P, Mo B. (2016). Big data in shipping-Challenges and opportunities. *International Conference on Computer Applications and Information Technology in the Maritime Industries*.
- Schiller, R. A., Ruggeri, F., Nishimoto, K., Sampaio, C. M. P., & Da Fonseca, R. P.. (2017). Shuttle tanker fuel consumption numerical analysis for improving ship efficiency. *Marine Systems & Ocean Technology*, 12(2), 80-92.
- Shao, W., Zhou, P., & Thong, S. K.. (2012). Development of a novel forward dynamic programming method for weather routing. *Journal of Marine Science & Technology*, 17(2), 239-251.
- Tillig, F., Ringsberg, J. W., Mao, W., & Ramne, B. . (2017). A generic energy systems model for efficient ship design and operation. *Proceedings of the Institution of Mechanical Engineers Part M Journal of Engineering for the Maritime Environment*, 231(2), 649-666.
- United Nations Conference on Trade and Development (UNCTAD). (2016). Review of maritime transport. *United Nations publication*, Sales No. E.12.II.D.17. New York and Geneva.
- Vergara J, Mckesson C, Walczak M. (2012). Sustainable energy for the marine sector. *Energy Policy*, 49(49): 333-345.
- Wang, K., Jiang, X., Yan, X., Lodewijks, G., Yuan, Y., Negenborn, R.R.. (2017). PSO-based method for safe sailing route and efficient speeds decision-support for seagoing ships encountering accidents. In: 14th IEEE International Conference on Networking, Sensing and Control. Calabria, Southern Italy, May 2017.
- Wren, & Kathy. (2014). Big data, big questions. *Science*, 344(6187), 982-983.
- Vettor, R., & Guedes Soares, C.. (2016). Development of a ship weather routing system. *Ocean Engineering*, 123, 1-14.
- Xie H. He Y. & Xie X. (2017). Exploring the factors influencing ecological land change for China's Beijing-Tianjin-Hebei Region using big data. *Journal of Cleaner Production*, V.142, 677-687.
- Yan, X., Sun, X., & Yin, Q.. (2015). Multiparameter sensitivity analysis of operational energy efficiency for inland river ships based on backpropagation neural network method. *Marine Technology Society Journal*, 49(1), 148-153.

Yang H., Ma X. & Xing Y. (2017). Trends in CO<sub>2</sub> Emissions from China-Oriented International Marine Transportation Activities and Policy Implications, *Energies*. 10: 980.

Zhao, F., Yang, W., Tan, W. W., Yu, W., Yang, J., & Chou, S. K.. (2016). Power management of vessel propulsion system for thrust efficiency and emissions mitigation. *Applied Energy*, 161(JAN.1), 124-132.