The 6th International Conference on Transportation Information and Safety, Oct 22 – Oct 24, 2021, Wuhan, China

Key Technology of Energy Efficiency Modeling and Optimization for Wing Sailboats

Zhongxi Huang
Marine Engineering College
Dalian Maritime University
Dalian, China
zxhuangzx@foxmail.com

Lianzhong Huang
Marine Engineering College
Dalian Maritime University
Dalian, China
huanglz@dlmu.edu.cn

Kai Wang *
Marine Engineering College
Dalian Maritime University
Dalian, China
kwang@dlmu.edu.cn

Ranqi Ma
Marine Engineering College
Dalian Maritime University
Dalian, China
ma_ranqi1989@163.com

Haoyang Zhao
Marine Engineering College
Dalian Maritime University
Dalian, China
m15969923307@163.com

Zhongyi Wang
Marine Engineering College
Dalian Maritime University
Dalian, China
wzywhk0991@163.com

2021 6th International Conference on Transportation Information and Safety (ICTIS) | 978-1-6654-9713-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICTIS54573.2021.9798535

***Abstract*—The application of wing sailboats can reduce the marine environmental pollution caused by ships. However, there is a great potential for the improvement of the wing sailboats energy efficiency. Therefore, it is of significance to explore the energy efficiency optimization method of wing sailboats. In this paper, key technologies for energy efficiency optimization of wing sailboats, including energy efficiency modeling and energy efficiency optimization control, were summarized. In addition, the existing problems on the energy efficiency optimization of wing sailboats were proposed. Finally, suggestions on energy efficiency optimization of wing sailboats were put forward, in order to promoting the development of the wing sailboats.**

Keywords—wing sailboats, energy efficiency optimization, green ships, EEDI, energy efficiency management

I. INTRODUCTION

In recent years, global warming and air pollution have become more and more serious, a large part of global greenhouse gas emissions and other substances, including NOx, SOx and particulate matter (PM) come from the shipping industry. To improve the air quality, some laws and regulations are introduced by the International Maritime Organization (IMO) aimed at reducing the ecological footprint of the shipping industry. For instance, the introduced SOx emissions limitation in Annex VI of MARPOL and the initial strategy on the reduction of GHG emissions aims to reduce the total GHG emissions from ships by at least 50% by 2050 [1-2]. But it is almost impossible to use conventional vessels to meet the laws and regulations. Therefore, the shipping industry needs to adopt new technologies to meet the stricter international and national regulations [3]. And according to generous reports concerning shipping costs, fuel consumption accounts for 30% - 55% of the total vessel managing capital [4-5]. Because of the rise of fuel prices and the pressure to reduce its impact on the environment, the shipping industry has faced great challenges in the past few years [6-9]. Some studies have shown that current marine propulsion around the world could be improved by introducing new propulsion technologies and using cleaner fuels [10-12]. So in order to address these challenges, adopting new green energy to replace part of traditional energy is of essence [13-15].

Guidelines proposed by the IMO Marine Environmental Protection Committee circular 815 (MEPC. 1 / CIRC. 815) pointed out that wind energy, as the auxiliary power of ship's main propulsion device, is an innovative energy efficiency technology. And the research of sailboat has always been a hotspot in shipping industry due to its advantages of energy conservation and environmental protection. There are several typical sails including square sails, skysails, Magnus roll sails and wings. The skysails are confined to a very narrow wind range; the square sails are less efficient at harnessing wind energy; the Magnus roll sails have high reliability and high costs, but extra power is needed to rotate during navigation [16-19]. The wings are variable radian aerodynamic structures, which have been used in recent years to replace the traditional sails, the aerodynamic performance and stability of the wings are better than the conventional sails, the wing assisted navigation technology is an availably way to use offshore wind energy [20]. Therefore, the adoption of wing assisted navigation technology is of great significance to the optimization of ship energy efficiency. When the wing assisted navigation technology is introduced into vessels, it is imperative that much attention should be paid to the optimization of its energy efficiency. However, at present, there is a potential in improving the energy efficiency of the wing sailboats. Therefore, the key technologies of modeling and optimization of the energy efficiency of the wing sailboats are fully analyzed and investigated, in order to promoting the development of the wing sailboats.

II. ENERGY EFFICIENCY MODELING TECHNOLOGIES OF WING SAILBOATS

Accurate model is important for energy efficiency optimization of the wing sailboats, and the thrust coefficient is greatly affected by the structure and aerodynamic characteristics of the wing [21]. Therefore, the wing shape should be optimized before modeling. There are generally two methods for wing shape optimization, including single point optimization and multi-point optimization. Single point optimization means the optimization based on only one characteristic, such as speed or wind direction [22]. While multi-point optimization refers to the optimization through selecting several single points in the continuous design area meanwhile considering corresponding weight of each point, so as to realize comprehensive optimization. Actually, the multi-point optimization method is generally used in the wing shape optimization [23].

Among the wing's parameters that influence the effect of wing, aspect ratio and camber ratio are the most important factors [24]. Zeng [25] conducted the wind tunnel tests, and concluded that a larger camber ratio can increase the thrust performance of the wing, but an excessive camber ratio will increase the lateral force and affect the ship stability. Viola et al. [26] proposed that the efficiency of the wing with large aspect ratio is higher than that of the wing with small aspect ratio when the total area and height of the sail are the same, but the interaction of multiple sails was not considered. Lee et al. [27] used viscous Navier Stokes flow solver for numerical aerodynamic analysis of multi sail optimization, and obtained the optimal solution with the maximum thrust coefficient of multi sail. In addition, the design of the new wing can also improve the thrust coefficient, Ma et al. [23] designed a coupling sail based on NACA airfoil and arc airfoil by using parametric section airfoil parametrization (PARSEC) method and particle swarm optimization algorithm; Li et al. [28] designed a variable camber wing with high propulsion coefficient by using wind tunnel testing and a two-dimensional simulation code based on the boundary element method with vortices; Sun et al. [29] designed a rectangular wing with three sharp sails, which can increase the lift drag ratio. The modeling and analysis of the wing sailboats can be carried out after designing the optimal shape of the wing.

A. Power System Modeling Technology for Wing Sailboats

The power system of the wing sailboats is basically in the form of "main engine and auxiliary sail". The main purpose of modeling the power system of the wing sailboats is to investigate the coupling interaction characteristics of the ship, engine, propeller and wing, which can lay the foundation for the optimization control of the wing sailboats. The key technologies about the modeling of the wing sailboats' power system mainly include the matching design of ship, engine, propeller and wing, as well as the energy transfer mode of the power system and the analysis of aerodynamic characteristic of the wing.

In general, poor matching between the engine and the propeller of the ship may be existed after installing the wing. Ren [30] proposed three solutions, including reducing the throttle opening of the main engine, reducing the propeller load and reducing the speed ratio of the propeller and the main engine. After solving the problem of matching, the ship, engine, propeller and wing can be modeled respectively, and then the the hybrid model of wing sailboats can be obtained as shown in Fig. 1.

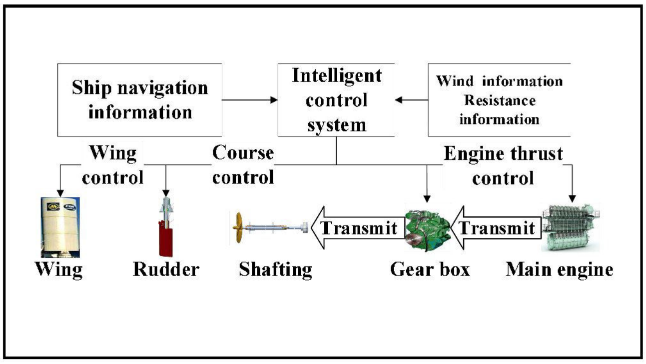

Fig. 1. Hybrid power model of wing sailboats

To solve the problem of establishing the transmission mode of the power system of the wing sailboats, several main procedures should be conducted. Firstly, the motion model of the wing sailboats can be established (Fig. 2) based on the force analysis of the wing; Then, the motion inertia mathematical model of the wing sailboats, mathematical model of the propeller and the main propulsion of the ship can be established respectively based on the MMG separation modeling idea; After that, the motion mathematical model of the 4-DOF wing sailboats including the characteristics of the main engine can be established; Afterwards, the energy transfer mode diagram of wing sailboats, as shown in Fig. 3, can be constructed by adding the wing rotation system. Finally, Simulink software can be used to establish the simulation motion model of the wing sailboats' power system. The results showed that the error rate between the simulation system and the actual value

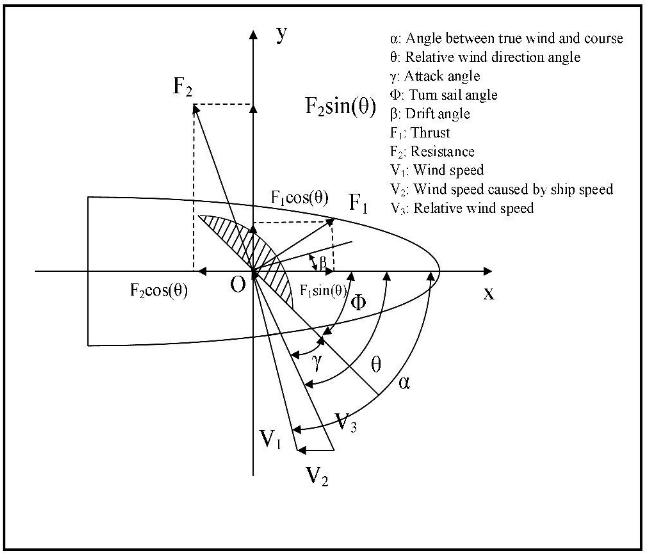

Fig. 2. Motion model of wing sailboats

deviate less than 3%, which can lay a theoretical foundation for the joint control strategy of the ship, engine, propeller and wing of the wind-diesel hybrid ship.

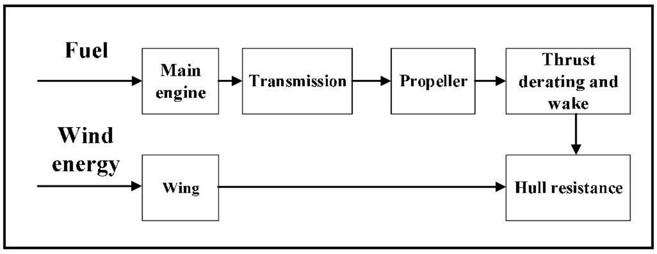

Fig. 3. Energy transfer mode diagram of wing sailboats

The results of aerodynamic characteristics of wings indicated that the CFD (Computational Fluid Dynamics) prediction of steady aerodynamic characteristics of wings are more accurate than the unsteady aerodynamic characteristics [31]. On the other hand, in order to evaluate the quality of driving force generated by wings and to build wing sailboats, it is necessary to evaluate the influence of wing-wing and wing-hull interaction [32].

In addition, in order to determine the disturbance of the wing to the diesel engine, the comprehensive mathematical model can be established by analyzing the thrust characteristics of the wing, the dynamic characteristics of the propeller, the resistance characteristics of the ship and the characteristics of diesel engine respectively. CFD method including Reynolds Average Navier-Stokes (RANS), Vortex Lattice Method (VLM) and so on, can also be used to establish the dynamic model of wing sailboats. The influence of mast on air flow and aerodynamic force can be studied

978-1-6654-9713-8/21/$31.00 ©2021 IEEE

based on RANS method, but it still exists some errors, which should be further analyzed under the specific situation [33]. However, the above method does not consider the influence of the wing on the ship drift angle. Kolk et al. [34] have given the RNAS-CFD simulation verification of the drift angle for bare shell case and additional case respectively, and described the verification method for point by point comparison and multi-point verification. Above all, the wing sailboats usually have large drift angles because of considerable side forces, mainly caused by the sail. a more accurate model can be obtained by adding a small correction term about the influence of the drift angle [35].

The dynamic system modeling of the wing sailboats is the basis of analyzing the energy efficiency of the wing sailboats. With the dynamic system model, the interaction relationship between ship, engine, propeller and wing can be analyzed, and then the contribution of the wing to the energy efficiency improvement of the ship can be calculated. Since many parameters are involved in the wing sailboats, their accuracy are of great importance. However, current modeling methods usually ignore or idealize some parameters. Therefore, future work needs to focus on establishing a more accurate wing sailboats' power system model, which can make a contribution to the energy efficiency optimization of the wing sailboats.

B. Energy Efficiency Modeling Technology for Wing Sailboats

1) EEDI Analysis of wing sailboats

Ship energy efficiency design index (EEDI) is essentially the proportional index of ship energy consumption converted into CO_2 emission. The higher the EEDI index, the lower the energy efficiency. The EEDI can be calculated as follows [36]:

$$EEDI_{attained} = \frac{P_{ME} \cdot C_{FME} \cdot SFC_{ME} + P_{AE} \cdot C_{FAE} \cdot SFC_{AE}}{f_i \cdot DWT \cdot V_{ref}} \quad (1)$$

where:

P_{ME} – 75% of the selected maximum continuous rating (SMCR)

C_{FME} – non-dimensional conversion factor between main engine fuel consumption and CO_2 emission

SFC_{ME} – main engine specific fuel oil consumption

P_{AE} – required auxiliary engine power to supply normal maximum sea loading

C_{FAE} – non-dimensional conversion factor between auxiliary engine fuel consumption and CO_2 emission

SFC_{AE} – auxiliary engine specific fuel oil consumption

$f_i = 1 + (0.08 \times LWT / DWT)$ – for ships built under Common Structural Rules

LWT – lightweight of the ship

DWT – deadweight on summer load draught

V_{ref} – ship speed on deep water corresponding to DWT and P_{ME}

As can be seen from equation (1), the application of wing can reduce the EEDI of ships. According to the 2013 guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI, among the technology of reducing propulsion power, wing assisted navigation belongs to B-2 innovative energy efficiency technology, namely, its energy-saving effect can be separated from the overall performance of the ship and analyzed separately. Therefore, the propulsion power generated by wing are usually calculated firstly, and then the EEDI of wing sailboats can be calculated by combining with EEDI calculation formula. Yu et al. [37] concluded that the wing assisted navigation can save 8.3% power and reduce the EEDI value by 5.5%. Gu et al. [38] calculated the EEDI value for the first wind assisted VLCC in China before and after installing sail, and the results showed that the EEDI value can be reduced by about 3.7% by adopting sail. Yang et al. [39] indicated that the EEDI values of the ship after installing sail can be reduced by 17.5%, and the target ship can meet the baseline requirements on more cases after installing sail. These methods are all based on the real ship data, the EEDI modeling technology for the design stage of the wing sailboats is also worthy of research.

2) EEOI Analysis of wing sailboats

Ship energy efficiency operation index (EEOI) refers to the mass ratio of CO_2 emitted per unit of transportation, which is a monitoring mechanism for long-term management of ship and fleet efficiency. The calculation formula is as follows [40]:

$$EEOI = \frac{\sum_j FC_{ij} \times C_{Fj}}{m_{cargo} \times D} \quad (2)$$

where:

j – fuel type

i – voyage number

FC_{ij} – mass of consumed fuel j at voyage i

C_{Fj} – fuel mass to CO_2 conversion factor of fuel j

m_{cargo} – cargo carried

D – distance travelled

There are many energy efficiency models based on artificial neural network and random forest algorithm for traditional ships. Firstly, the hull efficiency, ship resistance and main engine characteristics based on the ship parameters were analyzed, and then the main engine energy efficiency based on the collected data were calculated.

The method to establish the overall energy efficiency model of the wing sailboats is usually to increase the influence of the wing on the ship's energy efficiency on the basis of the traditional model. For example, the calculation of the fuel consumption rate of the main engine of the wing sailboats is shown in Fig. 4 [41]. In addition, there are other methods, such as the calculation of the power of the main engine based on the analysis of historical wind frequency distribution. [42], the overall energy efficiency and the characteristics of wing sailboats were analyzed by using the computational fluid dynamics (CFD) method Based on model test [43], and so on.

978-1-6654-9713-8/21/$31.00 ©2021 IEEE

Modeling the energy efficiency of the wing sailboats is the premise to optimize its energy efficiency. Only with the accurate model can researchers optimize the factors that affect the energy efficiency of the ship. At present, there are few methods based on the existing traditional ships to model the energy efficiency of wing sailboats, that will reduce the accuracy of modeling. In the future, it is necessary to improve the fuel consumption prediction model by using on-board measurement and ship behavior identification scheme, so as to establish a reliable model for different types of ships.

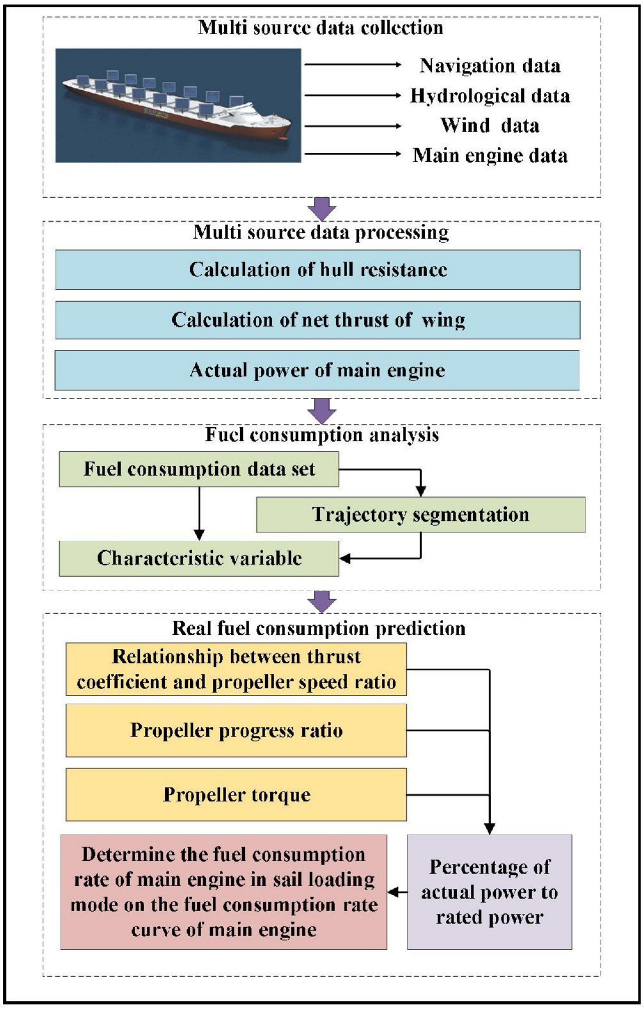

Fig. 4. Calculation of fuel consumption rate of wing sailboats

III. Energy Efficiency Optimization Technologies of Wing Sailboats

A. Energy Efficiency Optimization Technology of Wing Sailboats

The current energy efficiency optimization methods for the wing assisted navigation ship mainly include the optimization of the route of wing sailboats and the optimization of the speed of wing sailboats.

1) Route optimization

Because the thrust coefficient and lateral force coefficient of the wing are related the relative wind direction angle and relative wind speed. In addition, the wind field will also change when the ship is sailing in different routes, which has a great impact on the effect of the wing. Therefore, it is very meaningful to select the appropriate route for improving the energy efficiency of the wing. The basic optimization model is shown in Fig. 5.

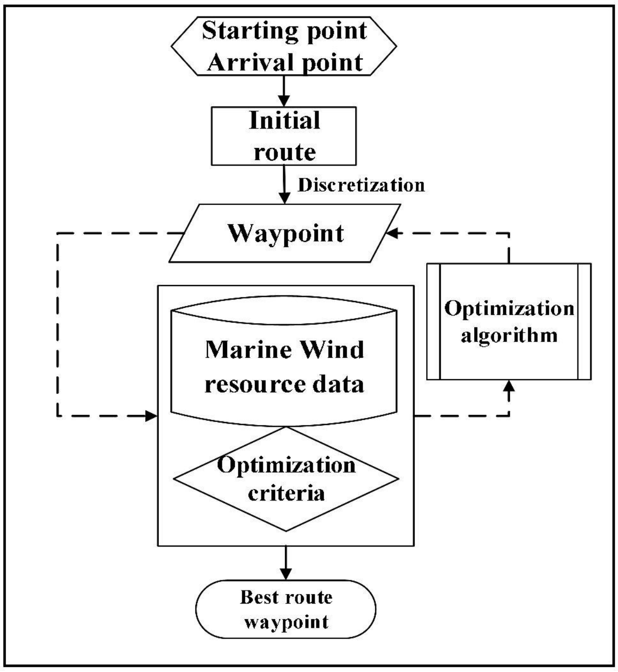

Fig. 5. Route optimization model of wing sailboats

In previous studies, there are two kinds of route optimization algorithms for wing sailboats. One method is based on the established energy efficiency model of wing sailboats. Firstly, the wind field data is stored in the cloud based on the cloud technology, and then the fuel saved by adopting sail according to different routes can be analyzed, and most fuel saving optimization function in the process of wing assisted navigation can be obtained [44]. The other method is to use CFD [45], and use FLUENT software to simulate the navigation characteristics of the wing, and then establish the route optimization function aiming at energy saving. In addition, a route optimization model can be established to maximize the use of marine wind resources in an appropriate way of detour. The route navigation algorithms for detour include a new passive navigation algorithm based on artificial potential field [46] and a parallel sailing navigation algorithm based on real-time weather information and motion state combined with fuzzy logic principle [47-48].

2) Speed optimization

The efficiency of the wings fluctuates greatly with the change of the relative wind speed, the utilization rate of wind energy and the thrust ratio of the wings are also different at different sailing speed. Therefore, it is significant to study the sailing speed optimization of the wing sailboats, in order to maximize energy saving and emission reduction [49]. Deng et al. [50] obtained a speed optimization scheme based on the principle of fuzzy logic and the motion model of the wing sailboats, by combining the extreme value optimization algorithm and the self-tuning fuzzy logic system. The improved ES algorithm was used to obtain optimal angle of attack of the wing sail, thus improving calculation speed.

At present, the optimization of the sail airfoil can only be applied to the design stage of the wing, which has certain limitations. At the same time, there are many geometric parameters, including camber ratio and aspect ratio, so the

978-1-6654-9713-8/21/$31.00 ©2021 IEEE

optimization of the airfoil is quite challenging. For the installed wings, only route and speed optimization can be carried out. The goal of route optimization is to save the sailing time or to reduce fuel consumption, which can fully use the marine wind resources. The advantage of route optimization is that it can make the best use of wind resources, while the disadvantage is that it requires high speed of meteorological information collection and transmission. In the future, the stochastic properties of weather and sea conditions should be integrated to calculate the optimal route which can be suitable for potential weather changes. Few research has been done on the speed optimization of the wing sailboats and the joint optimization scheme for the wing sailboats. Future work is needed to establish a scheme which can make the speed and course of the ship change with the wind speed and direction, so as to achieve the most efficient utilization of wind energy resources.

B. *Energy Efficiency Control Technology of Wing Sailboats*

The control technology of the wing sailboats is also an important factor for the wing assisted navigation. According to the principle of the wing, there is an optimal angle of attack under a certain relative wind direction angle, which makes the wing have the optimal thrust coefficient [51]. The angle of attack can be changed by controlling the rotary motion of the wing. Therefore, the current control method for the wing is based on the selection of the optimal angle of attack.

In general, several steps are needed to select the optimal angle of attack. Firstly, the optimal attack angle under different relative wind angles can be obtained based on the aerodynamic characteristics of the target wing as well as the thrust coefficient lateral force coefficient curve under different attack angles through wind tunnel test. Then, the PID control system was used to control the wing rotation according to the collected wind direction, wind speed and other information. During establishing control system, different modeling methods can be used, such as MMG separation modeling. After that, in order to achieve the maximum sail boosting effect and the optimal matching of ship, engine, propeller and wing, it is also important to adjust the speed of the main engine according to the actual conditions. In addition, the influence of wind on the hull itself and the characteristics of the main engine and propeller should be considered in the control system. As for the influence of wind on the hull, a quadratic linear regulator can be used to dynamically control the wing [52], the surge speed and bow angle of the sailboat can also be controlled according to the adaptive fuzzy control method [53]. In order to improve the stability of the ship, Viel et al. [54] designed a method which use rudder and angle sail controller to control the angle of the wing through adaptive adjustment of the wing. As for the influence of wind on the characteristics of the main engine and propeller, the main engine and wing joint control system can be designed to control the sail angle more accurately.

In addition to the optimization of the control algorithm of the wing sailboats, it is also necessary to make the energy efficiency system intelligent. Ship intelligent energy efficiency control system is a management system which can automatically collect data, analyze and evaluate of ship energy efficiency and energy consumption, create reports, generate early warnings in an emergency, upload data to database and integrate big data. Through the analysis of the ship operation status, the optimization scheme can be put forward, and suggestions on the course and speed can be put forward as well, so as to achieve energy saving and emission reduction which meets the green navigation [55].

The intelligent energy efficiency system can be divided into different functional modules, such as system management, data analysis, energy efficiency and energy consumption evaluation, energy efficiency management decision making and so on. The energy efficiency control system can make the users carry out corresponding operations on the browser [56]. Until now, limited studies have been done on the intelligent energy efficiency management system for the wing. The main way is to add the intelligent control module for the wing rotation based on the existing ship intelligent energy efficiency management system, by analyzing the collected wind direction and wind speed information and matching with the optimal attack angle database obtained by analyzing the aerodynamic characteristics of the wing, then the hydraulic system can be automatically controlled to make the wing angle to reach the optimal state [57].

At present, the best scheme to control the wing is to make the wing reach the best attack angle through the slewing mechanism. Therefore, the accuracy and reliability of the slewing mechanism are important. Meanwhile, a special fault diagnosis system for the wing slewing mechanism should be established to improve reliability and safety. For the energy efficiency system, a set of system should be established that can intelligently change the speed and course of the ship by analyzing the online wind field data, so as to achieve the most efficient utilization of wind energy. In addition, in order to avoid the possible mistakes caused by human and guarantee navigation safety, all kinds of operations that change the navigation state should be carried out automatically.

IV. Summary and Prospect

To meet the demand for "green" and "intelligent" requirements of the international community, the application of wing sailboats is a potential trend. The wing assisted navigation technology can achieve energy saving and emission reduction benefits for large ships, while there is much potential for the optimization of energy efficiency of wing sailboats. Based on the analysis of the key technologies of energy efficiency optimization of wing sailboats, the following conclusions can be obtained:

Wing assisted navigation is a kind of technology that is environmentally friendly and of high economic benefits, which has a broad prospect. However, there are still some problems and challenges although a lot of research have been done on wing assisted navigation:

- Due to many environmental factors are involved in the wing sailboats, the modeling of its motion mode and power system is complex. Meanwhile, the accuracy for calculation of EEOI and EEDI of the wing sailboats should be improved;
- As for wing sailboats optimization, little research has been done on ship speed optimization, and optimal solutions on the ship sailing speed in different environments are also lacking. In addition, the analysis of wind resources on the route is helpful to

978-1-6654-9713-8/21/$31.00 ©2021 IEEE

the route optimization of the wing sailboats. However, the research on the analysis and prediction methods of wind resources on the specific route is limited;

- Finally, the energy efficiency management system for the wing sailboats is not satisfactory, and the degree of intelligence for the optimization of course and speed should be improved.

Based on these problems and challenges, the future development of wing assisted navigation technology is prospected as follows:

- In order to improve the calculation accuracy of EEDI, EEOI and so on, more efforts should be made to explore the establishment of the wing assisted navigation model, various factors should be considered synthetically, the motion model should be improved, and the control of the power system should be more accurate. Besides, the traditional algorithm should be optimized, and better algorithm should be established;
- For the speed optimization method of the wing sailboats, it is necessary to further study and establish the optimal speed algorithm to achieve the purpose of dynamic optimization of the speed. It is also necessary to establish a wind resource analysis method and weather forecast method for the wing sailboats in combination with the aerodynamic characteristics of the sail, wind field characteristics and route information, so as to select the optimal sailing route;
- Establishing the intelligent ship energy efficiency management system and improving the optimization algorithm, so that the course and speed can be changed intelligently according to the meteorological information, so as to achieve the goal of maximum utilization of the ocean wind energy resources.

ACKNOWLEDGMENT

The authors are grateful to the support of the National Natural Science Foundation of China (51909020 and 52071045), the Project Funded by China Postdoctoral Science Foundation (2020M670735 and 2021T140080), the Natural Science Foundation of Liaoning Province (2019-BS-023), the Fund of National Engineering Research Center for Water Transport Safety (No. A2020001), the Project from Key Lab. of Marine Power Engineering and Tech. authorized by MOT (KLMPET2020-06), the Fundamental Research Funds for the Central Universities (3132019316). The authors are also thankful to the anonymous reviewers for their valuable comments and suggestions that significantly improved the quality of this paper.

REFERENCES

[1] C. Haehl, S. Spinler. Technology choice under emission regulation uncertainty in international container shipping [J]. European Journal of Operational Research, 2020, 284 (1): 14.

[2] S. Patrizia, G. Fancello. Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping [J]. Sustainability, 2020, 12 (8): 3220.

[3] M. Issa, H. Ibrahim, A. Ilinca. A review and economic analysis of different emission reduction techniques for marine diesel engines [J]. Open Journal of Marine Science, 2019, 9 (3): 148-171.

[4] B. D. Brouer, J. Fernando, C. E. M. Plum, D. Pisinger, M. M. Sigurd. A base integer programming model and benchmark suite for liner - shipping network design [J]. Transportation Science, 2014, 48 (2): 281-312.

[5] S. H. Jang, J. H. Choi. Comparison of fuel consumption and emission characteristics of various marine heavy fuel additives [J]. Applied Energy, 2016, 179: 36-44.

[6] J. Yuan, S. H. Ng. Emission reduction measures ranking under uncertainty [J]. Applied Energy, 2017, 188: 270–279.

[7] L. A. Hai, S. L. Wen, Y. Y. Hong, D. C. Yu, L. J. Zhang. Optimal sizing of hybrid PV/diesel/battery in ship power system [J]. Applied Energy, 2015, 158: 26-34.

[8] Y. J. Zhang, Z. Y. Wang. Investigating the price discovery and risk transfer functions in the crude oil and gasoline futures markets: Some empirical evidence [J]. Applied Energy, 2013, 104: 220-228.

[9] R. D. Geertsma, R. R. Negenborn, K. Visser, J. J. Hopman. Design and control of hybrid power and propulsion systems for smart ships: A review of developments [J]. Applied Energy, 2017, 194, 30-54.

[10] S. E. Hirdaris, Y. F. Cheng, P. Shallcross, J. Bonafoux, G. A. Sarris. Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion [J]. Ocean Engineering, 2014, 79, 101-130.

[11] J. Vergara, C. Mckesson, M. Walczak. Sustainable energy for the marine sector [J]. Energy Policy, 2012, 49 (OCT.): 333–345.

[12] V. Alfonsín, A. Suarez., A. Cancela, A. Sanchez, R. Maceiras. Modelization of hybrid systems with hydrogen and renewable energy oriented to electric propulsion in sailboats [J]. International Journal of Hydrogen Energy, 2014, 39,: 11763–11773.

[13] A. Essia, H. Cherif, K. Badreddinne. Optimization of a thruster sections by Prandtl's theory [J]. Renewable Energy, 2016, 87: 863-868.

[14] T. H. Nguyen, A. Prinz, T. Friiso, R. Nossum, I. Tyapin. A framework for data integration of offshore wind farms [J]. Renewable Energy, 2013, 60: 150-161.

[15] Y. Li, K. J. Paik, X. Tao, P. M. Carrica. Dynamic overset CFD simulations of wind turbine aerodynamics [J]. Renewable Energy, 2011, 37 (1): 285-298.

[16] M. Ebrahimi, A. Jahangirian. Aerodynamic Optimization of Airfoils Using Adaptive Parameterization and Genetic Algorithm [J]. Journal of Optimization Theory and Applications, 2014, 162 (1): 257-271.

[17] G. M. Dadd, D. A. Hudson, R. A. Shenoi. Determination of kite forces using three-dimensional flight trajectories for ship propulsion [J]. Renewable Energy, 2011, 36 (10): 2667–2678.

[18] L. Chen, S. Chen, Y. Wang. Analysis on sail selection and energy conservation of a Panamax bulk carrier [C] In: Advances in Energy Engineering (ICAEE), 2010 International Conference on, IEEE,: 182-185.

[19] A. Sedaghat. Magnus type wind turbines: Prospectus and challenges in design and modelling [J]. Renewable Energy, 2014, 62: 619-628.

[20] P. F. Rynne, K. D. von Ellenrieder. Development and Preliminary Experimental Validation of a Wind- and Solar-Powered Autonomous Surface Vehicle [J]. IEEE Journal of Oceanic Engineering, 2010, 35 (4): 971-983.

[21] B. Augier, P. Bot, F. Hauville, M. Durand. Dynamic behaviour of a flexible yacht sail plan [J]. Ocean Engineering, 2013, 66: 32-43.

[22] D. J. Poole, C. B. Allen, T. C. S. Rendall. Metric-Based Mathematical Derivation of Efficient Airfoil Design Variables [J]. AIAA Journal, 2015, 53 (5): 1349-1361.

[23] Y. Ma, H. Bi, M. Hu, Y. Zheng, L. Gan. Hard sail optimization and energy efficiency enhancement for sail-assisted vessel [J]. Ocean Engineering, 2019, 173: 687-699.

[24] J. He, Y. Hu, J. Tang, S. Xue. Research on sail aerodynamics performance and sail-assisted ship stability [J]. Journal of Wind Engineering & Industrial Aerodynamics, 2015, 146: 81-89.

[25] X. Zeng, Y. Hu, Y. Wang. Wind tunnel test on sails with different shape [J]. Journal of Shanghai Maritime University, 2010, 31 (04): 28-31. *(in Chinese)*

[26] I. M. Viola, M. Sacher, J. Xu, F. Wang. A numerical method for the design of ships with wind-assisted propulsion [J]. Ocean Engineering, 2015, 105: 33-42.

978-1-6654-9713-8/21/$31.00 ©2021 IEEE

[27] H. Lee, Y. Jo, D. J. Lee, S. Choi. Surrogate model based design optimization of multiple wing sails considering flow interaction effect [J]. Ocean Engineering, 2016, 121: 422-436.

[28] Q. Li, Y. Nihei, T. Nakashima, Y. Ikeda. A study on the performance of cascade hard sails and sail-equipped vessels [J]. Ocean Engineering, 2015, 98: 23-31.

[29] C. Sun, C. Dai. Experimental Study on Ground Effect of a Wing with Tip Sails [J]. Procedia Engineering, 2015, 126: 559-563.

[30] H. Y. Ren, G. T. WU, P. T. Sun, L. Z. Huang, Y. T. Zhao. Study on the effect of wing-diesel remodel ship on match among vessels [J]. Renewable Energy Resources, 2011, 29 (06): 58-61 + 67. *(in Chinese)*

[31] A. Persson, R. Lindstrand, S. Muggiasca, L. Larsson. CFD prediction of steady and unsteady upwind sail aerodynamics [J]. Ocean Engineering, 2017, 141: 543-554.

[32] T. Fujiwara, G. E Hearn, F. Kitamura, M. Ueno. Sail–sail and sail–hull interaction effects of hybrid-sail assisted bulk carrier [J]. Journal of Marine Science and Technology, 2005, 10 (2): 82-95.

[33] Y. Masuyama, Y. Tahara, T. Fukasawa, N. Maeda. Database of sail shapes versus sail performance and validation of numerical calculations for the upwind condition [J]. Journal of Marine Science and Technology, 2009, 14 (2): 137-160.

[34] N. J. van der Kolk, J. A. Keuning, R. H. M. Huijsmans. Part 1: Experimental validation of a RANS-CFD methodology for the hydrodynamics of wind-assisted ships operating at leeway angles [J]. Ocean Engineering, 2019, 178: 375-387.

[35] K. L. Wille, V. Hassani, F. Sprenger. Modeling and Course Control of Sailboats [J]. IFAC PapersOnLine, 2016, 49 (23): 532-539.

[36] P. Čudina. Analysis of the energy efficiency design index with a proposal for improvement [J]. Shipbuilding, 2015, 66 (3): 49-59.

[37] Y. U. Shengjie, Y. Xie, G. Zhou, S. Pang. Energy saving of propulsion with sail assistance in terms EEDI [J]. Navigation of China, 2017, 40 (03): 125-128 + 134. *(in Chinese)*

[38] Y. J. Gu, X. W. Tong. Study on calculation method of contribution of wing-sail propulsion technology to EEDI [J]. Shipbuilding of China, 2019, 60 (02): 107-116. *(in Chinese)*

[39] B. S. Yang, P. T. Sun, L. Z. Huang, H. M. Wang, H. Y. Ren. Energy efficiency design index of a sail-assistant ship [J]. Journal of Dalian Maritime University, 2011, 37 (04): 39-40 + 63. *(in Chinese)*

[40] H. Prastowo, T. Pitana, A. P. Mahdali. Activity-based fuel oil consumption estimation for calculating energy efficiency operational indicator (EEOI) in an indonesian merchant ship [J]. IOP Conference Series: Earth and Environmental Science, 2020, 557 (1): 012053.

[41] H. F. Chi, F. Q. Bao, X. G. Wu. The Influence of Wind-aided Sailing on the fuel Consumption rate of the Main Engine [J]. Energy Conservation & Environmental Protection in Transportation, 2019,15 (02): 44-47. *(in Chinese)*

[42] A. G. Li, L. Y. Chen, Y. F. Zhang. Sail design for high speed arrangement-preferred ship and comprehensive performance analysis [J]. Ship Engineering, 2015, 37 (07): 54-58. *(in Chinese)*

[43] H. M. Wang, G. T. Wu, B. S. Yang. Efficiency Analysis of Sail-Assisted Ship Based on CFD [J]. Shipbuilding of China, 2011, 52 (02): 25-33. *(in Chinese)*

[44] S. G. Jin, B. Yan. The study on optimization modeling of wind aids in sailing ship [J]. Ship Science and Technology, 2016, 38 (12): 46-48. *(in Chinese)*

[45] S. Guo, Y. D. Liu. Route optimization method for sail-assisted ship [J]. Journal of Dalian Maritime University, 2013, 39 (01): 35-38 + 42. *(in Chinese)*

[46] C. Pêtrès, M. A. Romero-Ramirez, F. Plumet. A potential field approach for reactive navigation of autonomous sailboats [J]. Robotics and Autonomous Systems, 2012, 60 (12): 1520-1527.

[47] Y. Deng, X. Zhang, G. Zhang, C. Huang. Parallel guidance and event-triggered robust fuzzy control for path following of autonomous wing-sailed catamaran [J]. Ocean Engineering, 2019, 190: 106442-.

[48] S. Marie, E. Courteille. Sail-assisted motor vessels weather routing using a fuzzy logic model[J]. Journal of Marine Science and Technology, 2014, 19 (3): 265-279.

[49] G. T. Wu, H. Y. Ren, L. Z. Huang, Z. H. Gan. Research on slow steaming modes for wing-diesel ship [J]. Navigation of China, 2011, 34 (04): 17-21. *(in Chinese)*

[50] Y. Deng, X. Zhang, G. Zhang. Fuzzy logic based speed optimization and path following control for sail-assisted ships [J]. Elsevier Ltd, 2019, 171: 300-310.

[51] S. Y. Xue, Y. H. Hu, J. H. He, X. M. Zeng. Best angle of attack of Circular-Arc sails determined by wind tunnel tests [J]. Navigation of China, 2014, 37 (03): 59-62 + 94. *(in Chinese)*

[52] K. L. Wille, V. Hassani, F. Sprenger. Roll stabilization control of sailboats [J]. IFAC PapersOnLine, 2016, 49 (23): 552-556.

[53] Y. Deng, X. Zhang, Q. Zhang, Y. Hu. Event-triggered composite adaptive fuzzy control of sailboat with heeling constraint [J]. Ocean Engineering, 2020, 211: 107627.

[54] C. Viel, U. Vautier, J. Wan, L. Jaulin. Position keeping control of an autonomous sailboat[J]. IFAC PapersOnLine, 2018, 51 (29): 14-19.

[55] J. Lin, H. L. Ge, X. L. Li, T. Lu. Design of shipping energy effi ciency management system based on data analysis [J]. Ship & Boat, 2018, 29 (S1): 127-131. *(in Chinese)*

[56] J. Wu, X. Y. Wan, Y. G. Sun, Y. Zhai. Several points to be concerned in the design of ship's "intelligent energy efficiency" [J]. Ship & Boat, 2018, 29 (S1): 42-51. *(in Chinese)*

[57] H. F. Chi, J. Zhou, P. L. Zhu. Research on energy efficiency control system of sailing aids [J]. Energy Conservation & Environmental Protection in Transportation, 2018, 14 (05): 29-33. *(in Chinese)*

978-1-6654-9713-8/21/$31.00 ©2021 IEEE