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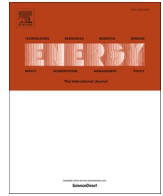
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Review

Wind-assisted propulsion system for shipping decarbonization: Technologies, applications and challenges

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ABSTRACT

Wind-assisted propulsion system (WAPS) is one of the important energy-saving measures for shipping decarbonization. The optimal design and operation control of wind-assisted ships can efficiently harvest and utilize wind energy, and thus further tapping the potential of improving the ship energy efficiency. However, there remains a shortage of the comprehensive analysis of the wind-assisted technologies to provide references for further study and practical applications of the WAPS. Thus, the present progress achieved in the key techniques, including the aerodynamics analysis for different sails, the optimal design and operation control of the ship adopting WAPS, as well as the comprehensive analysis of the sail-diesel hybrid propulsion system (SDHPS), are systematically analyzed. Additionally, the challenges encountered in the development of the WAPS are proposed, and prospective research directions are suggested to boost advancement of the WAPS for the shipping decarbonization. The investigation results indicate that the optimal design of sails and hybrid power systems, along with the applications of energy efficiency optimization strategies, can fully use the wind energy resources and reduce fuel usage of the ship equipped with WAPS. Additionally, it is anticipated that the wind-assisted technology incorporating complicated sea conditions can contribute to a further optimization of ship energy utilization, thereby promoting the low-carbon development of the shipping industry.

Nomenclatures and abbreviations

IMO	International Maritime Organization	GHG	Greenhouse gas
LES	Large Eddy Simulations	CFD	Computational fluid dynamics
PSO	Particle Swarm Optimization	AOA	Angle of attack
SRS	Segmental rigid sails	WAPS	Wind-assisted propulsion system
CPP	Controllable pitch propeller	MMG	Maneuvering Modeling Group
IPSO	Improved particle swarm optimization	EAE0	Enhanced artificial ecosystem-based optimization
GA	Genetic algorithm	NSGA-III	Non-dominated sorting genetic algorithm III

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EEDI	Energy Efficiency Design Index	PARSEC	Parametric section
SDHPS	Sail-diesel hybrid propulsion system	Y_H	The hull force on the Y-axis
X_H	The hull force on the X-axis	X_P	The propeller force on the X-axis
N_H	The torques of hull	N_P	The torques of propeller
Y_P	The propeller force on the Y-axis	Y_R	The rudder force on the Y-axis
X_R	The rudder force on the X-axis	X_{Wing}	The wing force on the X-axis
N_R	The torques of rudder	Y_{Wing}	The wing force on the Y-axis
X_{Wave}	The wave force on the X-axis	Z_{Wing}	The wing force on the Z-axis
Y_{Wave}	The wave force on the Y-axis	Z_{Wave}	The wave force on the Z-axis
N_{Wing}	The torques caused by the wing	Y	The sum of the external force on the Y-axis

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(continued)

X	The sum of the external force on the X-axis	m_x	Mass of sail-assisted ship on the X-axis
N	The sum of external torques	I_{zz}	Torques of inertia of the hull on the Z-axis
m_y	Mass of sail-assisted ship on the Y-axis	V_A	The propeller advance speed
J_{zz}	Additional inertia torques of the hull on the Z-axis	V	The sailing speed
ω	The wake coefficient	n_p	The propeller speed
J	The propeller advance coefficient	R	The ship resistance
D	The propeller diameter	K_T	Propeller thrust factor
t	The thrust derating factor	N_k	The number of sails
ρ	Sea water density	K_Q	The propeller torque coefficient
g_e	The specific fuel oil consumption rate	η_S	The transmission efficiency of the shaft
η_G	The transmission efficiency of the gearbox	η_R	The relative rotation efficiency of the propeller
η_H	The hull efficiency	η_O	The propeller open water efficiency
Q_B	The fuel consumption of the main engine per unit distance	V_A	The relative wind speed
θ	The relative wind angle	C_L	The lift coefficient of the sail
C_D	The resistance coefficient of the sail	C_X	The thrust coefficient of the sail
C_Y	The lateral force coefficient of the sail	F_X	The sail thrust along the sailing direction
F_Y	The sail transverse thrust along the board direction	F_L	The sail force perpendicular to the relative wind direction
F_D	The sail force along the relative wind direction	AOA	The angle of attack
φ	The sail azimuth angle	β	The relative wind direction angle
V_S'	The wind speed generated by the ship movement	V_t	The true wind speed

1. Introduction

Maritime transport has long been regarded as the backbone of global trade [1], with more than 80 % of global trade through maritime transportation [2]. With continuous development for the shipping industry, the pollution gas emissions from ships also increased year by year [3,4]. At present, the total shipping capacity of the existing large number of ships has reached about 2.1 billion tons [5,6]. The Fourth Greenhouse Gas Study Report by IMO (International Maritime Organization) indicates that carbon emissions of the shipping industry would

be increased by approximately 50 % by 2050 compared to the amount in 2008 [7,8]. To this end, IMO has proposed a series of relevant regulations on reducing greenhouse gas (GHG) emissions in 2018 [9], as represented in Fig. 1. Recently, IMO has updated the strategies aiming to decrease carbon intensity by 40 % by 2030 referring to the amount in 2008, and to achieve net-zero GHG emissions by 2050 [10]. However, there is still a significant gap between the current carbon emissions of the shipping industry and the emission reduction target for 2050 set by the IMO [11,12]. Therefore, some effective technologies and methods should be adopted to decrease CO₂ emissions effectively for the shipping industry [13,14].

In order to reduce GHG emissions and meet the increasingly stringent regulatory requirements, the strategies of adopting WAPS, ammonia, methanol and batteries have become main solutions to achieve the decarbonization for the shipping industry [15]. The ammonia, methanol and batteries technologies still face some challenges: 1) the production, storage and transportation of ammonia and methanol require specific facilities and technologies [16,17]; 2) the application of ammonia and methanol requires specific engines and combustion systems [18]. The WAPS has advantages of remarkable energy-saving and emission-reduction effects, low operating costs, mature technical foundation, and wide adaptability [19]. Therefore, the WAPS has become a more promising and practical option for the shipping industry to achieve decarbonization.

Under the background of low-carbon development for the shipping industry [20], the usage of wind energy, as renewable energy, has become a development trend to meet the requirements of the ship energy conservation and emission reduction [21]. The wind-assisted ship can effectively decrease energy usage and GHG emissions by utilizing the wind energy to provide auxiliary thrust during navigation [22]. In addition, the optimal operation control of the wind-assisted ship can significantly enhance the operational performance of the entire hybrid power system to efficiently harvest wind energy, thus further tapping the potential of reducing energy consumption [23]. Above all, the wind-assisted technology is one of the most effective ways to reduce ship CO₂ emissions, and thus realizing the green and low-carbon development for the maritime sector [24,25].

At present, WAPS techniques have been widely carried out, and rich research results have been accumulated in this field. Rehmatulla et al. [26] reviewed the economic barriers to ships adopting WAPS, and proposed the challenges facing the implementation of WAPS techniques in the maritime sector. Additionally, Chou et al. [27] reviewed the

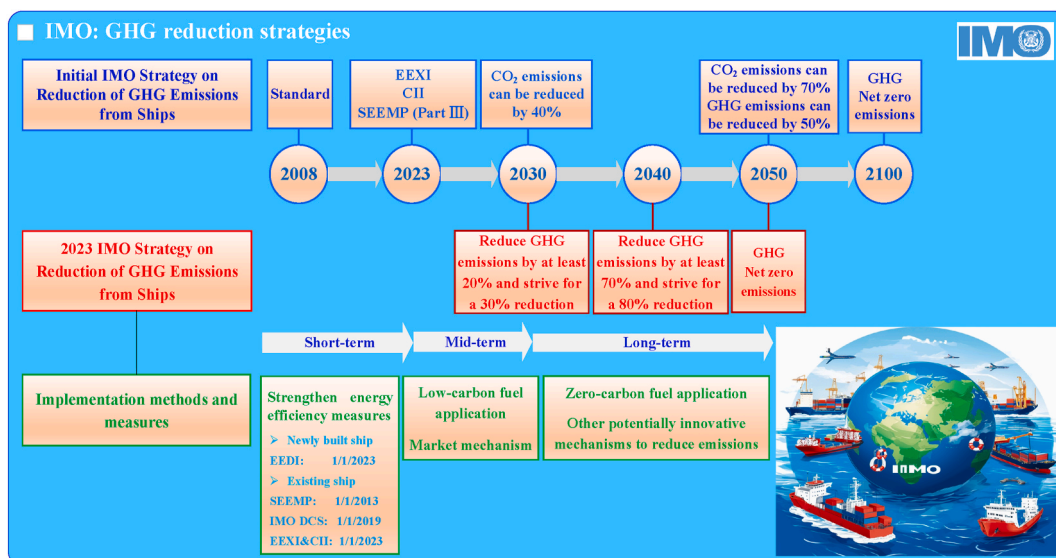


Fig. 1. The illustration of IMO GHG strategies proposed in 2018 [9].

current development of WAPS techniques in maritime transportation. They proposed potential fuel-saving effects and identified key factors influencing the operational efficiency of WAPS, including environmental, onboard, and commercial factors. Furthermore, Kolodziejski et al. [28] carried out a comprehensive review on the different type of sails in the maritime sector. The study also presented the latest developments and applications of WAPS for existing ships, as well as the future development potential of WAPS technologies.

Although the previous reviews on the WAPS have carried out the economic obstacles analysis, and the technical development and practical applications of WAPS, there remains a shortage of the comprehensive analysis of wind-assisted technologies to provide references for further research and practical applications of the WAPS. In order to fully use the wind energy resource, it is necessary to analyze the aerodynamics of sails and the coupling aerodynamics of multiple sails to improve the thrust effects of sails [29]. In addition, the optimal design of the ship adopting WAPS, including the design of the sail and the hybrid power system, is crucial in improving the reliability and energy-conservation effects [30]. Moreover, the operation control of the ship adopting WAPS can improve the navigation safety and the energy efficiency level [31]. Furthermore, the overall performance of the wind-assisted propulsion system in terms of the analysis on the economy, reliability, and energy-saving effect is significant to promote the practical applications of wind-assisted technologies [32].

With the continuous development of the shipping industry, the carbon emissions from maritime transportation have significantly increased. It is urgent to explore effective ways to reduce carbon emissions. The adoption of the WAPS can reduce output power of the main engine by using wind energy resources. Therefore, the WAPS can effectively reduce fuel consumption and carbon emissions during ship's voyage, thus achieving the shipping decarbonization. However, there

remains a shortage of comprehensive analysis on wind-assisted technologies to provide references for further research and practical applications of the WAPS. It is necessary to conduct a comprehensive analysis of the current progress and challenges of ships adopting WAPS based on the existing study, which can help identify effective solutions and novel methods to efficiently capture wind energy and further enhance the energy efficiency of ships. Nonetheless, a systematic and comprehensive analysis of wind-assisted technologies is still lacking. Such an analysis is crucial as it can offer valuable references for the in-depth study and practical implementation of ships equipped with WAPS. In this regard, the key technologies for the ship adopting WAPS are summarized, as shown in Fig. 2, and the current progresses made on the wind-assisted technologies, including the aerodynamics analysis of different sails, the optimal design of the ship adopting WAPS, the operation control of the wind-assisted ship, and the comprehensive analysis of the wind-assisted propulsion system, are comprehensively analyzed in this study. Based on these, the challenges and issues within wind-assisted techniques are carried out, and the prospective research directions are outlined to offer insights for the advancement of wind-assisted technologies for the shipping decarbonization. Above all, the main work and contributions of this review are as follows.

- 1) The key technologies for the optimal design and the operation optimization control of the ship adopting WAPS are discussed, including the aerodynamics analysis of different sails, the optimal design of the ship adopting WAPS, the operation control of the wind-assisted ship, and the comprehensive analysis of the wind-assisted propulsion system.
- 2) The challenges encountered in the development of the wind-assisted technologies are thoroughly analyzed, and future research directions for the advancement of wind-assisted technologies are proposed.

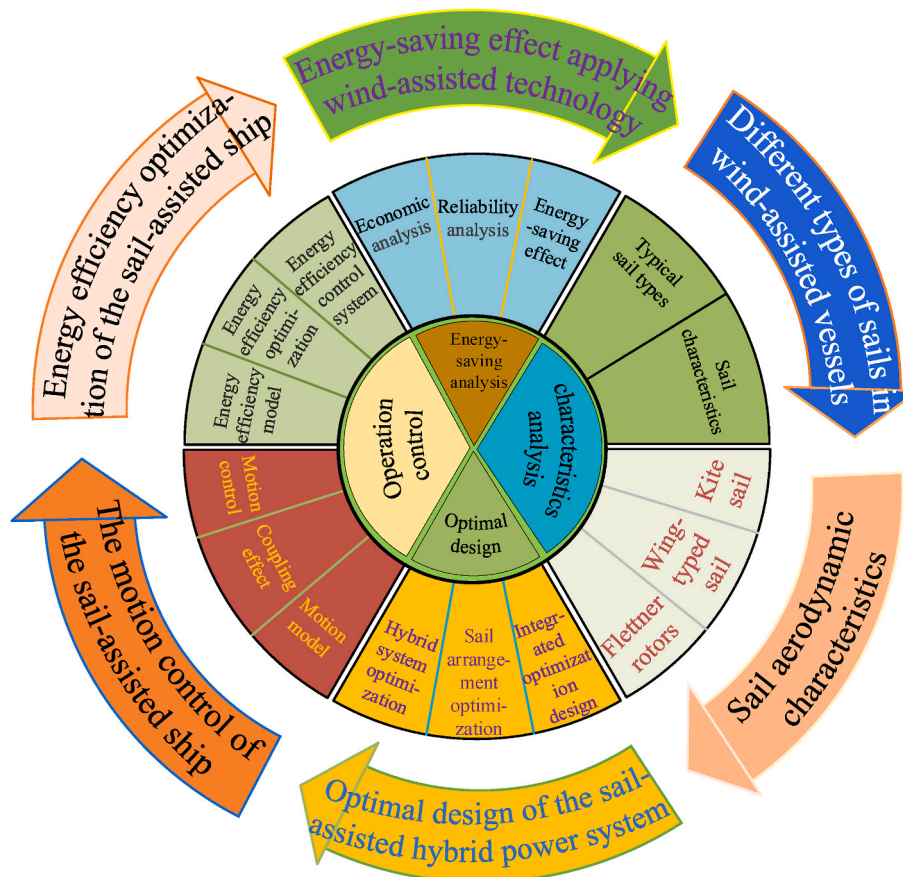
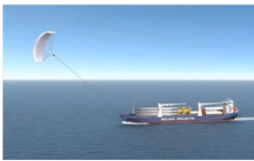


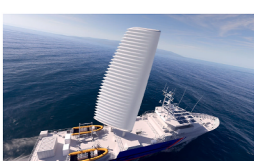
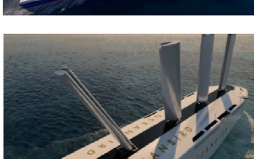


Fig. 2. The summary on the key technologies of the ship adopting WAPS.

Table 1
The characteristics of various types of sails.

Types	Advantages	Disadvantages
	<ol style="list-style-type: none"> 1 High working height; 2 Reduce the impact and twisting force of the waves on the ship; 3 No impact on port operations 	<ol style="list-style-type: none"> 1 Aerodynamic characteristics are not as good as wing-typed sail; 2 Complex control system and poor headwind performance; 3 Need large kite area; 4 High maintenance/operating costs
	<ol style="list-style-type: none"> 1 Simple structure and the most commonly used sail; 2 Suitable for harsh environment; 3 Low maintenance/operating costs; 4 Good headwind performance 	<ol style="list-style-type: none"> 1 Large sail area is required; 2 Large structural reinforcement is required; 3 Large weight and high center of gravity; 4 High investment cost
	<ol style="list-style-type: none"> 1 Works especially well in crosswind conditions; 2 Compact installation and low wind resistance; 3 Simple integration and low operating costs; 4 Suitable for harsh environment 	<ol style="list-style-type: none"> 1 Lift is very low in the head or tail wind; 2 Marine generator allowance is required; 3 There are challenges in the application on the container ships
	<ol style="list-style-type: none"> 1 Flexibly adapt to various navigation environments; 2 Improve the stability of ships; 3 It can be controlled by hydraulic devices or electric motors, and the operation is simple 	<ol style="list-style-type: none"> 1 High initial investment cost; 2 Complex maintenance and upkeep; 3 There exist compatibility issues with various ship types
	<ol style="list-style-type: none"> 1 The operation is flexible and can be adjusted based on various scenarios; 2 The control performance is good, and it can be folded at different angles; 3 Suitable for changing wind and sea conditions 	<ol style="list-style-type: none"> 1 The technology is complex and the cost is high; 2 Foldable wing sails are relatively large which occupy a considerable area of the deck; 3 The maintenance cost is high

3) This review offers potential future research directions, serving as a theoretical reference for further studies and applications aimed at enhancing the energy efficiency of wind-assisted ships, which is crucial for advancing the development of the low-carbon shipping.

The rest of this paper is arranged as described below: the aerodynamics analysis of different sails is illustrated in Section 2. Then, the optimal design of the ship adopting WAPS is discussed in Section 3. In addition, the operation control of the ship adopting WAPS is carried out in Section 4. After that, the comprehensive analysis of the wind-assisted propulsion system is summarized in Section 5. Moreover, the challenges and discussions of the wind-assisted ship are given in Section 6. Finally, the findings and subsequent research endeavors of the wind-assisted ship are illustrated in Section 7.

2. The aerodynamics analysis of different sails

2.1. Different types of sails in wind-assisted ships

The typical sails include the kite sail, wing-typed sail and Flettner rotor, etc. Among them, the kite sail is like a kite that is connected to the hull through a tow rope to provide auxiliary thrust for the ship navigation [33]. This type of sail does not occupy the deck space and does not affect the main scale of the ship. In addition, the shape of the wing-typed sail is similar to that of a wing. The wing-typed sail can generate auxiliary thrust for the ship through harvesting wind energy.

Moreover, the Flettner rotor works based on the Magnus effect [34], which can generate thrust when rotors rotate in the flowing air, thus providing auxiliary thrust for the ship navigation [35]. The characteristics of various types of sails are summarized in Table 1. The application of kite sail can reduce the impact and twisting force of the wave on the ship, and then enables a significant upwind and downwind performance. However, the kite sail has complex control system and poor headwind performance. For the wing-typed sail, it has strong adaptability and consumes less extra energy, which has achieved applications on some ships [36]. As for the Flettner rotor, it needs additional energy to drive the rotor, and the propulsion thrust of Flettner rotors can be improved by controlling the rotor speed [37]. However, the layout and parameters optimization of the rotor are significant to enhance the aerodynamics and energy efficiency of the ship [38]. Moreover, the telescopic wing sails and foldable wing sails can flexibly adapt to different navigational environments and can improve the stability as well as the energy-saving effects for the wind-assisted ship [39]. However, the construction of the telescopic wing sails and foldable wing sails needs higher initial investment cost than fixed wing sails, and the compatibility to various types of ships is also difficult [40]. Additionally, the maintenance and upkeep for the telescopic wing sails and foldable wing sails are relatively complex, and hence the maintenance cost is higher than other types of sails [41].

2.2. The sail aerodynamics analysis

The flow field distributions of sails under different conditions can be achieved through the aerodynamics characteristics analysis [42], which are solid foundations for the optimal design and the operation control of sails [43].

2.2.1. The aerodynamics analysis of kite sail

The kite sail converts wind energy into kinetic energy by the flying kites in front of the ship, which can pull the hull forward and provide auxiliary power for the ship navigation [44]. To analyze the performance of the kite sail, Bigi et al. [45] have carried out the dynamics analysis of the kite sail-assisted ship, and the results showed that the utilization of the kite sail can reduce energy usage effectively, meanwhile reducing the ship roll amplitude. Traut et al. [46] established a numerical model of the kite sail, and analyzed the dynamics performance based on the wind speed data for five navigation routes. The results showed that the propulsive power of the kite sail is 127 kW–461 kW, and the fuel consumption of the kite sail-powered ship can be reduced by 1 %–32 % on the target sailing route. Furthermore, Scupi et al. [47] used computational and experimental methods to study the aerodynamic characteristics of the kite sails. The time-averaged drag

coefficient obtained by wind tunnel measurements of a model kite scale and the Large Eddy Simulations (LES) of a full kite scale is analyzed. The results showed that the drag coefficient of the kite sail at zero yaw and pitch angles is 20 % lower than that of the flat plate with the same aspect ratio, which can provide references for the optimization control of the kite sail to improve the propulsion performance, and thus reducing fuel usage of the ship adopting WAPS.

2.2.2. The aerodynamics analysis of wing-typed sail

The invention of the wing-typed sail for ships is inspired by the aerodynamics theory of aircraft wing [48]. The difference in pressure between the top and bottom will be generated when the air flows through the wing-typed sail, and the pressure difference will be converted into the thrust to push the ship forward [49]. The performance of the wing-typed sail can be effectively enhanced by analyzing their aerodynamics characteristics using the computational fluid dynamics (CFD) method. Li et al. [50] conducted the aerodynamics analysis of the wing-typed sail in the atmospheric boundary layer above sea level by using the numerical simulation approach, and found that the increase of the average gradient wind speed can improve the lift coefficient of the wing-typed sail to a certain extent. In addition, Zhang et al. [51] carried out the sail aerodynamics performance parameter optimization through

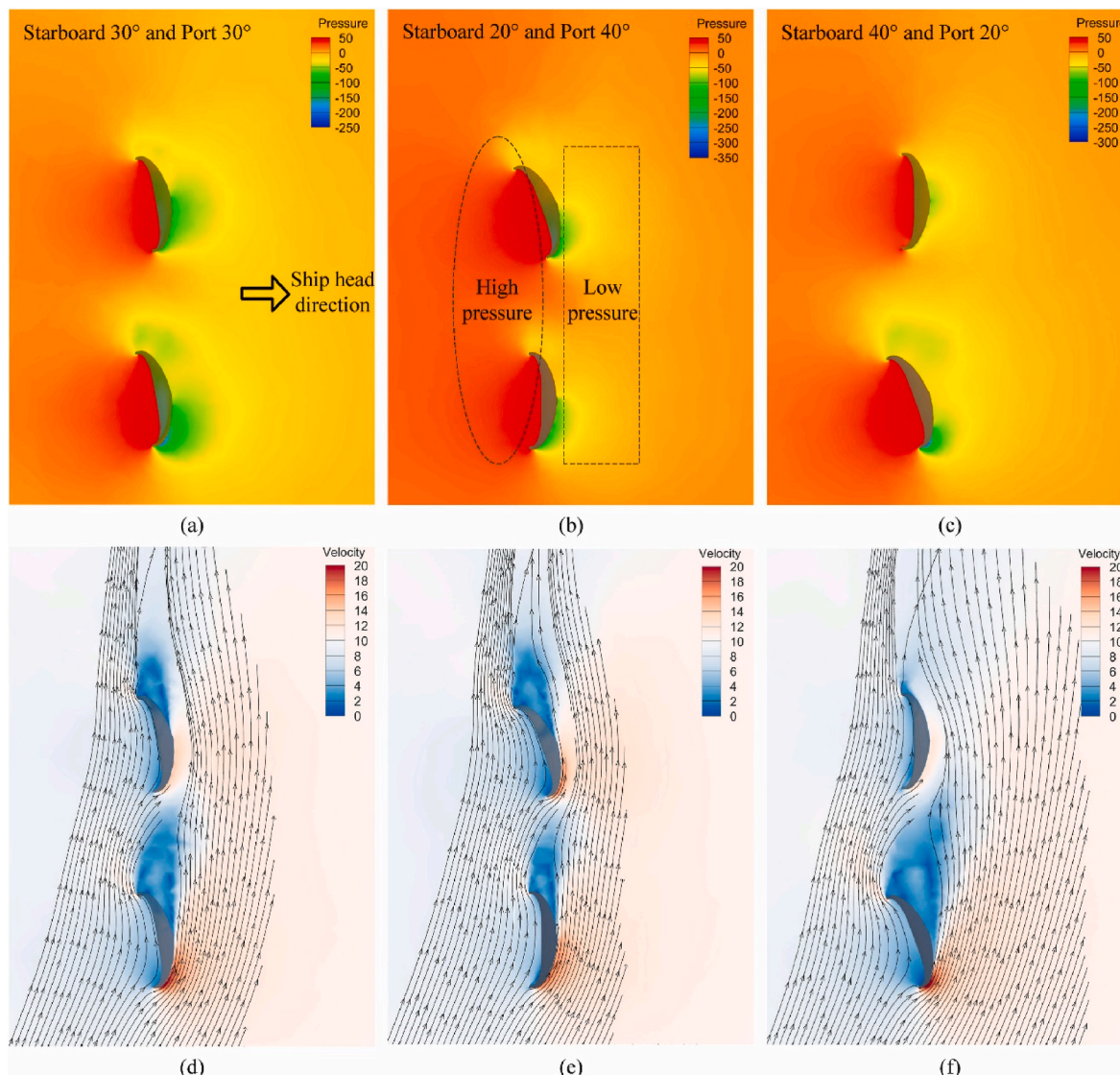


Fig. 3. The wing-typed sail aerodynamics analysis through the CFD method [51].

the CFD and Particle Swarm Optimization (PSO) algorithm, as shown in Fig. 3. The optimized sail demonstrates a 6.5 % increase in the thrust coefficient. Additionally, Kramer et al. [52] carried out the aerodynamics analysis of sails based on the CFD, and optimized the aerodynamics parameters of the wing-typed sails, which can achieve fuel consumption reduction by 17 %~65 %. Malmek et al. [53] introduced a rapid aerodynamic calculation method for wing-typed sails. This method integrates a semi-empirical lift line model with a potential flow-based interaction model to accurately capture 3D interaction effects. Moreover, Zhu et al. [54] carried out the numerical aerodynamics analysis of a novel crescent-section wing-typed sail. Findings revealed that the novel sail has higher efficiency than the traditional sail. Additionally, a case study demonstrated that a ship equipped with a crescent-section wing-typed sail can reduce energy usage by 9 % compared to the ship without sails. Furthermore, Li et al. [55] analyzed the aerodynamic performance based on the CFD approach and the energy conservation effect of the wing-typed sail adopting the circulation control technique. The study results indicated that the peak lift coefficient of the sail can be increased by 111 % at medium-strength jets, and the EEDI of the ship adopting wing-typed sail with circulation control can be reduced by about 10 % compared to the ship without WAPS.

In addition, the wind tunnel test plays a crucial role in exploring and validating the aerodynamics of the wing-typed sail by setting the actual flow field environments [56]. Li et al. [57] conducted the aerodynamics characteristics analysis of cascade sails through the wind tunnel test and numerical simulation, and analyzed how ship navigation performance is affected by speed, rudder angle, and drift angle. Zeng et al. [58] evaluated the aerodynamics of sails on the ship through the wind tunnel test, which can provide a reference for the evaluation and analysis for the aerodynamics of wind-assisted ships. Additionally, Zhang et al. [51] carried out research about the sails aerodynamics through the wind tunnel experiments, as shown in Fig. 4, which also validated the effectiveness of the aerodynamics analysis results based on the CFD approach.

2.2.3. The aerodynamics analysis of Flettner rotor

The Flettner rotor is a device applying the Magnus effect to generate lift [59,60]. The interaction between the rotor and wind can be better understood through the aerodynamic characteristics analysis of the Flettner rotor, which can promote the practical application of the Flettner rotor-assisted ship [61]. The dynamics model describing the aerodynamic characteristics of the Flettner rotor can be established by adopting the CFD analysis method [62], and then the aerodynamics performance of the Flettner rotor can be obtained [63]. Kwon et al. [64] analyzed the impact of the aspect ratio on the aerodynamic characteristics of the rotor by changing the rotor diameter under a constant height



Fig. 4. The wind tunnel test for the ship adopting WAPS [51].

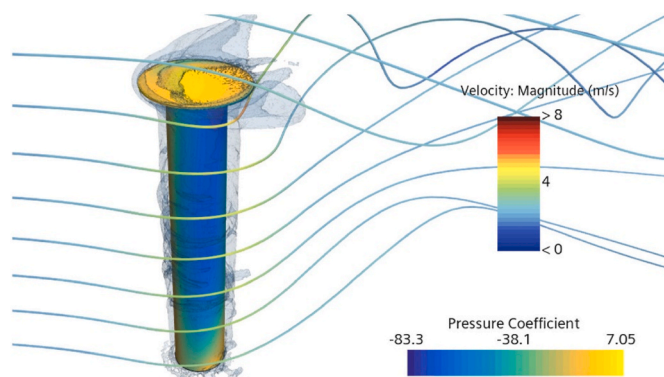


Fig. 5. Aerodynamics analysis of the Flettner rotor [64].

through the CFD approach, as presented in Fig. 5. Lu et al. [65] used the CFD method to evaluate impacts of Flettner rotor aerodynamics on the ship fuel usage. They found that increasing the rotor size can enhance the fuel efficiency. Additionally, Tillig et al. [66] proposed a novel CFD-based approach to analyze the aerodynamics and hydrodynamic interaction of the ship equipped with WAPS, which is crucial for the fuel efficiency enhancement of the wind-assisted ship. The research results showed that the oil tanker equipped with six Flettner rotors can save up to 30 % of the cost on the Pacific route. The potential savings of the Ro-Ro tanker equipped with four Flettner rotors are approximately 14 % in the Baltic Sea. Simulations with real weather conditions and two sample ships demonstrate the versatility and applicability of the developed method.

In addition, the wind tunnel test serves as an effective way for analyzing and evaluating the dynamic performance of the Flettner rotor [67]. Chen et al. [68] studied effects of the speed ratio, aspect ratio, endplate-to-cylinder diameter ratio and Reynolds number (Re) on the aerodynamic features of a solo Flettner rotor, and investigated the influence of the ratio of endplate diameter to cylinder diameter on the aerodynamics of double Flettner rotors through the wind tunnel test, as shown in Fig. 6. Additionally, Bordogna et al. [69] carried out the analysis for the influence of the Re on the aerodynamics of the Flettner rotor through the wind tunnel test, and then obtained the correlation among the Re, lift coefficient and drag coefficient at different speed ratios, which can provide references for the further research on the aerodynamics of the Flettner rotor.

2.2.4. The aerodynamics analysis of telescopic wing sails and foldable wing sails

Both foldable wings and telescopic wings can adapt to changing wind and sea conditions in comparison to fixed wing sails, which is of great significance for enhancing the energy-saving effect for the wind-assisted ship. Telescopic crescent-shaped wing sails have the function of telescoping and can be retracted or extended according to various navigational conditions. Zhu et al. [70,71] developed an improved high-fidelity CFD model to simulate the aerodynamics of the telescopic crescent-shaped wing sails under fully extended and retracted states. Results showed that the sail's lift and drag coefficient are 2.102 and 0.456 in the fully extended state, and the lift coefficient would be decreased by 8.9 % and the drag coefficient would be increased by 17.1 % when the sail is fully retracted. As for the foldable wings, the folding configuration of the foldable three-element wing sails is rather complex when considering the curvature of the sub-wings. Therefore, Jiang et al. [72] conducted numerical studies on the performance of foldable three-element wing-typed sails based on the CFD method, as shown in Fig. 7. The study found that the thrust performance of the foldable wing-typed sail can be improved under the fully folded state, and the thrust coefficient of the foldable wing-typed sail is 23.5 % higher than that of the original wing-typed sail at an 8° of AOA.

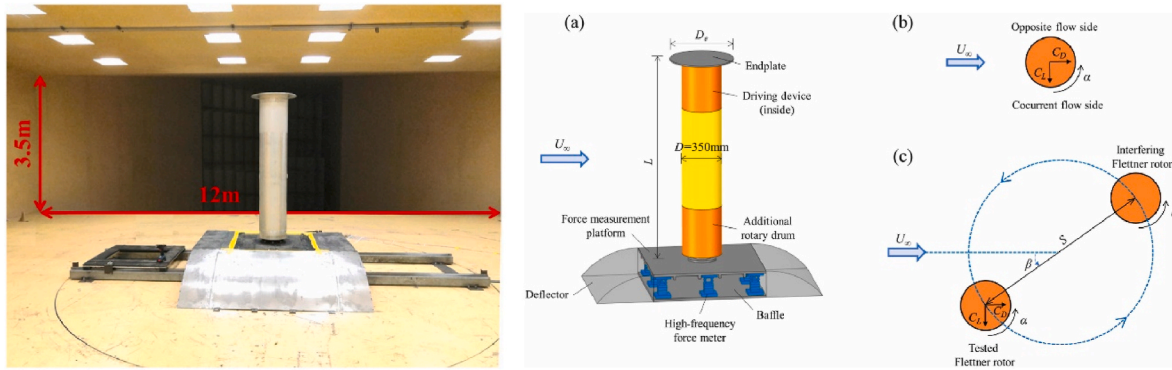


Fig. 6. Aerodynamics analysis of the Flettner rotor through the wind tunnel test [68].

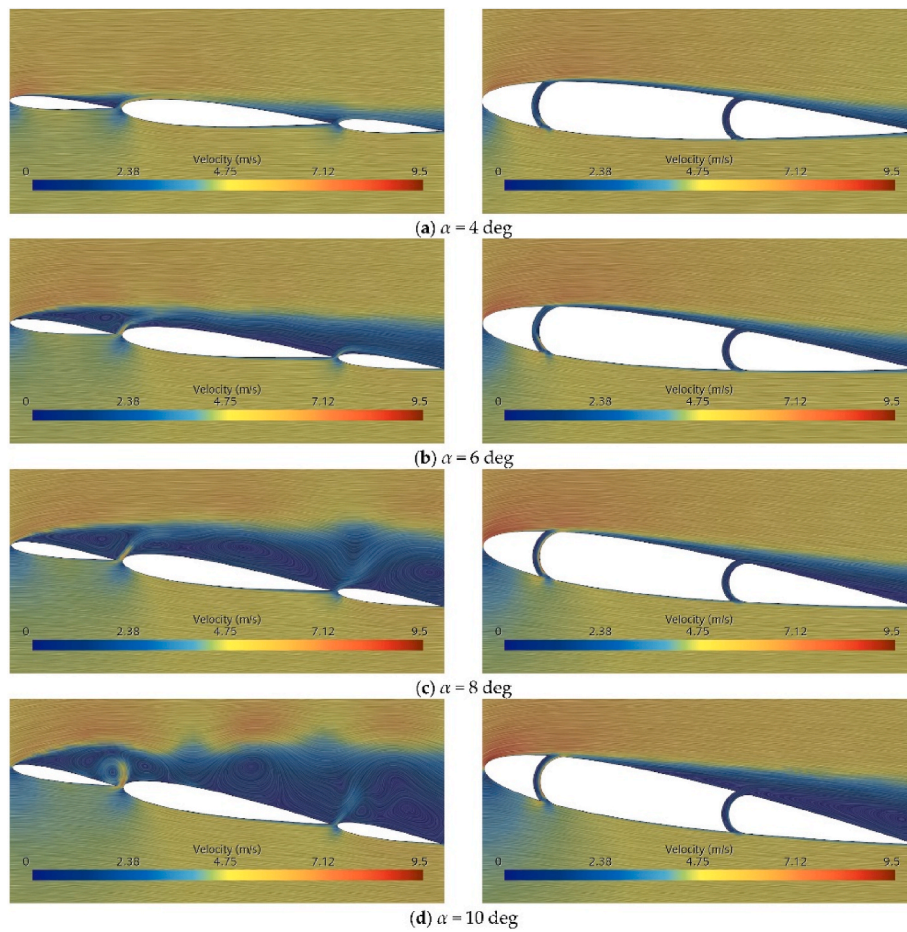


Fig. 7. Flow patterns around foldable three-element wing-typed sails at different AOA [72].

2.3. The coupling aerodynamics analysis of multiple sails

The application of multiple sails on the ship can make a certain mutual interference effect among the sails [73]. Therefore, the interference effect should be mitigated by appropriately arranging the relative positions of sails, to enhance the propulsion effect of the applied multiple sails on the ship [74]. Lee et al. [75] carried out the aerodynamic characteristics analysis between three identical wing-typed sails, which showed that the typical thrust coefficient on average could be reduced by 21%~43% in comparison with that of a single sail, owing to the interference effect of the multiple sails. Sun et al. [76] established a vortex panel method-based double-sails model, and then analyzed the influence of the chord length and AOA of the sail on the lift

coefficient. In addition, Zhang et al. [51] studied the interaction of two U-sails based on the CFD approach, and found that the downstream sail lies within the wake of the upstream sail during the synchronous operation, which would block the surrounding air flow significantly, and the larger the sail AOA, the more significant this phenomenon is. Furthermore, Zhang et al. [77] studied the effects of key parameters on the aerodynamic interaction and the propulsion potential of the combined system that is composed of a Flettner rotor and a U-shaped wing-typed sail, as illustrated in Fig. 8. The findings indicated that the interaction effect between the rotor and U-sail is inversely proportional to the sail spacing and proportional to the rotation ratio. The above investigations made great contributions in exploring the interference characteristics and influence laws of multiple sails.

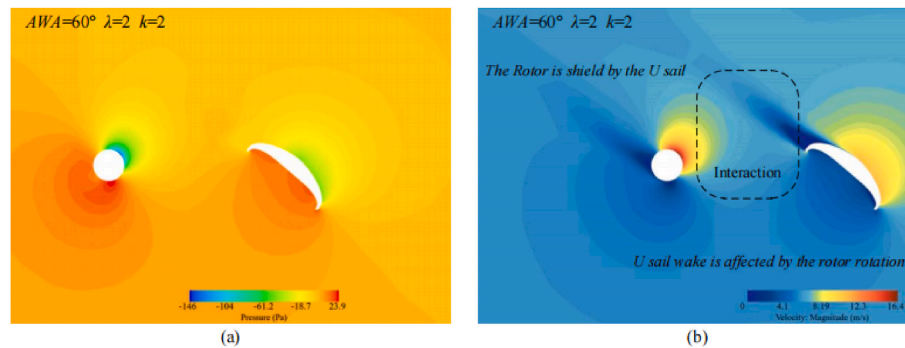


Fig. 8. The interaction effect analysis between the rotor and U-sail [77].

Table 2
The aerodynamics analysis of the typical sails.

Sail type	Method	Result/Effect	Reference
Kite sail	CFD	The propulsive power is 127 kW–461 kW, and the fuel usage can be reduced by 1 %–32 %	[46]
Kite sail	LES and wind tunnel test	The drag coefficient can be reduced by increasing the pitch angle of the kite sail	[47]
Wing-typed sail	CFD and PSO	The thrust coefficient of the system can be increased by 6.5 %	[51]
Wing-typed sail	CFD	The ship fuel usage can be saved by 17 %–65 %	[52]
Wing-typed sail	CFD	The maximum lift coefficient of the wing-typed sail can be increased by 111 %	[55]
Wing-typed sail	Wind tunnel test	The lift coefficient is reduced by 16 %–44 % and the drag coefficient is reduced by 11 %–42 %	[58]
Wing-typed sail	CFD	The average thrust coefficient of multiple sails is by 21 %–43 % lower than that of a single sail	[75]
Wing-typed sail	Vortex plate method	The total lift coefficient of sails increases with their distance and the length of the foresail chord	[76]
Flettner rotor	CFD	Properly increasing the rotor size can effectively improve the fuel saving efficiency	[65]
Flettner rotor	CFD	The fuel usage can be reduced by 30 % and 14 % for oil tankers on the Pacific route and Ro-Ro tankers in the Baltic Sea, respectively	[66]
Flettner rotor	Wind tunnel test	The aerodynamic interactions decrease with the increase of the spacing ratios	[68]
Flettner rotor	Wind tunnel test	With the increase of Reynolds, the lift coefficient also increases when the velocity ratio is 0–2.5	[69]

2.4. Summary

The sail aerodynamics performance analysis are solid foundations for the optimal design and the operation state optimization of sails to enhance the propulsion effect. The aerodynamic characteristics analysis of typical sails based on the CFD approach and wind tunnel test are summarized, as shown in Table 2.

As it can be seen, the propulsive power of the kite sail is 127 kW–461 kW, and the drag coefficient can be reduced by increasing the pitch angle of the kite sail through the wind tunnel test analysis. Additionally, the CFD and PSO analysis results showed that the thrust coefficient of the wing-typed sail can be increased by 6.5 %. Furthermore, increasing the sail chord length ratio can effectively improve its aerodynamics performance. Furthermore, Flettner rotors have good aerodynamics performance, which can be increased with the decrease of the spacing

ratios through the CFD and wind tunnel test analysis. Above all, the aerodynamics of sails can be obtained through the CFD approach and wind tunnel test, which can lay a solid foundation for the optimal design and operation control of sails. Although the aerodynamics analysis of typical sails has been extensively studied, several issues and challenges remain to be addressed.

- 1) The aerodynamics analysis of the kite sail, wing-typed sail and Flettner rotors can be achieved through the wind tunnel test and CFD approach. However, the effects of sail aerodynamics on the wind-assisted ship should be further studied by adopting the numerical simulation and experimental verification methods, which are significant to improve the ship energy efficiency.
- 2) The overall aerodynamics characteristics can be effectively enhanced through the arrangement optimization of sails to avoid the interference effect among multiple sails on a ship. However, the interference characteristics analysis of multiple sails based on the combination of numerical simulation and experimental verification methods need to be further studied, which is significant to reduce the mutual interference and improve the overall aerodynamics performance.
- 3) The dynamics analysis under the coupled effects of multiple sails interference and the ship motion needs to be further studied. It involves the coupled analysis of sail aerodynamics and ship hydrodynamics, which plays a significant role in optimizing the comprehensive performance and energy efficiency of the wind-assisted ship.
- 4) The overall boosting performance analysis of multiple sails based on the real ship operational data is still lacking, and the impact of the propulsive power characteristics of multiple sails on the comprehensive performance of the wind-assisted ship should be further analyzed.

3. The optimal design of the ship adopting WAPS

3.1. The optimal design of sails

The optimal design of the sail, including the shape and main parameters, can effectively improve the aerodynamics performance, thus improving the operation stability of the wind-assisted ship [78]. In terms of the sail shape and aerodynamics performance optimization, Guzelbulut et al. [79] optimized the crescent-shaped sail to improve the sail performance. The results showed that reducing the thickness and increasing the camber angle can effectively improve the thrust efficiency of the sail by 12.3 %. On this basis, Guzelbulut et al. [80] established an optimization scheme for the shape optimization of the Flettner rotor, which can increase the energy-saving effect by 2.7 %–4.06 %. Additionally, Li et al. [81] proposed a numerical simulation-based approach to increase the lift coefficient of Flettner rotors by optimizing the shape of the rotor, as illustrated in Fig. 9. In the aspect of the parameter optimal design, Cairns et al. [82] focused on the optimization of a

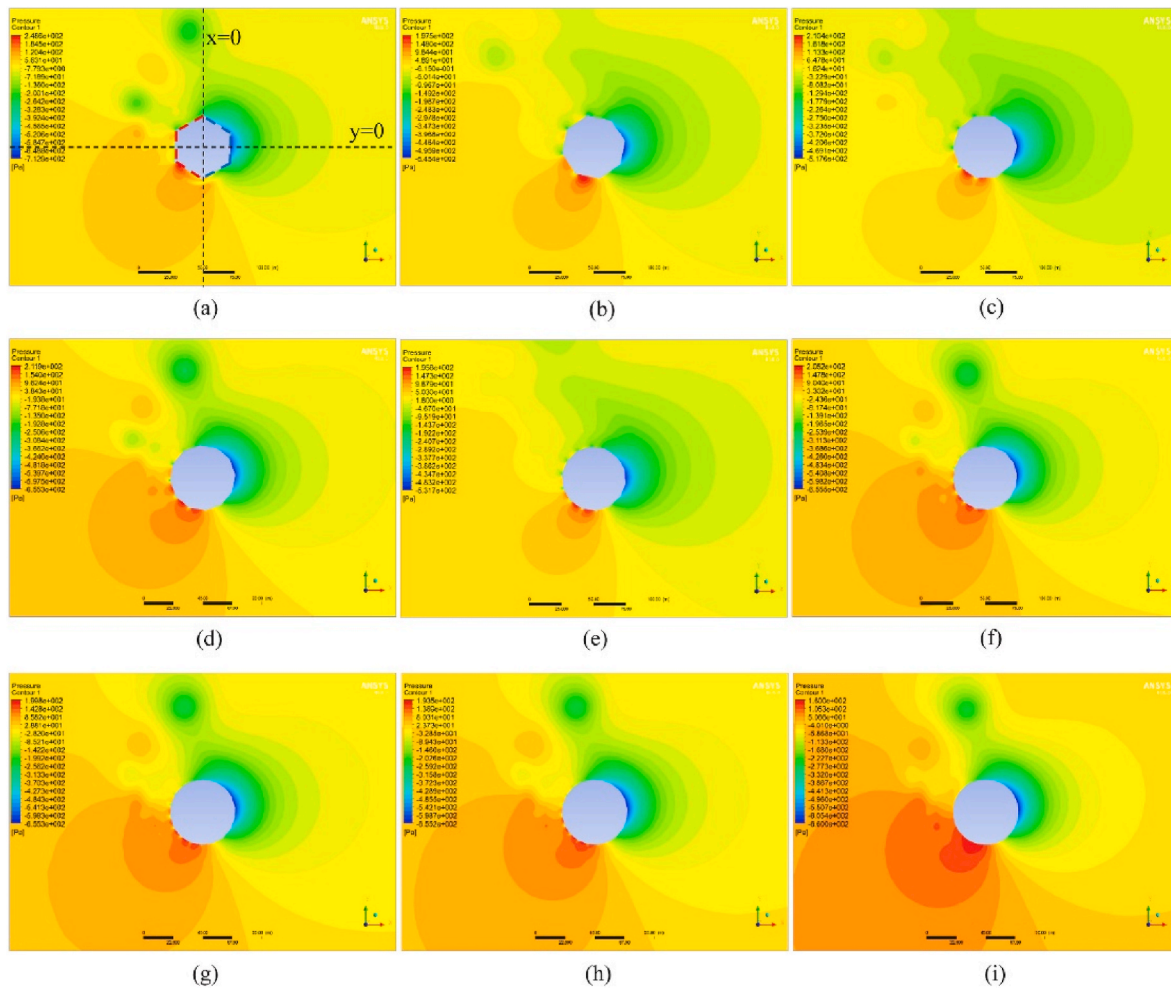


Fig. 9. The aerodynamic analysis of the sail [81].

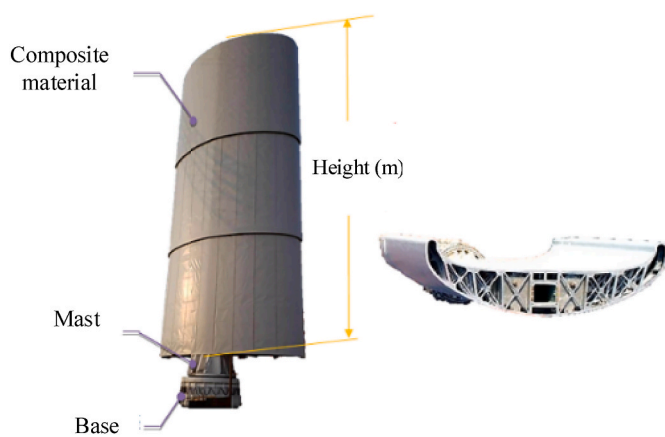


Fig. 10. The wing-typed sail built by the composite material.

wing-typed sail based on the CFD to achieve the high lift with the low resistance. Additionally, Ma et al. [83] developed a novel set of coupled wing-typed sails using the parametric section (PARSEC) airfoil parametrization method and PSO algorithm, which can improve the aerodynamics performance effectively.

The used material is of great significance for enhancing the strength of sails. The composite material has been used for the sail design due to the advantages of lightweight, corrosion resistance and fatigue resistance [84], as shown in Fig. 10. The application of composite material

can not only reduce the weight of the ship equipped with WAPS, but also improve the safety and fuel-efficiency performance of the ship. In addition, it is worth mentioning that the flexible carbon-fiber-reinforced polymer composites are also used to build the high-performance sails. The sails made of carbon fiber reinforced polymer composites have some excellent characteristics, which is important to improve the sail dynamics, thus enhancing the propulsion performance of the wind-assisted ship [85].

3.2. Arrangement optimization design of multiple sails

The arrangement optimization of multiple sails can enhance the overall performance of the wind-assisted system [86]. Makram et al. [87] used Taguchi method to construct nine different configurations for the wing-typed sails and analyzed the aerodynamics characteristics of each configuration. The obtained optimal configurations of the wing-typed sails can decrease energy usage by 20 %. Zeng et al. [88] conducted a CFD-based wake analysis method, which can realize the analysis of sail wake characteristics. In addition, Bordogna et al. [89] analyzed the effect of the arrangement on the aerodynamics characteristics of Flettner rotors through wind tunnel test, and found that the Flettner rotors arranged side-by-side can obtain better aerodynamics performance when the $AWA < 60^\circ$. However, when the $AWA > 60^\circ$, the arrangement of Flettner rotors in tandem can achieve better aerodynamics performance. Furthermore, Zhang et al. [90] focused on a new arrangement optimization method of Flettner rotors to reuse the wake energy, as presented in Fig. 11. The analysis results presented that the

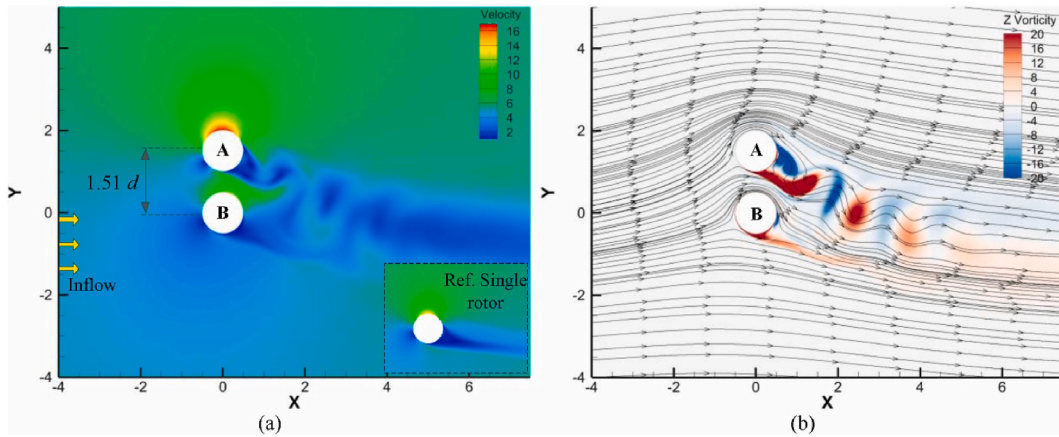


Fig. 11. The optimal arrangement of Flettner rotors [90].

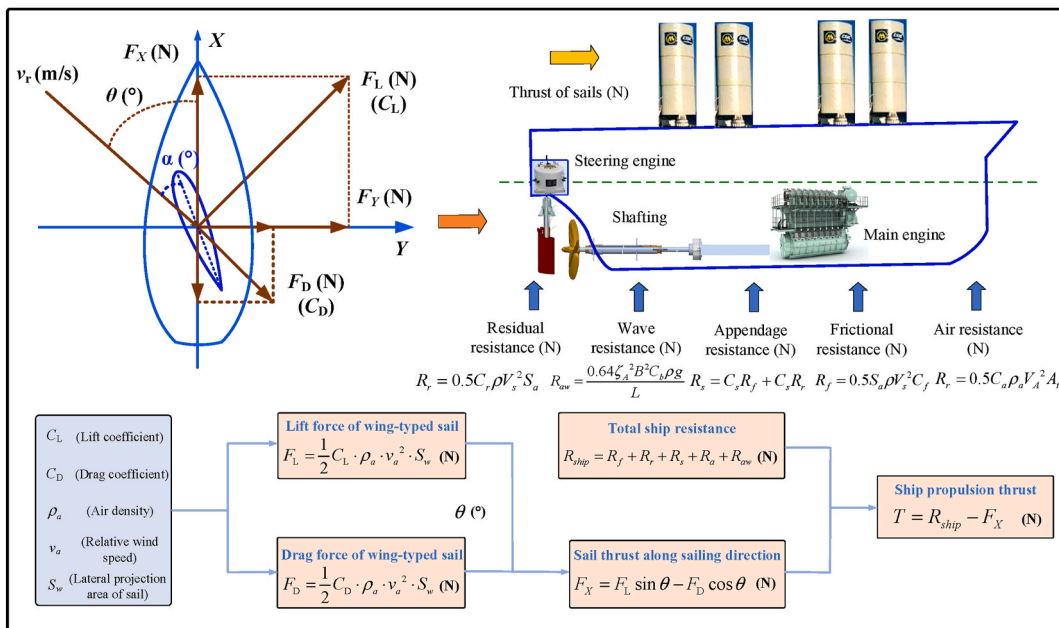


Fig. 12. Schematic of the relationship between aerodynamic force and propulsion demand.

average lift coefficient of the double rotors through the optimal arrangement can be increased by 22.98 %.

3.3. The optimization design of the SDHPS

The schematic of the relationship between aerodynamic force and propulsion demand is shown in Fig. 12. The ship adopting WAPS relies on the coordinated operation of sails and diesel engines to jointly overcome the total sailing resistance, thereby enabling the ship to move forward [91]. The total ship resistance mainly includes the residual resistance, wave resistance, appendage resistance, frictional resistance and air resistance [92]. In addition, the sail thrust can be calculated by the sail's aerodynamics analysis. Therefore, the ship's propulsion thrust can be expressed as the difference between the total resistance and the sail thrust, which is an important factor for subsequent fuel usage prediction and optimization of the ship adopting WAPS [93].

The optimal design of the SDHPS can increase wind energy utilization for enhancing the ship energy efficiency [94]. The interaction relationship among the sail, propeller and other propulsion devices can be achieved by the analysis of navigational environmental factors, as well as the ship main engine and propeller parameters, sail parameters,

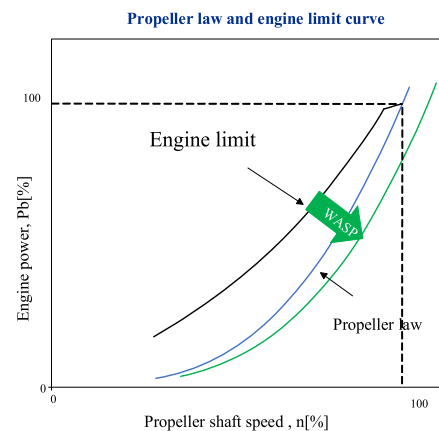


Fig. 13. Propeller law and engine limit curve.

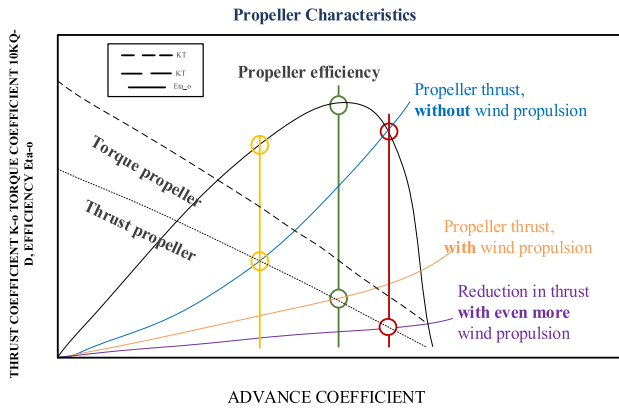


Fig. 14. Propeller characteristic curve.

and the hull parameters. On this basis, the optimal matching and design of the coupled ship-sail-engine-propeller system can be achieved to enhance the overall operation performance of the hybrid power system [95]. The matching and design optimization of the hybrid power system primarily encompass the following aspects: Firstly, the thrust and auxiliary propulsion power of the sail under different AOA should be

calculated according to the parameters of sails, and propulsion devices as well as the interactive information between sails and propulsion devices. In addition, the coupling characteristics of the sail thrust, ship main engine and propeller need to be analyzed to obtain the optimal matching scheme of the ship-sail-engine-propeller. The propeller characteristics and the matching efficiency of the system should also be analyzed and evaluated according to the propeller law and engine limit curve (Fig. 13) and the propeller characteristic curve (Fig. 14). Furthermore, the optimization matching scheme needs to be proposed to realize the optimum design of the SDHPS, for enhancing the fuel efficiency of the entire hybrid system.

To achieve the optimal design of the sail-assisted hybrid power system, Vigna et al. [96] constructed a numerical model of a Flettner rotor-assisted ship based on the matching design of the diesel engine, controllable pitch propeller (CPP) and Flettner rotor, as illustrated in Fig. 15. The experiment analysis results presented that the matching design of the diesel engine, CPP and Flettner rotor could reduce fuel consumption by 15%. Above all, the optimal design of the sail-diesel engine hybrid power system can enhance the wind energy utilization, thereby boosting the ship fuel efficiency. However, the optimization design methods for the hybrid power system, which comprehensively consider the coupling effects of the sail, propeller and engine characteristics, need to be further studied to enhance the comprehensive

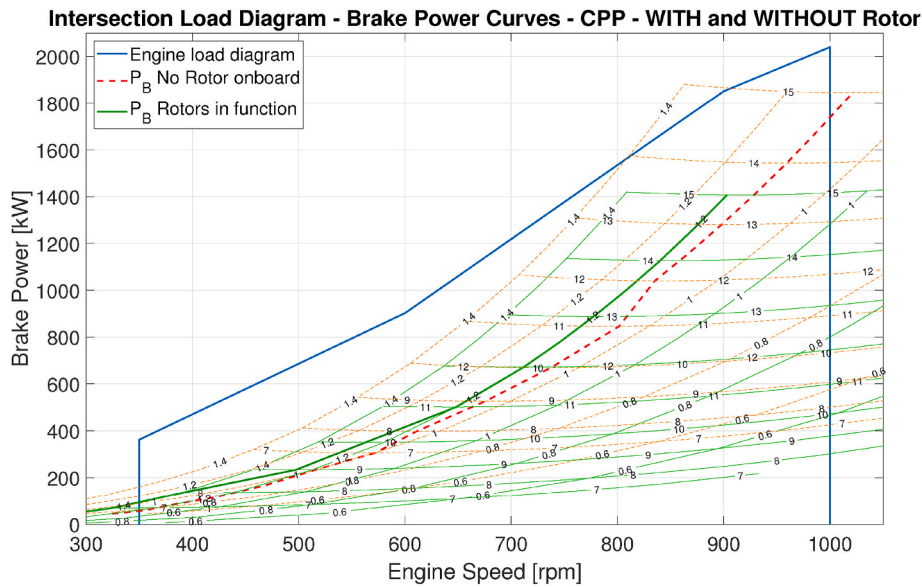


Fig. 15. Brake power curves-CPP-with and without rotor [96].

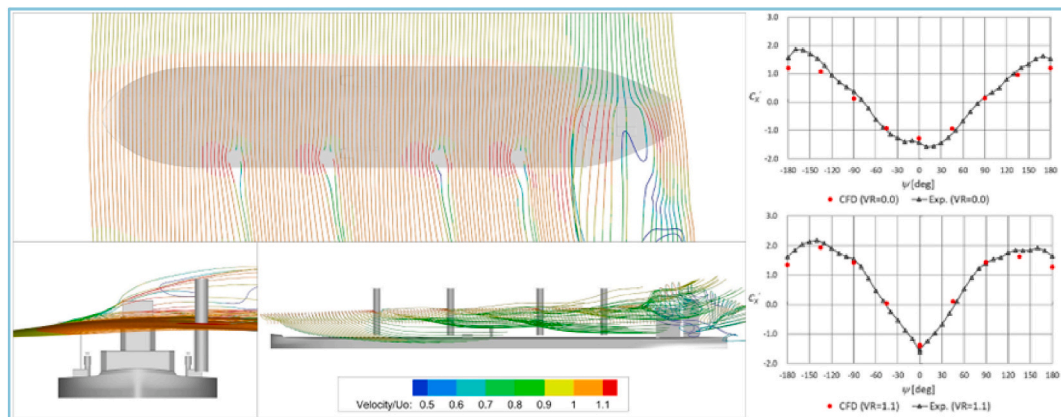


Fig. 16. Aerodynamics analysis of the Flettner rotor [98].

performance of the system.

3.4. The integrated optimization design of the ship adopting WAPS

Sails are the keys to capturing the wind energy for ships, and the hull design optimization also have a significant influence on the ship sailing resistance and energy efficiency. Therefore, the integrated analysis of the sail and hull would lay solid foundations for the optimal design of the ship adopting WAPS [97]. Kume et al. [98] analyzed the aerodynamics of the Flettner rotor-assisted ship through the wind tunnel test and CFD approach, as depicted in Fig. 16. The findings indicated that the rotor can generate thrust at almost all apparent wind angles except for the upwind area. Additionally, Schönborn et al. [99] conducted the research of the propulsion performance of Darrieus rotors mounted on the ship. The findings indicated that the Darrieus rotors can generate the direct thrust under the upwind conditions for the ship, while the Darrieus sail propulsion ability is not as good as the wing-typed sail propulsion effect.

Furthermore, Yasuda et al. [100] studied the CFD-based thrust characteristics analysis of two rigid sails by taking into account the interaction impacts between the sails and the hull, and the best performance can be achieved by using low AOA for foreside sail and high AOA for rear side sail when the relative wind direction is 150° , while the best effect is to adopt the high AOA of the front side sail and the low AOA of the rear side sail when the relative wind direction is 180° . Furthermore, the integrated coupling dynamics analysis of air-liquid-solid under the combined effects of wind and waves is crucial for boosting the fuel-efficiency effect of the ship adopting the WAPS. Yeon et al. [101] studied the performance of the Flettner rotor, and analyzed the influence of the foundation shape and the configuration of the rotating end plates on the rotor performance, as presented in Fig. 17. The findings indicated that the rotating end plate configuration can significantly improve the thrust of the sail, and the propulsion performance of the rotating end plate at 30° , 60° and 90° on the hull is 12 %, 34 % and 44 % higher than that of the original configuration. Moreover, Sun [102] proposed an energy-saving method for optimizing the sailing state of sail-assisted ships based on the CFD approach. The aerodynamic characteristics of sail-assisted ships under the coupling effect of air-liquid-solid were analyzed. The resistance, thrust, and lateral force of the ship in varied navigation circumstances were obtained. On these bases, the fuel usage of the ship within various sailing conditions was analyzed, and the

decision-making for the optimal sailing states under the coupling effect of air-liquid-solid was achieved by using the CFD method, which is crucial for further enhancing the overall efficiency of the wind-assisted ship.

3.5. Summary

The optimal design of the ship adopting WAPS has the potential to enhance the wind energy utilization, consequently boosting the overall fuel efficiency of ships. Nevertheless, there are still the following challenges.

- 1) An optimization design scheme of sails should be developed, taking into account the coupling effects of various factors, to achieve the optimal aerodynamics performance.
- 2) The optimization and matching design of the sail-assisted hybrid power system should combine the comprehensive analysis of the sail-assisted characteristics, power system operation characteristics, and ship propulsion characteristics.
- 3) Only by constructing an optimization design method based on the coupling mechanism of the system, can the efficient collaborative operation of the hybrid power sources be realized, which is the key to enhancing the comprehensive performance of the hybrid system.
- 4) The optimal design of the sail based on the aerodynamics analysis can effectively improve the boost performance, thus further increasing the thrust effect of the sails. However, the optimal design of sails based on the coupling dynamics analysis considering the coupling effects of the hull and environments need to be further studied and verified by experiments or practical applications.
- 5) The arrangement optimization of multiple sails can boost the overall performance of the wind-assisted system, thus decreasing the ship fuel consumption. However, the arrangement optimization method based on the coupling dynamics analysis for different types of ships and sails, as well as the number of sails need to be further studied and verified by experiments or practical applications.

4. The operation optimization and control of the ship adopting WAPS

The usage of sails makes the ship motion more complicated than the ship without sails [103]. The effective motion optimization control of

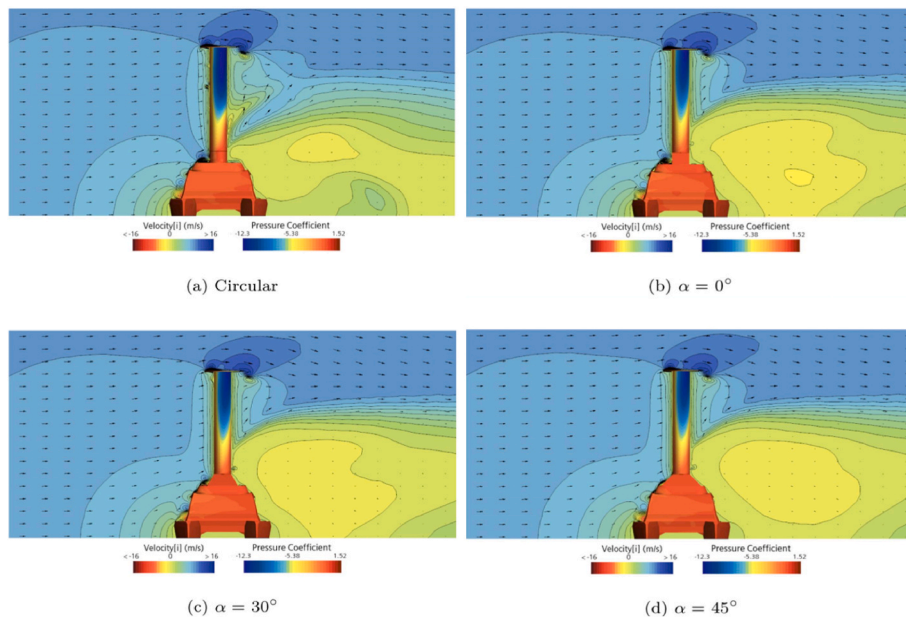


Fig. 17. The pressure distribution of rotor bottom configurations on the ship [101].

the ship equipped with WAPS can significantly enhance the navigation safety level of the ship [104]. Additionally, the operation control of the ship adopting WAPS also includes the energy efficiency optimization control, which is significant to fully use the wind energy resources and reduce energy consumption of the wind-assisted ship.

4.1. The motion analysis and control of the ship adopting WAPS

4.1.1. The motion model of the ship adopting WAPS

The forces are more complicated when the ship is equipped with sails due to the interference of load state and complex sea state, which would affect the motion state and the stability and safety of the ship adopting WAPS [105]. The motion state of the wind-assisted ship concerns six degrees of freedom, namely the sway, surge, heave, roll, pitch, and yaw, which is complex and ever-changing [106,107]. Therefore, it is significant to develop a motion model considering the coupling effect of complex navigational environments to realize the motion characteristics analysis and optimal control of the wind-assisted ship [108]. At present, the ship motion models mainly include the Abkowitz model and the Maneuvering Modeling Group (MMG) model. The Abkowitz model adopts the global model structure, in which the hydrodynamic force and torque are expressed as the function of motion parameters and rudder angles [109,110]. The MMG model adopts the separation model structure [111], which decomposes the hydrodynamic force and moment of the ship into the force and the moment acting on the hull, propeller and rudder [112,113]. The motion state, as well as the external forces and torque acting on the wind-assisted ship can be analyzed through the MMG model, and then the fuel saving and carbon emissions reduction by adopting the WAPS can be analyzed. The specific establishing processes of the MMG model and the fuel usage model for the ship adopting WAPS are depicted in Fig. 18 [114]. On this basis, the trajectory prediction of

the wind-assisted ship under complex sea conditions can be realized by establishing the motion model, which plays a vital role in the motion optimization control of the wind-assisted ship.

4.1.2. The coupling effect between the sail performance and ship motion

The sails mounted on the ship would affect the thrust and transverse force of the ship, and thus influencing the motion state of the ship adopting WAPS [115]. Meanwhile, changes of the ship motion state would in turn influence the operation states of the sail, and thus affecting the auxiliary thrust of the sails. Therefore, there is a certain coupling correlation between the sail performance and the ship motion [116]. The transverse force generated by the sails would cause the additional resistance due to the roll and yaw motion, and thus affecting the fuel usage of the wind-assisted ship [117]. In order to analyze the influence of roll on the aerodynamics performance of sails, Zhang et al. [118] studied the aerodynamic characteristics of double U-sails in the range of $0^\circ \sim 15^\circ$ roll angle through the CFD approach, as presented in Fig. 19. The average thrust of the sails can be decreased by 4.7 %, 13.5 % and 20.5 %, compared with the upright state when the heel angles are 5° , 10° and 15° , respectively. Additionally, Copuroglu et al. [119] evaluated the influence of ship rolls on the Flettner rotors through the CFD approach. The lift performance of the rotors declined as the roll angles increased. Furthermore, Kramer et al. [120] investigated the hydrodynamics characteristics of the wind-assisted cargo ship based on the CFD method, and analyzed how the rudder force varied in relation to the drift angle and rudder angle.

4.1.3. The motion control of the ship adopting WAPS

The motion model of the ship adopting WAPS needs to be validated by using the experimental data of the sail aerodynamic characteristics and the ship hydrodynamic characteristics, to enhance the precision of

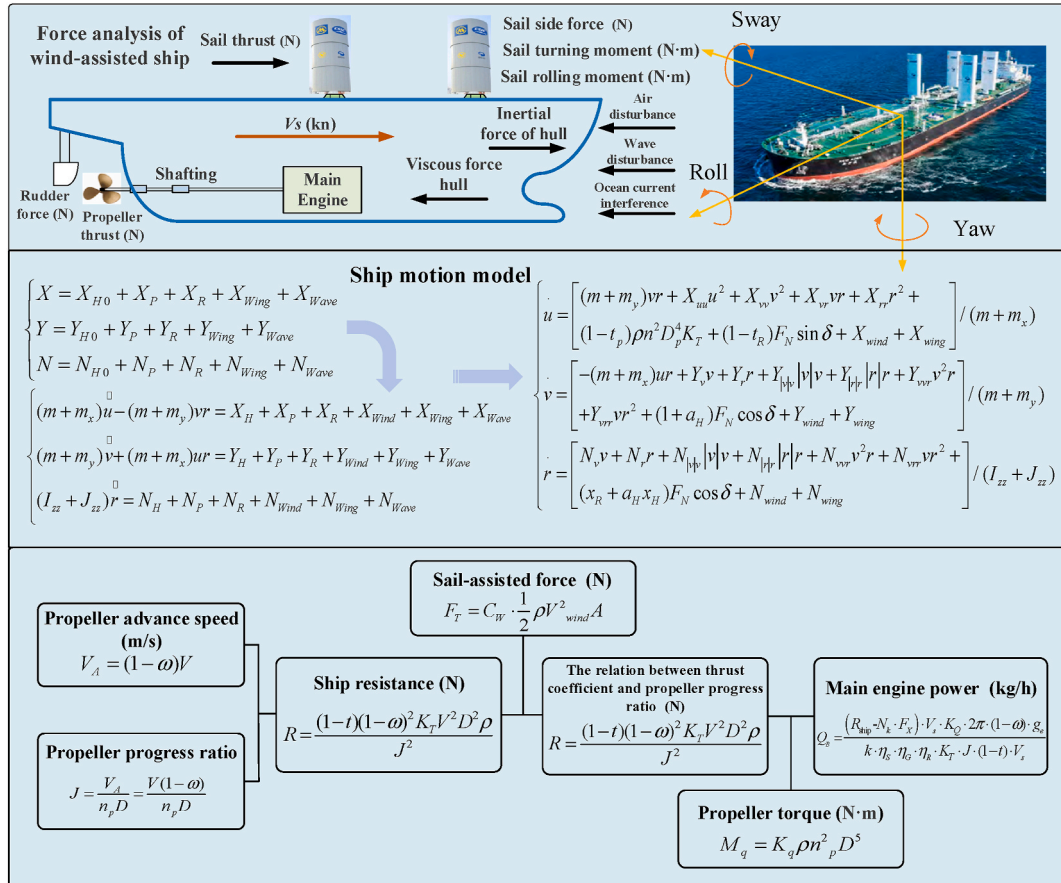


Fig. 18. The establishing processes of the motion model for the ship adopting WAPS.

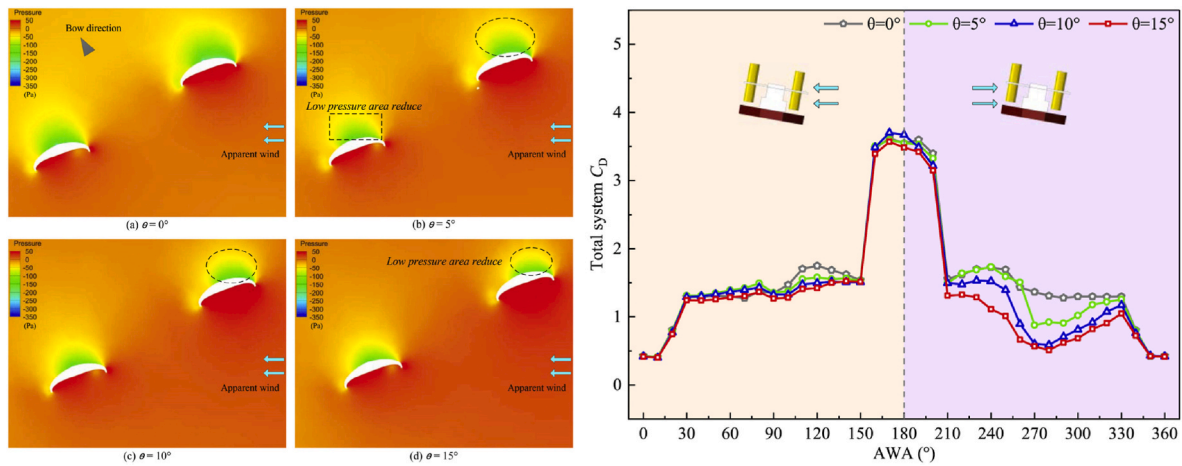


Fig. 19. The aerodynamic characteristics of sails under different roll angles [118].

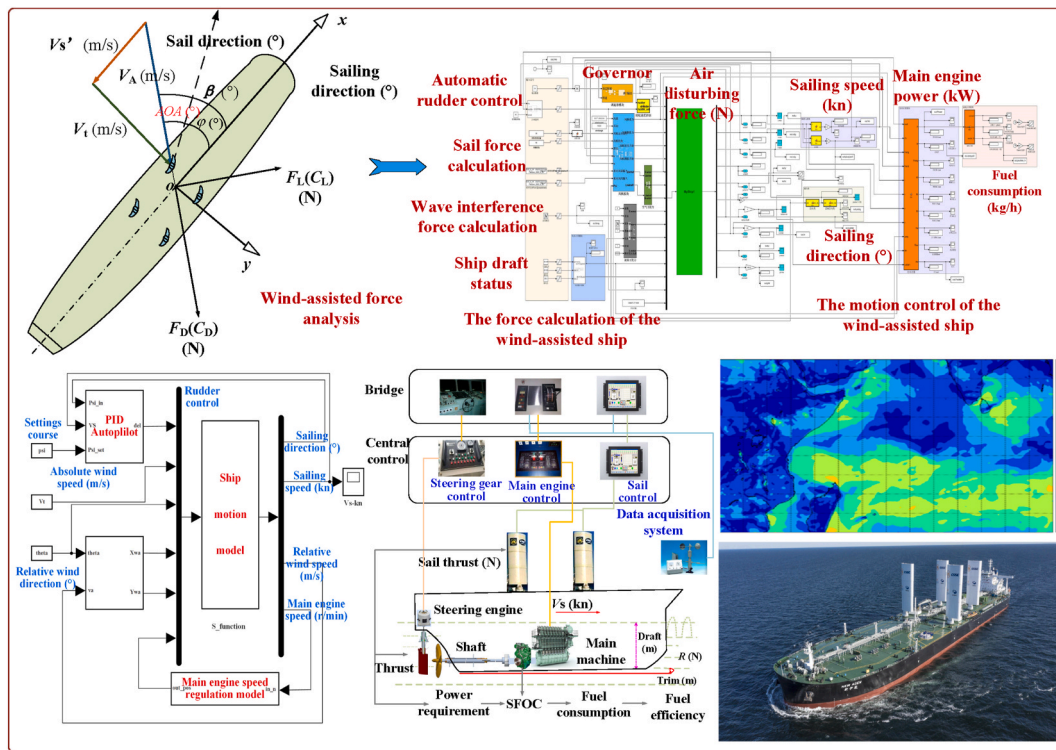


Fig. 20. The processes of the motion optimization control for the wind-assisted ship.

the model. Based on this, further research could be conducted on the motion characteristics of the wind-assisted ship. These characteristics serve as solid foundations for the motion optimization control of the wind-assisted ship under complex and changeable sailing conditions [121]. The motion optimization control of the ship adopting WAPS is designed to maximize the usage of the wind energy to achieve the optimal propulsion performance. The processes of the motion optimization control are illustrated in Fig. 20. During the optimization process, the ship fuel efficiency in diverse sea conditions and motion states should be firstly analyzed. Then, the optimal motion state of the ship adopting WAPS corresponding to the best fuel usage efficiency should be determined. Finally, the optimal motion state can be achieved through the proposed control algorithm, thereby enhancing the ship energy efficiency, meanwhile satisfying the stability requirements.

4.2. Energy efficiency optimization control of the ship adopting WAPS

4.2.1. Fuel usage efficiency model of the ship adopting WAPS

The fuel usage efficiency of the ship adopting WAPS is closely associated with multiple factors, including navigational environment, operation state of the sail, sailing speed, and sailing route [122]. Therefore, the construction of the energy efficiency model considering complex influencing factors is crucial for achieving the fuel efficiency optimization of the ship equipped with WAPS [123]. The energy transferring dynamics of the sail-diesel hybrid power system are illustrated in Fig. 21. The operational characteristics of sails, and thrust performance of the propeller, as well as the operating parameters of the diesel engine vary in response to the external navigational conditions during the working process of the hybrid power system [124], and thus affecting the fuel usage rate of the diesel engine [125]. Ruan et al. [126] examined the aerodynamic performance of the wing-typed sail and the

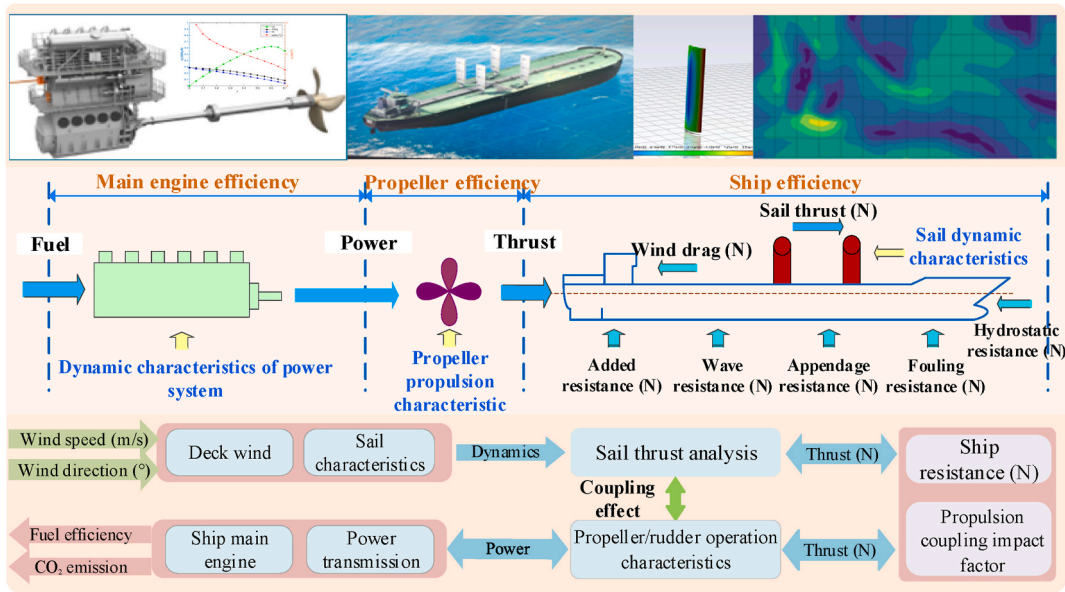


Fig. 21. The energy transferring dynamics of the sail-diesel hybrid propulsion system.

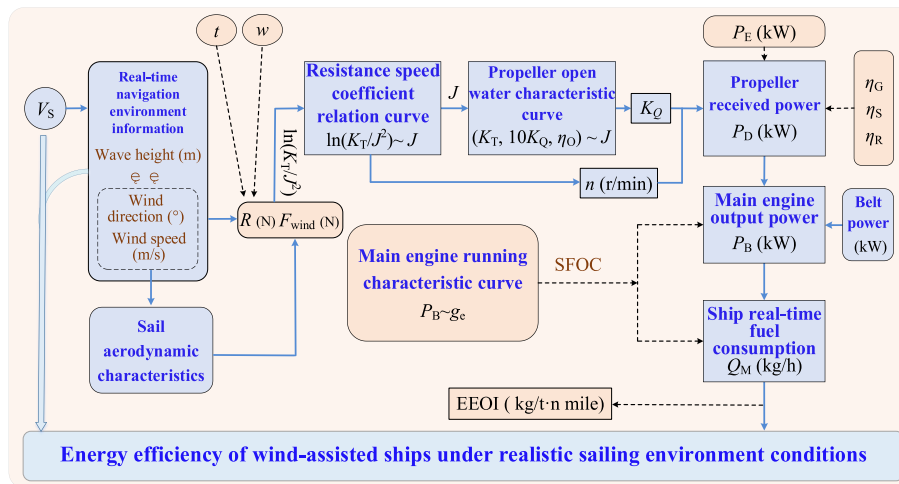


Fig. 22. The establishing processes of the fuel usage model for the ship adopting WAPS [123].

energy transferring dynamics within the hybrid power system, which is crucial for developing the fuel usage efficiency model of the wind-assisted ship.

The fuel usage efficiency of the ship adopting WAPS is affected by various environmental factors, including wind, waves, and currents [127]. The complexity of the ship navigational state, sail operation, and

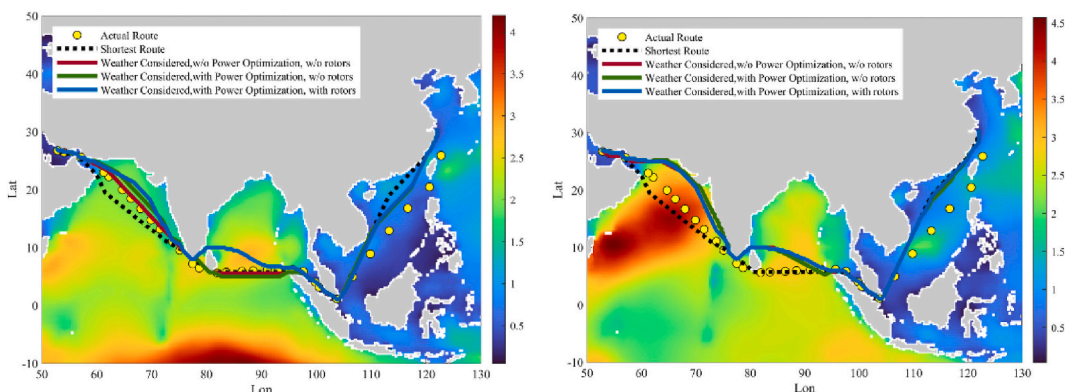


Fig. 23. The sailing route optimization for the ship adopting WAPS [130].

propulsion system behavior under various environmental conditions, makes it difficult to develop an accurate fuel usage efficiency model for ships adopting WAPS [128]. Consequently, it is essential to develop a fuel usage model that comprehensively consider the influence of multiple factors, including the sail thrust characteristics, ship resistance characteristics, propeller propulsion characteristics and the diesel energy consumption characteristics, in order to actually describe the energy usage of the ship adopting WAPS across diverse wind energy

resources [129]. The establishing processes of the fuel usage model for the ship equipped WAPS are shown in Fig. 22 [123]. The real-time environmental information should be firstly obtained, and then the sail thrust and the effective propeller thrust, as well as the sailing resistance of the wind-assisted ship under different motion states need to be calculated. On these bases, the fuel usage of the ship adopting WAPS can be determined across different operational states, thereby achieving the model establishment of fuel usage efficiency for the ship adopting

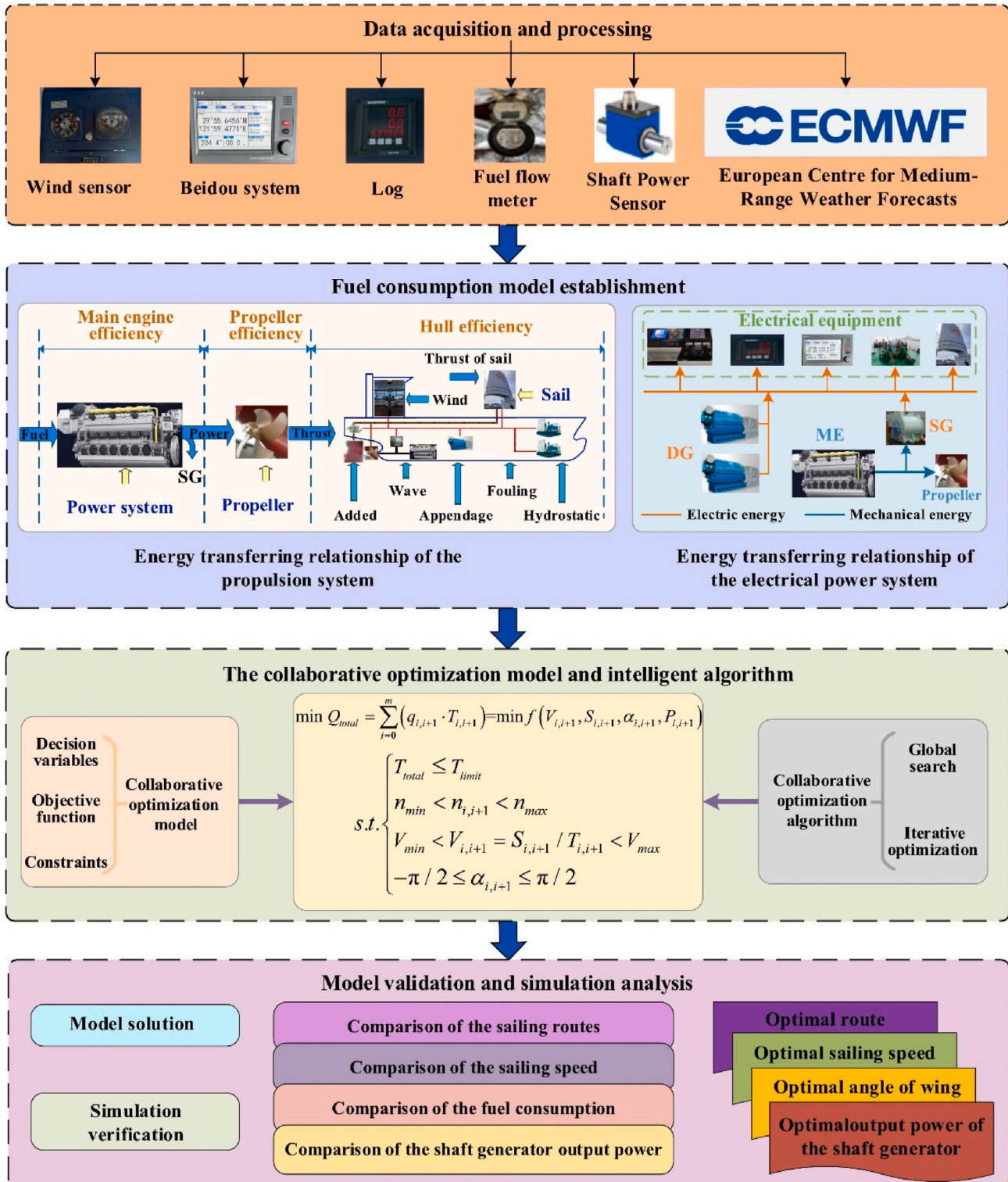


Fig. 24. Collaborative optimization processes for the ship adopting WAPS [136].

WAPS.

4.2.2. Energy efficiency optimization of the ship adopting WAPS

It is of great significance to carry out sailing route optimization of ships adopting WAPS for making full usage of wind energy resources, and enhancing the effect of fuel saving and emission reduction due to various wind energy resources within different sailing routes. Sun et al. [130] presented a decision-making approach by using the A* algorithm to obtain the more favorable crosswind, which can increase the sail thrust along the sailing route and thus enhancing the fuel efficiency of the ship adopting WAPS, as shown in Fig. 23. In addition, Li et al. [131] carried out the research on the sailing route optimization for a 76000 DWT wind-assisted ship and verified the effectiveness of the proposed route optimization model. Furthermore, Guzelbulut et al. [132] optimized the sailing route of the ship adopting WAPS based on the artificial neural networks. The optimization results showed that the overall energy usage of the ship adopting WAPS can be reduced by 9.7 %.

As for the collaborative optimization of the ship adopting WAPS, Duan et al. [133] analyzed the coordinated optimization of sail's AOA and sailing speed of the ship adopting WAPS, which can reduce CO₂ emissions of the ship by 4.5 % on a typical sailing route. In addition, the joint optimization and control of the SDHPS, considering coupling effects of multiple factors, is crucial for further enhancing the fuel efficiency of the ship adopting WAPS [134]. Wang et al. [135] developed a coordinated optimization model for the sailing route, sailing speed, and sail's AOA in ships equipped with WAPS, and came up with an algorithm based on the PSO to jointly optimize these parameters, achieving an 8.9 % reduction in CO₂ emissions. Furthermore, Liu et al. [136] proposed a comprehensive fuel efficiency optimization approach for the ship adopting WAPS, which can realize the joint optimization of sailing speed, sailing direction and sail's AOA, enabling to reduce fuel consumption by 5.25 %.

The collaborative optimization processes for the ship adopting WAPS include the data acquisition and processing, the fuel consumption model, the collaborative optimization model and advanced solution algorithms, as well as model validations, as shown in Fig. 24 [136]. Firstly, the operation data and navigational environment data of the wind-assisted ship can be acquired through various sensors. Then, the energy efficiency model of the ship adopting WAPS can be established based on the analyses of energy transferring relationship of the ship adopting WAPS. The optimization of fuel usage efficiency can be

realized through the application of the collaborative optimization model and advanced solution algorithms to identify the optimal sailing speed, sailing route and the sail's AOA, thus improving the overall energy efficiency of the wind-assisted ship. Finally, the optimization results can be verified through model verification or simulation analysis.

4.2.3. The comparative analysis of different optimization algorithms

The application of optimization algorithms in the field of energy efficiency optimization for the wind-assisted ship holds significant theoretical and practical significance [137]. An efficient optimization algorithm is related to its inherent mathematical properties and converge speed [138,139]. The common optimization methods include the PSO, GA (Genetic algorithm) and surrogate models, etc. [140].

The comparative analysis on the performance of different optimization algorithms under various scenarios is summarized in Table 3. Wang et al. [141] used the Improved Particle Swarm Optimization (IPSO) algorithm to optimize the sailing speed, sailing route, trim, and sail's AOA of the ship adopting WAPS, achieving an 8.6 % reduction in ship fuel usage with the number of iterations of 35 for the algorithm, while the traditional PSO-based ship fuel usage can be decreased by 6.98 % with the number of iterations of 20. Although the convergence speed of the IPSO is decreased compared to the traditional PSO, its optimization effect has effectively improved. Additionally, Lan et al. [142] conducted a joint optimization of sailing speed, trim and sail's rotation angle for the wing-typed sail-assisted ship by using the enhanced artificial ecosystem-based optimization (EAEO), which can reduce the ship fuel usage by 8.74 % with the number of iterations of 20. The EAEO has faster converge speed and better optimization effect compared to the PSO and GA algorithms. Moreover, Cairns et al. [143] carried out the optimization analysis of the wing-typed sail's design through the surrogate model. The results showed that the lift coefficient of the wing-typed sail can be increased by 13.17 %, meanwhile the application of the surrogate model can reduce the iteration number of the optimization algorithms (with number of iterations of 18) and improve the computational efficiency. Furthermore, the optimization algorithms have been demonstrated for the energy efficiency optimization of ships without WAPS. For example, Li et al. [144] used the NSGA-III (Non-dominated sorting genetic algorithm III) to achieve the joint optimization of ship's sailing route, speed, and trim, achieving a 4.54 % reduction in the ship fuel usage with 249 iterations for the algorithm.

4.3. The control system and strategy of the wind-assisted ship

The control system and strategy are significant to achieve the optimization control of the ship adopting WAPS to enhance the safety, usage effects of the wind energy resource, as well as the ship energy efficiency [145].

4.3.1. The data monitoring and control system

The typical data acquisition and control system of the ship adopting WAPS is depicted in Fig. 25, which composes the data acquisition unit, and the display and control unit. The data acquisition and control system have the functions of operational data acquisition, navigational environment data acquisition, and the decision-making and optimization control of the sailing route, sailing speed, as well as the operational state of sails and power system under various navigational conditions to achieve the efficient usage of wind energy, and hence reducing pollutant gas emissions [123]. Among them, the ship operational data can be obtained through the data acquisition unit consisting of the shaft power meter, GPS, engine control unit (ECU), and fuel flow meter. Among them, the shaft speed and shaft power of the ship can be measured by the shaft power meter. In addition, the navigational environment data can be acquired through the navigational environment data acquisition unit, and then the acquired data can be transmitted to the ship through the satellite communication. Additionally, the operation parameters of the

Table 3
Comparative analysis of different optimization methods under various scenarios.

Optimization target	Algorithm/Surrogate models	Optimization effect	Number of iterations	Reference
Sailing speed, route, sail's AOA and trim	IPSO	The fuel usage can be reduced by 8.60 %	35	[141]
Sailing speed, route, sail's AOA and trim	PSO	The fuel usage can be reduced by 6.98 %	20	[141]
Sailing speed, trim and sail's rotation angle	EAEO	The fuel usage can be reduced by 8.74 %	20	[142]
Sailing speed, trim and sail's rotation angle	PSO	The fuel usage can be reduced by 5.08 %	47	[142]
Sailing speed, trim and sail's rotation angle	GA	The fuel usage can be reduced by 6.12 %	68	[142]
Optimization of the wing-shaped design	Surrogate model	Lift coefficient of wing sail can be increased by 13.17 %	18	[143]
Optimization of sailing route, speed and trim	NSGA-III	The fuel usage can be reduced by 4.54 %	249	[144]

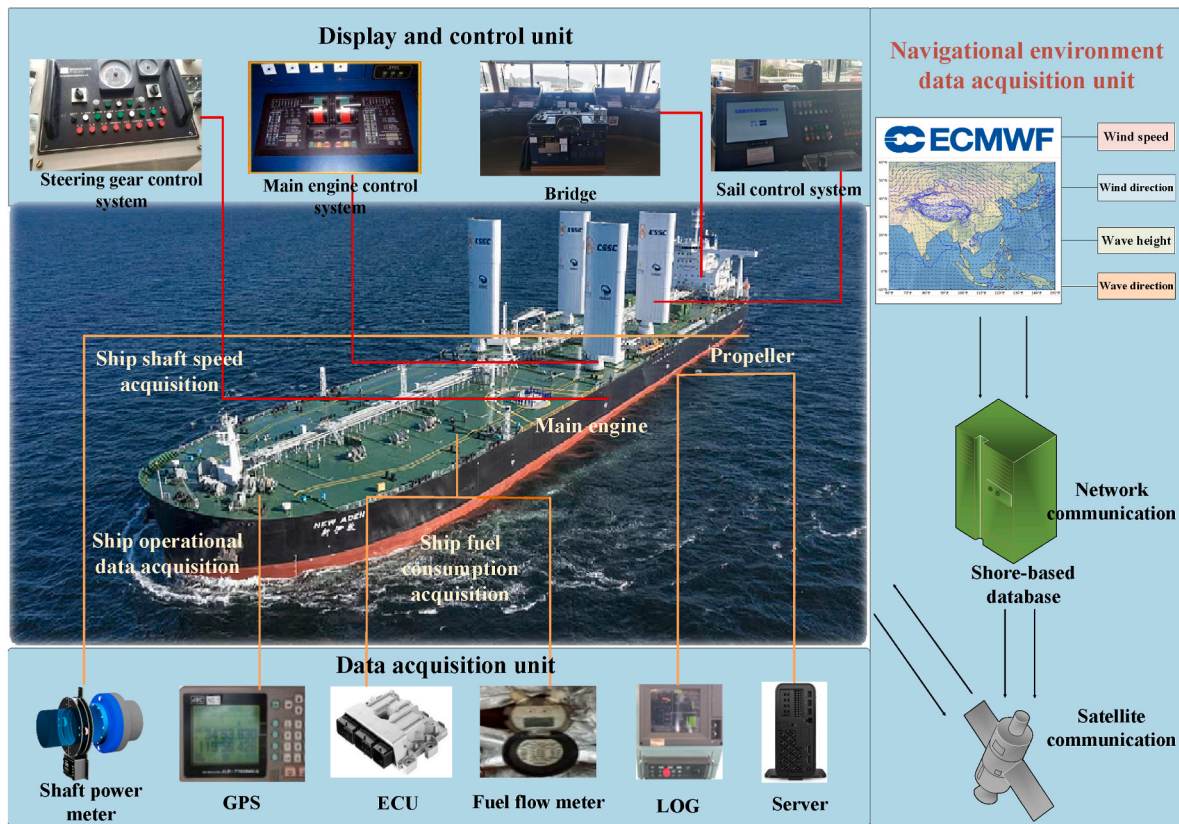


Fig. 25. The data acquisition and control system for the ship adopting WAPS.

engine can be monitored through the ECU. Moreover, the instantaneous and cumulative fuel consumption can be measured by the fuel flow meter, and the sailing speed and position information can be obtained by the GPS and LOG.

The integrated optimization control of the main engine, sail and steering gear of the ship adopting WAPS can be realized through the control system. Among them, the steering gear, the main engine and the sail can be controlled by the steering gear control system, the main engine control system and the sail control system, respectively. In this way, the utilization efficiency of wind energy resources can be enhanced and the energy efficiency of the ship adopting WAPS can be improved through the cooperative optimization control of the sailing route, sailing speed and the sails' AOA. However, more influencing factors need to be considered for the ship equipped with WAPS due to the lateral force and yawing moment caused by the usage of sails. At the same time, the complex and changeable navigational environment, including different meteorological conditions, would affect the accuracy of the acquisition system of the ship adopting WAPS [146]. Therefore, the effective control strategies and algorithms based on the acquired accurate data for the ship equipped with WAPS is crucial to further enhance the utilization efficiency of wind energy resources and reduce carbon emissions of the wind-assisted ship.

4.3.2. The optimization control strategy of the ship adopting WAPS

It is critical for formulating effective sail control strategy, rudder angle control strategy, energy management strategy, and data analysis and optimization strategy, which are significant to enhance the fuel usage efficiency of the ship adopting WAPS [147,148]. The sail control strategy adopting the effective control algorithm can achieve the optimization control of the sail's AOA and height of the sails to improve the sail-assisted effects according to the real-time wind speed, wind direction, and other factors [149]. In addition, the rudder angle control strategy can achieve the control of rudder angles by comprehensively

considering the influence of the sail on the ship course, sailing speed and other factors, thus improving the ship energy-saving effect [150]. Furthermore, the energy management strategy adopting the joint optimization model and algorithm of ship energy efficiency can achieve effective energy management of the sail-assisted hybrid power system. Moreover, the data analysis and optimization strategy can facilitate to the optimization control of the sail, rudder and the energy system, thus enhancing the fuel-saving effects of the WAPS.

4.4. Summary

The optimal control of the wind-assisted ship is the key to further enhance the ship energy-saving performance. Although some scholars have carried out relevant research on the motion control and fuel usage efficiency control for the ship adopting WAPS, the following problems and issues still need to be further solved.

- 1) The motion of the ship adopting WAPS is affected by a variety of complex factors during navigation. How to jointly adjust the sail state and ship state under complex and variable navigational conditions is still a key issue to be solved. Improving fuel efficiency while maintaining the stability of the wind-assisted ship is of great importance.
- 2) The motion optimization control for the wind-assisted ship can be achieved based on the motion characteristics analysis and the optimization control algorithm. However, how to achieve the coordinate optimization control of the sail operation state and ship motion state under complex and variable navigational conditions is still a challenge.
- 3) There is a certain coupling correlation between the sail performance and ship motion, thus affecting the energy efficiency of the wind-assisted ship. However, a key issue that needs to be resolved is how to jointly control the operation states of the ship and sails in

response to the intricate real-time marine environment to improve the fuel usage efficiency of the wind-assisted ship.

- 4) The coupling effects of diverse environmental factors on the ship navigation state, sail state and power system operation state need to be further studied. Therefore, it is significant to establish an energy efficiency model of the wind-assisted ship through the coupling effects of the sail thrust characteristics, ship resistance characteristics, propeller propulsion characteristics, and the main diesel engine fuel consumption characteristics under the influence of multiple environmental factors.
- 5) Under the coupled influence of diverse factors, the integrated optimization and control of the hybrid power system can significantly improve the fuel usage efficiency of ships adopting WAPS. Some scholars have concentrated on the combined optimization of fuel usage efficiency for wind-assisted ships. However, the research on the effective joint optimization algorithms and control strategies of fuel usage efficiency for ships equipped with WAPS considering multiple environmental factors needs to be strengthened, which is significant to further achieve the goal of fuel usage and CO₂ emissions reduction.

5. Comprehensive analysis of the WAPS

5.1. Economic analysis of the ship adopting WAPS

Under the background of increasing environmental concerns and rising fossil fuel prices, the shipping industry is actively exploring the feasibility of the wind energy, which can be accurately evaluated through the economic analysis of WAPS [151]. The payback period, or return on investment, is not only dependent on the net fuel savings offered by WAPS compared to the marine alternative fuels, but is also affected by fuel price and associated incentives or penalties [152]. Talluri et al. [153] conducted the analysis on the economic and environmental performance of WAPS. The results showed that the Flettner rotor can significantly reduce fuel consumption by 20 %, and can reduce cost by 3 %–17 % compared to the conventional diesel engine-powered propulsion system for certain specific sailing routes. Additionally, the WAPS can reduce the dependence on the international fuel market, reduce the operational risk caused by oil price fluctuations, and provide a more stable economic environment for ship operations [154]. Under the general trend of pursuing green and low-carbon development of the maritime sector, the WAPS is of great significance in enhancing economics and facilitating the sustainable progress of the maritime sector by effectively decreasing fuel consumption of ships.

5.2. Reliability analysis of the ship adopting WAPS

The operation and maintenance are significant guarantees for the reliable operation of the WAPS, which is significant to enhance the practical application effects and navigational safety of the wind-assisted ship. For the sail control achieved by the hydraulic system, hydraulic pumps, hydraulic valves, hydraulic cylinders and other components

often have internal leaks, which would cause the sail to be unable to lift as designed, thus affecting the sail-assisted propulsion effect and the navigational safety of the ship adopting WAPS [155]. Ma et al. [156] proposed a fault diagnosis method for the hydraulic system leakage based on the wavelet packet transform and support vector machine methods, as depicted in Fig. 26. The findings indicated that the accuracy of the proposed methods is as high as 97.5 %. In addition, the diagnosing leakage faults holds significant importance in enhancing the propulsion effectiveness of WAPS. Ma et al. [157] proposed a leakage fault diagnosis method and established a simulation model for analyzing different features of leakage faults in the hydraulic system. The diagnostic results showed that the accuracy of the proposed methods is 94 %. Above all, the reliability analysis is crucial for enhancing the safety and stability of the ship adopting WAPS.

5.3. Energy efficiency design index analysis of the ship adopting WAPS

IMO proposed the Energy Efficiency Design Index (EEDI) as an important index to evaluate the energy efficiency level for the newly-built ship [158]. The lower the EEDI value, the higher the energy efficiency level [144]. Wind energy, as a renewable energy source, is important to improve the energy efficiency for ocean-going ships [159]. The fuel efficiency level of the wind-assisted ship can be analyzed and evaluated by calculating the EEDI before and after the installation of sails. Ma et al. [160] suggested the utilization of wind field probability matrix, and built the sail force matrix for the navigation route. On this basis, the thrust generated by the wing-typed sail was calculated to evaluate its energy-saving potential, which is critical for advancing the practical application of the wind-assisted technology for shipping decarbonization.

5.4. Route adaptability analysis based on wind energy resources analysis

The route adaptability analysis of the ship adopting WAPS based on the typical wind energy resources is crucial for enhancing the energy-saving effect of WAPS, due to the complicated and various wind energy resources within different sailing areas [161]. Therefore, the analysis of the wind energy is crucial for optimizing the operation of the ship adopting WAPS. Elyouncha et al. [162] adopted Bayesian inversion method to jointly retrieve the sea surface wind velocity vector through the satellite SAR data, which can provide the accurate marine meteorological environment data for the fuel-conservation effect analysis of the ship adopting WAPS. In addition, Chadee et al. [163] analyzed the distributional characteristics of wind speed, wind direction, and wind energy density in the Caribbean Sea, as shown in Fig. 27. Wang et al. [164] adopted the intelligent optimization algorithm to analyze the meteorological environment data of typical sea areas. The multi-dimensional meteorological data from various sea areas, including wind speed, wind direction, wave height and cycle frequency, can provide support for analyzing the energy-saving potential of the wind-assisted ship [165].

Additionally, the wind energy resources of different sailing routes



Fig. 26. Leakage diagnosis and analysis of the sail hydraulic system [156].

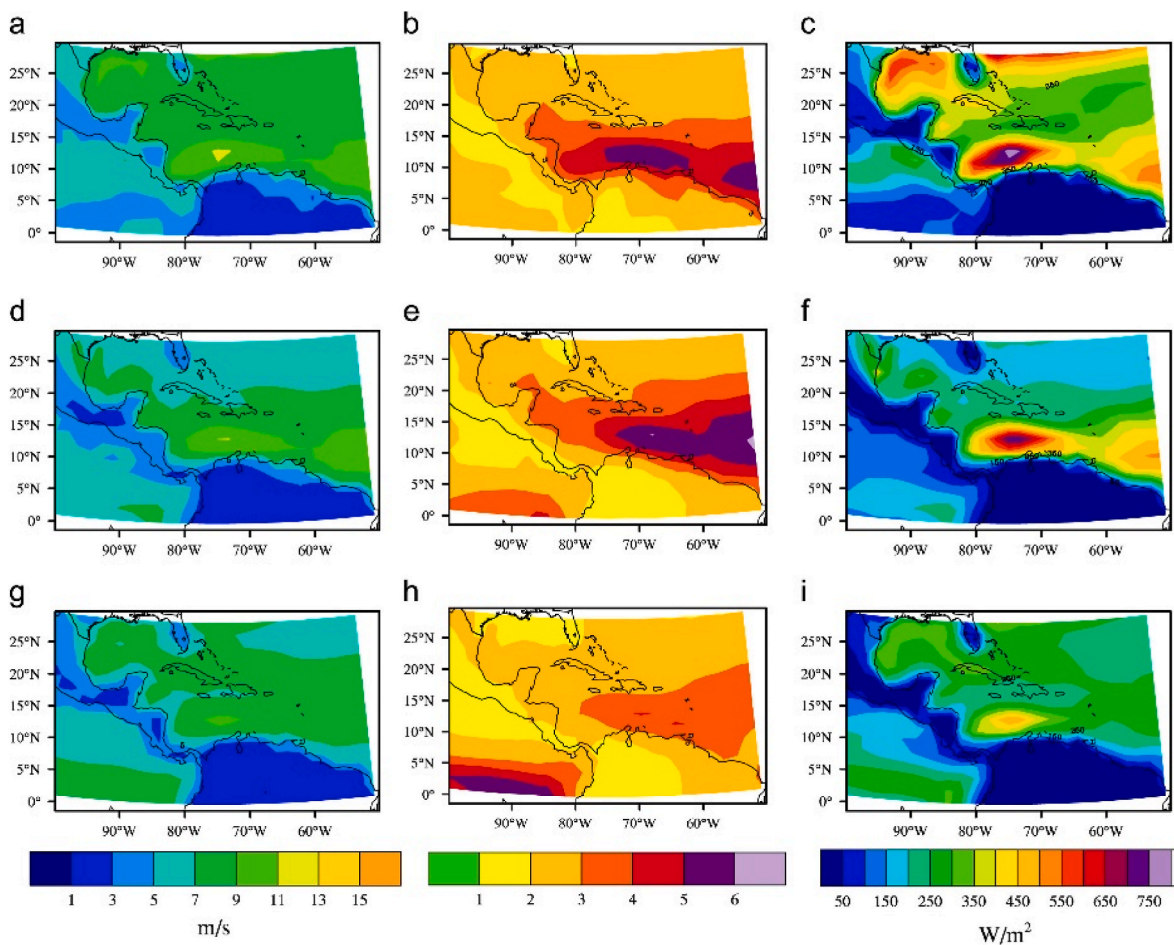


Fig. 27. Analysis of the wind energy resources in the Caribbean Sea [163].

and regions are complex and changeable, and the wind energy resources are various for different navigational regions and routes. Thereby, choosing suitable sailing route or region, in which the wind energy can be effectively used to reduce ship energy consumption, is important for the energy saving and emission reduction of the ship adopting WAPS. Wind energy resources in different sailing routes are complex, thus leading to different propulsion effects of WAPS. The applicability of WAPS for different sailing routes or areas is influenced by various factors, including wind speed, wind direction, and marine environment [166]. In addition, the advantages of the WAPS are not obvious for sailing routes with scarce wind energy resources and those with complex and changeable wind directions [167]. Therefore, it is necessary to conduct an analysis of wind characteristics for the target sailing route or navigational area before applying the WAPS, as well as an analysis of the energy-saving effect and economic benefits by adopting the WAPS [168]. Liu et al. [169] studied the wind energy density in the South China Sea, and the Bay of Bengal as well as the Arabian Sea. The findings showed that the available wind energy resources of the South China Sea in winter and summer differ greatly when the ship course is different. The characteristics of available wind energy resources in the Bay of Bengal and the Arabian Sea are similar, and the West-East course can make more efficient utilization of the wind energy in summer. The research results can provide a theoretical basis for the optimization of course, speed and sails for the ship adopting WAPS.

5.5. The energy-saving effect analysis of the wind-assisted ship

5.5.1. Practical application analysis

The effective wind energy usage can significantly improve the energy

efficiency level of large ocean-going ships, thus achieving the energy saving and emission reduction [170]. In recent years, the wind-assisted propulsion system has gained extensive research and application on various ships. The summary of the typical available wind-assisted ships is given in Fig. 28. As it can be seen, the wing-typed sails are mainly adopted for bulk carriers, oil tankers, which can effectively reduce fuel consumption by more than 8 %. In addition, the Flettner rotors are mainly used for oil tankers, Ro-Ro-ships, which can effectively reduce the fuel consumption by more than 5 %. Furthermore, the kite sails have been used for cargo ships, which can effectively save more than 10 % of fuel usage for a certain voyage. In summary, the application of WAPS on real ships is crucial for enhancing the energy efficiency of ships.

5.5.2. The effectiveness of energy conservation across various scenarios

The effectiveness of energy conservation analysis of typical wind-assisted ships across various scenarios is shown in Table 4. As it can be seen, the effectiveness of energy conservation of various wind-assisted ships on different sailing routes are different. The cargo ship using kite sail have good energy-saving effects on the Hamburg-Houston route, and the fuel usage can be reduced by 15 %~35 %. The fuel consumption of bulk carrier using wing-typed sail can be reduced by 20 %~30 % on the Yokohama-Seattle route. In addition, the fuel consumption of Ro-Ro ships with Flettner rotors can be reduced by 25 % on the North Europe sailing route. Overall, the utilization of various sail types can efficiently enhance the energy efficiency of the ship adopting WAPS, thereby promoting the green and low-carbon development of the maritime sector.



Fig. 28. Summary of the typical wind-assisted ships.

6. Challenges and discussions

The application of WAPS is crucial for enhancing the fuel usage efficiency and reducing energy consumption, as well as contributing to the green and low-carbon development of the shipping industry. Nevertheless, numerous uncertainties still exist in the implementation of wind-assisted ships. The accurate data acquisition is crucial for the performance assessment and optimization of the WAPS. The complex and changeable weather conditions and marine environment would lead to significant uncertainties in the collected data of the ship adopting WAPS. Therefore, the data acquisition accuracy and the installation position of the data acquisition device are of great significance for improving the propulsion performance of the wind-assisted ship [182]. Additionally, there are also uncertainties in the suitability of sail-assisted technologies and ships. Various types of sails have different characteristics, and thus the suitability of sails for different ships needs to be further studied. Moreover, the coupling relationship between sails and ship power system is complex, and there is a lack of the coordination theory and method. Furthermore, the initial investment cost adopting sail-assisted technologies is difficult to estimate, and its operating costs and benefits are affected by a variety of uncertainties, such as fuel prices, sail maintenance costs, sailing routes and meteorological conditions, which make it difficult for shipowners and investors to make decisions.

In recent years, various new types of sails are now attracting attention in addition to the well-known wing-typed sails, Flettner rotors and kite sails. In particular, the novel wing-typed sails suitable for special

conditions, including the ventilated foil system, telescopic wing sails, polar wing sails and foldable wing sails, have been widely studied and applied [152,183], as shown in Fig. 29. In addition, the propulsion performance of the sail can be enhanced through the bionic structures. For example, the wing sail cavity can replicate the bone honeycomb structure, which can increase the overall strength and reduce the weight of the ship. Folding sails can be designed to retract like fins, and the sails can be designed as the shape of the wings of gliding birds, such as the albatrosses, to efficiently use wind energy resources [184]. These sails can adapt to changing and complex sea conditions, and can meet the safety requirements of the wing-typed sail structure under special working conditions. In recent years, the development of telescopic wing sails and foldable wing sails has attracted more and more attention. Foldable wing sails can achieve folding and unfolding through the rotation of various parts [185], which can adapt to the changing wind and sea conditions [186]. As for the telescopic wing sails, they mainly change the shape through the telescopic movement, and their extension and contraction proceed in a straight line along a specific direction [187]. The telescopic and foldable wings have advantages of convenient storage, space saving, and easy unfolding and folding processes. More importantly, they have strong adaptability, namely they can be flexibly applied to different scenarios, and adapt to different navigational environments, which can improve the stability and safety, as well as the energy-saving effects for the wind-assisted ship [188].

In addition, under the general trend of the emission reduction, as well as the green and low-carbon development of the maritime sector,

Table 4
The energy-saving analysis of typical wind-assisted ships.

Sail type	Applied ship type	Sailing route	Energy-saving effect	Literature
Kite sail	RO-RO cargo ship	Indeterminate	16 %	[28]
Kite sail	Cargo ship	Hamburg-Houston	15 %–35 %	[145]
Wing-typed sail	Bulk carrier	Pacific Ocean, Indian Ocean, and Atlantic	14 %	[171]
Wing-typed sail	Cargo ship	North America-Japan	5 %	[172]
Wing-typed sail	Bulk carrier	China-Brazil	19.5 t emissions	[173]
Wing-typed sail	VLCC	Singapore-Cape Town	5.48 %	[174]
Wing-typed sail	Bulk carrier	Yokohama-Seattle	20 %–30 %	[175]
Flettner rotor	Oil tanker	London-Milford Haven	14 %	[46]
Flettner rotor	Container ship	Yantian-Felixstowe	2 %	[46]
Flettner rotor	Oil tanker, Ro-Ro-ship	Pacific route, Baltic route	30 %, 14 %	[66]
Flettner rotor	RO-RO ship	North Sea	6.1 %	[176]
Flettner rotor	Bulk carrier	Vancouver-Nantong	12.5 %	[177]
Flettner rotor	RO-RO ship	Ireland, Europe, and England	10 %	[178]
Flettner rotor	Cargo ship	China-Australia	10 %	[179]
Flettner rotor	RO-RO ship	North Europe	25 %	[180]
Flettner rotor	Bulk/oil carrier	Chile-Japan	6 %	[181]

the wind and battery-powered ships as well as the wind and marine alternative fuel powered ships have attracted much more attentions. The wind and battery-powered ships can completely avoid the fossil fuel pollution emissions, but there are problems such as the short battery life, difficult system integration, and high initial investment [189]. The wind and alternative fuel-powered ships can compensate for the instability of

wind energy with marine alternative fuels, which are cleaner and have lower carbon emissions compared to the traditional fuel, but also have shortcomings, such as inadequate supply infrastructure, high fuel costs, and complex environmental impact assessments [190]. Above all, the combination of wind and battery, and the combination of wind and marine alternative fuels have their pros and cons. With the advancement of technology and the improvement of infrastructure in the future, new energy is expected to be more widely used in wind-assisted ships, thus achieving green and low-carbon shipping industry.

Moreover, the sail angle control adopting effective control algorithms can achieve the optimization control of sail rotation angles, thus improving the sail thrust and energy-saving effects for the wind-assisted ship. However, more advanced algorithms should be proposed to precisely control the sail angle especially under complex and changeable meteorological conditions [191]. In addition, the control of the rudder angle can reduce the ship sailing resistance and enhance the ship maneuvering stability. However, the precise control of the rudder angle requires consideration of the ship course control, as well as the deviation of the ship course caused by the lateral force of sails [192]. Additionally, how to achieve the global optimization of rudder angle control, propulsion system and route planning remains a key focus of industry research [132]. Moreover, effective management strategies can reduce the operating costs and decrease GHG emissions of ships. Nevertheless, the energy transferring relationship of the wind-assisted hybrid power system also needs to be considered for achieving effective energy management strategies [123]. Furthermore, the data analysis and optimization are the prerequisite for achieving the effective sail angle control, rudder angle control and energy management strategies of wind-assisted ships. Effective data analysis and optimization measures should be able to solve issues, including the data transmission delay, errors, deviations, or interruptions, which can further enhance the accuracy of the data and can lay solid foundation for the subsequent research on the energy efficiency optimization of wind-assisted ships [193].

Furthermore, the life cycle analysis of the wind-assisted propulsion system should be carried out, which can quantify the GHG emissions of each stage of the WAPS from the raw material acquisition, manufacturing, operation, and the scrap recycling, as well as the GHG emissions in the entire process, thus providing support for the emission reduction target of the global shipping industry.



Fig. 29. The illustration of the novel wind-assisted ships.

7. Conclusions and future research

The application of wind-assisted technologies can effectively enhance the energy efficiency of the wind-assisted ship. A comprehensive review of existing studies on wind-assisted technologies, including the aerodynamics analysis of different sails, the optimal design of the ship adopting WAPS, the operation control of the wind-assisted ship, and the comprehensive analysis of the wind-assisted propulsion system, are carried out. In addition, the challenges faced by the research and practical applications of wind-assisted technologies are proposed. The main conclusions are summarized as follows.

- 1) The aerodynamics of different sails can be improved through the wind tunnel test and CFD approach, which is significant to make full usage of wind energy resources, and thus enhancing the fuel usage efficiency of the wind-assisted ship. In addition, the overall aerodynamics performance of the ship adopting WAPS can be effectively improved through the optimization of the sail arrangement to avoid the interference effect among multiple sails on the ship. However, the interference characteristics analysis of multiple sails based on the combination of numerical simulation and experimental verification methods need to be further studied, which is significant to reduce the mutual interference among sails and improve the overall aerodynamics performance of sails.
- 2) The optimal design of the sail, including the shape and main parameters, can also improve the aerodynamics performance and the operation stability of the ship adopting WAPS. Additionally, optimizing the layout of multiple sails and carrying out the optimal design of the SDHPS can increase the wind energy utilization to enhance the ship energy efficiency. Furthermore, the integrated analysis of the sail and hull would provide the basis for the optimal design of the wind-assisted ship. However, the analysis on the optimal design of sails based on the coupling dynamics analysis considering the coupling effects of the hull and various environments is still lacking. In addition, the optimization and matching design of the sail-assisted hybrid power system considering the WAPS characteristics, power system operation characteristics and the ship propulsion characteristics should be further studied.
- 3) The navigation safety of the ship could be enhanced through the motion optimization control of the ship adopting WAPS. In addition, the operation control of the ship equipped with WAPS in the aspect of energy efficiency optimization is significant to maximize utilization of wind energy resources and reduce ship carbon emissions. However, the research on the effective joint optimization algorithms and control strategies for improving energy efficiency of the ship adopting WAPS considering the influence of multiple environmental factors needs to be strengthened, which is significant to reduce the ship fuel consumption and CO₂ emissions.
- 4) The economic and reliability analysis of the ships equipped with WAPS are important guarantees for the reliable operation of the WAPS and navigational safety of the wind-assisted ships. In addition, the application of the WAPS on the real ship shows a good energy-saving effect, and the fuel efficiency of the ship adopting WAPS could be effectively improved through the applications of different types of sails, thus promoting the low-carbon advancement of the maritime sector. However, the research on relevant standards for the applications of the wind-assisted technologies is still lacking, including the technical standards for application, energy efficiency evaluation standards, and the operation safety standards. Additionally, the experimental verification should be strengthened for the analysis of sail aerodynamics characteristics, and the validation analysis of different sails in various scenarios should be carried out, to provide references for the practical applications of the wind-assisted technologies.

Although extensive studies on the key technologies of the wind-

assisted propulsion system have been carried out, there still exist some challenges need to be further investigated and solved.

- 1) The sail aerodynamics performance is affected by the airflow from multiple directions. Therefore, it is necessary to consider three-dimensional effects, including the change of lift, drag and torque in different directions to achieve accurate aerodynamics characteristics analysis of sails. In addition, the analysis on the interference characteristics of multiple sails requires a combination of numerical simulation and experimental verification methods to determine the optimal sail configurations, thus reducing the mutual interference between multiple sails.
- 2) The optimal design of the sail-assisted hybrid power system is affected by a variety of uncertain factors, such as the time-varying wind speed and sea state. How to consider those factors comprehensively in the optimal design of the system is still a challenge. Furthermore, the analysis on the aerodynamics characteristics and energy efficiency optimization results of different sail arrangements for various types of ships are also the keys to improving the energy-saving effects of the wind-assisted ship. Moreover, the optimization results of sail arrangements based on the coupling aerodynamics analysis need to be verified through experiment tests, and how to effectively combine the theoretical research on the sail optimization arrangement with practical engineering applications is also a challenge.
- 3) For the motion control of the wind-assisted ship, the motion characteristics under complex navigational conditions, especially considering the interaction between the sail aerodynamics and the ship hydrodynamics, need to be further studied. In addition, the motion of the wind-assisted ship is affected by the coupling influence of multiple physical fields, such as wind, wave and current. How to accurately describe the coupling relationship of multiple physical fields and achieve the adaptive and joint optimization control of the wind-assisted ship under complex navigational environment needs to be further studied.
- 4) In terms of the optimization of energy efficiency for the wind-assisted ship, further research on the asynchronous operation control of sails in terms of AOA, and especially the effectiveness analysis under dynamic wind energy resources should be carried out. In addition, how to analyze the effect of sails on the operational characteristics of the rudder and main engine, and realize the cooperative optimization control of sails, main engine and rudder in the case of single sail failure and unbalanced wind energy resources are the keys to enhancing the performance of the WAPS in the practical applications. Furthermore, the modeling and dynamic optimization of the WAPS under complex and variable conditions are also the keys to enhancing the fuel usage efficiency of the ship adopting WAPS.
- 5) Regarding the real-world application of the ship adopting WAPS, the experimental verification process should be strengthened for the aerodynamics analysis of various sails, and the applicability verification analysis of different sails should be carried out, to provide references for the practical applications of the wind-assisted technologies. In addition, the research on relevant standards for the applications of wind-assisted technologies need to be proposed, including the technical standards for application, energy efficiency evaluation standards, operation safety standards, etc. Finally, the analysis of the economy, applicability and reliability of different types of sails should be strengthened to promote the practical applications of wind-assisted technologies.

CRediT authorship contribution statement

Kai Wang: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Zhongwei Li:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Xing Liu:**

Writing – original draft, Visualization, Conceptualization. **Zhiqiang Hu:** Writing – review & editing, Funding acquisition, Formal analysis. **Lianzhong Huang:** Supervision, Funding acquisition, Conceptualization. **Qiushi Song:** Writing – original draft, Validation, Methodology. **Hongzhi Liang:** Writing – original draft, Validation. **Xiaoli Jiang:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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