DOI: 10.15480/882.9349

Eighth International Symposium on Marine Propulsors
smp'24, Berlin, Germany, March 2024.

An investigation into the factors influencing EEDI's contribution to wing sail-assisted technology

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ABSTRACT

Wing sail-assisted technology is an option for the cargo ship retrofitted or designed to meet the requirement of EEXI or EEDI. In this paper, the factors influencing the EEDI contribution of wing sails for a VLCC have been carried out based on the wind tunnel and tank model test results, including the arrangements of sails, the total area of sails, the sailing speeds of the ship, and wind probabilities along the main global routes. Investigation of the influence of the side force induced by the sails into the net EEDI contribution was also provided considering drift and rudder angle variation of the ship.

The conclusions obtained in this study show that wind probability is a sensitive factor, and when following the method in MEPC.1/Circ.896, the EEDI contribution of four sails for the VLCC can reach almost 6%. The EEDI contribution of the sails tends to increase as the ship speed decreases. The total area of the sails has a greater effect on the EEDI contribution than the sail arrangement. Wing sails' contribution to EEDI will be overestimated by the method described in MEPC.1/Circ.896, which ignores variations in the drift and rudder angle of the ship, compared to MMG-based model results.

Keywords
Wing sail-assisted technology, EEDI, Wind tunnel model test, MMG model, wind probability

1 INTRODUCTION

In the current context of carbon peak and carbon neutrality, wing sail technology using wind energy is one of the energy-saving and emission-reduction technologies that the shipping industry is focusing on. Extensive theoretical research and practical ship applications have proven that the technology is one of the potentially effective techniques for reducing the Energy Efficiency Design Index (EEDI) of ships (Todd et al 2021). Figures 1 to 4 show several full-scale sea trials and applications of wing sails on large ocean-going ships in recent years.


Figure 1 New Vitality


Figure 2 New Aden


Figure 3 Shofu Maru

Figure 4 Pyxis Ocean

The 65th Marine Environment Protection Committee first issued guidance on attained EEDI calculation method for innovative energy efficiency technologies (MEPC 2013), which include wind-assisted systems. Several researchers have evaluated the EEDI contribution of different types of wind-assisted systems following the guidance (Yoshimura et al 2016; Leopaul 2021). Evaluation of the occurrence probability of wind for the use of the wind-assisted systems in calculating attained EEDI was also carried out by Kaneko & Tsujimoto (2021). The revised guidance MEPC.1/Circ.896, which provides a detailed description of EEDI calculation methods for innovative energy efficiency technologies such as wind-assisted systems, has been amended specifically for the thrust matrix acquisition method used by wind-assisted systems (MEPC 2021). Researchers have also conducted research using the guidance's amended methodology. The WiSP2 project led by MARIN and ABS has investigated the EEDI contributions of different wind technologies, including a comparison of the primary and wind-assisted systems (Comoros & RINA 2021).

In this paper, the effect of different factors influencing the contribution of sails' EEDI was evaluated and analyzed referring to the method provided in MEPC.1/Circ.815 firstly, including the arrangements of sails, the total area of sails, and the sailing speed of the ship. Furthermore, the impact of wind probability on the EEDI contribution of sails over global shipping routes has been evaluated using the recently issued MEPC.1/Circ.896. Finally, utilizing MMG-based ship motion equations, an investigation of the impact of the side force caused by the sails into the net EEDI contribution was performed, taking drift and rudder angle change of the ship into consideration (Yasukawa 2015). The findings of this study are useful for the development of the EEDI calculating method as well as the design of wing sail-assisted ships.

2 EEDI CALCULATION METHOD FOR WING SAIL-ASSISTED SHIP

2.1 Calculation method of attained EEDI in MEPC.1/Circ.815

A methodological framework for calculating attained EEDI when a ship is equipped with wind-assisted systems has been provided in MEPC.1/Circ.815. The formula is expressed as:

$$\begin{aligned}&\frac{\prod_{j=1}^{M} f_j(\sum_{i=1}^{n\mathrm{ME}} P_{\mathrm{ME}(i)}\cdot C_{\mathrm{FME}(i)}\cdot SFC_{\mathrm{ME}(i)})}{f_\mathrm{i}\cdot f_\mathrm{c}\cdot Capacity\cdot f_\mathrm{w}\cdot V_\mathrm{ref}}\\&+\frac{P_\mathrm{AE}\cdot C_\mathrm{FAE}\cdot SFC_\mathrm{AE}}{f_\mathrm{i}\cdot f_\mathrm{c}\cdot Capacity\cdot f_\mathrm{w}\cdot V_\mathrm{ref}}\\&+\frac{(\prod_{j=1}^{M} f_j\cdot\sum_{i=1}^{n\mathrm{PTI}} P_{\mathrm{PTI}(i)}-\sum_{i=1}^{n\mathrm{eff}} f_{\mathrm{eff}(i)}\cdot P_{\mathrm{AEeff}(i)})C_\mathrm{FAE}\cdot SFC_\mathrm{AE}}{f_\mathrm{i}\cdot f_\mathrm{c}\cdot Capacity\cdot f_\mathrm{w}\cdot V_\mathrm{ref}}\\&-\frac{\sum_{i=1}^{n\mathrm{eff}} f_{\mathrm{eff}(i)}\cdot P_{\mathrm{eff}(i)}\cdot C_\mathrm{FME}\cdot SFC_\mathrm{ME}}{f_\mathrm{i}\cdot f_\mathrm{c}\cdot Capacity\cdot f_\mathrm{w}\cdot V_\mathrm{ref}}\end{aligned}\tag{1}$$

According to the guidance, the wing sail-assisted technology belongs to the B-2 category of innovative energy efficiency technologies. The following formula is used to determine the effective propulsion power reduction generated by the wing sail-assisted systems:

$$\begin{aligned}\left(f_{eff}\cdot P_{eff}\right)=&\left(\frac{0.5144\cdot V_\mathrm{ref}}{\eta_\mathrm{T}}\sum_{i=1}^{m}\sum_{j=1}^{n}F\left(V_\mathrm{ref}\right)_{i,j}\cdot W_{i,j}\right)\\&-\left(\sum_{i=1}^{m}\sum_{j=1}^{n}P\left(V_\mathrm{ref}\right)_{i,j}\cdot W_{i,j}\right)\end{aligned}\tag{2}$$

2.2 Calculation method of attained EEDI in MEPC.1/Circ.896

In the recently implemented MEPC.1/Circ.896, the formula and calculation method for a ship's attained EEDI with the installation of the wind-assisted propulsion system is presented in detail. The EEDI calculation formula is almost the same as the formula in MEPC.1/Circ.815. The formula used to calculate the effective propulsion power reduction generated by the sail system is not the same and is expressed as:

$$\begin{aligned}\left(f_\mathrm{eff}\cdot P_\mathrm{eff}\right)=&(\frac{1}{\sum_{k=1}^{q}W_k})\cdot((\frac{0.5144\cdot V_\mathrm{ref}}{\eta_\mathrm{D}}\sum_{k=1}^{q}F\left(V_\mathrm{ref}\right)_k\cdot W_k)\\&-(\sum_{k=1}^{q}P\left(V_\mathrm{ref}\right)_k\cdot W_k))\end{aligned}\tag{3}$$

Where $F(V_\mathrm{ref})_k$ is the force matrix of the wind-assisted systems for a given ship speed. The elements of the matrix satisfy $F_1-F_k\geq 0\Lambda F_k-F_{k-1}\geq 0$, i.e., all elements in the thrust matrix are sorted in descending order. W_k is the global wind probability matrix. Each matrix element represents the probability of wind speed and wind angle relative to the ships heading, and satisfy $\sum_{k=1}^{q-1}W_k<\frac{1}{2}\Lambda\sum_{k=1}^{q}W_k\geq\frac{1}{2}$, which determines the number of elements q in the matrix $F(V_\mathrm{ref})_k$ that actually participate in the calculation. When $\frac{1}{2}$ becomes 1, the results of the calculation are the same as those using the method in MEPC.1/Circ.815. $P(V_\mathrm{ref})_k$ represents the power demand for the operation of the wind-assisted systems. As can be seen, the former term of Equation (3) defines the propulsion power related to the wind-assisted system, containing the product of the ship speed, the thrust matrix of the wind-assisted systems, and the wind probability matrix. The latter term of the formula is the power required to operate the wind propulsion system, which is neglected in this work because of the minimal energy requirements.

2.3 Calculation method of attained EEDI using MMG-based ship motion equations

Since the addition of the wind-assisted systems generates longitudinal force, they also generate lateral force, yaw moment, and heel moment, which causes the change of hull drift angle, heel angle, and rudder angle (Chen et al 2016), thus affecting the net thrust of the wind-assisted system along the longitudinal direction of the ship, together with EEDI contribution. In order to evaluate the net thrust of the sails and their EEDI contribution, the four-degree-of-freedom mathematical model provided by the Maneuvering Model Group (MMG) in Japan for the ship was used. In essence, the methods in MEPC.1/Circ.815 and MEPC.1/Circ.896 consider the ship's sailing speed to be constant. This assumption does not apply to all scenarios. For example, to maintain the reference speed V_ref, the main engine power required will be larger than the Maximum Continuous Rating (MCR), because the presence of wing sails at the bow windward will increase resistance, particularly at high wind speeds. As a result, the sail thrust cannot be estimated theoretically by maintaining the reference speed constant as per MEPC.1/Circ.815 and MEPC.1/Circ.896. In such instances, the steady sailing parameters of the sail-assisted ship can be solved by keeping the engine power output constant. Thus, using MMG-based ship motion equations, both constant sailing speed and constant engine power output modes are included (Chen et al 2023a).

2.3.1 Mathematical model of constant sailing speed mode

Based on the MMG model, the equations for the steady sailing state of a wing sail-assisted ship are expressed as:

$$\begin{aligned}\sum X &= X_{\mathrm{H}}(u,v)+X_{\mathrm{P}}(u,v,n)+X_{\mathrm{R}}(u,v,\delta)+X_{\mathrm{a}}(u,v)\\&+X_{\mathrm{w}}(u,v)=0\end{aligned} \tag{4}$$

$$\begin{aligned}\sum Y &= Y_{\mathrm{H}}(u,v)+Y_{\mathrm{R}}(u,v,\delta)+Y_{\mathrm{a}}(u,v)\\&+Y_{\mathrm{w}}(u,v)=0\end{aligned} \tag{5}$$

$$\begin{aligned}\sum K &= K_{\mathrm{H}}(u,v)+K_{\mathrm{R}}(u,v,\delta)+K_{\mathrm{a}}(u,v)+K_{\mathrm{w}}(u,v)\\&+m\cdot g\cdot h\cdot\sin\phi=0\end{aligned} \tag{6}$$

$$\begin{aligned}\sum N &= N_{\mathrm{H}}(u,v)+N_{\mathrm{R}}(u,v,\delta)+N_{\mathrm{a}}(u,v)\\&+N_{\mathrm{w}}(u,v)=0\end{aligned} \tag{7}$$

From the set of Equations (4) to (7), it can be seen that the model contains five unknowns, which are *u, v, n, δ, Φ*. In order to solve nonlinear equations, one equation is still needed. According to the guidance, the reference speed V_{ref} for calculating the thrust matrix of the wind-assisted system is the same as that of a ship without wind-assisted systems. Constant sailing speed is expressed as:

$$V^2 = u^2 + v^2 \tag{8}$$

2.3.2 Mathematical model of constant engine power output mode

The MMG-based ship motion equations for constant engine power output mode is the same as the constant sailing speed mode. In order to solve nonlinear Equations (4) to (7), constant engine power is expressed as:

$$\begin{aligned}P_{\mathrm{ME}} &= \mathrm{MCR} = P_{\mathrm{db}}/\eta_{\mathrm{s}} = 2\cdot\pi\cdot n\cdot Q/\eta_{\mathrm{s}}\\&= 2\cdot\pi\cdot K_{\mathrm{Q}}(J)\cdot\rho\cdot n^3\cdot D^5/\eta_{\mathrm{D}}/\eta_{\mathrm{s}}\end{aligned} \tag{9}$$

2.3.3 Calculation of net thrust for wing sails

The delivered power *P* of the propeller related to true wind speed and wind direction is expressed as:

$$P_{\mathrm{T}} = T\cdot V\cdot(1-w_{\mathrm{p0}}) \tag{10}$$

$$P_{\mathrm{db}} = P_{\mathrm{T}}/\eta_0(J)/\eta_{\mathrm{R}} \tag{11}$$

Based on the calculation results of propeller thrust for ships with and without sails, the net thrust of wing sails can be expressed as:

$$T_{sails} = T_{withoutsails} - T_{withsails} \tag{12}$$

2.3.4 Calculation of the net attained EEDI for wing sails

In terms of the physical definition of EEDI, the total attained EEDI of a wing sail-assisted ship is calculated using the following formula, taking the main engine, auxiliary engine, and sails into account separately:

$$\begin{aligned}A_{\mathrm{EEDI}} &= A_{\mathrm{EEDI\text{-}ME}} + A_{\mathrm{EEDI\text{-}AE}} + A_{\mathrm{EEDI\text{-}sail}}\\&= \sum\frac{P_{\mathrm{ME}}(k)\cdot SFC_{\mathrm{ME}}(k)\cdot C_{\mathrm{F\text{-}ME}}\cdot W_k}{C_{\mathrm{Capacity}}\cdot V(k)} + \sum\frac{P_{\mathrm{AE}}\cdot SFC_{\mathrm{AE}}\cdot C_{\mathrm{F\text{-}AE}}\cdot W_k}{C_{\mathrm{Capacity}}\cdot V(k)}\\&+\sum\frac{P_{\mathrm{sail}}(k)\cdot SFC_{\mathrm{ME}}(k)\cdot C_{\mathrm{F\text{-}ME}}\cdot W_k}{C_{\mathrm{Capacity}}\cdot V(k)}\end{aligned} \tag{13}$$

Where the subscripts "ME", "AE", and "sail" represent the main engine, auxiliary engine, and sails respectively. $P_{\mathrm{ME}}(k)$, $V(k)$ represents the ship's engine power and sailing speed which can be obtained according to the MMG-based model by using the constant sailing speed mode or constant engine power output mode. $P_{\mathrm{sail}}(k)$ represents the available power of the sails, which is ignored as before. SFC_{ME} is expressed as：

$$SFC_{\mathrm{ME}} = A\cdot P_{\mathrm{ME}}{}^3 + B\cdot P_{\mathrm{ME}}{}^2 + C\cdot P_{\mathrm{ME}} + D \tag{14}$$

Where coefficients *A*, *B*, *C* and *D* are obtained by fitting from the fuel consumption curve of the main engine.

With reference to the rudder angle thresholds $\delta_{\max}$, heel angle thresholds $\Phi_{\max}$, and the main engine power thresholds for steady straight sailing of a wing sail-assisted ship, the conditions for carrying out the solution of steady straight sailing with constant speed and power output mode are as follows (Chen et al 2023b):

a. Calculate the required power output of the main engine $P_{\mathrm{ME}}(k)$ when $|\delta|<\delta_{\max}$, $|\Phi|<\Phi_{\max}$, $0.25\mathrm{MCR} \leqslant P_{\mathrm{ME}}(k) \leqslant \mathrm{MCR}$ and maintain the reference speed V_{ref}.

b. Calculate the attained sailing speed $V(k)$ when $|\delta|<\delta_{\max}$, $|\Phi|<\Phi_{\max}$, $P_{\mathrm{ME}}(k) < 0.25\mathrm{MCR}$ or $P_{\mathrm{ME}}(k) > \mathrm{MCR}$, and the engine power $P_{\mathrm{ME}}(k)$ is fixed as MCR.

c. When $|\delta| > \delta_{\max}$ or $|\Phi| > \Phi_{\max}$, retract the sails and update the corresponding aerodynamic database of the ship.

3 RESEARCH OBJECT

The research object in this work is an oil tanker equipped with two pairs of wing sails arranged symmetrically on port and starboard. The main parameters of the VLCC and wing sails are listed in Table 1.

Table 1. Principal particulars of the sail-assisted VLCC

Contents	Parameters	Value
VLCC	Length between perpendiculars	326.60 m
	Breadth	60.00 m
	Scantling draft	21.80 m
	Capacity	30700.00DWT
	Maximum continuous rating of main engine	22500.00 kW
	Power of auxiliary engine	650.00 kW
Wing sails	Maximum number of sails	4
	Span length	35.60 m
	Chord length	14.60 m

4 ACQUISITION OF FLUID DYNAMIC COEFFICIENTS

The tank model test and the wind tunnel model test were used to determine the output power of the propeller at various speeds and the wind force coefficients, which include longitudinal force, lateral force, heeling moment, and yaw moment for the ship at different relative wind angles with and without sails. Figures 5 to 8 show typical photos of the model experiment. If the main engine delivered efficiency and the total efficiency η_{D} are 0.99 and 0.803 respectively, and the main engine power is 75% MCR, the sailing speed is 15.21 kn. In wind tunnel tests, the ship was tested with all four sails installed, only the front two sails, only the rear two sails, and no sails. The two front sails and the two rear sails are identical in shape and only the transverse distance between the sails is different, with the distance of the two rear sails being greater than that of the two front sails. The optimal sail angle of attack is the same for the different arrangements.

In the MMG-based model, the hydrodynamic coefficients of hull/propeller/rudder and their mutual interference factors are obtained based on the empirical formula (Chen 2011). The wave height and mean wave period corresponding to each Beaufort wind condition are generated based on the wind speed range in MEPC.1/Circ.896, and the AQWA software then calculates the wave drift forces. When the MMG-based mathematical model is solved, a database is created and accessible.

Figure 5 Tank model test

Figure 6 Wind tunnel model test for ship with four sails

Figure 7 Wind tunnel model test for ship with two front sails

Figure 8 Wind tunnel model test for ship with two rear sails

5 CALCULATION RESULTS OF ATTAINED EEDI

5.1 Effect of wing sail arrangement

The average thrust of sails and attained EEDI calculation results for different sail arrangements were first calculated using the method in MEPC.1/Circ.815 based on the wind probability statistics of main global shipping routes, as shown in Table 2. When using the formula in the guidance, each correction coefficient was assumed to be 1 and C_F to be 3.114 (MEPC 2012).

Table 2. Results for sails with different arrangements

Cases	Average thrust of sails (kN)	EEDI ($g\ CO_2/ton \cdot nmile$)
With two front sails	29.9	1.8098
With two rear sails	29.3	1.8104
With four sails	50.9	1.7886
Value at baseline		2.5598

As shown in Table 2,

- The average thrust generated by the two rear sails is somewhat less than the average thrust generated by the two front sails, and the attained EEDI is slightly higher.
- Comparing the results of the four sails with the two front sails only and the two rear sails only, it can be seen that the average thrust provided by the sails in the presence of four sails is less than the linear summation state of the two front sails only and the two rear sails only, which is caused by the unfavorable sail-sail interaction.
- Compared to the value at the baseline, the attained EEDI for the VLCC with four sails together decreased by about 30.1% when using the EEDI calculation method in MEPC.1/Circ.815.

5.2 Effect of ship speed

The attained EEDI for the VLCC with and without four sails equipped at different sailing speeds were then calculated using the EEDI calculation method in MEPC.1/Circ.815. The results are shown in Table 3.

Table 3. Results for sail-assisted ship with different speeds

Speed (kn)	Average thrust of sails (kN)		ΔEEDI ($g\ CO_2/ton \cdot nmile$)
	VLCC	VLCC+4sails	(VLCC+4sails)-(VLCC)
15.21	—	50.9	0.0514
15.00	—	51.2	0.0517
14.00	—	52.8	0.0541
12.00	—	56.5	0.0599
10.00	—	60.7	0.0662

As shown in Table 3,

- As speed decreases, the EEDI contribution of the sails obtained from the main global shipping routes increases slightly. This is consistent with the apparent wind angle changing with speed, i.e., the apparent wind angle, which is calculated based on the wind probability of the main global shipping routes, tends to increase as the ship's sailing speed decreases, resulting in an increase in the thrust coefficient of the sails.
- The variation of speed is particularly significant for the change in attained EEDI of VLCC with or without sails, and a speed reduction can significantly reduce the attained EEDI of the ship.
- The ship's speed has a greater impact on the ship's attained EEDI than the total area of sails installed.

5.3 Effect of wind probabilities along the main global shipping routes.

According to the methods described in MEPC.1/Circ.815 and MEPC.1/Circ.896, which use 100% and 50% wind statistics over the main global shipping routes, respectively, the attained EEDI for the VLCC with and without four sails was determined. The results are shown in Table 4.

Table 4. Comparison of EEDI calculation results with different wind probabilities

Contents	EEDI (g CO_2/ton · nmile)
Value at baseline	2.5598
VLCC	1.8400
VLCC+4sails (MEPC.1/Circ.815, 100%)	1.7886
VLCC+4sails (MEPC.1/Circ.896, 50%)	1.7373

Figure 9 compares the obtained EEDI for the ship with and without four sails using the method specified in the newly implemented MEPC.1/Circ.896. The curves with different line shapes in the figure represent the reference lines at different phases.

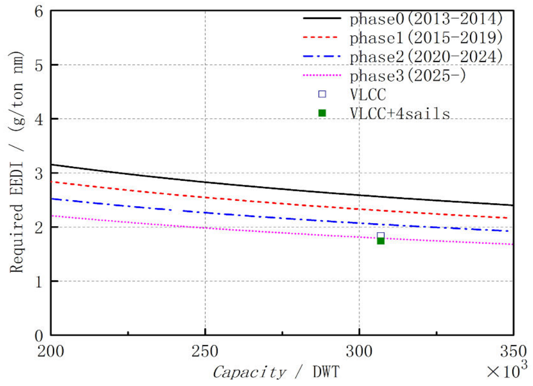

Figure 9 EEDI calculation results for ship with and without four sails using method in MEPC.1/Circ.896

As shown in Table 4 and Figure 9,

- Compared with the results obtained according to MEPC.1/Circ.815, the attained EEDI calculated using the method in MEPC.1/Circ.896 is further reduced, which improves the contribution of the sails.
- The attained EEDI for the ship with four sails decreased by approximately 5.6%, which is a reduction of approximately 32.1% compared to the baseline value, meeting the EEDI phase 3 requirements.

5.4 Effect of the side force induced by the sails

Figure 10 shows the calculation results of the thrust of the sails obtained with the MMG-based mathematical model and the MEPC.1/Circ.896 at absolute wind speeds of 7.5 m/s and 17.5 m/s (Chen et al 2023a).

Here, the net thrust of the sails obtained by the MMG mathematical model is based on the aerodynamic wind tunnel model results of the VLCC with and without sails, and the difference in propeller thrust is calculated by numerically solving the four-degree-of-freedom straight sailing equations of motion, taking into account the changes in hull drift angle and rudder angle after the installation of sails. The thrust obtained by the MEPC.1/Circ.896 is based on wind tunnel test results, which are calculated based on the difference of longitudinal force coefficients of the hull with and without sails. The comparison between the two cases is based on the same aerodynamic model test results of VLCC with and without sails. The difference reflects the variation effects of the ship's drift angle, rudder angle, and SFC_{ME}. Since the port and starboard are symmetrical, only the absolute wind angle range of 0~180° is analyzed.

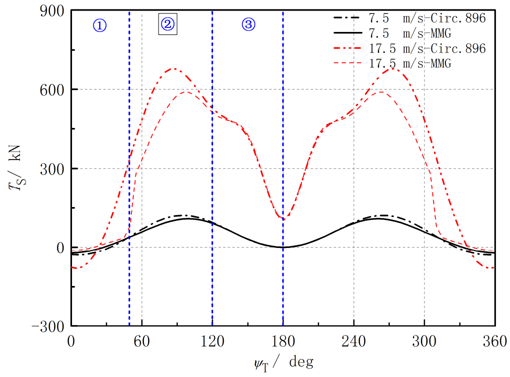

Figure 10 Comparison of thrust of sails between MMG-based method and MEPC.1/Circ.896

As shown in Figure 10, three regions are identified by the absolute wind angle in the horizontal coordinate. In region ①, the thrust contribution of the sails is negative or the effective thrust value is very small, and this part is set to zero after sorting and adopting [1/2] probability element in the subsequent EEDI calculation (MEPC 2021). Therefore, it's not analyzed. In region ②, in which the sails make a thrust contribution, the thrust contribution of the sails obtained by the mathematical model is slightly reduced due to the influence of the hull drift angle and rudder angle. This can be verified by comparing the rudder angle of the VLCC with and without sails in Figure 11, where the maximum increase in rudder angle with the sails is about 3.8°, i.e., at this wind speed, the rudder angle of the ship with the sails increases due to the effect of the sails, resulting in an increase in the resistance, which offsets the thrust contribution of the sails to some extent, therefore the net thrust obtained by the mathematical model is somewhat lower than the results obtained by MEPC.1/Circ.896. In region ③, the thrust obtained by the two different methods is equivalent, which is also confirmed by the almost same rudder angle in Figure 11.

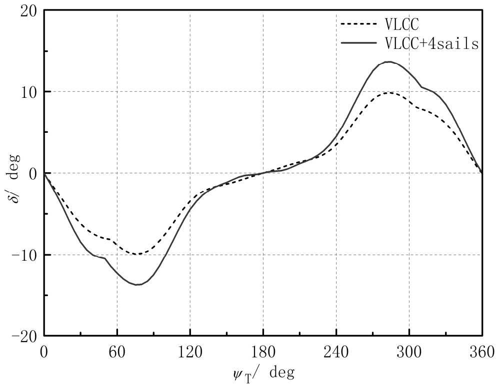

Figure 11 Curves of rudder angle (absolute wind speed is 17.5m/s, Combination of constant sailing speed and constant engine power)

In summary, it can be seen from the comparison that the thrust contribution of the wing sails obtained by the mathematical model is different compared to the method provided in MEPC.1/Circ.896, especially in the case that the wind comes from the lateral direction. The net thrust contribution of the sails for each wind speed range needs to be considered when calculating the subsequent EEDI contribution of the sails. Table 5 compares the results of the wing sail EEDI contribution calculations based on the MEPC.1/Circ.896 document with the MMG-based model method.

Table 5. Comparison of EEDI contribution with different methods

Method	EEDI / (g CO_2/ton · nmile)		ΔEEDI (g CO_2/ton · nmile)
	VLCC	VLCC+4sails	
MEPC.1/Circ.896	1.8400	1.7373	0.1027
MMG-based model	1.8100	1.7153	0.0947

As can be seen in Table 5, the EEDI contribution for the wing sails calculated using the MMG model is slightly lower than the value obtained using the method in MEPC.1/Circ.896 when considering the effect of the side force induced by the sails.

6 CONCLUSIONS

Based on the speed-performance results predicted by tank tests and the thrust coefficient results of the sails under different arrangements obtained from wind tunnel model tests, the effects of several influencing factors on the EEDI contribution of the sails were evaluated, according to the EEDI calculation method for wind-assisted ships in MEPC.1/Circ.815 and MEPC.1/Circ.896 using the example of a 300,000 DWT VLCC. The influence of the sail-induced lateral force on the net EEDI contribution was also investigated by the MMG-based model, taking into account the drift and rudder angle variation of the ship. The results of the investigation are summarized below:

- The probability of wind along the main global shipping routes is a sensitive factor and using the method in MEPC.1/Circ.896, the EEDI contribution of four sails for the VLCC can reach almost 6.0%.
- The EEDI contribution of the sails tends to increase as the ship speed decreases. The total area of the sails has a greater influence on the EEDI contribution than the sail arrangement.
- The results show that the variation of the ship speed has a significant impact on the attained EEDI of the ship.
- The results show that the method provided in MEPC.1/Circ.896 overestimates the EEDI contribution of wing sails compared to MMG-based model results. That is, there are some differences between the net EEDI calculation results considering the effects of changes in hull drift angle and rudder angle caused by the lateral force of the sails and the EEDI results by directly adopting MEPC.1/Circ.896, but the differences in the cases calculated in this work are not significant. Further comparative analysis is required to assess the ships with substantial wind propulsion power.

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