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Research of Sail Height Adjustment on Sail-Assisted Ship in Different Loading and Wind Conditions

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Abstract: The relationship between ship stability and sail area is firstly investigated based on the sail-assisted ship's stability in this paper. Then a height-adjustable sail structure is proposed that could be automatically adjusted according to the wind conditions, ship loading and other requirements. The influences on the sail height in different ship load conditions, different wind apparent velocity and wind direction are analyzed of a sail-assisted bulk carrier. Finally a control procedure of sail height adjustment in real time is proposed according to the actual load conditions, wind conditions, ship velocity and other parameters to make the best use of wind energy, which is significant for the practical application of sail-assisting technology in the future.

Key words: Sail height, height adjustable, wind influential factor, control procedure.

Nomenclature

A	Lateral windage area of hull, m^2
C_H	Lateral force coefficient
C_{HB}	Transverse wind pressure coefficient of the hull (approximate 1.25)
C_D, C_L	Drag and lift force coefficient of the sail
C_T, C_H	Thrust and drift force coefficient of the sail
F_D, F_L	Drag and lift force of the sail, N
T, H	Thrust and drift force of the sail acting on the ship, N
Cz	Aspect ratio of sail
C, C', Cs	Area coefficient of the sail
d	Draft, m
H_S	Sail height, m
H_M	Height of the lower edge of the sail above the base line, m
K	Criterion coefficients of weather
l_q^*	Minimum overturning lever of ship, m
M_{fs}	Moment of wind acting on the sail, Nm
M_{fb}	Moment of wind acting on the hull, Nm
M_q^*	Minimum overturning moment, Nm
M_f	Wind heeling moment, Nm
n	Number of sails
S	Total sail area, m^2
W_S	Sail chord, m
$Z_1=Z_A-d$	Lever of wind pressure, where Z_A is the height between wind centre on the ship & the baseline, m
$Z_2=Zs-d$	Lever of heeling, where Z_S is the height between the centre of sail area and the baseline, m
Z_g	Height of center of gravity above the keel in a loading condition of the ship, m
α	Sail attack angle between relative wind direction and arc sail,°
a_{TM}	Sail optimal angle of attack,°
φ	Ship heading angle relative to apparent wind,°
θ	Sail rotating angle between ship navigation direction and arc sail,°
ρ	Density of air, kg/m^3
γ	Leeway angle,°
v_b	Apparent wind speed, m/s
v_z	Absolute wind speed (True wind speed), m/s
v_c	Ship navigating speed, m/s
Δ'	Ship displacement weight, N

1. Introduction

Research work on ship sail-assisting technology was carried out since 1970's and in recent years domestic and international research projects on sailing-assisted ship have increased. Sparenberg and Wiersma [1] discussed the maximum thrust of sails when sailing close to wind and the influence of the gap between sails and hull and the influence of a reduction of the heeling force and the heeling moment

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on the maximum thrust. Duckworth [2] discussed the application of elevated sails (kites) for fuel saving auxiliary propulsion of commercial vessels. Fujiwara et al. [3, 4] investigated the aerodynamic characteristics of single isolated hybrid-sails of different size and aspect ratio in 2003, and investigated sail-sail and sail-hull interaction effects of a hybrid-sail assisted bulk carrier in 2005. Masuyama et al. [5] investigated the database of sail shapes versus sail performance and validation of numerical calculations for the upwind condition. Gerhardt et al. [6] investigated the unsteady aerodynamic phenomena associated with sailing upwind in waves on a simplified 2D geometry. Viola and Flay [7] discussed the pressure distributions on upwind sails and related to the flow field around the headsail and the mast/mainsail. Augier et al. [8] presented a full scale experimental study on the aero-elastic wind/sails/rig interaction in real navigation conditions with the aim to give an experimental validation of unsteady FSI (fluid structure interaction) models applied to yacht sails. Viola et al. [9] presented the aerodynamics of a sailing yacht with different sail trims and simulated using computational fluid dynamics. The drive force distribution on both sails showed that the fore part of the genoa (fore sail) provides the majority of the drive force and that the effect of the aft sail is mostly to produce an upwash effect on the genoa. Li et al. [10] proposed a type of hard sail and investigated the performance of cascade sails and considered the aerodynamic interaction between the sails on commercial vessels for utilizing wind energy. Viola et al. [11] presented a numerical investigation on the potential of wind-assisted propulsion for merchant ships. Leloup et al. [12] developed a performance prediction program dedicated to merchant ships to assess fuel saving abilities of a kite and found that the fuel saving predicted is about 10% for a wind velocity of 9.77 ms^{-1} and reaches more than 50% for a wind velocity of 15.68 ms^{-1} on a 50,000 dwt tanker using a 320 m^2 kite.

By now these studies mostly concentrate on fixed sail structure, performance analysis of sails. However, for the ocean-going ship there are few studies particular to the adjustable height sails. In ship navigation conditions of different wind and loading it is necessary to adjust sail area automatically in order to ensure the ship sufficient stability and meanwhile obtain the maximum thrust force. This paper takes a bulk carrier as example. Firstly the relationship between sail working area and ship stability is discussed and a height-adjustable sail is proposed. Then the influences on the sail height in different ship load conditions, different wind apparent velocity and wind direction are analyzed. Lastly control flow diagram of sail height adjustment is proposed. This height could be automatically adjusted according to the wind conditions, ship loading and other parameters to make the best use of wind energy, which is significant for the practical application of sail-assisting technology in the future.

2. Height-Adjustable Sail Structure

2.1 Determination of Sail Working Area

Sail working area and the number of sails are comprehensively determined according to the principal particulars of ship, the arrangement on deck for sails and the ship stability and maneuverability requirements. If the sail area is small, a single sail could get better aerodynamic performance. If the sail area is large, multi-sails could be fitted to meet stability requirements. It is difficult to exactly determine the sail area without specific specification at present. But several formulas could be used. One of the methods is to assume some certain percentage of energy and estimate the sail area and then the ship stability will be checked to meet the requirements. But this method could not make full use of wind energy. There are also some empirical formula such as S = $C'\Delta^{2/3}$ (in Japan), S = $C \cdot L \cdot B$ (in Germany) and S = $Cs\Delta^{2/3}$ (in China). These formulas could not exactly reflect the relation between sail area and the ship stability.

Actually the sail area could be concluded as following based on the stability of the sail-assisted ship.

According to stability criteria $K = M_q^*/M_f \geq 1$ when rolling angle and flooding angle are constant, the minimum overturning lever lq^* is confirmed. Based on $K = M_q^*/M_f \geq 1$ the following relations could be obtained:

$$M_f = \frac{1}{k} M_q^* \tag{1}$$

$$M_q^* = l_q^* \Delta' \tag{2}$$

$$M_{fb} = C_{Hb} \sin^2\varphi \frac{1}{2} \rho {v_b}^2 A Z_1 \tag{3}$$

$$M_{fs} = \frac{1}{2} C_H \rho {v_b}^2 S Z_2 \tag{4}$$

Unless the influence from the center of gravity and the weight of sails and affiliates are considered, sail area S and heeling lever Z_2 are concluded on the basis of Eqs. (1)-(4).

$$M_{fs} = M_f - M_{fb} = 0.5 C_H \rho {v_b}^2 S Z_2 \tag{5}$$

The relation between sail area S and heeling lever Z_2 is provided as :

$$SZ_2 = \frac{\frac{1}{K} M_q^* - \frac{1}{2} C_{HB} \sin^2\varphi \rho {v_b}^2 A Z_1}{\frac{1}{2} C_H \rho {v_b}^2} \tag{6}$$

In Eq. (6) the value of $K \geq 1$. When the value of K is determined the right part is also determined which could be defined as Y_X. The symbol of lever Z_2, Eq. (6) is described as:

$$S(\frac{1}{2} H_S + H_M - \mathrm{d}) = Y_X \tag{7}$$

where:

$$S = \mathrm{n} H_S W_S = \mathrm{n} \mathrm{H}_S^2 / C_Z \tag{8}$$

H_S/W_S is defined as C_Z, which is normally between 1.2~1.6 where H_S and W_S is the height and chord of the sail, n is the number of sails.

In Eqs. (7) and (8) assuming the unchanged sail chord the following equation could be expressed as:

$$\frac{S^2}{2\mathrm{n}W_S} + (H_M - d)S - Y_X = 0 \tag{9}$$

Assuming the unchanged aspect ratio the following equation could be expressed as:

$$\frac{C_Z S^3}{\mathrm{n}} - 4(H_M - d)S^2 + 8Y_X (H_M - d)S - 4{Y_X}^2 = 0 \tag{10}$$

Here it could be seen that there is a certain relation between sail area and ship draft. Therefore the corresponding sail area could be obtained depending on the ship draft produced by ship loading capacity. By adjusting sail area with the greatest thrust force of sail under necessary ship stability the maximum sail area could be determined with different ship drafts.

2.2 Sail Structure

In order to meet the requirements of adjusting the sail area according to the ship's stability a wind-sail structure was designed to control sail area with fixed sail chord and adjustable height. As shown in Fig. 1 sail transverse frames move up or down sail for adjusting the sail height to meet operational requirements. Four circular grooves could be located at the outer mast section through the top to the bottom. These grooves make transverse frames slide up or down freely along the mast groove by use of inhaul cable. Transverse frames are embedded in track of vertical main mast. They can slide up and down driven by two inhaul cables distributed in the main mast. In addition four electromagnetic switches are installed in the fixed position of the main mast while two pieces of opposing electromagnets are fixed on the each transverse frame which contact with the main Mast (see Fig. 2). When the sail transverse frame arrives at the corresponding position, transverse frame will fix on the corresponding position under the action of

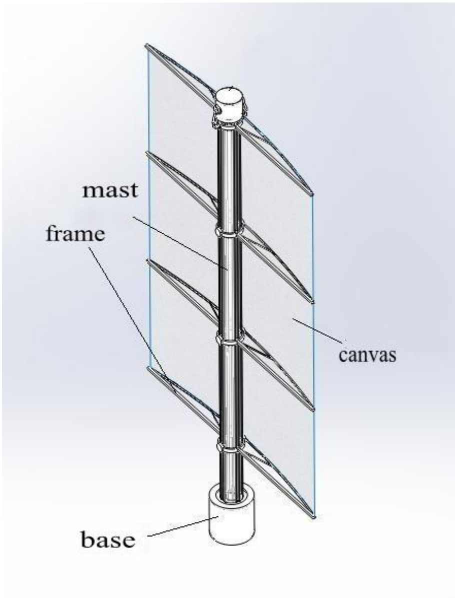

Fig. 1 Sail structure of adjustable height.

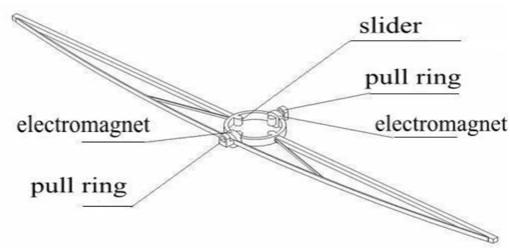

Fig. 2 Sail transverse frames structure.

electromagnetic force from the electromagnetic switch. The whole sail area will be changed by adjusting the height of sail.

2.3 Sail Installation

A 48000DWT ocean-going bulk carrier is selected and researched as a sail-assisted ship in this paper, whose main parameters are shown in Table 1.

The ship navigates regularly on Singapore—Shanghai—Busan route. The wind velocity and wind direction remain stable and available and wind velocity is about 5-20 m/s according to the preliminary analysis of the wind resource on this route.

According to the structure characteristics of the ship two rows of sail with four sails on the port and starboard side respectively will be installed symmetrically on the upper deck of target ship. The distance between the center of sail base and the center line of the hull is about 13.13 m and the chord of sail should not be more than 26.26 m. In order to increase the effective area of the sail the chord of sail could be designed as 20 m. The lower end of the sail from baseline height is about 34.93 m according to the sight requirement of the bridge.

2.4 Force Analysis of Sail Model

When a sail-assisted ship is navigating at a certain speed *Vc* in direction X, the wind-force diagram is shown in Fig. 3.

The aerodynamic forces acting on the sail model can be decomposed as forces and momentum in the wind-axis coordinate system as shown in Fig. 3. Here, the axis L means the wind lift force, while axis D means the wind resistant force. The aerodynamic wind forces acting on the sail could be decomposed as the drag force F_D and lift force F_L. The direction of F_D is the same as the airflow; the direction of F_L is perpendicular

Table 1 Principal ship particulars of 48000DWT bulk carrier.

Dimension	Symbol	Unit	Data
LENTH O.A.	LOA	m	189.90
LENTH B.P.	LBP	m	183.00
BREADTH (MLD.)	B	m	32.26
DEPTH (MLD.)	D	m	15.70
DISPLACEMENT	Δ	m3	52,848.00
TRIAL VELOCITY	V	kn	14.20

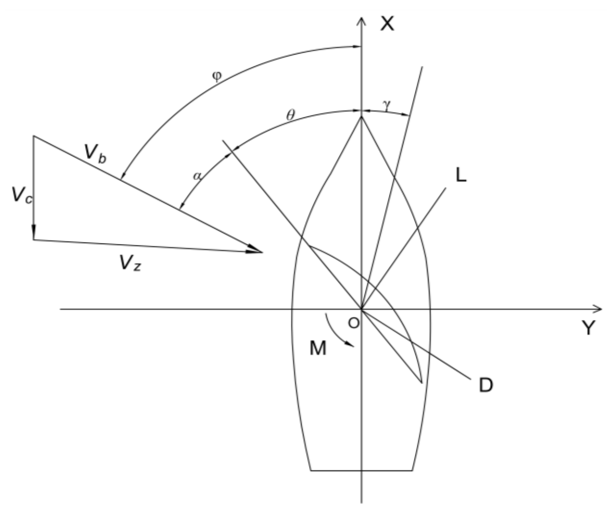

Fig. 3 The forces acting on the sail.

to the airflow. M is the sail rotating moment generated by the wind on the sail mast and the reference point of the moment is the coordinate origin O.

Therefore, the thrust force acting on the ship is

$$T = F_L \sin\varphi - F_D \cos\varphi \tag{11}$$

The drift force acting on the ship is

$$H = F_L \cos\varphi + F_D \sin\varphi \tag{12}$$

The thrust force and drift force could be expressed in form of dimensionless index as

$$C_T = C_L \sin\varphi - C_D \cos\varphi \tag{13}$$

$$C_H = C_L \cos\varphi + C_D \sin\varphi \tag{14}$$

where:

$$C_T = \frac{T}{\frac{1}{2}\rho_0 V_b^2 S};\quad C_H = \frac{H}{\frac{1}{2}\rho_0 V_b^2 S};$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho_0 V_b^2 S};\quad C_D = \frac{F_D}{\frac{1}{2}\rho_0 V_b^2 S}$$

Here, C_L, C_D could be measured by the wind tunnel test.

3. Influential Factors of Sail Height

The stability of sail-assisted ship has direct relationship with sail area (sail height) which is mainly reflected by the height restrictions of sails in different loading conditions as well as sea conditions such as wind direction and wind velocity etc. The confirmation for the final height of sail should also involve other situations such as construction costs and ship manoeuvrability etc. This paper assumes that the chord of sails remains the same.

3.1 Influence of Sail Height in Different Loading Conditions

In order to study the influence of different ship loading conditions for sail height, four kinds of typical ship loading conditions are assumed with the apparent wind velocity of 15 m/s, the limited height of sails and the thrust force acting on the ship by sails are calculated under the minimum requirement of stability.

When the structure of sail and sail area are determined, the sails should rotate at an optimal attack angle of a_{TM} in the actual sail operation process in order to obtain the maximum thrust for the ship. According to the wind tunnel test for sail model each of the apparent wind angle φ has a corresponding optimal attack angle of a_{TM} and a maximum thrust coefficient C_{TM} which is shown in Fig. 4. When the apparent wind angle is in the range of 60° to 180°, the thrust coefficient of the sail C_{TM} is larger. For $90° \le \varphi \le 150°$ the scope of a_{TM} maintains near 25° to 30° and for $150° \le \varphi \le 180°$ the scope of a_{TM} is 30° to 90°.

Under different ship loading and wind angle conditions the limited heights of sails are calculated according to corresponding a_{TM} and related parameters from loading manual of the target ship. The maximum thrust force could be calculated and the corresponding limited heights of sails will be obtained as shown in Fig. 5.

As shown in Fig. 5 in the same wind direction and attack angle the limited height of sails could be sorted in ascending order as ballast departure, full loaded departure, ballast arrival, full loaded arrival. The ascending order for the minimum heeling moments about four kinds of typical loading conditions is the same resulted from calculation. The calculated results indicate that the larger the minimum overturning moment of ship is, the higher the limited height of sail is. In any loading conditions the changing trend of the limited height of sails is consistent. From the curve the limited height of sails do not smoothly change with increasing apparent wind angle, which is due to the different variation trend of the maximum thrust force and drift force with increasing apparent wind angle. These curves for diffident limited height of sails could be plotted according to different loading conditions as the main reference data of sail height adjustment during ship navigation.

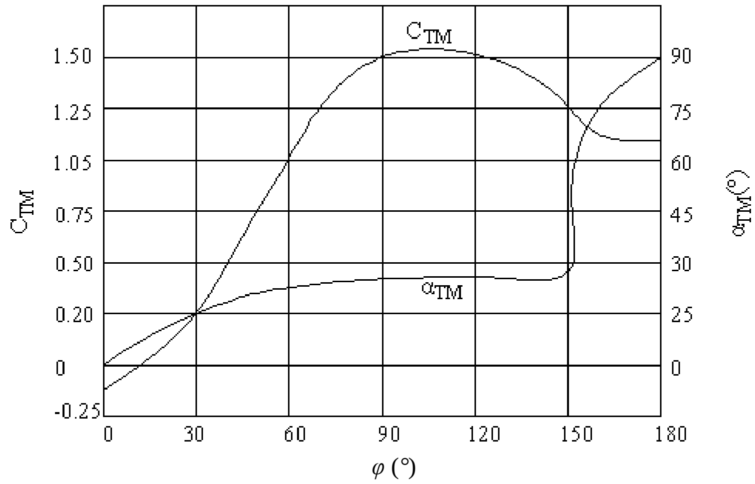

Fig. 4 Optimal sail attack angle and maximum thrust coefficient in different apparent wind angle φ.

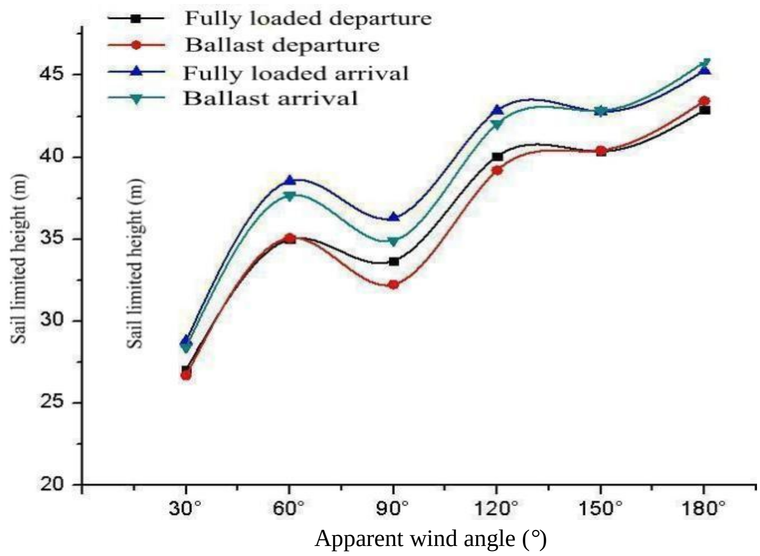

Fig. 5 Sail limited height corresponding to optimal attack angle in different loading conditions.

3.2 Influence of Sail Height in Different Wind Velocity

The wind conditions often change at sea. The apparent wind velocity will also change even if the ship velocity remains constant. The friction between the sea surface and the wind above produces a boundary layer where the true wind velocity increases with height. The mean velocity $\bar{V}$ profile for height less than about 100 m from the ground is given by the following log-law equation:

$$\bar{V} = \frac{U_*}{k}\ln(\frac{Z}{Z_0}) \quad (15)$$

where, the roughness length Z_0 is typically 0.2 mm for flows over the sea in racing conditions, a characteristic roughness of the sea surface. k is the von Karman constant which is normally taken as 0.4. And U_* is the friction velocity. According to the vector sum of this shear profile with the ship velocity the apparent wind velocity and direction both vary with height. Flay [13] investigated the apparent wind velocity and indicated the apparent velocity does not change greatly with height. So this case is not considered in the paper. Supposed the apparent wind velocity is 10 m/s, 15 m/s, 20 m/s, and 25 m/s respectively in condition of full loaded departure, the corresponding limited height of sails are calculated as shown in Fig. 6 when the thrust force of sail remains at maximum.

Some results could be concluded from Fig. 6 as following:

(1) Under the same ship loading and apparent wind angle condition the bigger the apparent wind velocity is, the lower the limited height of sails is—which could satisfy the lowest requirement of ship stability.

(2) In conditions of different apparent wind velocity the changing trend of the limited height of sails is consistent. The greater the wind velocity is, the narrower the adjustable range of sail height is. The range of adjustable height of sails is wide at low wind velocity.

(3) Maximum limited height of sails locate from 120° to 180°, namely in this range of angle the sail could be fully opened to achieve maximum thrust force for the ship and obtain the best effect for sail-assisted ship.

3.3 Influence of Sail Height in Different Apparent Wind Direction

In case of full loaded departure with apparent wind velocity of 15 m/s limited height of sails in different apparent wind angles will be calculated as shown in Fig. 7.

From Fig. 7 some results could be concluded as following:

(1) The limited height of sails is relatively large when lateral force coefficient C_H is minimal;

(2) The sails cannot make effective thrust when the apparent wind angle is less than 30°;

(3) The sails could obtain relatively large thrust force when the angle of attack is around 90° within the apparent wind angle from 30° to 90°. The sails could also obtain larger thrust force when the angle of attack is around 30° within the apparent wind angle from 90° to 150°;

(4) Except for a few of maximum points the sail thrust force reaches its maximum value when the apparent wind angle is 90°and the angle of attack is 90°. But considering the actual construction problems of sail device this maximum height is not practical.

4. Adjustment of Sail Height

The relationship between sail area and ship stability is discussed in terms of different ship loading conditions, different apparent wind angles and different apparent wind velocities in order to take full advantage of offshore wind energy. On the basis of fixed sail chord and ship stability requirements sail height could be adjusted under the condition of different

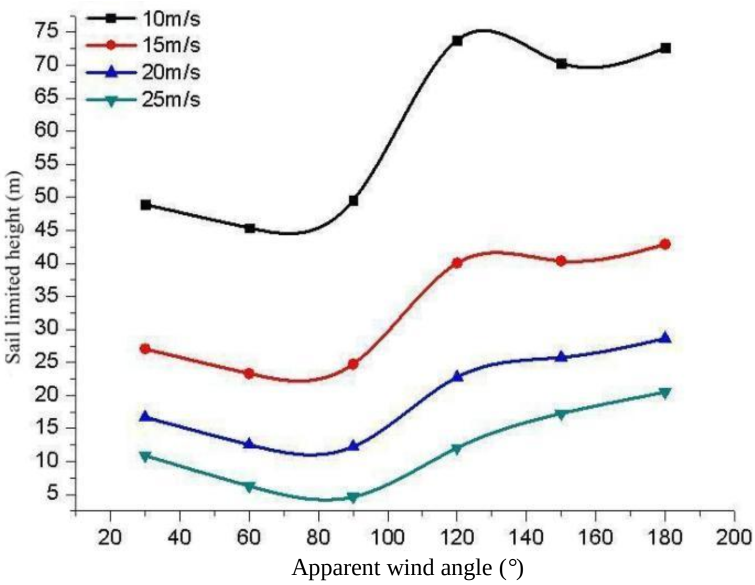

Fig. 6 Limited height of sails corresponding to different apparent wind velocities.

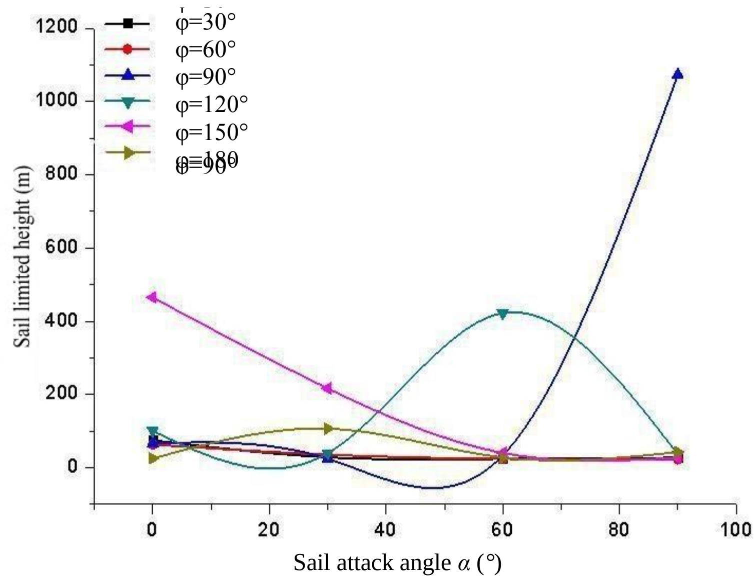

Fig. 7 Limited height of sails corresponding to different apparent wind angles.

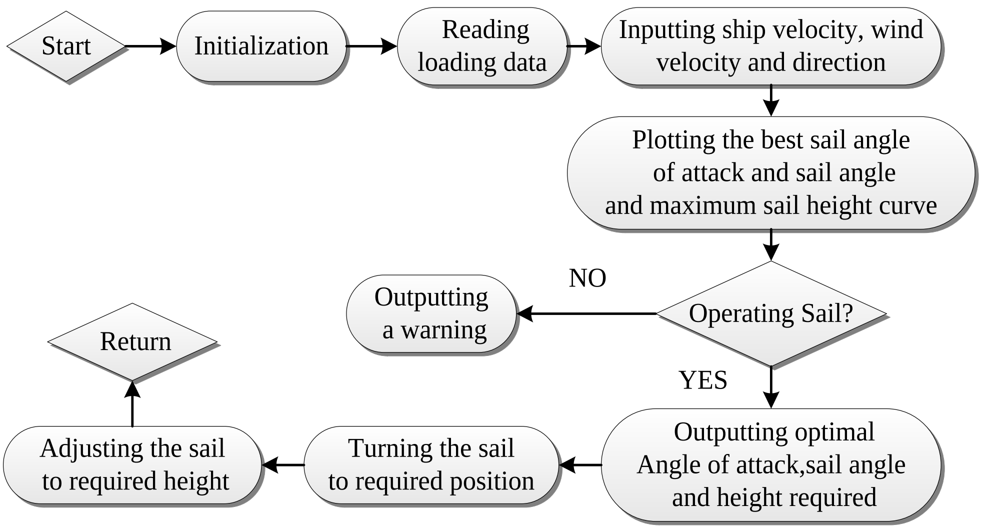

Fig. 8 Control flow chart of sail height adjustment.

wind and ship loading while the driving-force effect of the sail also reaches its maximum.

The sail height could be automatically adjusted by computer according to wind conditions and ship loading conditions. The maximum limited sail-height curve could be drawn in advance and sail-height adjustment procedures could be programmed depending on different circumstances. Firstly a mathematical model of the controlled-object should be established and the external signal should be acquired and collected. Secondly on the basis of the identification results the optimal sail height should be calculated by use of some decision-making method. Finally the adjustment of sail height could be carried out and the required actions will be performed by operating sail device in order to achieve adaptive control of sail-height.

The sail height adjustment process is shown in Fig. 8.

The desired maximum sail height could be automatically adjusted by means of automatic control device based on the actual wind conditions and other ship conditions in order to secure shipping safety at sea. When the wind conditions or ship loading conditions have changed the adjustment procedure should be re-executed again until another desired height has been obtained.

5. Conclusion

According to the actual loading conditions, wind conditions, ship velocity and other parameters the sail height could be controlled in real time through self-adaptive control in order to achieve the efficient use of wind energy. The results of the investigation are summarized below:

(1) As shown in Fig. 5 the larger the minimum overturning moment of the ship is, the higher the limited height of sail is. These results of different limited height of sails could be stored according to diffident loading conditions as reference data for sail-height adjustment.

(2) As indicated in Fig. 6 the bigger the apparent wind velocity is, the lower the limited height of sails is which could satisfy the lowest requirement of ship stability. The sail should keep its height less than the maximum limited height in order to guarantee the stability requirement of the ship.

(3) Maximum limited height of sails locate at the apparent wind angle from 120° to 180°, namely in this range of angle sail will be fully opened to achieve the maximum thrust force and obtain the best effect for sail-assisted ship. The limited height of sails is relatively larger when the lateral force coefficient is minimal. But the sails cannot basically produce effective thrust when the apparent wind angle is less than 30°.

(4) The control flow chart of sail height adjustment is shown in Fig. 8 which could provide guidance for the development of sail-assisting technology.

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