Feasibility Study of Wing Sail Technology for Commercial Ship

Mohamad Amirul Asraf bin Mohamed Nadzri and Yaseen Adnan Ahmed*

School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding email: adnanahmed@utm.my

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ABSTRACT

In the 21st century, the growth in the price of fossil fuels and climate change prompted the shipping industry to consider alternative methods to minimise the use of fossil fuels. Wind assisted propulsion system, in this regard, is quickly becoming one of the most popular and efficient methods of reducing both fuel usage and carbon dioxide emissions from ships. This study aims to perform numerous analyses on a model of an oil tanker that is outfitted with several solid vertical sails on its deck. ANSYS Fluent platform is used to run the simulations and the thrust produced by the solid sails at various apparent wind angles is determined. The fuel consumption is then calculated for a particular voyage of that tanker before and after installation of sail to find out the percentage of reduction in fuel consumption. It is proven that using the wing-sail with or without a fowler flap can save fuel and reduce carbon dioxide emissions by 1.64 to 2.08 percent, respectively. In addition, the ship's intact stability has been investigated using MAXSURF software and validated against the fulfilment of the weather criteria. The selected ship was found to have good stability after the installation of wing sail.

Keywords: *Wing-sail, Fowler flap, Fuel saving, CO_2 emission, Ship stability*

1.0 INTRODUCTION

Wind energy has been used since many years ago to propel a ship as the form of sail and with the advancement of technology, people started to limit the use of sails only on small boats as high-power engines are now available to propel the bigger commercial vessels. Nowadays, cargo shipping is used as a medium of transport around the world because it is an inexpensive and convenient way to do international trade. However, a negative impact has been observed in the shipping industry in terms of greenhouse gas emissions and harmful liquid substances.

A lot of studies have been done to reduce the pollution in the marine sector. The use of renewable energy is found to be one of the best alternatives so far. As wind is the most commonly available source of renewable energy at offshore, many researchers are now revisiting the possibility of using wind propulsion technologies to minimize the environmental effect of commercial shipping.

Wind power has been used for centuries to provide the main thrust through sail technology. In terms of providing sufficient main thrust for large maritime shipping, sail assistance is not recommended, but it can offer considerable economic and environmental advantages by reducing fuel consumption. Drag and Lift forces can be generated with the use of sail [1], both of which can be harnessed for towing. Figure 1 shows the coordinate system, where α is the angle of attack, β is the wind angle, X is the forward force and Y is the side force.

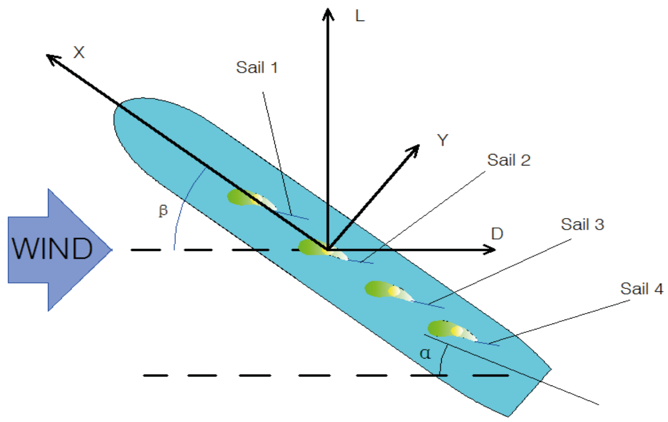


Figure 1: Coordinate system of the cascade sails for an imaginary ship [2]

The use of sail is considered for power generation by investigating analytically the effect of crosswinds [3]. The effectiveness of wing sail is highly dependent on its aerodynamic performances, which could be accurately predicted in the form of aerodynamic forces acting on it. Thus, the design of sail becomes a researcher topic to improve the thrust forces and more reliable aerodynamic performance. The purpose of this study is to investigate different aspects of wing sails for improved aerodynamic performance. Using computational fluid dynamics (CFD), the sail parameters are investigated, including the gaps and rotation angles, and the best parameter is chosen for a commercial ship. The effects of having onboard wing sails on ship's stability has also been analysed and presented in this paper.

2.0 LITERATURE REVIEW

2.1 Sail on Commercial Ship

The rigid wing sail has been used on a variety of ships due to its environmental and energy-saving properties. Two rectangular rigid wing sails with a total sail area of 194.4 m^2 were installed on the "Shin Aitoku Maru" in Japan in 1980, making it the world's first modern sail-assisted commercial tanker. Oil tankers can save 8.5 percent per year after four years of actual sailing when compared to conventional ships [4]. Although the international oil price fluctuates greatly, research on sail-assisted vessels varies by country. China Shipbuilding Group delivered the world's first Very Large Crude Carrier (VLCC) with wing sails, "Kai Li," in 2018. (Figure 2). The trial study showed that the VLCC's energy-saving efficiency is obvious [5].

Figure 2: "Kai Li" VLCC with wing sail

2.2 Wing sail Principle

Lift and drag are vital forces used for take-off, cruising and landing in aviation. It is important to understand how these forces function and know how to manage them with the use of power and flight controls to fly. In the maritime industry, this idea could be used to boost aerodynamic efficiency by increasing lift forces and decreasing drag forces by installing wing sails in vessels. Figure 3 shows the forces that act on a wing sail. Drag is the force that acts opposite the direction of motion. Lift is the force that acts at a right angle in the direction of drag. Thrust is the force required to overcome the drag and to generate the lift force.

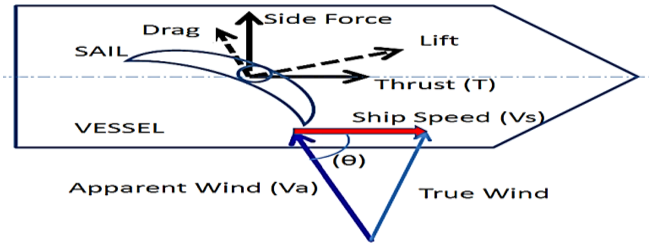


Figure 3: Forces acting on a wing sail [6]

Wing sail is a rigid or semi-rigid framework similar to a vertically fixed aircraft wing on a boat to provide thrust from the wind's action. There are different wing sail designs and the invention of the wing sail has been carried out from time to time to enhance the wing sail's performance. High-lift devices have been developed to improve the overall lift coefficient (C_{LMAX}). Increasing the camber of the aerofoil or delaying the boundary layer separation are two common forms of increasing C_{LMAX}. The typical way to lift the camber is by using trailing-edge flaps [7]. In order to increase the lift coefficient, flaps are used and there are many types of flaps widely used, as shown in Figure 4 among which fowler flap shows the best results.

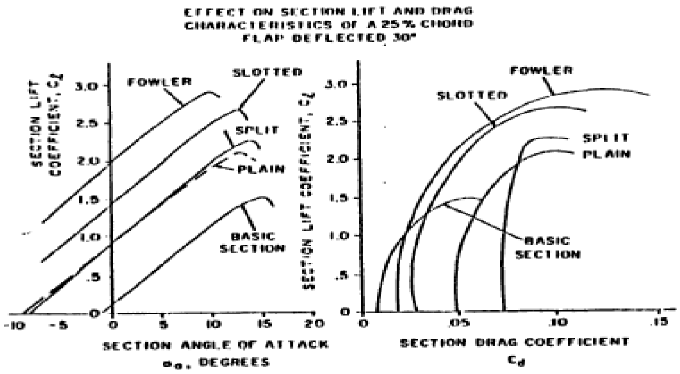


Figure 4: Effect of Flaps on Lift and Drag Coefficients [8]

2.3 Sailing vessel Stability

The righting moment curve represents a sailing vessel's ability to endure the influence of the wind as shown in Figure 5. Some of the most important parameters that describe the stability of the sailing vessel are the area under the righting moment curve up to the angle of vanishing stability, the righting lever at 90 degrees of heel and the down flooding angle [9]. The curve's form and the range of positive stability are also essential. Different criteria in general, demand minimum values for these characteristics. Apart from the righting moment curve, several features of the vessel must be known for classic methods such as displacement under various loading conditions, sail area and overall configuration with and without sails.

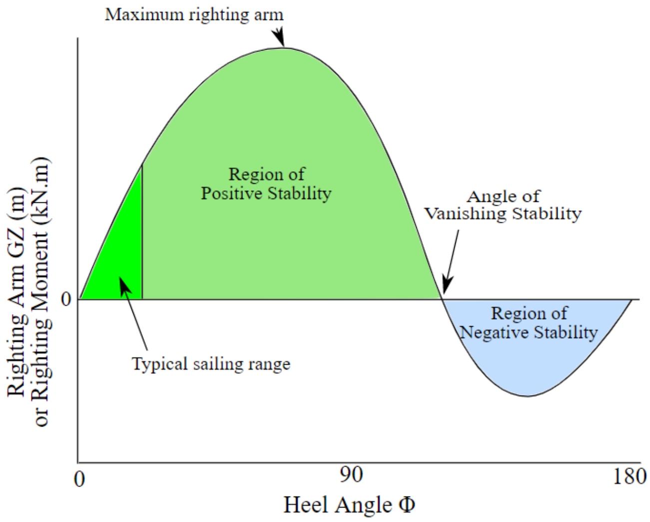


Figure 5: Righting Arm curve

Static and dynamic stability are the two basic types of requirements that are usually provided together. The righting arm (GZ) curve is calculated and compared to the heeling arm curve produced by a stationary wind in the first type. Both trajectories are displayed simultaneously, and the stable heel angle is defined at the point where they cross. This angle must be less than a specific value set by the relevant administration.

The second kind of requirement is known as "dynamic stability," and it refers to a vessel's ability to endure a gust of wind. The area under the wind heeling arm curve represents the work performed by a gust, while the area under the righting arm curve represents the energy absorbed by the vessel. The angle at which these areas are equal determines how dynamically a vessel will be heeled by the gust. There are numerous ways to illustrate the heeling arm curve depending on the administration. In some cases, such as in the case of static stability, (formula-pressure-angle) are offered, whereas, in others, a set area value is required. The American Coastguard Agency's (USCG) requirements are based on the same idea, however, the minimum values in both static and dynamic stability are presented as numbers.

3.0 METHODOLOGY

3.1 Target Ship

Ship selection based on the characteristics and requirements of the assisted sail device, those ship types, such as bulk carriers, oil tankers, passenger ships and some barges can be chosen as the target ships for wing sail installation. Those types of ships should have an open deck area, without extensive superstructure or deck machinery. The mounting site should also be carefully chosen to ensure that forces can be safely transferred to the ship's structure. Oil tanker vessels which TRANSKO YUDHISTIRA was chosen to be the target ship in this study. Considering the total length of the ship, the number of wing sails to be installed will vary. It will also depend on the load the vessel carries as well as the availability of space on deck. Other factors such as the material of the wing sails must be chosen perfectly to keep the loading on the vessel on acceptable limits to prevent stress-related problems. The characteristics of the target vessel are listed in Table 1 and the general arrangement is shown in Figure 6.

Table 1: Characteristics of the target vessel

Characteristic	Unit	Value
Overall length	m	108
Breadth	m	19
Draft	m	6
Speed design	knot	12.5
Deadweight	tons	9406.1

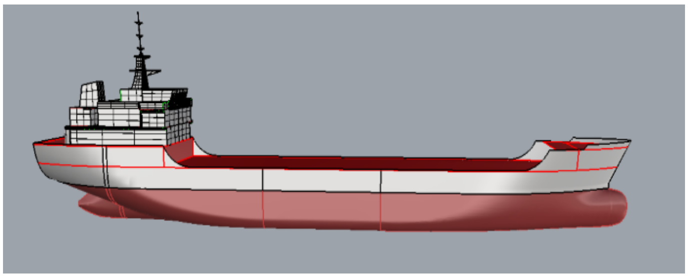


Figure 6: Oil tanker model

3.2 Wing sail Geometry

The area of the wing sail plays an important role in the generation of thrust by the wing sail. A higher surface area usually will produce more thrust. However, the maximum sail area to be designed is dependent on the displacement volume of a particular ship. Based on the ship's characteristics, four sets of wing sails 9.6 m wide and 12 m high were installed on the target ship, the aspect ratio of the wing sails was 1.2 and the camber ratio 0.15. The main dimensions of the wing sails are shown in Table 2.

Table 2: Main dimensions of the wing sail

Characteristic	**Unit**	**Value**
Chord of the aerofoil	m	9.6
Height	m	12
Aspect ratio	-	1.2
Camber ratio	-	0.15

3.3 Material Selection

Material selection is a viable process in this research as it determines the durability of the wing sail. The material should be selected in such a way that the sail would be able to work even in the most extreme weather condition. The material must be of the type that has good mechanical properties, higher strength, corrosion resistance and also cost effective to choose. In this research, Carbon Fibre Reinforces Polymer (CFRP) is used for the rigid wing sail because CFRP is very light in weight and has excellent strength. Besides, Aluminium is chosen for the sail mast.

3.4 Modelling of Aerofoil in ANSYS

The shape of aerofoil needs to be select appropriately for the simulation in this study. It is well-known that standard aerofoil shapes are developed by the National Advisory Committee for Aeronautics (NACA) which are designed from past experiences of known shapes and experimental modifications of those shapes. NACA aerofoil series which comprise the basic 4-digit and 5-digit series is created by superimposing a simple mean-line shape with a thickness distribution along the length of the aerofoil. The new series is developed which is 6-digit series that have more complicated shapes and is derived from using theoretical reasoning rather than geometrical reasoning. The most popular series in the NACA aerofoil 4-digit database are NACA 4412 and NACA 6412. These are widely used in designing the wing sail. This study compares the performance of both of NACA aerofoil 4-digit series and choose the one with improved the aerodynamic efficiency for the wing sail.

To compare the performance of these two aerofoils, simulations were done at various angles of attack. The aerofoils are first modelled in Solidwork, and later imported to ANSYS to run for a simulation. Table 3 shows the necessary inputs used in this simulation. The cross-section of the aerofoil modelled and the corresponding domain mesh around it is shown in Figure 7.

Table 3: Simulation parameters for the proposed design of wing sail

ANSYS Fluent: Proposed wing sail modelling	
Aerofoil type	NACA 4412/ NACA 6412
Design model	3D
Chord length	9.6
Number of Wing sail simulated	1
Solver	Density - Based
Material	Ideal gas
Boundary Inlet Velocity	1.67 m/s

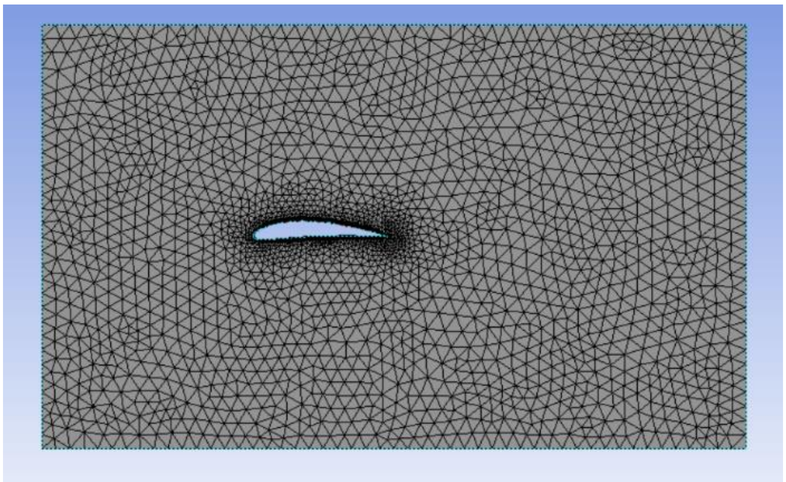


Figure 7: Meshing in ANSYS Fluent for the aerofoil

The simulation starts with the grid independence study, and we choose NACA 4412 for this purpose. The aim of this investigation is to get an optimal mesh size that gives the nearest lift and drag coefficient to the experimental data. The results are shown in Figure 8 for a better understanding. It shows that with the element value 234666, the simulation calculates the C_L= 0.4540, whereas the experiment gives C_L= 0.4833. Although the predicted value is not much accurate (error 2.93%), the results could be improved by reducing the cell size, which needs high speed computers.

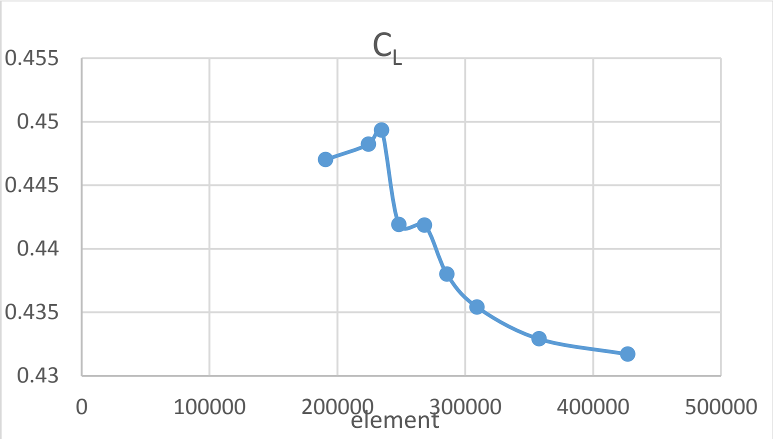


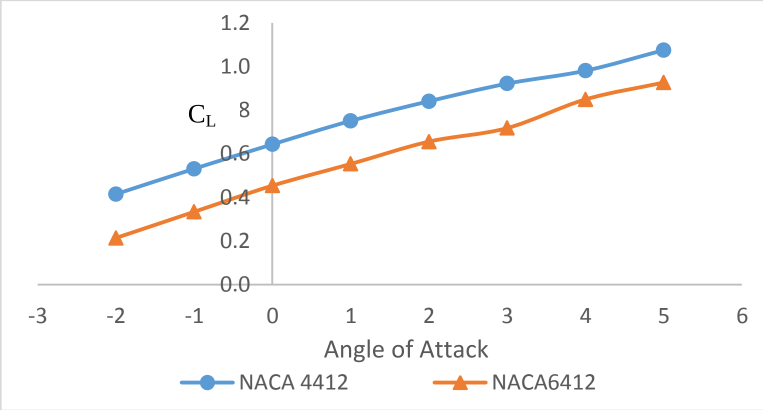
Figure 8: Grid Independence for NACA 4412 aerofoil

In this study, the simulation is performed without considering the superstructure above the vessel's waterline and no structures other than the aerofoil shaped wing sails are considered. For wind, an average speed of 1.675 m/s is used and the Reynolds number is calculated accordingly, as shown in Equation (1).

$$Re = \frac{\rho v}{\mu} \tag{1}$$

Where μ is the viscosity coefficient and ρ is the density of air at 30℃. The results of NACA aerofoils at Re = $1x10^6$ are compared with each other**.** The objective of this simulation is to find the lift and drag coefficient at various angles of attacks and choose the best aerofoil for wing sail design.

Figure 9 shows that the coefficient of drag and lift increases as the attacking angle increases which are expected and NACA 4412 has a higher coefficient of lift value than NACA 6412. The increase in lift is due to increased static pressure at the lower surface of the wing. The maximum C_L/C_D ratio of NACA 4412 is generated at an angle of attack of 2 degrees and 4 degrees for NACA 6412, however the ratio is always bigger for NACA 4412. Thus, NACA 4412 is chosen in this study for further investigation while designing the wing sail.



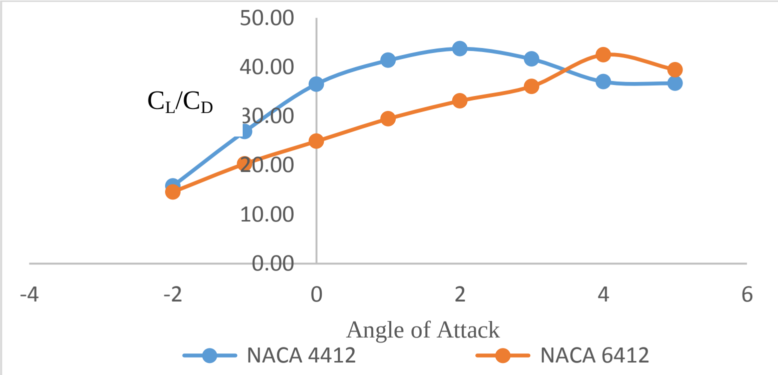


Figure 9: Coefficient of lift NACA 4412 and NACA 6412 vs angle of attack (top), C_L/C_D NACA 5412 and NACA 6412 vs angle of attack (bottom)

3.5 High lift device analysis

A comprehensive analysis of the main types of sailing [10] has found that the wing sail has the advantages of good performance for assisted propulsion, simple structure and convenient operation. It can be seen from the literature review [11] that flaps in the wing sail can extend the entire sail wind area and adjust the shape of the sail camber to increase the lifting power. Thus, NACA 4412 and the fowler flap (the most efficient among others flaps) has been chosen for this study. The analysis of the flap assisted wing sail is done for zero-degree angle of attack and with various flap angles. The results obtained are presented in Table 4.

Table 4: Simulation results for NACA 4412 with flap

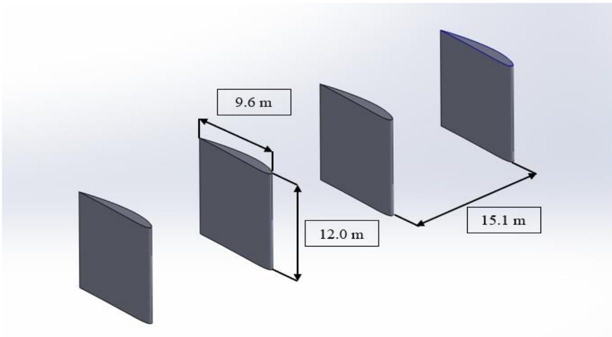
AOA	Flap Angle	Lift Force(N)	C_L	C_D
	0	71.03	0.5474	0.0166
	10	184.9	1.1829	0.0303
0	20	299.57	1.7811	0.0539
	30	389.14	2.2738	0.0891
	40	455.23	2.7007	0.1302

4.0 RESULTS AND DISCUSSION

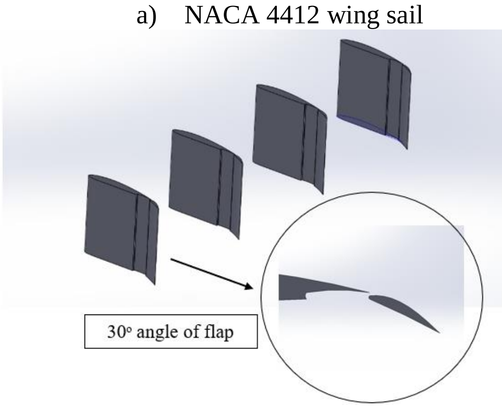
4.1 Wing sail set-up

The four sails of NACA 4412 aerofoil intended to installed on the target ship are modelled with and without flaps in SOLIDWORKS and imported to ANSYS Fluent to calculate the thrust at maximum wind speed and different wind directions and sail orientations. The apparent wind is created by combining the "induced wind" (the airflow felt due to the ship's forward motion) and the "true wind" (the direction of the wind if the ship were stationary). The model made in SOLIDWORKS is shown in Figure 10. ANSY Fluent is then used to calculate the lift and drag coefficient for each aerofoil for different wind and sail conditions. The thrust force and drift force acting on the ship are then calculated using Equation (2) and (3).

$$T = F_L \sin\theta - F_D \cos\theta \qquad (2)$$
$$N = F_L \cos\theta - F_D \sin\theta \qquad (3)$$



a) NACA 4412 wing sail



b) Fowler Wing Sail with flap at 30°

Figure 10: Modelling of Wing sail in ANSYS

Figure 11 below shows the domain parameters setting before running the simulation. Vertical wind was used to get the lift and drag force with the difference angle of attack. The thrust force and drift force are then calculated using those value.

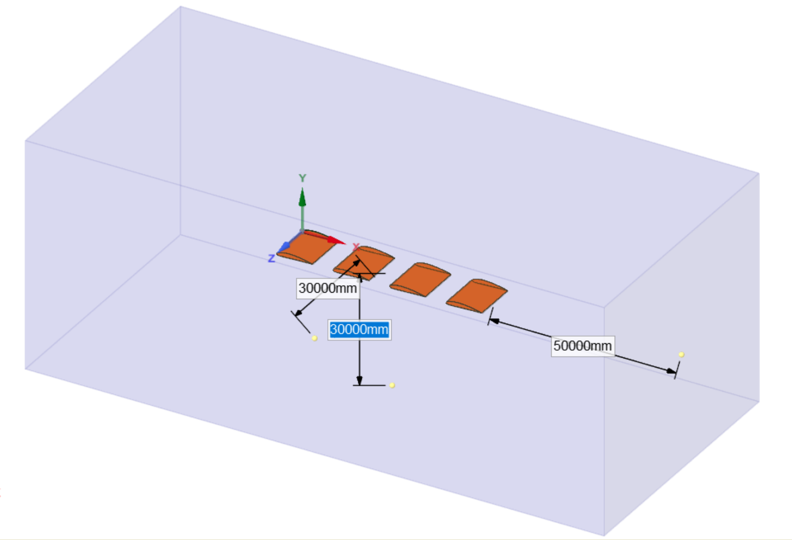


Figure 11: Domain Parameter of aerofoil

In this study, the simulations are focusing on the two condition of sail orientations which are 90 and 180 degrees and having different apparent wind angle conditions from beam wind, broad reach wind and down wind. The simulations are run with Apparent Wind Speed (AWS) of 4.37 m/s. The illustration of Apparent Wind Angle (AWS) is shown in the Figure 12.

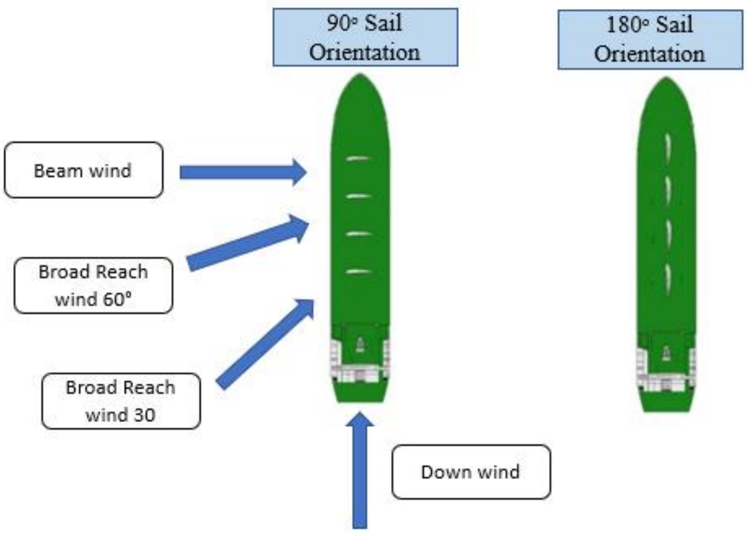
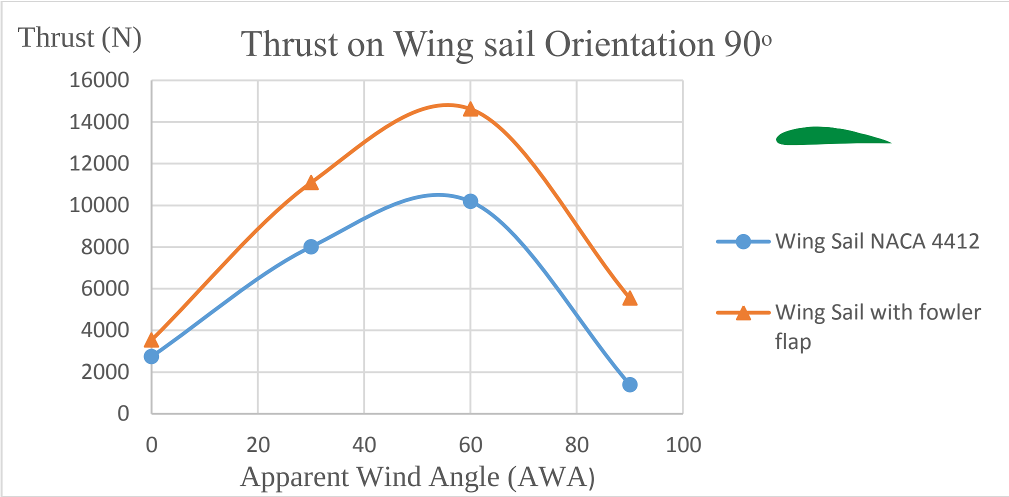
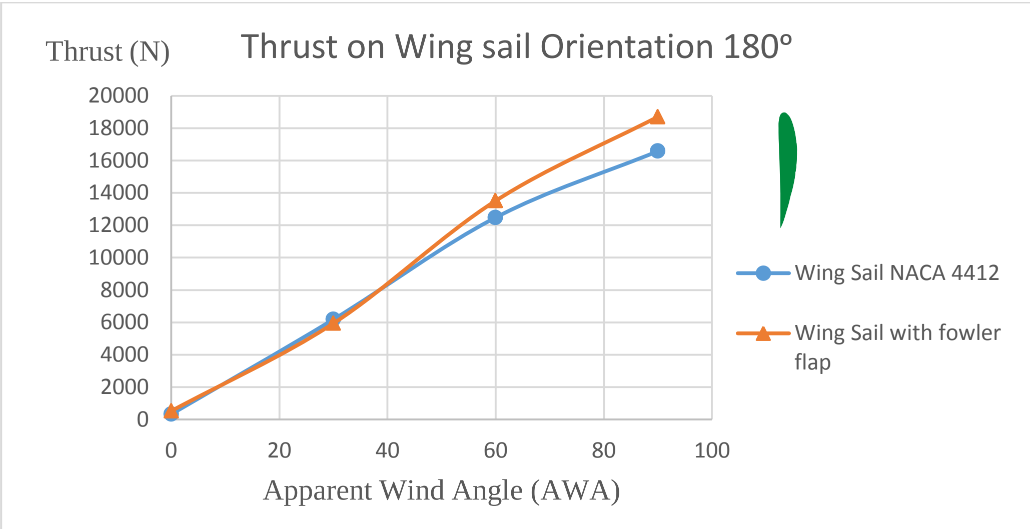


Figure 12: Apparent Wind Condition

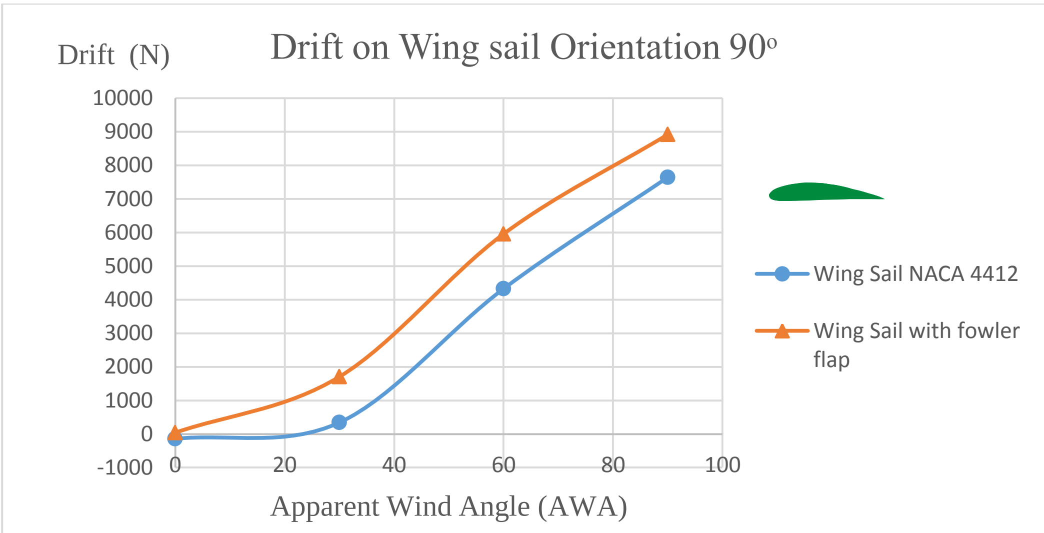
Two different types of wing-sails have been analysed in this simulation. The first of which is a NACA Series 4412 wing sail with a total chord length of 9.6 metres and the second is a fowler flap assisted NACA Series 4412. The system of fowler flap-assisted wing-sail uses a sliding flap technique, hence the angle of the flap can be set to any suitable value (here we set is at 30^0). The results of these two different types of wing sail are then compared for different sailing mode (sail orientation) and for different apparent wind angles. Figure 13 shows the results of the calculated thrust and drift forces for the wing sail and flap assisted wing sail with various sail orientations and wind directions.



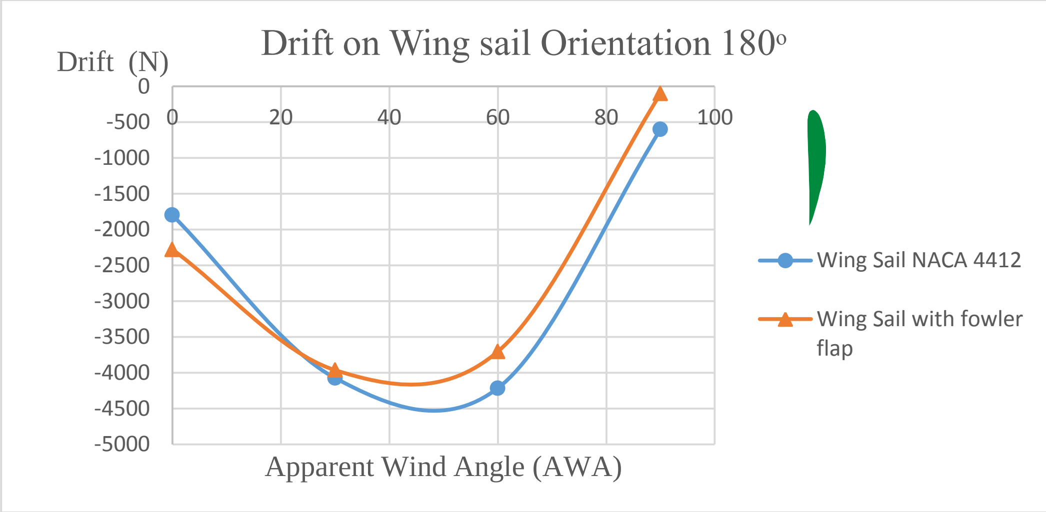
(a) Thrust force on sail orientation 90°



(b) Thrust force on sail orientation 180°



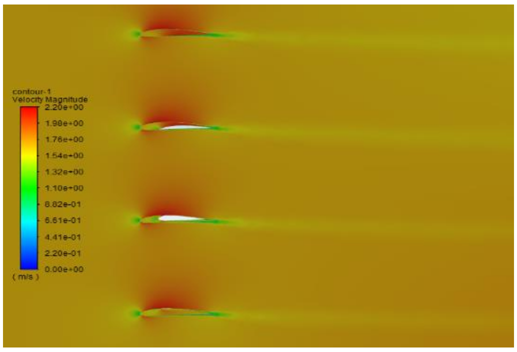
(c) Drift force on sail orientation 90°



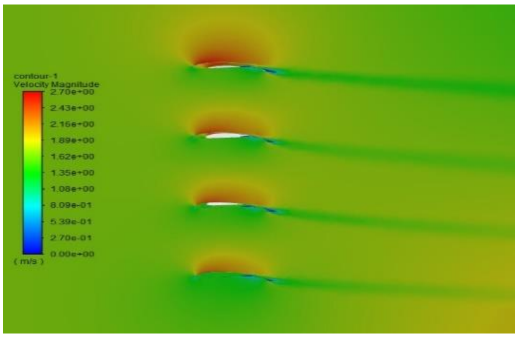
(d) Drift force on sail orientation 180°

Figure 13: Comparison Thrust and Drift force of both condition

The figure shows that the value of thrust for sail with fowler flap is always greater than the sail without flap. This is because the sail with fowler can manipulate the apparent wind speed and increase the trust. This can be understood by seeing the Figure 14, which shows the velocity contour around an aerofoil of wing sail NACA 4412 and wing sail with fowler flap at a 0 degrees angle of attack.



(a) NACA 4412 wing sail



(b) Wing sail with fowler flap at 30°

Figure 14: Velocity contour of sail

4.2 Ship Routes

In order to measure the effectiveness of using wing sail in terms of fuel saving, a particular ship route from the port of Meulaboh, Indonesia to the port of Klang, Malaysia is selected (Figure 15). An oil tanker below 50,000 DWT is considered the small ship tank size, the route is selected as port-to-port. According to the sea route calculator, the distance between the two ports is 598.8 nautical miles and it would require a total of 110 hours travelling time between the two ports, following the shortest possible route.

Figure 15: Proposed Ship routes from Meulaboh to Klang port

Both types of wing-sails are used for this particular route and the results of fuel consumption for the tanker without wing-sail, with wing-sail NACA 4412 and fowler flap assisted wing-sail are compared. The fuel consumption is computed using the engine's specifications and the route chosen by the vessel. The net power, fuel consumption, and overall fuel savings of the ship using wing-sail technologies are then estimated to generate an average net power output. The following Equation (4) is used to calculate the total amount of fuel required for this journey.

$$FC = \frac{SFC \times BP \times time}{1 \times 10^6} \tag{4}$$

Where,

SFC = Specific fuel consumption (g/kWh)
BP = Brake Power (kW)
Time = Journey time take (hr)

The Brake Power in Equation (4) is calculated using Equation (5).

$$B.P. = \frac{P_{mb}\ x\ L\ x\ A_c\ x\ N}{60000} \tag{5}$$

Where,

Pmb = Brake mean power
L = Length of stroke (m)
Ac = cylinder area (m2)
N = RPM

By obtaining the average net power output of the wind sail, total fuel savings can be determined by applying the following Equations (6).

$$FS = \frac{SFC \times Avg\ net\ Power \times time}{1 \times 10^6} \quad (6)$$

The comparison of the fuel consumption of original ship, ship with wing sail and fowler flap 30^0 assisted wing sail is shown in Figure 16.

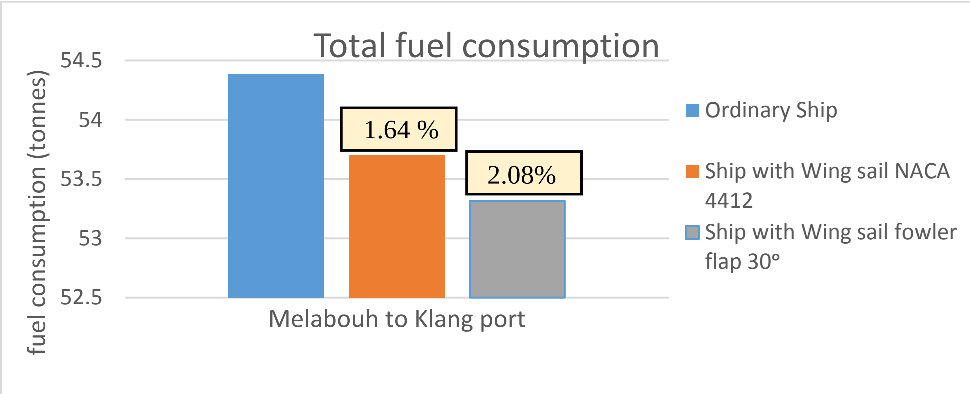


Figure 16: Comparison of fuel consumption

Refer to the graph, we can see that the wing-sail is effective enough to reduce the fuel consumption by 1.64% comparing to without wing-sail in that particular ship voyage. In addition, the best wing-sail for maintaining fuel saving is fowler flap assisted wing-sail, which can save fuel up to 2.08% with flap at 30 degrees. Hence, we can conclude that utilizing wing-sail could serve a ship to improve its performance in terms of fuel saving and reduce CO_2 emission. Besides, this research project is also validated with the reference from paper Dominic & Hannan [12] that obtained the wing sail-assisted ship propulsion can reduce the fuel-saving average by 0.46%. Thus, the wind-assisted ship propulsion has been found effective enough in reducing the fuel-consumption by assisting the ship propulsion in terms of producing extra thrust.

4.3 Stability of sail assisted ship

The ship's stability must not be significantly affected at high wind speeds as one of the most important requirements of a modern wind-powered vessel. A ship is constantly influenced by external forces such as wind and waves, as well as internal forces that can compromise the ship's overall stability. Due to the action of forces and moments acting on a large area of sail, the intact stability characteristic of a sail-assisted ship differs slightly from that of a ship without sail. Due to the relative wind flow on the sails, the rolling angle of the ship may increase. The large sailing ship may capsize due to a lack of adequate intact stability.

According to Lloyd's/ Wolfson, Germanischer Lloyd's (GL), Bureau Veritas (BV), USCG, Ateliers et Chantiers du Havre (ACH), [13], there are several criteria and methods for evaluating the stability of a sail-assisted ship. The recommended stability criteria on sail-assisted ship are as follow:

1. Weather criteria, $K \geq 1$
2. Metacentric height, $GM > 0.3$ m

4.3.1 Weather Criteria (K) for Sail Assisted Ship

The weather criteria K for the sail assisted ship suggested as the ratio of Maximum heeling moment (M_q) to Wind Heeling Moment (M_f); ($K = \frac{M_q}{M_f}$).

4.3.1.1 Maximum Heeling Moment (M_q):

The maximum heeling moment is defined as the moment that a ship can withstand in severe wind and wave conditions. In general, wind is taken into account when assessing stability due to heeling. The ship will overturn if the heeling moment reaches or exceeds this criterion. The maximum heeling moment formulated is as Equation (7).

$$M_f = h_2 \ x \, \Delta \tag{7}$$

Where, Δ = Vessel displacement in tones, h_2 = Gust wind heeling arm

4.3.1.2 Wind Heeling Moment (M_f):

When a ship is exposed to a beam wind, the wind pressure acts on the part of the ship above the waterline, while the water resistance to the ship's lateral motion acts on the opposite side below the waterline. The ship begins to heel as a result of this. The wind heeling moment is determined by the wind velocity and the ship's lateral windage profile, which includes the sail. As a result, the wind heeling moment varies with wind velocity and sail rotational position. Aside from these factors, the type of wing sail, sail structure, control system, and operational condition all influence the amount of heeling generated by the sail.

The wind heeling moment (M_f) is a combining of the moment acting on the ship structure (M_{fb}) and the moment acting on sail due to wind (M_{fs}) as follow the Equation (8) below.

$$M_f = M_{fb} + M_{fs} \tag{8}$$

The method is used to calculate the heeling moment coefficient caused by the wind acting on the ship's water above the parts. The following formula (8) is used to calculate the heeling moment due to wind using that method.

$$M_{fb} = C_k + q + A_L + H_L \tag{9}$$

Where,

C_k = Heeling moment coefficient
q = 0.5 x V_s^2 x ρ
A_L = Lateral area
H_L = The ratio of lateral area to length of ship

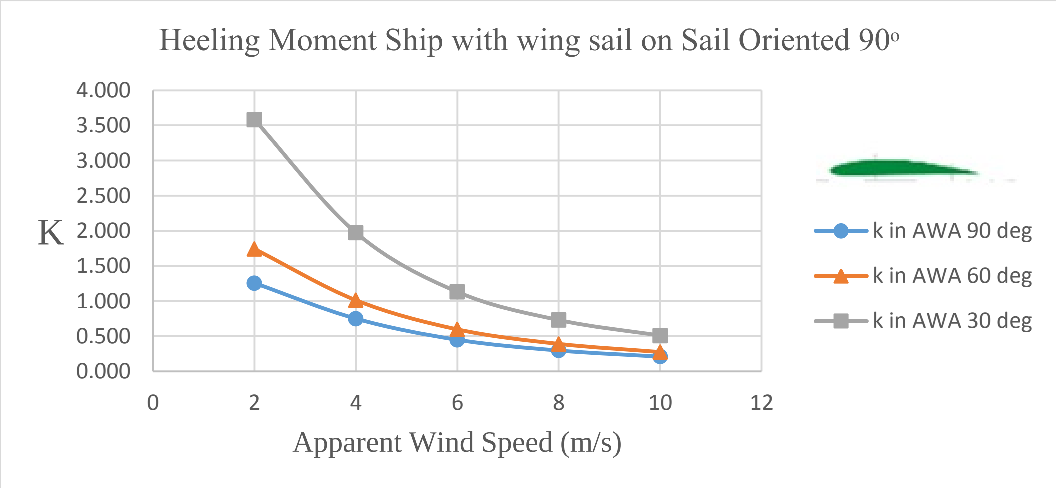
This Equation (10) is used to calculate the heeling moment caused by the sail:

$$M_{fs} = F_H + Z_1 \tag{10}$$

Where,

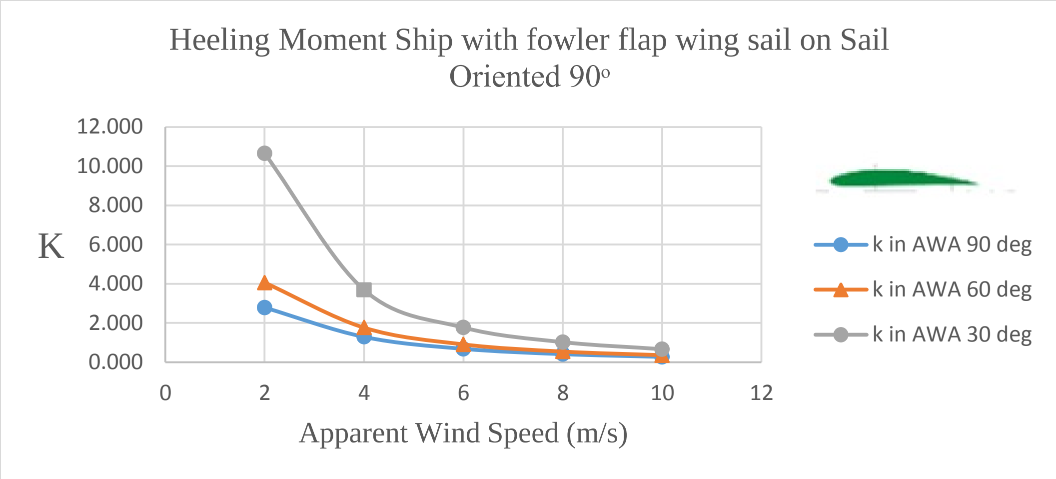
F_H = Heeling force
Z_1 = Lever of healing

The wind heeling moment is calculated for various apparent wind angles (AWA) in both conditions of wing sail which is NACA 4412 and wing sail with fowler flap by using Equations (6) to (9)**.** Figure 17 shows the result of the calculation of heeling moment caused by wind on the free surface of hull and wind moment acting on the sails for both conditions, i.e., with flap and without flap. The results show that the sail orientation 180^0 always has a larger value of K compared to sail orientation 90^0 since the sail has a larger area for both cases. In case of sail orientation 90^0, for flap assisted sail, the value of K is less than 1 for the wind speed beyond 6 m/s and for apparent wind angle 90^0 and 60^0, whereas for sail without flap, the value is quite less. In case of apparent wind angle 30^0, the condition is quite relaxed as the value of K is larger than 1 for wind speed 10 m/s for both cases.

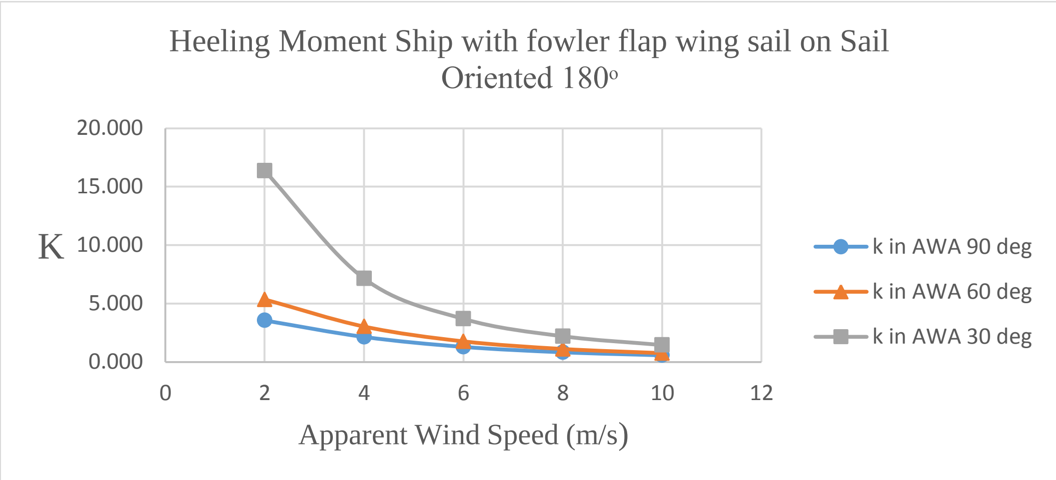


(a) K value of wing sail on sail orientation 90°

(b) K value of wing sail on sail orientation 180°



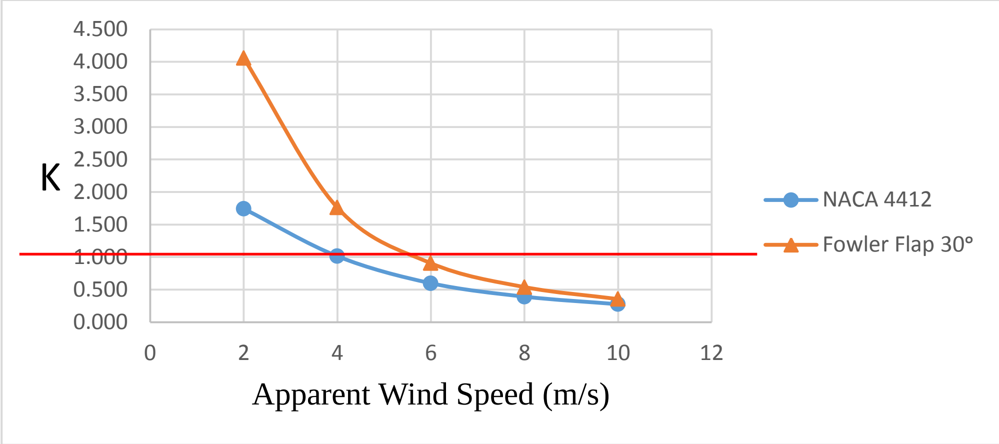
(c) K value of fowler flap wing sail on sail orientation 90°



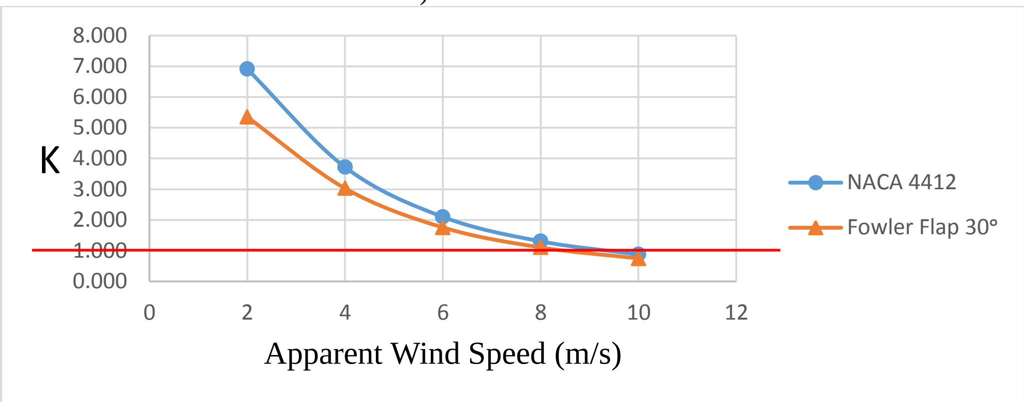
(d) K value of fowler flap wing sail on sail orientation 90°

Figure 17: Comparison of the weather criteria, K of both condition with two angle of sail orientation

Figure 18 clearly shows that the value of weather criteria, K is different at different conditions. For an example, in the figure shows the comparison of the K value for similar apparent wind angle (AWA) which is 60^0 and different sail orientations, which are 90° and 180°. Figure 18(a) shows that at sail oriented 90^0, K<1 occurs at wind speed 4 m/s for sail without flap and at 6m/s for flap assited sail. On the other hand, for the sail orientation 180^0, K<1 occurs at a higher wind speed comparing to sail orientation 90^0.



a) 90° Sail Orientation



a) 180° Sail Orientation

Figure 18: Comparison the value of K

4.3.2 Metacentric Height (GM)

The metacentric height (GM) is a measurement of the initial static stability of a floating body. A larger metacentric height implies greater initial stability against overturning According to IS code 2008, the initial metacentric height for a ship greater than 24 m length must be greater than 0.15 m in general criteria, but it is recommended that it should be greater than 0.30 m in the case of a sail-assisted large ship [12]. The value of initial metacentric height is determined as Equation (11):

$$GM = KM - KG \tag{11}$$

The value of metacentric height (GM) is calculated after the installation of sail, hence the value of KG is calculated first with addition the weight of sail to get the KG_{new}.

4.3.3 Intact Stability Curve Before and After Sail Installation

Maxsurf Stability is used to obtain intact stability curves both before and after the sail installation. The large angle stability analysis was performed in Maxsurf using the IMO criteria MSC 267 (85) code on intact stability, with the results of the GZ curve plotted in Figure 19.

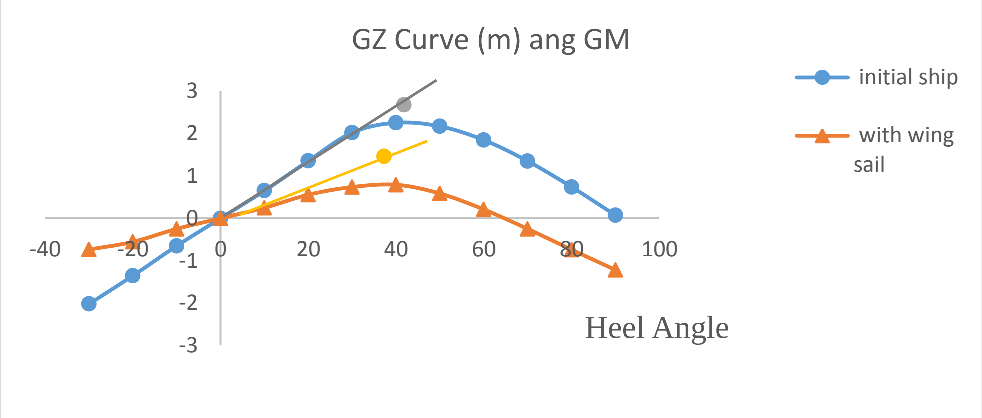


Figure 19: Comparison between GZ for initial ship and ship with sail

Table 5: Simulation results for NACA 4412 with flap

Type	Initial GM (m)	Maximum GZ (m)
Before Sail installation	2.68	2.258 at 41.8°
After Sail installation	1.46	0.798 at 37.7°

From the Table 5 it is clear that the initial metacentric height GM is different and it is significantly higher than the value suggested by the weather criteria for sail-assisted ships. Therefore, the ship is considered as stable after the sail installation as the GM is greater than 0.3 m. The GZ values for different heels are reduced after the sail installation, but have successfully passed the IMO criteria.

5.0 CONCLUSION

This study investigates the effectiveness of using wind-assisted technology for harnessing wind energy for commercial ships. For this purpose, an oil tanker TRANSKO YUDHISTIRA is outfitted with four hard wing sails with and without fowler flap. The NACA 4412 profile is used as the wing sail section, and CFD simulations are done to perform a numerical analysis of the aerodynamic characteristics (lift and drag) of a 3D wing sail. The materials suitable for the construction of the sail mast and the sail body are recommended after reviewing various research papers. The flow field of a four-wing sail system is simulated using ANSYS Fluent, and the amount of total thrust generated by the four wing sails is estimated for various wind directions and sail orientations. It has been found that a wing sail without flap and a fowler flap assisted wing sail can save up to 1.64% 2.08% fuel, respectively when comparing with the original ship. The stability analysis for the sail-assisted ship is also carried out by combining various stability requirements with a primary focus on weather criteria fulfilment. The initial metacentric height has found to be 2.68 m and 1.46 m, respectively, after and before the sail installation, hence the value of both cases has passed the intact stability criteria which needs to be greater than 0.3 m. Maximum heeling moment and wind heeling moment are calculated to evaluate the weather criteria for various cases of apparent wind directions and sail orientations. MAXSURF is used to perform an intact stability analysis and the stability curves are compared. The values of K (weather criteria) are calculated for both cases i.e., ship with sail and fowler flap assisted sail. It is concluded that the wing sail orientation 180^0 always possesses a larger value of K comparing to sail orientation 90^0 since the sail has a larger area. However, the criteria to satisfy the weather condition (K>1), i.e., permissible wind speed for sailing without sacrificing the stability mainly depends on apparent wind speed and sail orientation very much.

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