FINAL PROJECT – TF 181801

DESIGN AND ANALYSIS MULTI-ELEMENT WINGSAIL BY USING COMPUTATIONAL FLUID DYNAMICS

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DESIGN AND ANALYSIS MULTI-ELEMENT WINGSAIL BY USING COMPUTATIONAL FLUID DYNAMICS

FINAL PROJECT

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ADMISSION SHEET

DESIGN AND ANALYSIS MULTI-ELEMENT WINGSAIL BY USING COMPUTATIONAL FLUID DYNAMICS

FINAL PROJECT

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in
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Engineering Physics Department
Faculty of Industrial Technology
Institut Teknologi Sepuluh Nopember

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Abstract

Issues about waste energy in fossil fuel oil used for transportation are happening right now. Alternative energy as a option to handle the wasted energy and global warming. This research discuss about wingsail for alternative energy and development in conventional sail. Traditional sails as known in history as main option as vessels propulsion. And for its development, the analysis on wingsail about previous research design as conventional wingsail. The structure of wingsail built in two model NACA airfoil for first element and second element. The wingsail model in this research built in America's Cup Class (ACC) wingsail. Comparing base wingsail and ACC, has different number of control arm that can control shape of wingsail on foot, head and leech. As the results from analysis, that ACC wingsail can provide more power than base wingsail. With gaining more thrust force at 30° apparent wind angle with 5189.6 Newton for ACC wingsail and 4744.9 Newton for base wingsail. The thrust force itself has to be convert to yacht velocity. Yacht type used in this analyse is modified yacht same TP52 with 15.85 metres long and 4.4 metres with LWL 15.45 metres. Generated velocity by thrust force at 30° wind angle and 15 knots wind speed, 16 knots for base wingsail and 18 knots for ACC wingsail.

Keyword: Aerodynamics, Wingsail, Sailing, Thrust Force.

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FOREWORD

Praise be to Allah SWT over the abundance of His mercy and guidance, the authors were able to complete the final report entitled "**Design and Analysis Multi-Element Wingsail by Using Computational Fluid Dynamics**". This final project goal is to analyse the optimisation of ACC wingsail from base wingsail.

The implementation of this Final Project can't be separated from the help of various parties. Therefore the authors thank to:

1. Agus Muhammad Hatta, S.T, M.Si, Ph.D as Head Department of Physics Engineering Institut Teknologi Sepuluh Nopember
2. Gunawan Nugroho, S.T, M.T, Ph.D as a supervisor who always patiently provide guidance, motivation, and instructions in completing this research and as the head of the Laboratory of Energy Engineering and Environmental Conditioning which has supported the simulation activies.
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5. Both parents, Didik Giantoro and Siti Rahayu also my brothers who always gave prayer and motivation.
6. All lecturer and employee of Engineering Physics Institut Teknologi Sepuluh Nopember has been take part to help author finish in college.
7. Member of UKM Maritime Challenge ITS has been take part to help author finish in college.
8. Friends of Engineering Physics Study Group of Energy Engineering and Environmental Conditioning Laboratory.
9. Graduates of 2013 and 2014 who have passed or not who can be mentioned one by one.

If in this report there is a mistake then suggestions and positive criticism from all parties is expected. The authors hope this report can develop perception that is useful for readers.

Surabaya, 28 January 2019

Authors

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GRAPHS

NOMENCLATURES

Symbol	Unit	Description
α	(°) Degree	Angle of attack of the main (element 1)
c	m	Total chord of the wingsail
c_1	m	Chord of the main (element 1)
c_2	m	Chord of the flap (element 2)
δ	(°) Degree	Flap deflection angle, boundary layer thickness
e_1	m	Thickness of the main (element 1)
e_2	m	Thickness of the flap (element 2)
g	%width	Non-dimensional slot width (g/c_1)
h	m	Mast height
S_v	m^2	Reference area
x_r	-	Flap rotation axis position
L	N	Lift force
D	N	Drag force
P_A	N	Lift component/Lift force
R_A	N	Resistance component/Resistance force
β_{AW}	(°) Degree	Apparent wind angle
F_T	N	Total aero dynamics force/ Thrust force
F_{LAT}	N	Heeling force component
F_R	N	Driving force component
F_{VERT}	N	Downward force component
R_T	N	Total hull resistance
S	m^2	Wetted surface
P	kg/m^3	Density of fluid
V_S	Knots	Boat Velocity
C_T	-	Coefficient of total hull resistance

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CHAPTER I
INTRODUCTION

1.1 Backgrounds

The development in aerodynamics in the world rapidly and some science aerodynamics developed in all field. Development of aerodynamics itself in field of sailing rapidly developed. Unfortunately, there is few available information can be openly access from every literature about to design Wingsail for yacht. Although, many research conducted to multi-element wingsail for aircraft, flow domain very different for yacht neither aircraft, as well as performance goals. Wings on aircraft operate in Reynolds number more than 10 million compared with yacht sail Reynolds number in the region of 0.2 to 8 million. Whereas aircraft wings at cruise are designed for minimum drag at a required lift force, yacht wings must provide maximum thrust for specific roll/pitching moments, as well as sailing on either tack, and therefore the optimisation problems are very different [1].

Research into wings for aircraft has resulted in many high-lift devices which are perfect for yachts. While the aerodynamic drag is important in yacht performance, the largest limiting factor for speed is hydrodynamic drag. High-lift devices allow exceptionally high lift coefficients with an increase in drag. The drag is still often several times smaller than conventional rigs while the lift coefficient is 2-3 times larger. [1].

Wing sails are inherently more efficient than traditional soft sails. The separation bubbles from large high drag profiled masts can be eliminated, and wings, with their low drag coefficients, can reduce the aerodynamic drag on a yacht resulting in better performance than traditional rigs [2]. that a wing of (n+1)-elements will generally have a higher maximum lift coefficient than a wing of n-elements. The slot allows the recovery of pressure, reducing adverse pressure gradients on the suction side of the aerofoil delaying stall and resulting in higher maximum lift [3].

The other main benefit of rigid sails for yachts is that the hull can be significantly lighter than with traditional soft sails. The mainsheet loads required to maintain leech/sail shape are several tonnes for high-performance yachts [4]. This entire load is transferred and spread through the hull from the mainsheet anchor point. Having the rigidity built into the sail reduces the weight in the hull and minimises stress concentrations as a mainsheet only has to counter the wing's pitching moment which is generally very small [5]. Rigidity also means a wing sail has extremely good predictable and constant lift and drag results at different angles of attack [6].If the vehicle is being propelled substantially towards the wind the trim is usually adjusted to provide the maximum possible aerodynamic efficiency, commonly termed the lift/drag ratio; which is the ratio of the output force resolved into components at right angles to the wind and in the direction of the wind. If the direction is broadly across the wind the trim is adjusted to provide the maximum force available without stalling, and if the travel is generally downwind then the downwind component of force is maximised, with stalling deliberately enabled if found more effective [7].

In this research has to be intend to develop a sailing technology that has been developed in developed countries currently is sea transportation that used renewable energy. This matter caused by increasingly price of fossil fuel that take effect in expensively cost of ship operation. Moreover spreading impact of using it that not suitable for environment to cause pollution to broad sea. Burn waste of fossil fuel produces various pollution, like air pollution either sea water pollution. The pollution that happen gradually cause environment pollution and take effect of global warming, therefore need to be done an anticipation by reduce of using fossil fuel and start change over utilize renewable energy like photovoltaic, wind propulsion, and/or water.

1.2 Problems

The problem to be solved in this final project are as follows:

1. Effect variation angle of attack and flap deflection in changing of lift force and drag force on Multi-Element Wingsail?
2. Effect changing of lift force and drag force affect to yacht velocity?

1.3 Scopes of work

Scopes of work on this final project are as follows:

1. The flow used in this research is steady state flow
2. Density fluid is incompressible
3. Rigging part and hull are negligible
4. Trailing flap element in design with variation of deflection angle $\delta=15°$ and $25°$
5. The geometry used in this research is real scale
6. The condition on sailing are normal condition, downward and upward moment are negligible.

1.4 Objective

The objective of this final project are as follows:

1. Knowing effect of angle of attack variation affect in changing of lift force and drag force on multi-element wingsail
2. Knowing result of yacht velocity produced from lift force and drag force on wingsail

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CHAPTER II
BASIC THEORY AND REVIEWS

2.1 Sails

A sail is a tensile structure made from fabric or other membrane materials that uses wind power to propel sailing craft including sailing ships, sailboats, windsurfers, ice boat and even sail-powered land vehicles. Sails may be made from a combination of woven materials including canvas or polyester cloth, laminated membranes or bonded filaments usually in a three or four side shape.

Sail is a device that provides propulsive force via combination of lift and drag, depending on its angle of attack, its angle with respect to the apparent wind. Apparent wind is the air velocity experienced on the moving craft and is the combined effect of the true wind velocity with the velocity of the sailing craft's orientation to the wind or point of sail. On point of sail where it is possible to align the leading edge of the sail with the apparent wind the sail may act as an airfoil generating propulsive force as air passes along its surface just as an airplane wing generates lift which predominates over aerodynamics drag retarding forward motion. The more that the angle of attack diverges from the apparent wind as a sailing craft turns downwind, the more drag increase and lift decrease as propulsive forces, until a sail going downwind is predominated by drag forces. Sail are unable to generate propulsive force if they are aligned too closely to the wind. [8].

2.2 Lift Force and Drag Force

When an object moves through the fluid it will cause an interaction between the body and the fluid. The interaction takes place in the form of forces on the fluid and object interface. This can be described in the wall shear stress ($\tau\omega$) due to the viscous effect and the normal stress due to pressure (ρ). The distribution of shear stress and pressure occurring is shown on below

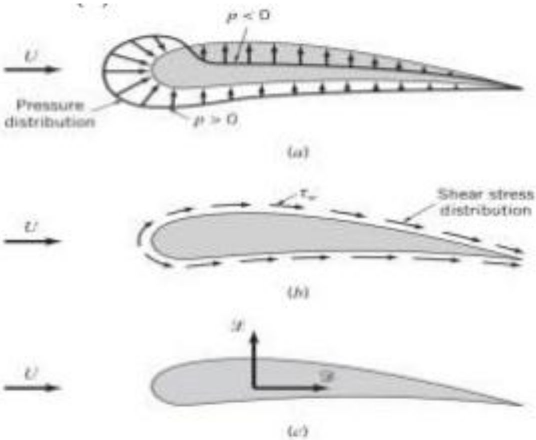

Figure 2. 1 Forces of fluid around an two dimensional object (a) pressure force, (b) viscous force, (c) resultant force(lift and drag) **[9]**

2.3 Load distribution

The performance of a sailing yacht is affected by a large number of parameters, some which are controllable, and other which are not. Apperley et al. Those showing the force are affected load to sail and make various force projected to other ways. Like heeling force are affected to performance of sailing yacht also hydrodynamics force too. These are load distribution showed below

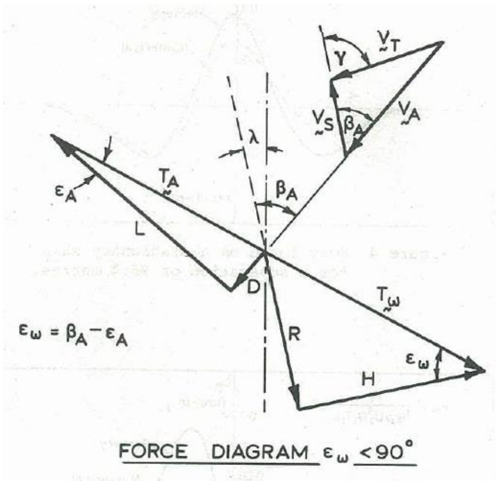

Figure 2. 2 Load distribution vector for angle of resultant hydrodynamics forces(ε_ω)<90°

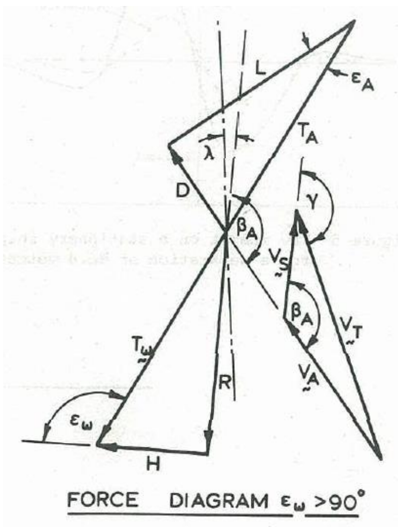

Figure 2. 3 Load distribution vector for angle of resultant hydrodynamics forces(ε_ω)>90°

Figure above showing the hydrodynamics force depend on the drag angle. For aerodynamics force both upwind and downwind use the difference method to predicted yacht velocity produced from force on sail. When upwind the yacht controlling must be got equilibrium between lift and drag force by adjusting the sheet. If it not balance at certain roll moment it will be hard to control the yacht, more heeling moment causing the yacht will got capsize. And more important, it hard for yacht to be controlled when in no go zone. Likewise when downwind more harder than upwind because to get more power the sail must at the right place at pitch moment to produce power from drag force. More drag force that mean more pitching force.

2.4 Wingsail

Wingsail are modern wing sloop rig, the construction of wingsail are of two airfoil. Most wingsail are builded in rigid sail and it usually supported by jib(soft sail). Wingsail itself has control arm to adjust chamber for optimum sailing. On a conventional sails, chamber change passively. On a wingsail change in chamber requires a mechanism. Change in chamber has to be adjusted wind speed on its surface caused lift and drag force. On wingsail flap adjust as wind speed change. Straighter chamber as wind speed increase, more curver as it decreases. The construction of wingsail as shown.

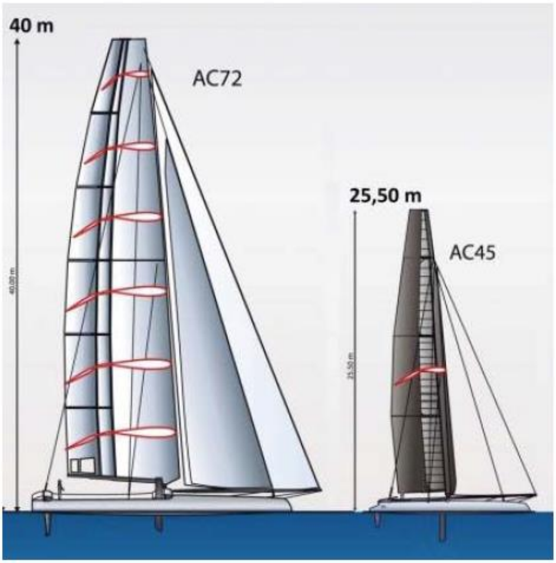

Figure 2. 4 Wingsail on AC72 catamaran and AC45 catamaran

Compare with cnventional sail wingsails tipically are fixed surface area. But conventional sails can be more furled easily. But there some wingsails with soft construction can be dropped. Rigid wingsails must be removed when exposure to wind is undesirable.

Point of sail of wingsail compared with conventional sail

- Close-hauled: At 30° apparent wind, the wingsail has 10° angle of attack and more lift, compared to the conventional sail, 15° for the jib and 20° for the mainsail.
- Beam reach: At 90° apparent wind angle, the wingsail positioned across the boat to functions efficiently as a wing for providing forward lift, whereas the jib of the conventional sail plan suffers from being difficult to shape as wing (the main sail is still relatively efficient)
- Broad reach: At 135° apparent wind angle, the wingsail may be eased in such a manner that it still functions efficiently as wing, whereas the jib and main sail no longer provide lift, instead they present themselves perpendicular to the wind and provide force from drag only

Wingsail are expected to sail faster than the wind when upwind at 1.2 times the speed of true wind, and downwind at 1.6 times the speed of true wind. But in fact Emiratez Team New Zealand (ETNZ) proved faster by the fastest sail record are over 2.2 time of true wind speed, sailing 47.57 knots in 21.8 true wind speed.

2.5 Sailing

In sense of working mechanism of the sail can be analogous to wing and / or part of wings. Particularly can be mentioned at the time of sailing, the sail affected by the wind will form resembles the shape of the airfoil due to the relationship between flow velocity and pressure. High pressure areas are at the upwind and low-pressure areas or suction areas are downwind. The advantage of using the sail as an alternative to propulsion is very good, the lack of a conventional sail of geometric shapes that adjust conditions or not keep the user must always set the mainsheet when maneuver or changing wind direction or change the angle of attack. But it has been overcome by the wing sails are classified in rigid sails.

The value of lift and drag force by using equation of resistance for whole dimension of the sail:

$$R_A = \frac{1}{2}\rho C_R \, SA \, V_A^2 \tag{2.1}$$

And equation to express power(lift)for whole dimension of the sail:

$$P_A = \frac{1}{2}\rho C_P \, SA \, V_A^2 \tag{2.2}$$

R_A and P_A in equation 2.1 and 2.2 also known as lift and drag equation can be achieved with equation:

$$D = R_A = N\sin\alpha + A\cos\alpha \tag{2.3}$$

$$L = P_A = N\cos\alpha - A\sin\alpha \tag{2.4}$$

In equation 2.3 and 2.4 where N is normal force that perpendicular to airfoil, A is axial force that parallel to airfoil and α also as known as β_{AW} apparent wind angle.

From the value of R_A and P_A to be express value of driving force(F_R) and heeling force(F_{LAT}) with equation:

$$F_{LAT} = P_A\cos\beta_{AW} + R_A\sin\beta_{AW} \tag{2.5}$$

$$F_R = P_A\sin\beta_{AW} - R_A\cos\beta_{AW} \tag{2.6}$$

Driving force and Heeling force are components of the total aerodynamics force on sail as known thrust force by sail can be calculate as:

$$F_T = F_R + F_{LAT} + F_{VERT} \quad (2.7)$$

Note the F_{VERT} acts downwards for boats heeling away from the wind, but negligible at normal conditions.

The appeal of physics is equally hard to explain. For some, finding the correct explanation of familiar or exotic phenomena offers greater exhilaration than a successful day of sailing. Although the core of physics has a special elegance, much of day-to-day science lacks the seductive atmosphere of profundity. This is certainly the case for the physics of sailing, which is dominated by numerical calculations and enmeshed in the cumbersome apparatus and intimidating mathematics of fluid mechanics. [8]

Sailing has been divided on two method that is upwind and downwind, both upwind and downwind been divided too in more little scale at different angle of attack when sailing as known as point of sail. In point of sail degree of wind speed facing the vessels depends on controlling the sail. To controlling the sail is not as be the same as the boat heading. Maximum mast rotation between area <180°. And the change in β_{AW} are depend where the wind come from.

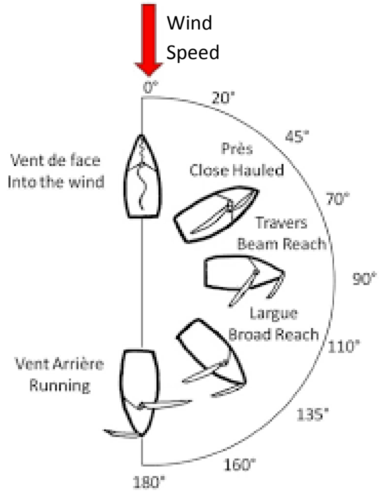

Figure 2. 5 Point of sail

2.5.1 Downwind

Sailing with the wind is surely the oldest and simplest type of sailing. In its primitive form, it is hardly sailing at all. When the wind is behind, standing up in a canoe or mounting a small tree on a raft could be considered downwind sailing.

It is logical to wonder how fast a boat can go when sailing downwind. Physics gives clues about how to make faster sailing craft for both upwind and downwind sailing. The starting point is a general discussion of speed. Sailboat speeds are determined by the wind's force and water's opposing force. Newton's simple characterization of the forces provides reasonable estimates of sailboat speeds. A more complicated description of the forces is needed for upwind sailing. [8]

Downwind sailing are about how sailing vessels sail at high degree of angle attack are about $\alpha > 90°$. Where the wind come from behind.

2.5.2 Upwind

Sailing against the wind is mysterious. It is easier to sail upwind than to understand it. Sitting on a sailboat, you see the water moving past from bow to stern. The wind is coming slightly from the side, but it can also be mostly from the bow.

Lift is the key. Sailing upwind, is possible only because the wind's force is not parallel to the wind direction, and the water's force is not parallel to its motion relative to the boat. Combining lift from the wind with lift from the water produces the miracle of upwind sailing. Lift also produces the miracle of flight, but sailing upwind is more complicated. Birds and airplanes must contend with only a single fluid air. Sailing is the story of two fluids (air and water), and the boat that lies at their interface. [8]

Upwind sailing is signature version of upwind, whereas smallest degree of angle attack that sailing vessels can still produce sailing speed none at no go zone condition.

2.6 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a science used to predict fluid flow, mass transfer and heat, and other phenomena that use mathematical equations based on finite element. In the CFD is used the equation of conservation of mass, energy conservation, and conservation of momentum to produce the required prediction data such as pressure, velocity, temperature, and vector. The simulated geometry will be divided into small parts called the volume control. In each volume control will be done mathematical calculations. The more volume controls created, the more calculations will be made and the more heavy the computer works. In doing the simulation using CFD, there are three stages that must be implemented that is.

a. Pre-Processing

At this stage the formation of geometry to be simulated and defining the boundary condition. Making geometry can use software AutoCAD, CATIA, ICEM, Solidwork, and so forth which is similar software. The process after geometry is meshing, meshing is the process of dividing the geometry into a small volume control that becomes the place of mathematical calculation. The more control the volume created the better the results obtained.

b. Processing

At this stage will be calculated parameters or data that has been entered and will be processed analysis. The modelling used is flow turbulence modelling using Reynold Averaged Navier-Stokes method. In CFD, RANS are the most widely used turbulent modelling approach. In this approach, the Navier-Stokes equation is divided into average components and fluctuates. The total velocity u is a function of average velocity and fluctuation velocity as shown in the equation below.

$$u_i = \overline{u_\iota} + \acute{u}_\iota \tag{2.8}$$

The continuity and momentum equations that combine these instantaneous flow variables are derived from

$$\frac{\partial \rho}{\partial t} + \frac{\partial y}{\partial X_i}(\rho u_i) = 0 \tag{2.9}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_i}\left(-\rho\overline{\acute{u}_\iota \acute{u}_\iota}\right) \tag{2.10}$$

The above equation (in Cartesian tensor form) is known as the RANS equation, and additional Reynolds stresses need to be applied to the Boussinesq Hypothesis model in relating Reynolds voltages and average speed

$$-\rho\overline{\acute{u}_i\acute{u}_j} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \qquad (2.11)$$

c. Post-Processing

This last stage is the stage where the calculated data can be seen in several forms such as graphics, images, and animations with certain colour patterns. In this stage showing the results of the analysis of an object to be analyse. And showing the results of the computation from the equation model from processing stage.

2.7 Velocity Prediction Program

VPP is a method to predict the yacht velocity by calculating the hull resistance to get the force needed to drive the boat. The component of total hull resistance can be expressed.

$$R_T = 0.5\rho S V_S^2 . C_T \qquad (3.1)$$

The calculation be done with numerical software from the resistance can be predict the boat velocity by standard operational velocity. After that can be calculate the force given of the sail and compare with the force given of the hull resistance.

2.8 Hull Resistance

In this case the hull are using for the analysis of using wingsails on the monohull yacht 52 feet class, similar with TP52 yacht. By modification on few part. With specification maximum hull length of 15.85 metres with 15.143 metres LWL, beam width of 4.43 metres, keel draft of 3.5 metres and spinnaker hoist height of 22.4 metres along. With a minimum total weight of 6,975 kilograms

Figure 3. 1 TransPac 52 Yacht generation 2011 (design by judel/vrolijk & co)

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CHAPTER III
RESEARCH METHODOLOGY

3.1 Methodology

The methodology of this final project is based on the methodology according to the following flow diagram:

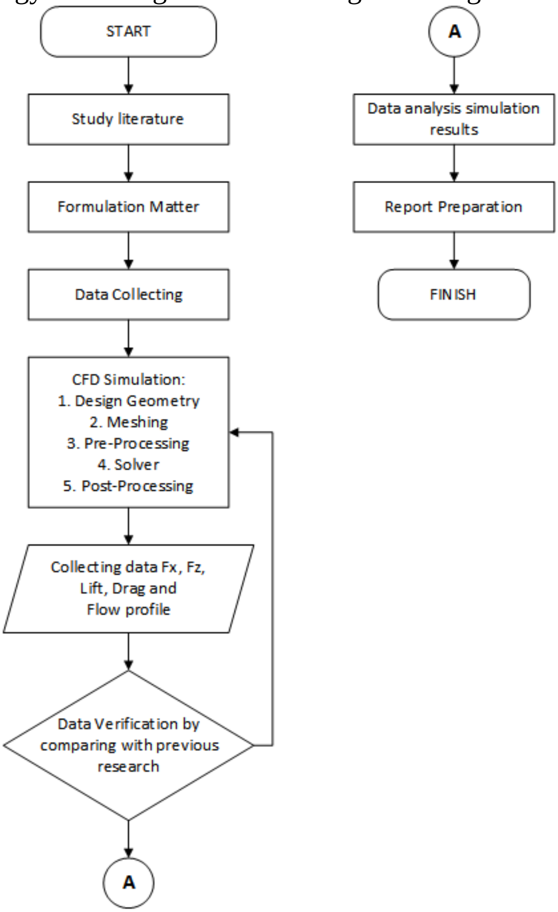


Figure 3. 2 Flow Charts

Based on the above flow charts this research use the method of Computational Fluid Dynamics and uses a Computational Fluid Dynamics software from building the geometry until analysis can be described as follows:

3.2 Design Geometry

The simulation begins by creating the geometry of the object used using data from the airfoiltools based website software. The object used is wing sails with geometry for first element use symmetry airfoils with maximum thickness of 25% chord. Second element use symmetry with maximum thickness of 10% chord.

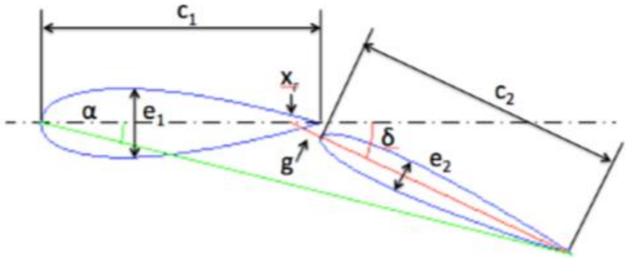


Figure 3.3 Multi-element Wingsail Geometry with 2 element **[10]**

The section of wingsail then build to 3D geometry that has been planned both of base wingsail and America’s Cup Class from the document AC Class Rule copyright by Golden Gate Yacht Club. The different of both wingsail are base wingsail just controlled by two control arm that on the base and top of the wingsail. For ACC wingsail has more control arm on its flap section.

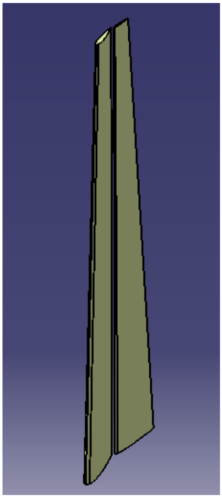


Figure 3.4 Base Wingsail with 15°deflection(a)

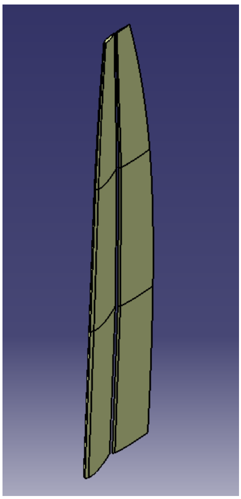
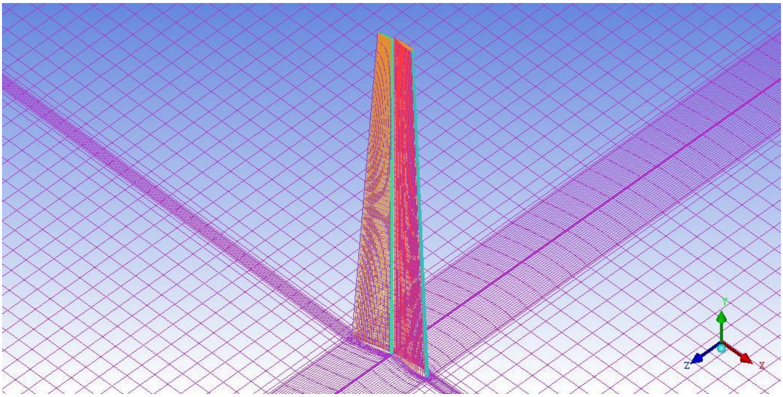


Figure 3.5 America's Cup Wingsail with 15°deflection(a)

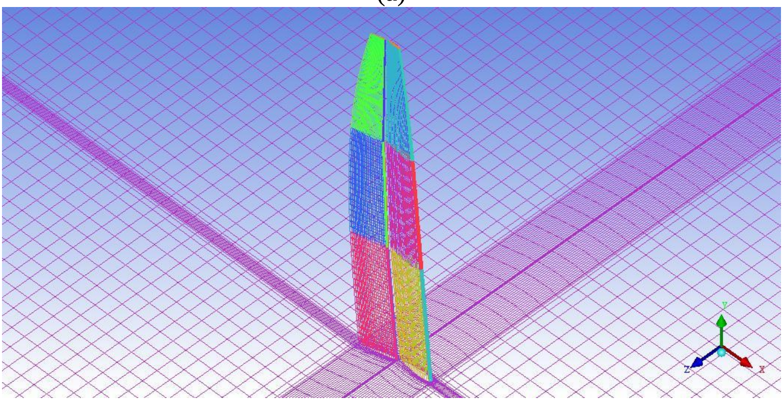
3.3 Meshing

At this step meshing created mostly same as geometry, basically the meshing formation is to enclose existing geometry with certain meshing elements. The function of elements itself as a finite volume for matemathics calculation to indicate that simulation with physics input.

Base geometry with 15° and all variations deflection flap are use ~0.75 million elements as shown below



(a)



(b)

Figure 3.6 Meshing of base wingsail 15° deflection(a) AC Class Cup Mod 15° deflection(b)

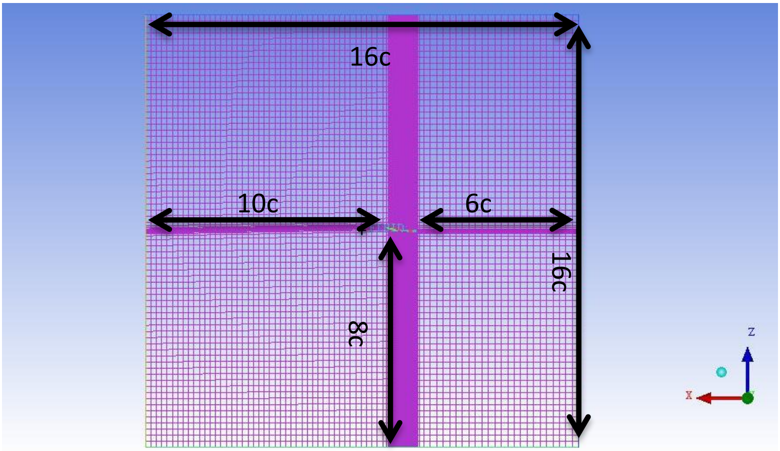


Figure 3.7 Domain computation meshing

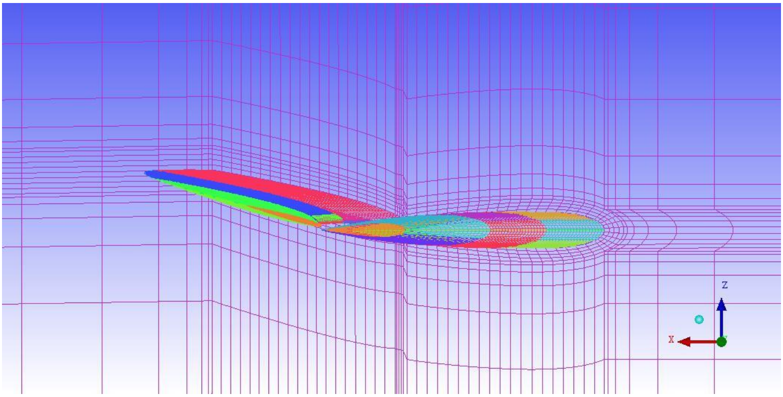


Figure 3. 8 Meshing inflation growth around geometry

The domain configuration used H-meshing type in the setting are followed by the front of wingsail facing are inlet also the windward side or the left side of wingsail are inlet, for the top side of the domain are inlet. The leeward side or the right side of the wingsail are outlet and behind the wingsail are outlet. The bottom side and airfoil are wall. The bottom side as wall are act as sea surface. And for the inflation growth meshing are used in this meshing.

3.4 Pre-Processing

On the pre-processing are prepare the simulation by configure the unit of the fluid flows characteristic to get better setup while the simulation running in this case use an incompressible flow that's mean the configuration of the boundary inlet as inlet velocity and outlet as pressure outlet and the analysis type are steady-state and use Reynold Averaged Navier-Stokes equation incompressible with k-ω model equation. One the main problem, it turbulence modelling is the accurate prediction of flow separation from a smooth surface. For this reason, author used k-ω turbulence model to advance for the application of the analysis on this research. On the simulation used setup with:

Table 3. 1 Simulation configuration setup

Viscous model	k-ω SST	
Fluid Density	1.225 kg/m^3	
Velocity	15 knot	
Dynamic Viscosity	1.831 x 10^{-5} kg/ m·s	
Domain Setup		
Inlet	Velocity Inlet	15 knot
Outlet	Pressure Outlet	0 Pa
Wall	No slip wall	

.

CHAPTER IV
DATA ANALYSIS AND DISCUSSION

4.1 Result Data Analysis

From the results data analysis showing that ACC wingsail provide more power to propel the sailing vessels its cause by the aerodynamics shape of the wingsail itself and the more surface of the ACC wingsail and ACC wingsail has more aerodynamics shape than base wingsail.

For the simulation in this research based on previous research on the effect of sail loading distribution by calculating lift and resistant force on sail as shown below:

a. Coefficient Lift and Coefficient Drag

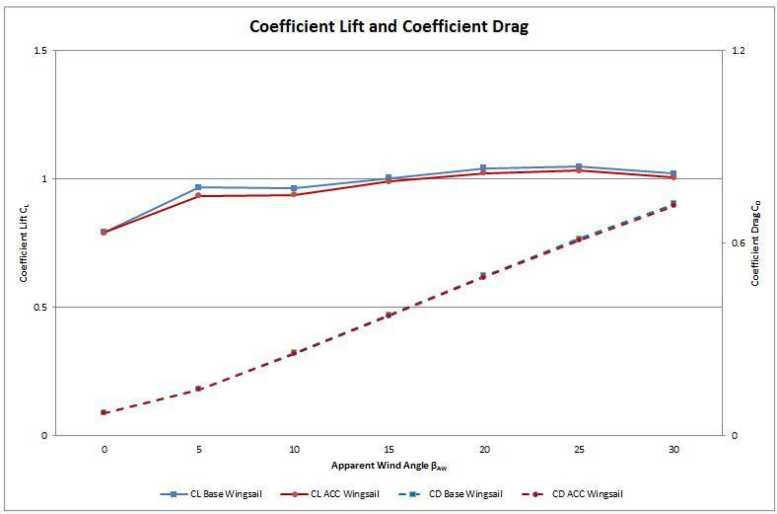


Figure 4. 1 Coefficient lift and Coefficient Drag for base and ACC wingsail with 15° deflection flap

Results from the analysis comparing the coefficient lift on both wingsail with 15° deflection flap as shown on the figure 4.1, increasing of the Base wingsail on ACC wingsail. The significant difference value at 5° and 10° apparent wind angle with increasing value 3.65% and 2.7%. And In coefficient drag ACC wingsail slightly small coefficient drag than Base wingsail at 25° and 30° with increasing value 0.9% and 0.77%. Depend on its coefficient both lift and drag ACC wingsail has more bigger surface than Base wingsail.

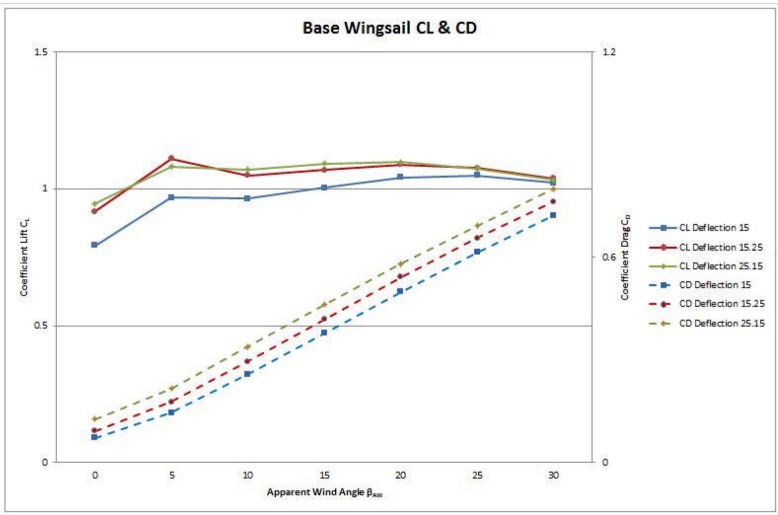


Figure 4. 2 Correlation CL & CD in all variation Base Wingsail

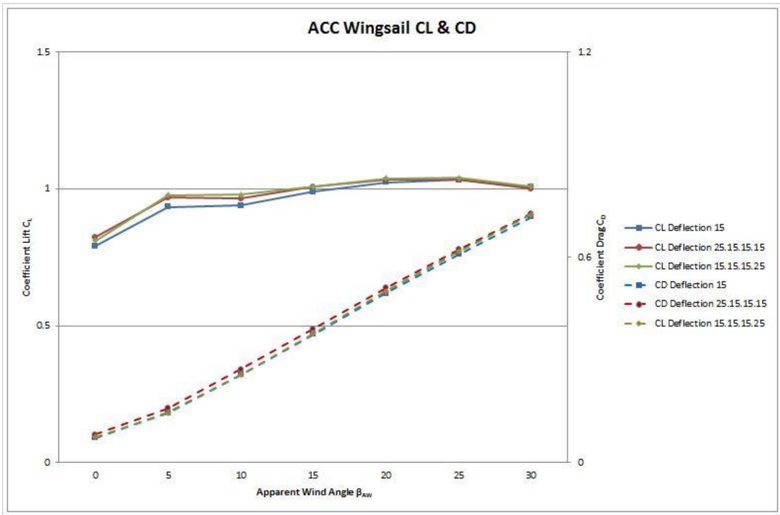


Figure 4. 3 Correlation CL & CD in all variation ACC Wingsail

As shown on graph higher coefficient lift has on base wingsail It's because the same condition apply with base wingsail that has more smaller surface than ACC wingsail, so Base wingsail has advantage to gaining higher coefficient lift and drag. But see on figure 4.3 ACC wingsail more stable in any apparent wind angle than base wingsail.

b. twist

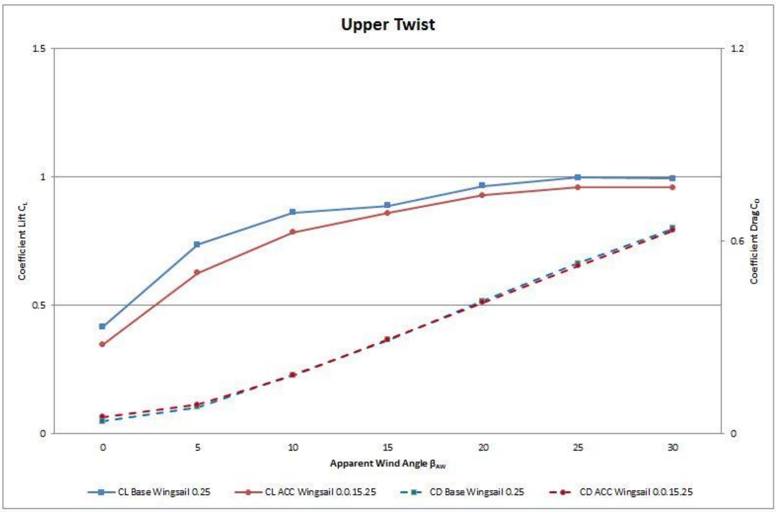


Figure 4. 4 Upper twist variation for Base wingsail and ACC wingsail

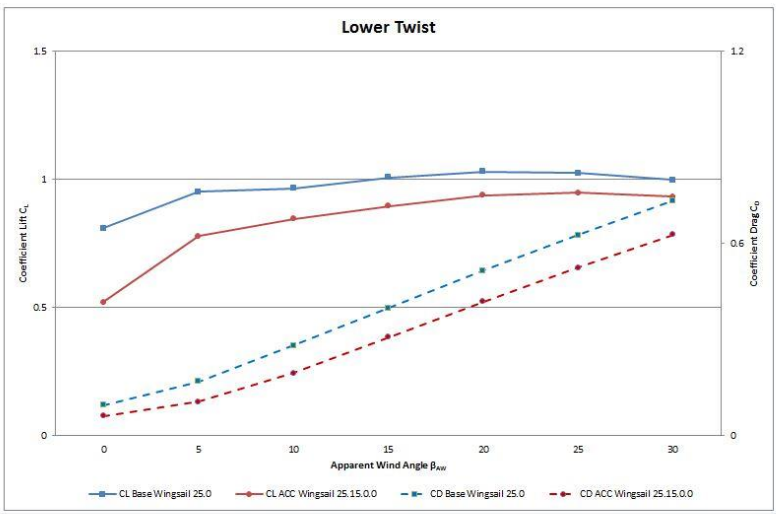


Figure 4. 5 Lower twist variation for Base wingsail and ACC wingsail

On the graph shown that the lift coefficient and drag coefficient between two variation twist at the base(lower) of the wingsail and top(upper) of the wingsail. Same condition before the ACC wingsail has small coefficient lift than base wingsail. But in this condition the increasing of drag coefficient at base wingsail and decreasing of drag coefficient at ACC wingsail when gaining deflection at lower of the wingsail. At the result the base wingsail weakness at the lower part of the wingsail. And the ACC wingsail has more aerodynamic shape at the tail end of the wingsail resulting the aerodynamic phenomena between both wingsail.

c. Aerodynamics Force 15° Flap Deflection

Figure 4. 6 Lift Force component Base and ACC wingsail with 15° deflection flap

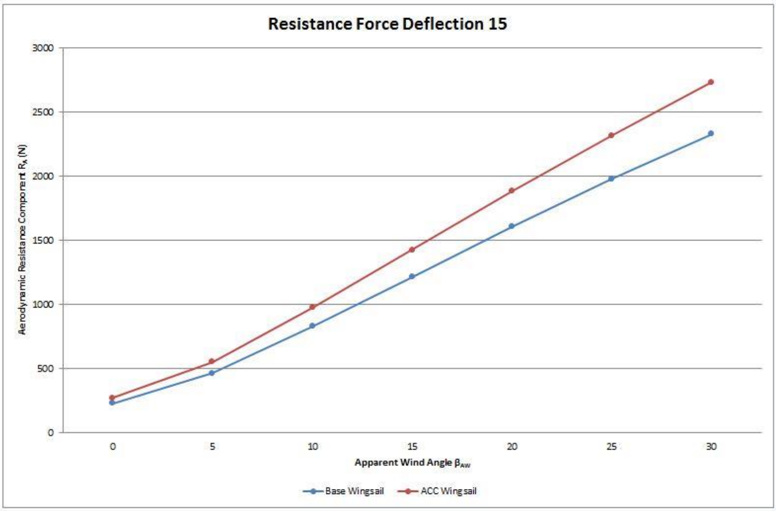


Figure 4. 7 Resistant Force component Base and ACC wingsail with 15° deflection flap

On the graph shown that the lift and resistant load value for ACC wingsail are more dominant than base wingsail both upwind at 0° apparent wind angle base wingsail has value of 2787.1 Newton and ACC wingsail are 3287.8 Newton. For upwind load value more affected by lift force for this case ACC provide more 500.7 newton force more than base wingsail. For at maximum difference load value affected by drag force at 30° apparent wind angle for base wingsail 4391 Newton and for ACC wingsail are 5141.5 Newton. At 30° apparent wind angle ACC wingsail more dominant with 750.5 more newton force.

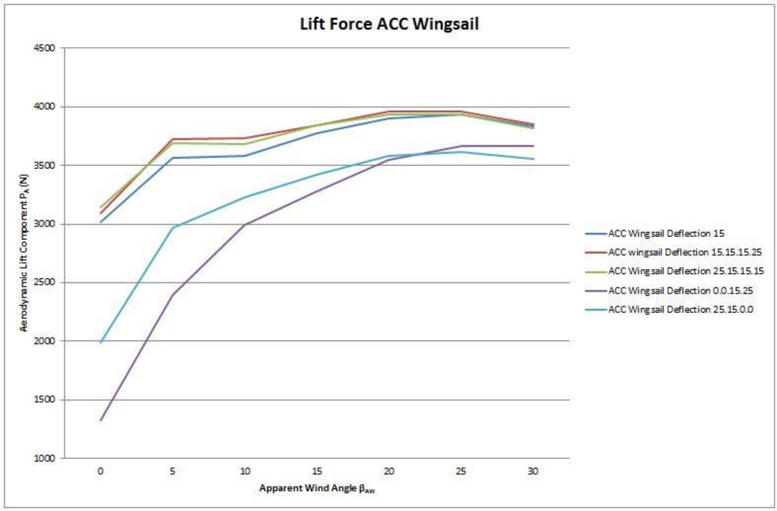


Figure 4. 8 Correlation lift force in all variation ACC Wingsail

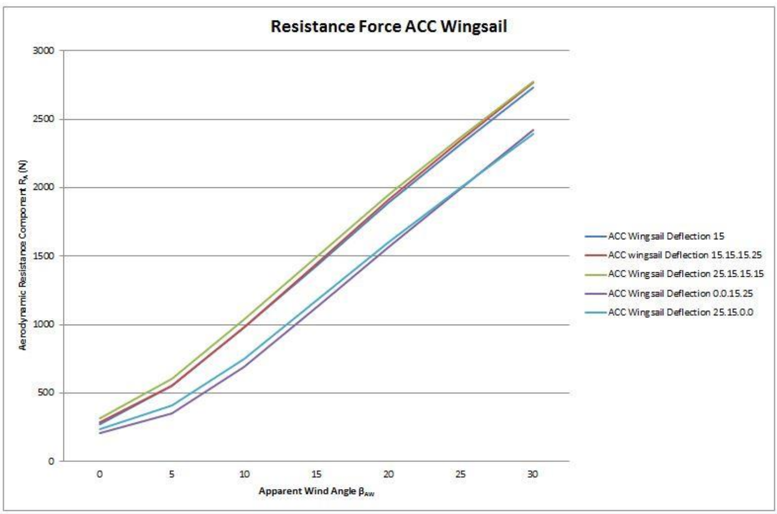


Figure 4. 9 Correlation resistance force in all variation ACC Wingsail

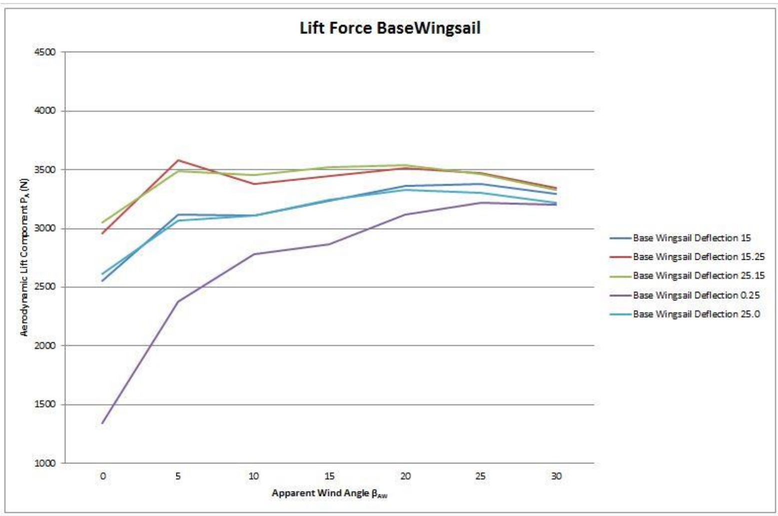


Figure 4. 10 Correlation lift force in all variation Base Wingsail

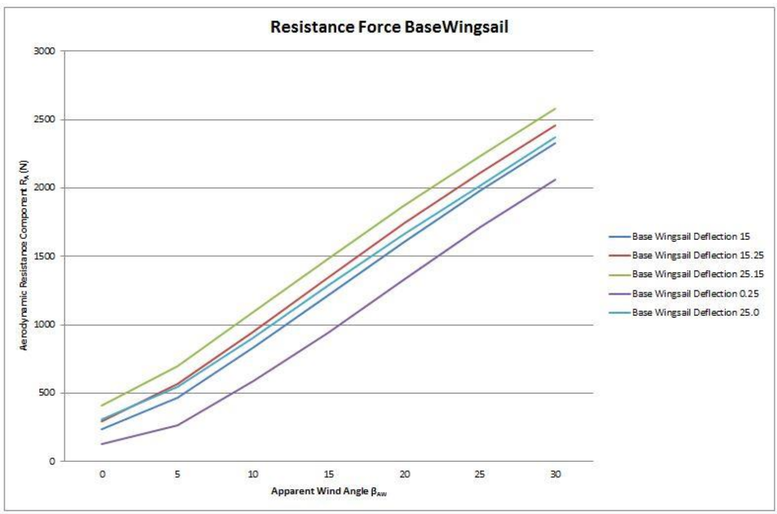


Figure 4. 11 Correlation Resistance force in all variation Base Wingsail

In all 4 of the graph shown that ACC wingsail dominant in both lift force and resistance force. The result between lift force and resistance force can gain power on thrusting power but depend on the deflection arm variation can get the higher thrust force.

d. Thrust force 15° Flap Deflection

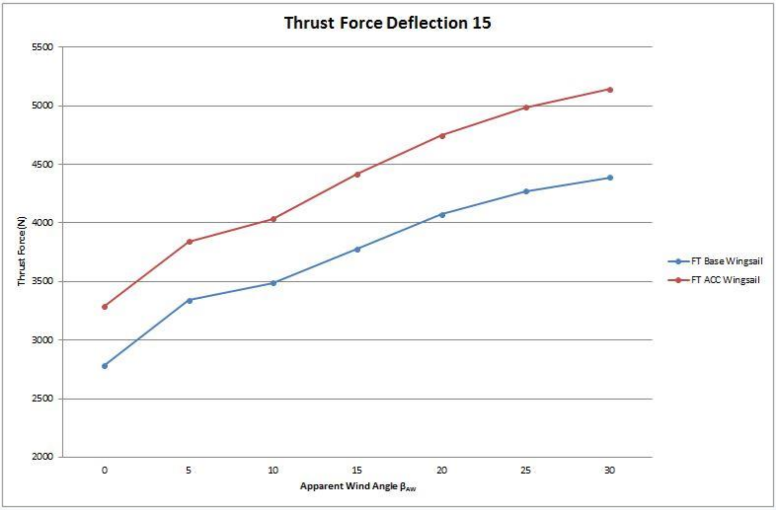
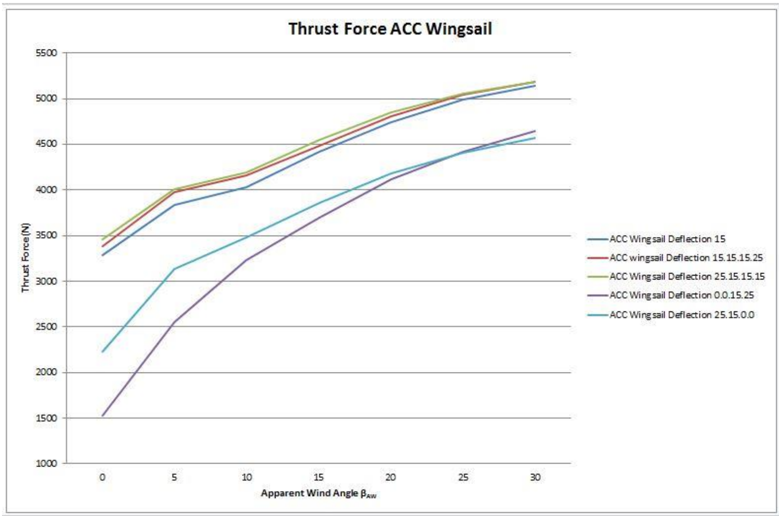
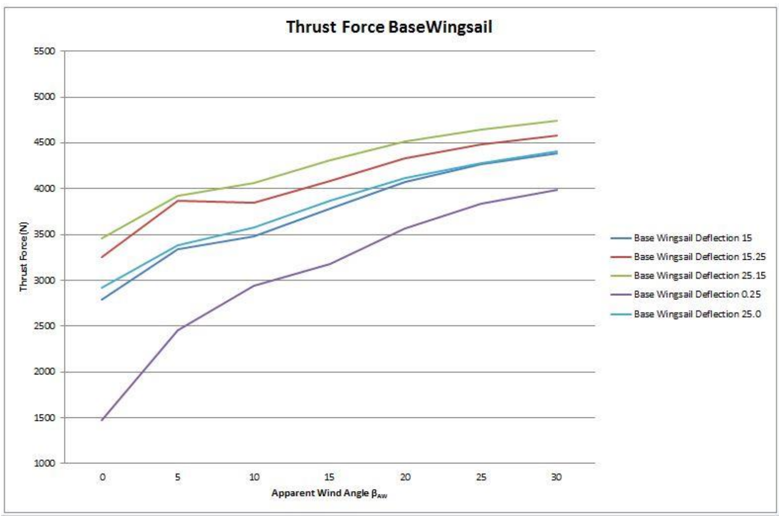


Figure 4. 12 Total Aerodynamics Force Base and ACC wingsail with 15° deflection flap



(a)



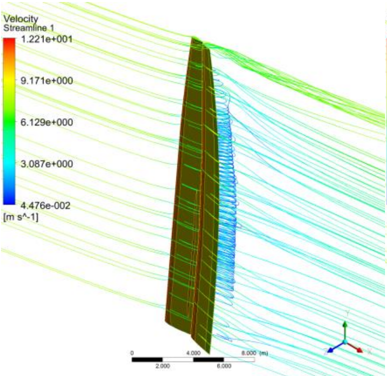
(b)

Figure 4. 13 Total Aerodynamics Force ACC wingsail in all variations(a) and Base wingsail in all variations(b)

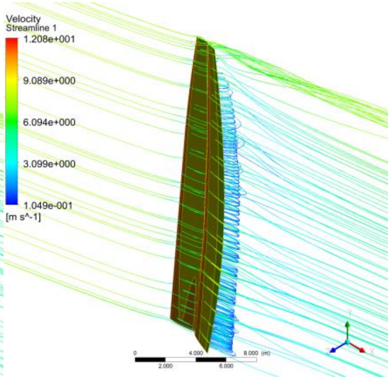
Thrust force generate boats speed are the total of aerodynamics force on sail. The ACC wingsail provide more force than base wingsail on both flap deflections. Higher force at β_{AW} = 30°, the analysis from graph 4.12, 4.13(a) and 4.13(b) ACC wingsail provide more for because the surface area of the ACC wingsail more wider than base wingsail. And ACC wingsail has aerodynamics model than base wingsail has more stiff model. And the aero-hydrodynamics use in sailing use both lift and drag.

4.2 Flow analysis

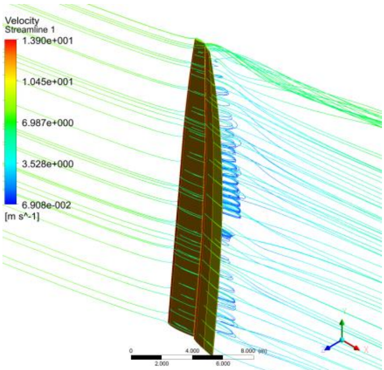
The flow profile of the base wingsail and ACC wingsail shown the base wingsail produce more vortex at top tip of the wingsail but ACC wingsail can minimalize the vortex because of ACC wingsail have more power arm to control the deflection of its flap shown on figure 4.7. And the flow dragged and concern the force on the center of effort of the wingsail to gaining more power from the lift and drag to propel the sailing vessels. The force that apply more power are resultant of the lift and drag. At 10° of apparent wind angle didn't find any turbulence that means at this angle produce more lift force and drag force. On both deflection angle didn't show stall on the both pressure side and suction side of the main element. But on the flap element stall begin showed caused by flow of the gap collide with the flow on suction side. Small lift force are caused the small apparent wind angle



(a)

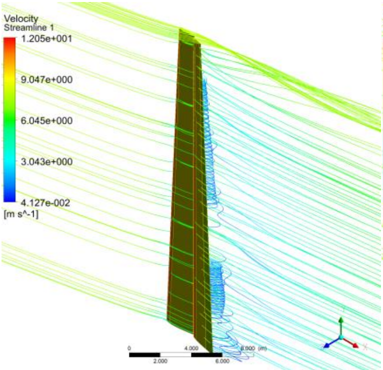


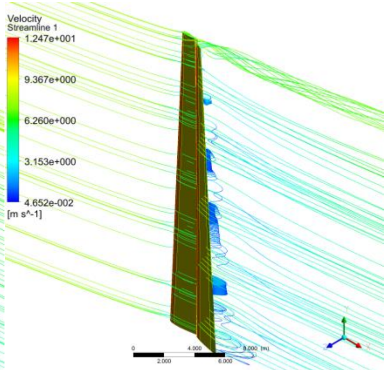
(b)



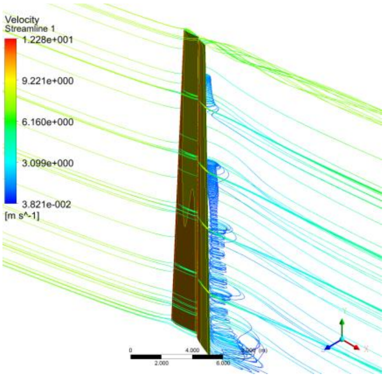
(c)

Figure 4. 14 Flow Profile at β_{AW} 10 degree ACC wingsail (a) δ = 15° (b) δ = 25.15.15.15° (c) δ =15.15.15.25°





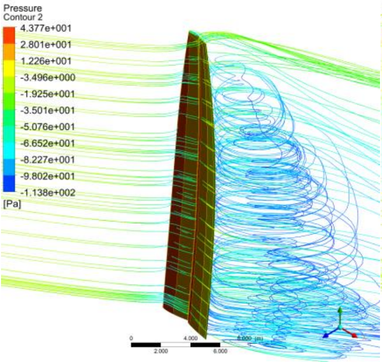
(a) (b)



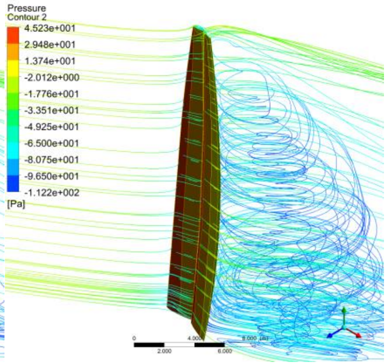
(c)

Figure 4. 15 Flow Profile at β_{AW} 10 degree Base wingsail (a) $\delta = 15°$ (b) $\delta = 15.25°$ (c) $\delta = 25.15°$

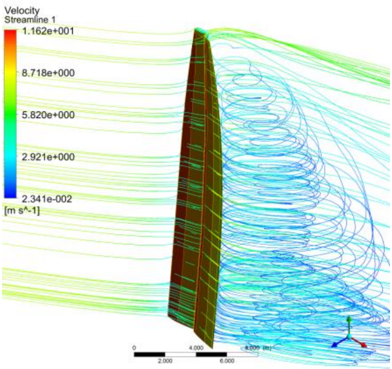
Flow profile of both wingsail at 30° apparent wind angle begin showing stall on the suction side on the main element and flap element that axial force of the wingsail are minimalize showed at figure 4.8. But at this angle both wingsail produce higher lift force it caused by the pressure at the suction side and pressure side near equilibrium on the both side. At this apparent wind angle and at 10° apparent wind angle as known as upwind sailing its mean sailing need more lift power than drag power.



(a)

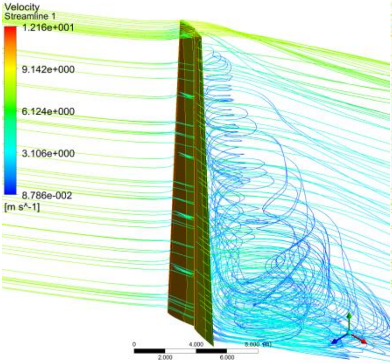


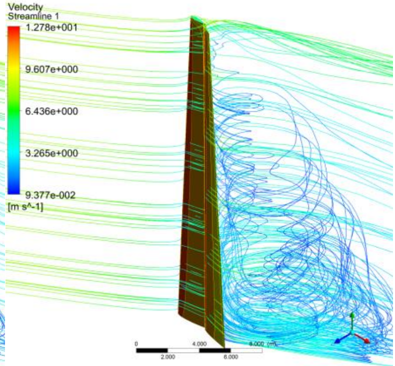
(b)



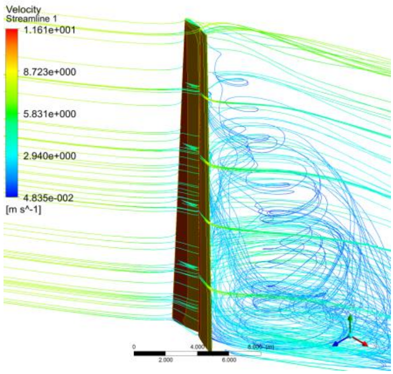
(c)

Figure 4. 16 Flow Profile at β_{AW} 30 degree ACC wingsail (a) δ = 15° (b) δ = 25.15.15.15° (c) δ =15.15.15.25°





(a) (b)

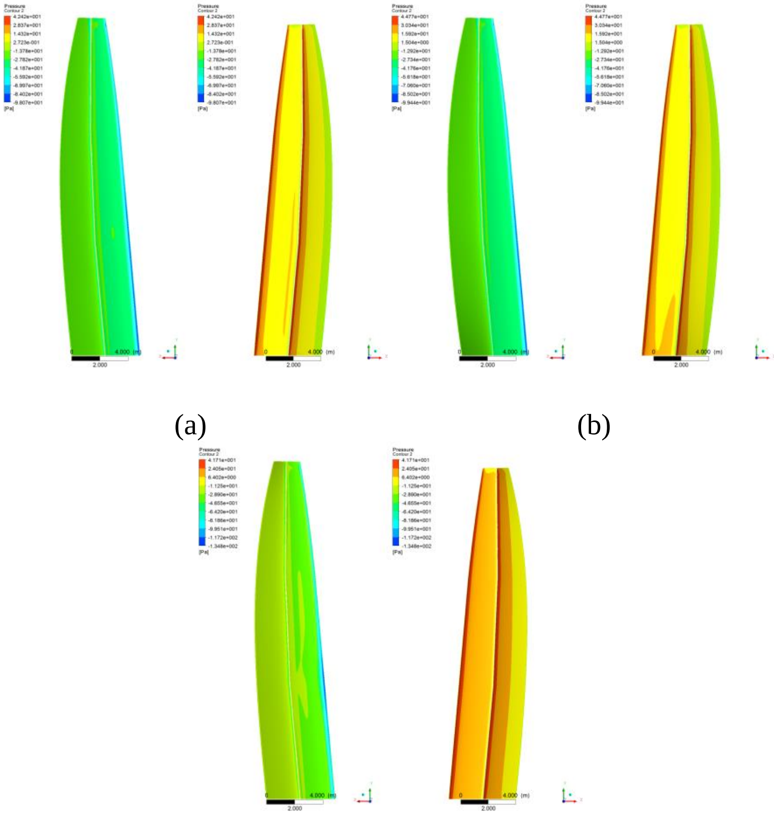


(c)

Figure 4. 17 Flow Profile at β_{AW} 30 degree Base wingsail (a) $\delta = 15°$ (b) $\delta = 15.25°$ (c) $\delta = 25.15°$

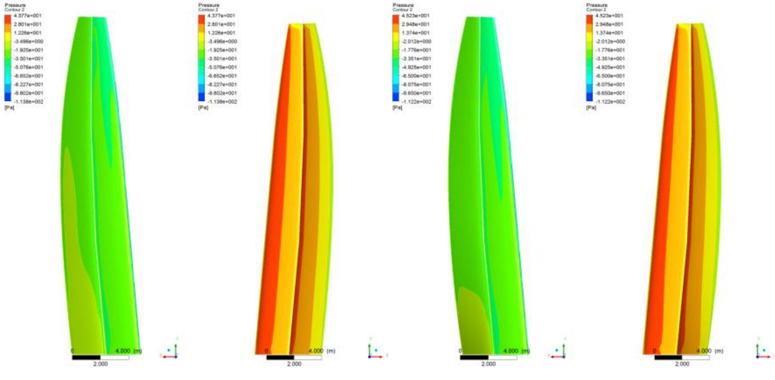
4.3 Pressure Distribution

The Pressure distribution of the base wingsail and ACC wingsail to analyse in changing of deflection because in the area of wider deflection angle provide higher pressure it’s because the wind speed slowly passing the gap at the wider deflection. And the results of different deflection can cause the heeling moment or heeling force. And the higher apparent wind cause gaining in heeling moment and heeling force.

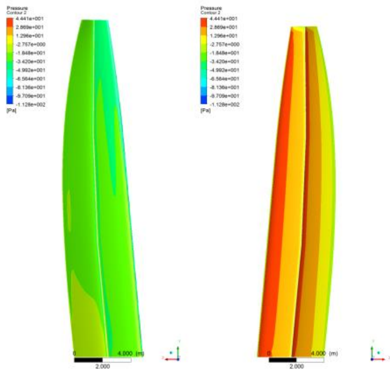


(c)

Figure 4. 18 Pressure distribution at β_{AW} 10 degree ACC wingsail (a) δ = 15° (b) δ = 25.15.15.15° (c) δ =15.15.15.25°



(a) (b)



(c)

Figure 4. 19 Pressure distribution at β_{AW} 30 degree ACC wingsail (a) δ = 15° (b) δ = 25.15.15.15° (c) δ =15.15.15.25°

As shown above the increasing apparent wind angle it will be showing the pressure increasing at the area has wider deflection angle.

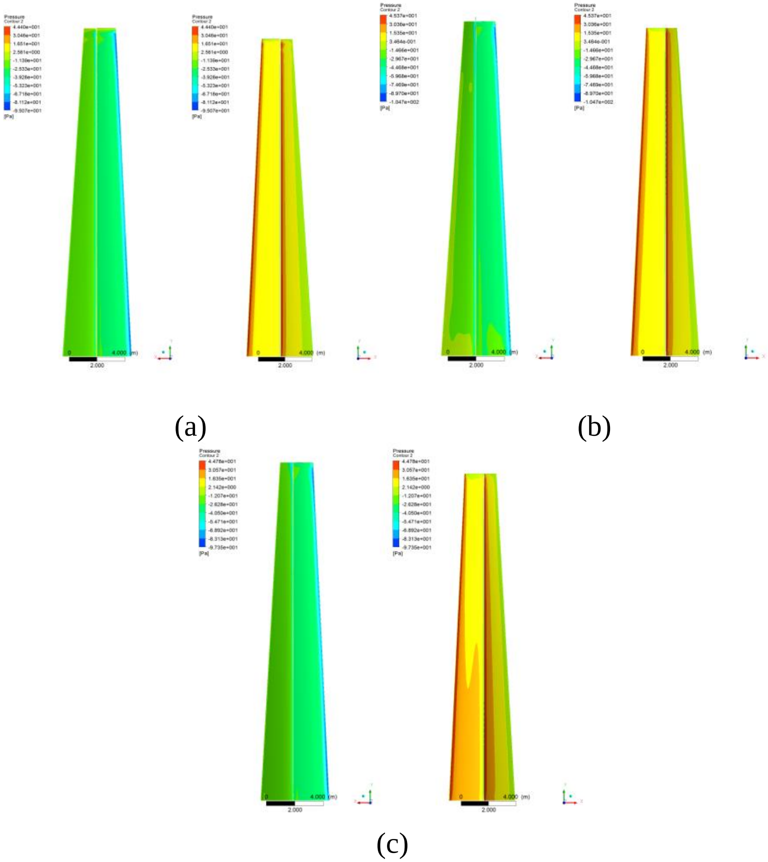
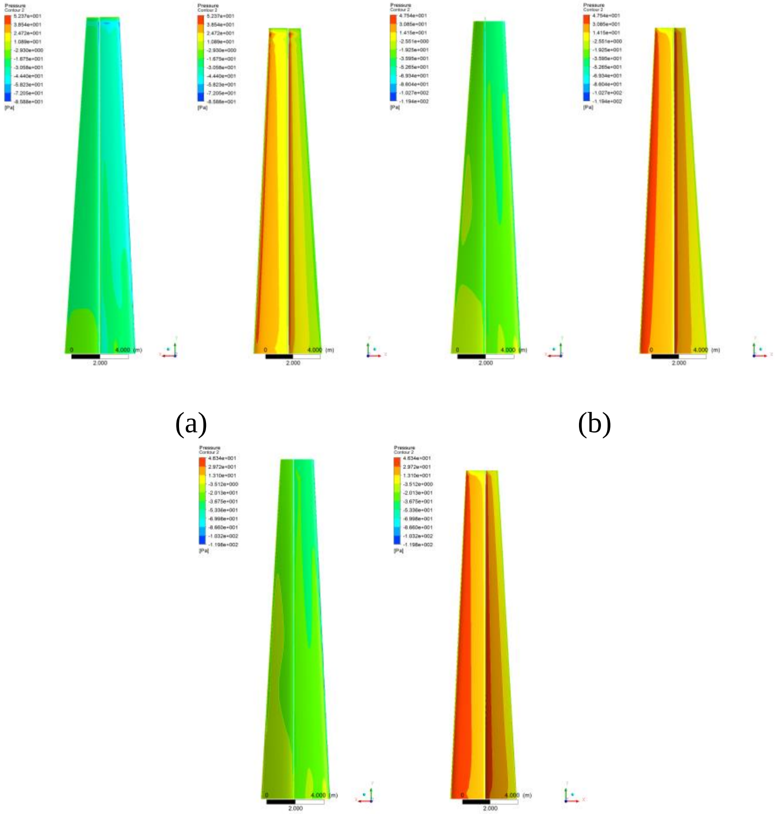


Figure 4. 20 Pressure distribution at β_{AW} 10 degree Base wingsail (a) δ = 15° (b) δ = 25.15.15.15° (c) δ =15.15.15.25°



(a) (b)

(c)

Figure 4. 21 Pressure distribution at β_{AW} 30 degree ACC wingsail (a) δ = 15° (b) δ = 25.15.15.15° (c) δ =15.15.15.25°

In the graph above different between ACC wingsail and base wingsail the ACC wingsail slightly gaining pressure at the base part of the wingsail different on base wingsail has gaining more pressure at the lower part at the wingsail. The gaining pressure itself can be cause gaining heeling moment of the yacht that can be made the yacht unstable. The different of both wingsail is the shape the base wingsail is more stiff than ACC wingsail. That can be reduce stalling at the suction side of the wingsail.

4.4 Yacht Velocity Prediction

Generate the thrust force of the wingsail to yacht velocity by calculating the resistance on hull the velocity of the boat at wind speed at 15 knots with operational β_{AW} 30° is 18 knots at ACC wingsail deflection configuration 15.15.15.25 at standard or lower speed for ACC wingsail at 13 knots for β_{AW} 15°. For the base wingsail with deflection configuration 25.15 the maximum speed at 16 knots. Different speed output determine from thrust force. And thrust force itself affected by the area of the sail, deflection and $\beta_{AW.}$

4.5 Discussion

From the research that ACC wingsail design provide more efficient force cause by geometry of wingsail itself are more wider than base wingsail and for the trailing edge from acc wingsail provide more aerodynamics because the model of ACC wingsails has more control arm that can control at different angle at different level flap. The ACC wingsail flap divide by 3 flap element to provide more controlling aerodynamics to affects force and loading to wingsail to get better performance sailing. But there must be a problem in this case. On ACC wingsail got more broader wetted surface area that mean can be more provide heeling force than base wingsail. From the previous research by Blakeley et al, on the experiment investigate the aerodynamic force of main element and flap element of wingsail by using NACA 0018 as main and NACA 0008 as flap for the best result by depend on main element thickness 25% chord symmetry airfoil and flap element thickness 10% chord symmetry airfoil. The yacht between base wingsail and ACC wingsail has slight difference because the advantage of the shape and the controlling arm on the wingsail didn’t showed because in this case didn’t simulated with heeling, rolling and pitching of the yacht itself. The wingsail itself was the only propulsion used to estimate the yacht velocity, the fore or jib sail didn’t analysed. And the operational apparent wind angle maximum at 30°.

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CHAPTER V
CLOSING

5.1 Conclusion

From this research has been shown that are more aerodynamics geometry can provide more lift force and resistance force. And for indicating more detail against interaction of fluid around surface of wingsail better viscous model are suggested. In this research are use k-Omega SST turbulence model that are poor model for indicating bubble separation on wingsail surface. For n+1 high lift device are more suitable if analysis can be deeper. As in this case, wingsail as high lift device it must be more interaction between fluid and wingsail affected for efficiency. More thrust force showing that sailing vessels sail faster as the effect of the load distribution. The results of the thrust force affected by lift force and resistance force depend on the geometry of the wingsail. ACC wingsail are recent geometry are better, simple and easy to used. The performance of ACC wingsail are tested on many research and experiments. The wingsail are recent future model of sailing than traditional sailing cloth. But, on the maintenance rigid wingsail is more difficult. Its need to be developed for folded wingsail and keep it performance. And the involving of the shape of airfoil on wingsail and deflection arm. Because at this case the different angle at each deflection arm cause increasing pressure at the part which deflection arm increasing. Also the gap between two airfoil take effect of the aerodynamic force from the wingsail. Deflection at 25 degree are to wider and can be reduce aerodynamics force along wingsail absolutely at the 15 degree is the maximum deflection. The ACC wingsail take advantage of the base wingsail because has more area and controlling arm, the advantage is gaining more thrust force and can be more controlling the flow along the wingsail with control arm. The difference of yacht velocity that affected to with the shape and flow of fluid along the wingsail that can be resistance for the yacht velocity.

5.2 Suggest

For better analytical there must be used more advance turbulence model that can be predict advance fluid phenomena. And for future research may can be predict the separation bubble that can affect the flow on wingsail surface. By using transient turbulene model. The more optimum analyse is more about the wingsail at more apparent wind angle bigger than 30 degree for analyse the full downwind sailing and the structural analyse for detect the bending or crack on the wingsail. And the choice of the hull to maximum analyse at yacht velocity at hydrodynamics analysis.

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APPENDICES

Table analyse on both wingsail

Base Wingsail		Def Conf : 25.15								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	3054	409.3	3054	409.3	0.947475	0.126981	3054	-409.3	3463.3
15	5	3535	389.6	3487.592	696.213	1.081993	0.215994	3535	-389.6	3924.6
15	10	3589	478.2	3451.436	1094.158	1.070776	0.339452	3589	-478.2	4067.2
15	15	3788	524.2	3523.254	1486.745	1.093056	0.461249	3788	-524.2	4312.2
15	20	3967	547.8	3540.402	1871.558	1.098376	0.580633	3967	-547.8	4514.8
15	25	4086	558.5	3467.141	2232.991	1.075648	0.692764	4086	-558.5	4644.5
15	30	4176	568.9	3332.072	2580.682	1.033744	0.800632	4176	-568.9	4744.9

ACC Wingsail		Def Conf : 25.15.15.15								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	3142	312.8	3142	312.8	0.824451	0.082078	3142	-312.8	3454.8
15	5	3729	279.3	3690.467	603.2409	0.968367	0.158289	3729	-279.3	4008.3
15	10	3804	384.6	3679.424	1039.315	0.96547	0.272713	3804	-384.6	4188.6
15	15	4098	446.8	3842.724	1492.216	1.008319	0.391553	4098	-446.8	4544.8
15	20	4364	483.4	3935.486	1946.823	1.03266	0.510841	4364	-483.4	4847.4
15	25	4570	486.7	3936.138	2372.465	1.032831	0.622528	4570	-486.7	5056.7
15	30	4694	495.6	3817.323	2776.202	1.001654	0.728467	4694	-495.6	5189.6

Base Wingsail		Def Conf : 15.25								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	2959	295.7	2959	295.7	0.918002	0.091738	2959	-295.7	3254.7
15	5	3617	254.7	3581.038	568.9731	1.110983	0.176519	3617	-254.7	3871.7
15	10	3495	350	3381.126	951.5831	1.048963	0.29522	3495	-350	3845
15	15	3678	408.6	3446.922	1346.614	1.069375	0.417774	3678	-408.6	4086.6
15	20	3896	441.2	3510.143	1747.103	1.088989	0.542022	3896	-441.2	4337.2
15	25	4040	448.5	3471.939	2113.857	1.077136	0.655804	4040	-448.5	4488.5
15	30	4128	455.2	3347.353	2458.215	1.038485	0.762638	4128	-455.2	4583.2

ACC Wingsail		Def Conf : 15.15.15.25								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	3095	286.7	3095	286.7	0.812119	0.075229	3095	-286.7	3381.7
15	5	3759	223.1	3725.251	549.8695	0.977495	0.144284	3759	-223.1	3982.1
15	10	3844	315.9	3730.746	978.6044	0.978936	0.256783	3844	-315.9	4159.9
15	15	4085	396.3	3843.237	1440.072	1.008454	0.377871	4085	-396.3	4481.3
15	20	4373	438.6	3959.266	1907.803	1.038899	0.500602	4373	-438.6	4811.6
15	25	4586	455.2	3963.952	2350.679	1.040129	0.616811	4586	-455.2	5041.2
15	30	4717	469.5	3850.292	2765.099	1.010305	0.725554	4717	-469.5	5186.5

Base Wingsail		Def Conf : 0.25								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	1343	127	1343	127	0.416653	0.039402	1343	-127	1470
15	5	2391	59.9	2376.681	268.0614	0.737343	0.083164	2391	-59.9	2450.9
15	10	2839	101	2778.331	592.4528	0.861951	0.183803	2839	-101	2940
15	15	3013	169.3	2866.517	943.3530	0.889310	0.292666	3013	-169.3	3182.3
15	20	3384	187.9	3115.654	1333.964	0.966602	0.413850	3384	-187.9	3571.9
15	25	3642	190	3220.476	1711.374	0.999122	0.530938	3642	-190	3832
15	30	3808	184.1	3205.775	2063.435	0.994561	0.640161	3808	-184.1	3992.1

ACC Wingsail		Def Conf : 0.0.15.25								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	1323	203.2	1323	203.2	0.347151	0.053319	1323	-203.2	1526.2
15	5	2413	141	2391.529	350.7703	0.627530	0.092041	2413	-141	2554
15	10	3066	162	2991.290	691.9442	0.784910	0.181564	3066	-162	3228
15	15	3457	235.2	3278.331	1121.923	0.860224	0.294390	3457	-235.2	3692.2
15	20	3865	254.9	3544.731	1561.436	0.930127	0.409716	3865	-254.9	4119.9
15	25	4161	259.3	3661.562	1993.520	0.960783	0.523094	4161	-259.3	4420.3
15	30	4382	264.4	3662.723	2419.977	0.961088	0.634995	4382	-264.4	4646.4

Base Wingsail		Def Conf : 25.0								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	2610	309.1	2610	309.1	0.809728	0.095895	2610	-309.1	2919.1
15	5	3108	278.9	3071.865	548.7188	0.953017	0.170235	3108	-278.9	3386.9
15	10	3222	354.8	3111.440	908.9042	0.965295	0.281979	3222	-354.8	3576.8
15	15	3470	403.4	3247.356	1287.757	1.007461	0.399514	3470	-403.4	3873.4
15	20	3694	425.7	3325.627	1663.450	1.031744	0.516070	3694	-425.7	4119.7
15	25	3847	433	3303.572	2018.244	1.024902	0.626141	3847	-433	4280
15	30	3971	441.7	3218.137	2368.023	0.998397	0.734656	3971	-441.7	4412.7

ACC Wingsail		Def Conf : 25.15.0.0								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	1992	234.7	1992	234.7	0.522695	0.061585	1992	-234.7	2226.7
15	5	2995	144.9	2970.974	405.3801	0.779575	0.106371	2995	-144.9	3139.9
15	10	3306	177.2	3225.004	748.5888	0.846231	0.196427	3306	-177.2	3483.2
15	15	3607	249.4	3419.545	1174.462	0.897278	0.308175	3607	-249.4	3856.4
15	20	3909	278.3	3578.074	1598.473	0.938876	0.419435	3909	-278.3	4187.3
15	25	4120	285.6	3613.288	2000.029	0.948116	0.524802	4120	-285.6	4405.6
15	30	4279	294.4	3558.523	2394.458	0.933746	0.628299	4279	-294.4	4573.4

Base Wingsail		Deflection 15°								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	2555	232.1	2555	232.1	0.792665	0.072007	2555	-232.1	2787.1
15	5	3151	193.7	3122.127	467.5907	0.968611	0.145066	3151	-193.7	3344.7
15	10	3205	281.1	3107.496	833.3719	0.964072	0.258546	3205	-281.1	3486.1
15	15	3441	338.2	3236.218	1217.272	1.004006	0.377647	3441	-338.2	3779.2
15	20	3709	363.5	3360.996	1610.131	1.042717	0.499530	3709	-363.5	4072.5
15	25	3904	366.5	3383.336	1982.064	1.049648	0.614917	3904	-366.5	4270.5
15	30	4019	372	3294.556	2331.662	1.022105	0.723376	4019	-372	4391

ACC Wingsail		Deflection 15°								
V_A	β_{AW}	N	A	P_A	R_A	C_L	C_D	F_{LAT}	F_R	F_T
15	0	3015	272.8	3015	272.8	0.791127	0.071582	3015	-272.8	3287.8
15	5	3596	241.4	3561.277	553.8935	0.934468	0.14534	3596	-241.4	3837.4
15	10	3693	340.8	3577.716	976.9052	0.938782	0.256337	3693	-340.8	4033.8
15	15	4017	403.1	3775.794	1429.041	0.990757	0.374976	4017	-403.1	4420.1
15	20	4311	437.4	3901.415	1885.470	1.023720	0.494742	4311	-437.4	4748.4
15	25	4547	441.1	3934.565	2321.418	1.032418	0.609133	4547	-441.1	4988.1
15	30	4691	450.5	3837.275	2735.644	1.006889	0.717825	4691	-450.5	5141.5

Table hydrodynamics resistance of hull

Speed (knot)	Froude Number LWL	Froude Number Vol.	Holtrop Ressist (N)	Holtrop Power (kW)
5	0.211	0.693	489.72	1.26
5.625	0.237	0.78	638.87	1.849
6.25	0.264	0.866	830.87	2.671
6.875	0.29	0.953	1082.08	3.827
7.5	0.317	1.04	1408.74	5.435
8.125	0.343	1.126	1819.68	7.606
8.75	0.369	1.213	2314.97	10.421
9.375	0.396	1.299	2890.04	13.938
10	0.422	1.386	2943.17	15.141
10.625	0.449	1.473	2898.43	15.843
11.25	0.475	1.559	2864.74	16.58
11.875	0.501	1.646	2842.03	17.362
12.5	0.528	1.733	2830.25	18.2
13.125	0.554	1.819	2868.64	19.369
13.75	0.58	1.906	3133.32	22.164
14.375	0.607	1.993	3409.55	25.214
15	0.633	2.079	3697.38	28.531
15.625	0.66	2.166	3996.88	32.128
16.25	0.686	2.252	4308.1	36.014
16.875	0.712	2.339	4631.07	40.203
17.5	0.739	2.426	4965.84	44.706
18.125	0.765	2.512	5312.45	49.535
18.75	0.792	2.599	5670.92	54.701
19.375	0.818	2.686	6041.27	60.216
20	0.844	2.772	6423.53	66.091

Speed (knot)	Froude Number LWL	Froude Number Vol.	Holtrop Ressist (N)	Holtrop Power (kW)
20.625	0.871	2.859	6817.69	72.339
21.25	0.897	2.945	7223.76	78.97
21.875	0.923	3.032	7641.73	85.996
22.5	0.95	3.119	8071.6	93.429
23.125	0.976	3.205	8513.33	101.279
23.75	1.003	3.292	8966.91	109.558
24.375	1.029	3.379	9432.31	118.277
25	1.055	3.465	9909.49	127.447
25.625	1.082	3.552	10398.42	137.079
26.25	1.108	3.638	10899.06	147.183
26.875	1.135	3.725	11411.36	157.77
27.5	1.161	3.812	11935.26	168.851
28.125	1.187	3.898	12470.73	180.436
28.75	1.214	3.985	13017.72	192.536
29.375	1.24	4.072	13576.15	205.16
30	1.266	4.158	14145.99	218.32

Author profile

Author was born on May 3, 1994 in Surabaya, Indonesia. Is the second child from four siblings. Author was sail through formal academy in SDN Banyu Urip III Surabaya, SMPN 33 Surabaya, SMA GEMA 45 Surabaya, and finally be a student on engineering physics department Institut Teknologi Sepuluh Nopember in 2013, through SBMPTN test. Beside as a student, author activity was more on sport especially in sailing. In junior high school till senior high school author join and doing social project in author home town in Surabaya, the social project is an association of youth to develop a culture in Banyu Urip, Putat Jaya and around. As a student, author recently recognize about sailing sport and steep into sailing. Author also ever join in international sailing competition twice in 2014 and 2017. In 2014, author join as a member/competitor of Indonesia team in Atlantic Challenge International(ACI) 2014, Vannes France. In 2017, author join as a member/competitor of Indonesia team in Student Yachting World Cup(SYWoC) 2017, Marseille, France. Proved by certificate that signed by president of the event between that author just as official at national sailing competition in Indonesia. Author hope, can develop sailing culture in Indonesia, and Indonesia can compete with the world like few century ago at the time Majapahit Kingdom which overcome Nusantara state. Author can be contact by e-mail : tomyreynaldi.ep@gmail.com.