

Analyzing the Effect of Biplane Design in Rigid Wing Sails Using CFD Simulation

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Abstract: The biplane design was used in several fields, including aviation, racing cars, and sailboats, but the research on bisail is quite few. However, bisail can bring many advantages such as increasing lift coefficient C_l , and enhancing the structural integrity. The possibility to replace the monosail by bisail with a higher aerodynamic efficiency are be detected. In this case. The research simulates and compares a rigid NACA0012 of chord length 1 m and a bisail with the same wing section but two parallel smaller wings with chord length 0.5 m each with separation 0.5m under Reynolds number 700k in ANSYS 2024 R1 student. In the simulation, the quadrilateral mesh and cell number 57k are finally used. For the results, the thrust coefficient C_t is compared in different angles of attack in both monosail and bisail. The best angle of attack in each driving direction is calculated. In addition, the parallel bisail is not better than the monosail for the current setting.

Keywords: Biplane, Angle of Attack, Airfoils, Lift and Drag Coefficient, NACA0012, CFD Simulation

1. Introduction

The biplane design has a great history and has been used in various contexts over time. Its application in sailboats appears to be an advancement. Although the origin of multiple wings can date to ancient Greece around 470 BC with the trireme—an ancient warship which used a main sail for regular navigation and a smaller sail for escape during battles [1]—the biplane design's influence on modern sailboats is more specialized as military using. During the Age of Sail, biplane design in sailboats was very popular in ocean-going ships, with sailboats often set with more than one mast. Compared to the trireme, these new designs can provide more power, driving the sailboats by only wind for no paddles. Those designs for sailing can adapt to dangerous conditions in the ocean [2]. However, the invention of steam engines, improved by innovator James Watt, transformed the focus from wind power to steam propulsion, leading to a dramatic decline in the use of traditional sailboats [3]. Until

the 21st century, sailboats restarted to play a new modern role in sports racing, where biplane designs are design for supreme performance. Modern biplane sailboats can achieve a significant high speed of over 100 km/h, showcasing the huge aerodynamic potential.

Biplane design in aviation is a similar case. A dramatic improvement was expected to offer double the lift compared to monoplanes, though this advantage did not become that high founded by many research, the decrease of the lift due to the "biplane effect" is only half as great if the lift is produced by the curvature as if it is produced by the angle of attack (AoA) higher lift coefficients which means the biplane design can get some benefits in lift [4]. In max research, he found an internal impact of two parallel airfoils and researched the design in a biplane. In the biplane design, the double foils can offer a larger total wing area, which means a larger lift force is produced. In the early biplane designs, for the same wingspan as a monoplane, a biplane can produce a larger lift force which means easier to fly. For the same total wing area, the biplane has a shorter airfoil which means more flexibility in the sky. On another hand, a larger wing area means a larger drag force, so the speed of the biplane is not an advantage of the design.

In sailing, the biplane design is expected to improve aerodynamic efficiency, potentially offering a better lift-to-drag ratio and enhanced wind utilization. Additionally, having more sails can improve structural integrity, as smaller sails on each mast may enhance stability [5]. Not as same as biplane, the angel of attack in sailboats should be considered in a larger angel which over the stalling. Unlike the biplane, which has been research quite completely, the biplane sailboats are less mentioned. In this research, its potential advantages in sailing, particularly in improving lift-to-drag ratios and aerodynamics have been researched. The research may have considerable potential to influence future sailboat designs, particularly in competitive sailing where aerodynamic efficiency is in the first place.

This thesis explores the application of biplane designs in sailboats by CFD in a 2D simulation. The simulation aims to determine whether a biplane design can offer a larger lift-to-drag ratio compared to a monoplane design in aviation. The simulation focuses on a sailboat with a total chord length of 1m, utilizing the NACA 0012 airfoil for analysis. The data generated from simulations are compared with the data made in the wind tunnel from Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree AoA for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines [6].

2. Methodology

2.1. CFD Model

In this study, the simulations were performed on the Ansys Fluent 2024R1 using the RANS model of $k - \Omega$ SST developed by [7].

For the k-omega SST model, except for solving the conservation equations, the equations of k (turbulent kinetic energy) and omega (specific turbulent dissipation rate) are also solved. The equations of k and omega are given by Eq 1 and Eq 2:

$$\frac{D\rho k}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (1)$$

$$\frac{D\rho \omega}{Dt} = \frac{\gamma}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (2)$$

$$\nu_t = \frac{a_1 k}{\max(a_1 \omega; \Omega F_2)} \quad (3)$$

In the equations, the $\sigma_k, \sigma_\omega, \beta^*, \beta_\gamma$ are constants. The $(1-F_1)$ is the blending function. The v_t is the eddy viscosity and is given by Eq 3. The Ω in Eq 3 is the vorticity, and F_2 is another blending function.

2.2. Geometry Choosing

NACA0012 was applied in the simulations. Since for sailboats the sail needs to generate lift from both sides to better adapt to different wind directions, the airfoil of a rigid sail should be symmetric. NACA0012 airfoil is a classical symmetric airfoil, so it was applied.

Figure 1 demonstrates the geometry and flow domain. For the size of the geometry, the chord length of the single airfoil c_1 is 1m, while the chord length of the bisail c_2 is 0.5m. The distance between the two airfoils for bisail is c_2 , and they were placed symmetrically concerning the x-axis. In addition, the depth of the geometry is 1m for both monosail and bisail, granting the total project areas for the two kind of sails are equal. Regarding the calculation of the lift and drag coefficients, the lift or drag force generated on a 1 m^2 area was divided by the dynamics pressure and the area 1 m^2 for both kinds of sails. In this way, instead of obtaining two different coefficients for the two airfoils in bisail, one coefficient of net force can make the comparison between two kinds of sail convenient.

2.3. Flow Domain

The airfoil was plotted from the origin, while the rectangle was drawn from the point 10% of the chord length away from the origin in the x-positive direction. The domain size referred to in the paper by [8]. For both sails, the domain size is the same. The height of the rectangle is 10m, and the width is 6m, which are $10c_1$ and $6c_1$ for a single sail and $20c_2$ and $12c_2$ for bisail. There is also a semicircle in front of the rectangle, with a diameter equal to the height of the rectangle.

Two types of inlet and outlet settings were applied to ensure the inlet free stream flow could go through the airfoil. Figure 2 demonstrates the two settings. Setting 1 [Figure 2(a)] was used for the AoA range of 0-140 degrees (not including the 140 degrees) while setting 2 [Figure 2(b)] was used for 140-180 degrees. The reason of choosing 140 degrees as the dividing point will be discussed later.

As for the setting of the free stream flow from the inlet, a velocity of 10.225 m/s and Reynolds number 700k were chosen for the research. The choosing of this Reynolds number is based on the speed of wind in the sea which can be assumed to be about 10m/s [9]. Since the chord length is equal to 1m, the fluid density of air is 1.225 kg/m^3 , and the viscosity is about $1.7894 \times 10^{-5}\text{ kg/m}\cdot\text{s}$, the Reynolds number was calculated to be close to 700k. Therefore, the 700k Reynolds number was selected as a condition where the speed of the sea breeze is 10.225 m/s. For the outlet's setting, the flow direction is determined by the neighbouring cell. Additionally, the turbulent intensity and the turbulent viscosity ratio for both inlet and outlet were set to 5% and 10 respectively.

2.4. Mesh Drawing

2.4.1. Two Types of Meshes

The mesh mentioned above is the optimized mesh. The optimized mesh was chosen through the process of convergent test and validation test. Two different meshes, quadrilateral and triangular mesh, were used in the convergent test, in order to find out which performed better. The quadrilateral mesh is a type of mesh that is widely used in 2-dimensional airfoil simulation. The triangular mesh is constructed based on the mesh shown in Zeng et al.'s [8] research paper. For the quadrilateral mesh, several edge size controls were applied to ensure mesh refinement around the airfoil. On the other

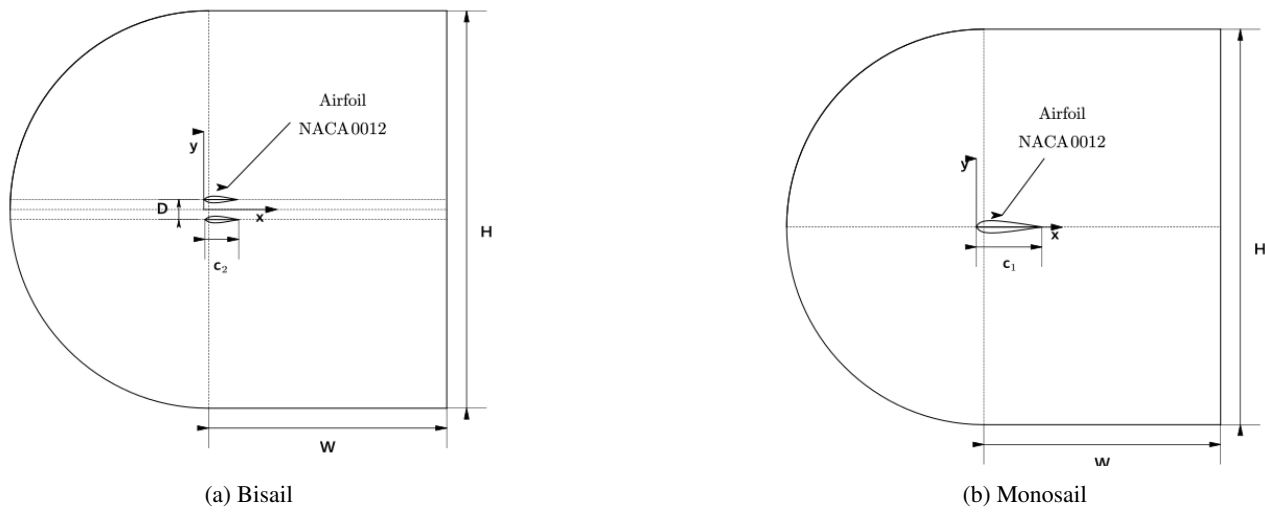


Figure 1: Sketch of geometry and flow domain

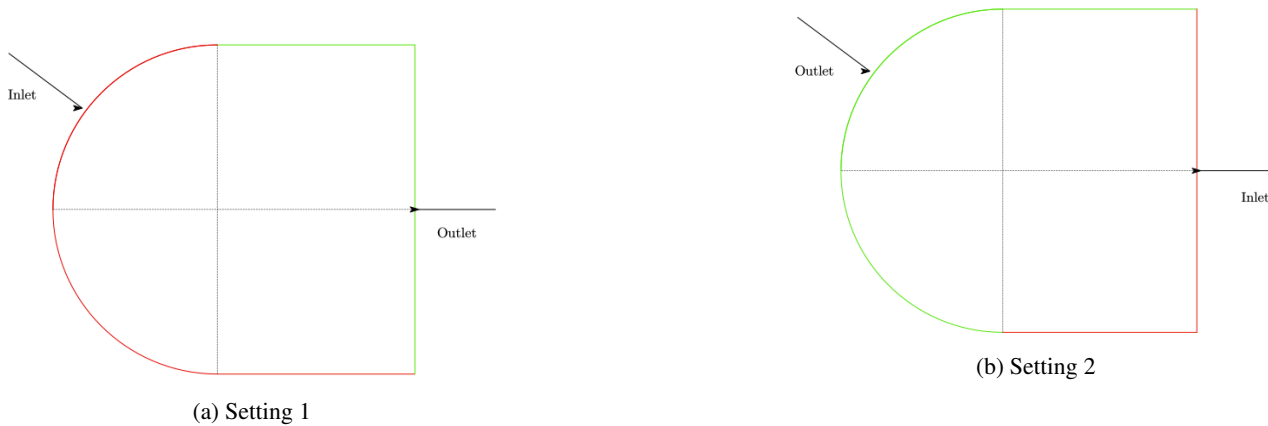


Figure 2: Sketch of inlet and outlet setting

hand, for the triangular mesh, two face size controls were applied respectively on the circle and rhombus near the airfoil to better capture the vortex after stall. In addition, inflation was used to refine the mesh around the airfoil and capture the boundary layer. The two kinds of meshes are shown in Figure 3.

2.4.2. Cell number convergent test

The purpose of the cell number convergent test is to figure out the optimized mesh which can use a small number of cells while still obtaining a satisfactory result, to save the calculation power and time. To conduct this test, several meshes with different cell numbers were applied to calculate the lift coefficient and drag coefficient at the AoA of 12 degrees. After that, when the result becomes convergent is evaluated.

To obtain meshes with different cell numbers, edge size controls in the quadrilateral meshes and face sizing in the triangular meshes were changed for every mesh. Table 1 and Table 2 indicate the different cell numbers, the number of divisions around the airfoil, and the thickness of the first layer which is adjacent to the airfoil wall for the triangular and quadrilateral meshes used in the convergent test.

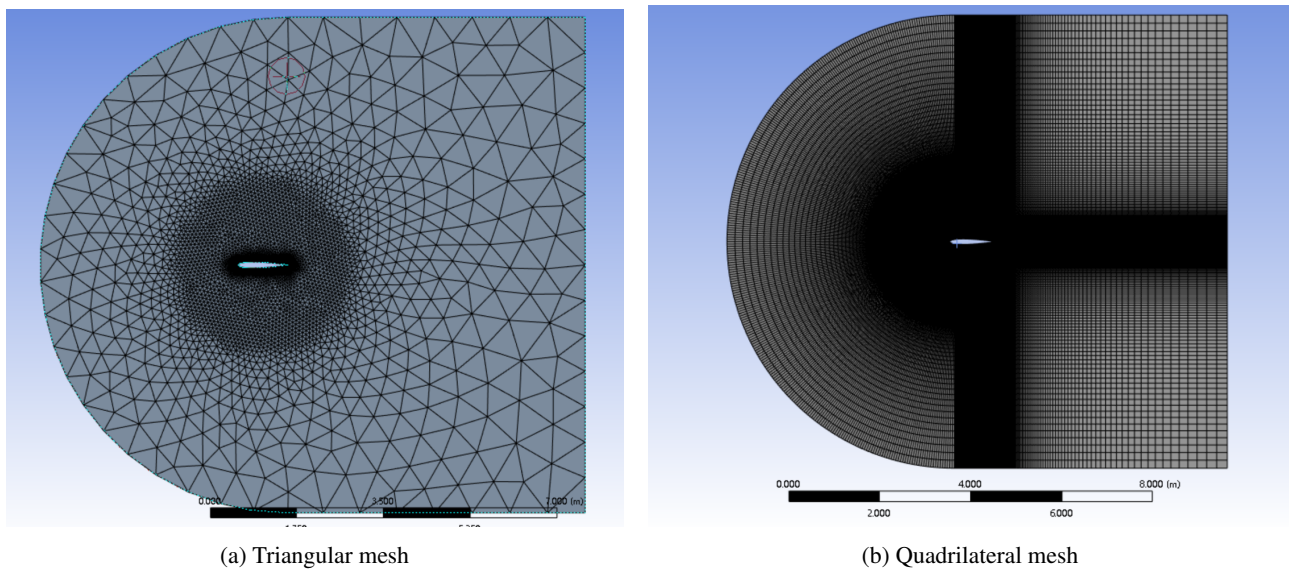


Figure 3: Triangular mesh and Quadrilateral mesh of airfoil

Table 1: Sample table title

cell numbers divisions	
6k	160
13.5k	240
24k	320
37.5k	400
57k	550
82.5k	600
111k	770
200k	800
242k	880
450k	1200

Table 2: Sample table title

cell numbers divisions	
5.04k	300
103k	400
158k	500
243k	800
308k	900
724k	1000

The results of quadrilateral and triangular mesh are shown in Figure 4. It can be seen that both coefficients of quadrilateral mesh become convergent at cell number 56,600, while both coefficients of triangular mesh are convergent at cell number 243,000.

After determining the optimized cell number of either quadrilateral or triangular mesh, the comparison between the two kinds of meshes can be conducted. This comparison is achieved by measuring the total wall clock time used for the cell number at which the results are first convergent. The time taken for the quadrilateral meshing(57k) is less than that of the triangular meshing(240k), which used 26 seconds and 56 seconds respectively. So the quadrilateral meshing with 57k cells number was used in the simulations.

Since the results from the 57k quadrilateral mesh were found to be convergent, the mesh for the bisail (Figure 5) was drawn based on the 57k quadrilateral mesh, with the same domain size and similar cell number. To ensure accuracy, the convergent test for the bisail mesh was conducted. The parameters for the bisail meshes that were used for the convergent test are listed in Table 3

Figure 6 proves that the 57k bisail mesh can basically make the coefficients of the bisail become convergent. Therefore, the 57k bisail mesh was applied in the following studies. It is also shown

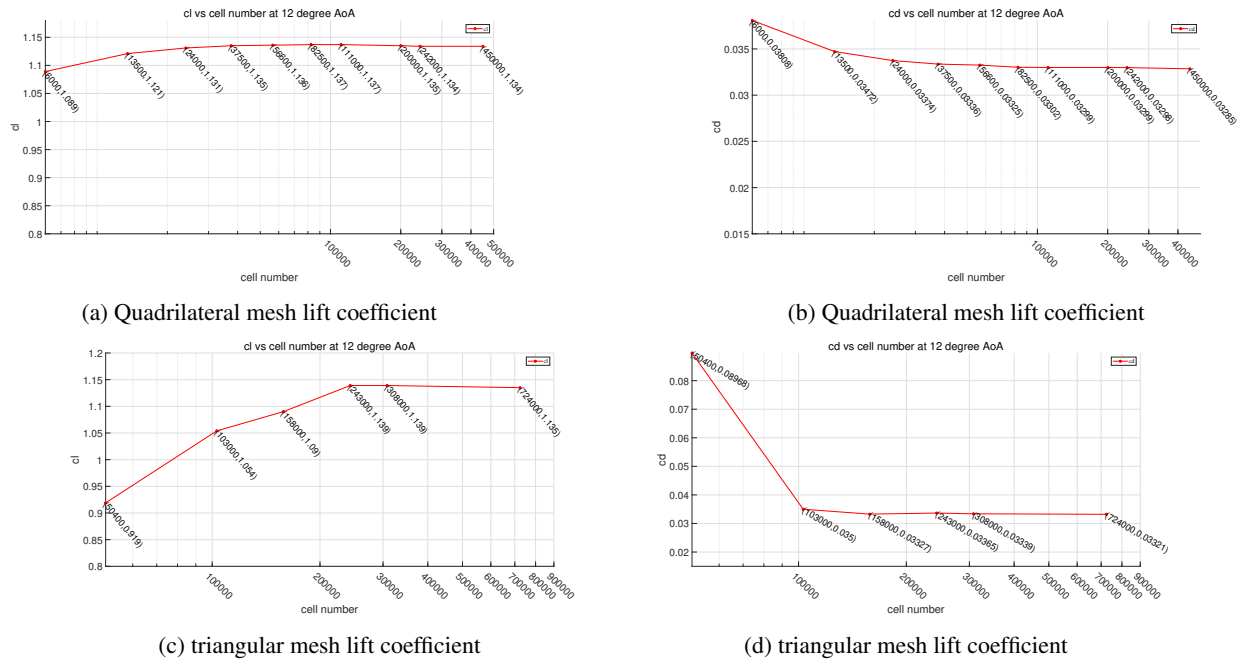


Figure 4: The optimized AoA α of the highest c_l for experiment data, bisail, and monosail vs β

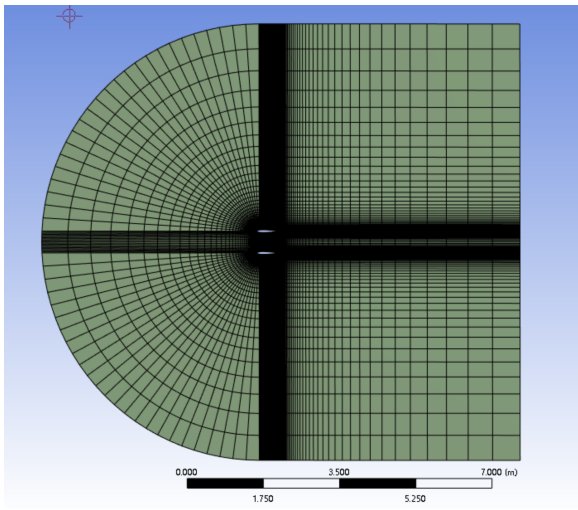
in Figure 6 that the convergent results of the quadrilateral mesh of bisail are close to the results gained from the finest triangular mesh. This alignment can indicate that the converged result of the quadrilateral mesh is likely to be accurate.

Table 3: Basail	
cell number division	
2.76E+04	190
4.02E+04	230
5.74E+04	276
8.34E+04	332
1.20E+05	398
4.79E+05	794

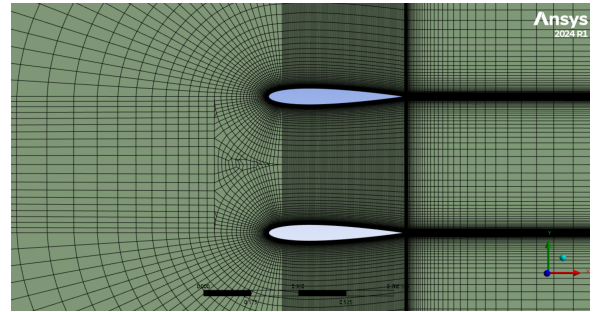
2.4.3. Monosail validation test

Validation test was employed to check the accuracy of the results. The coefficients attained by the monosail 57k mesh from 0 to 180 degrees (with the step of 5 degrees) were compared with the single airfoil experimental data published by [6] who conducted their experiments in a wind tunnel.

The results of the simulations were obtained by two inlet and outlet settings. The reason why the first setting end and the second setting start at 140 degrees is that the curves of these two settings intersect near 140 degrees. In addition, selecting 140 degrees as the dividing point is also in concern of the smoothness of the resulting curve.

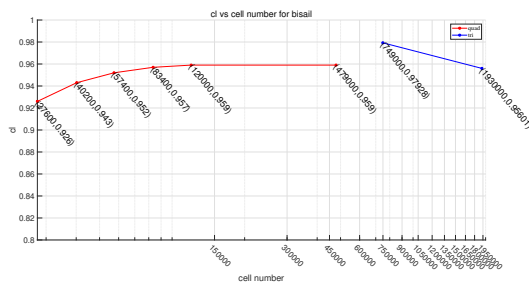


(a) Bisail mesh for the whole domain

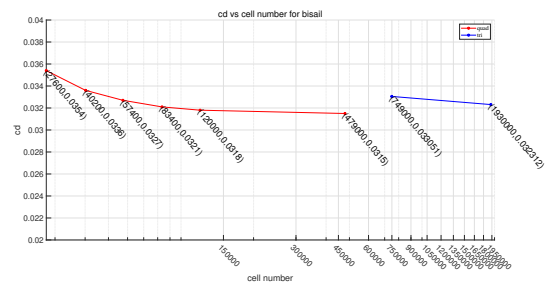


(b) Detail bisail mesh

Figure 5: Bisail mesh



(a) C_l convergent test



(b) C_d convergent test

Figure 6: Bisail convergent test

Figure 7 shows the comparison for the validation. The lift coefficient Figure 7(a) demonstrates that the coefficient when $AoA=15$ degree has a large error and becomes the highest lift coefficient for the monosail. However, the highest coefficient of the experimental data occurs in advance of 15 degrees at 11 degrees, which should be the stall angle for the experiment. The angle range of 25 to 60 degrees and 120 to 160 degrees also show some errors.

On the other hand, the drag coefficient Figure 7(b) shows that the result in the angle range of 75 to 95 degrees has a considerably large error, with the coefficients dropping significantly compared to the experiment data.

However, the simulation from Zeng et al. [8], who used the Large Eddy Simulation (LES) and Improved Delayed Detached Eddy Simulation (IDDES) respectively, also obtained results with large error and a pitch for the lift coefficient in the angle range just after the stall angle from the experiment. In addition, they also gained some relatively inaccurate drag coefficient in the angle that was near 90 degrees.

According to [8], the failure to simulate the change of the flow form attached to separation is the result that leads to the error around the angle just after the stall angle.

Since the simulation model of LES and IDDES are more advanced and accurate than the RANS model and they also obtain inaccurate results in similar angle regions, improving the accuracy of the results using RANS may not be effective. Furthermore, the errors except that at 15 degrees for the lift

coefficient and 85 to 95 degrees for the drag coefficient are relatively small. Therefore, the 57k mesh for monosail passed the validation test and can be applied in later studies.

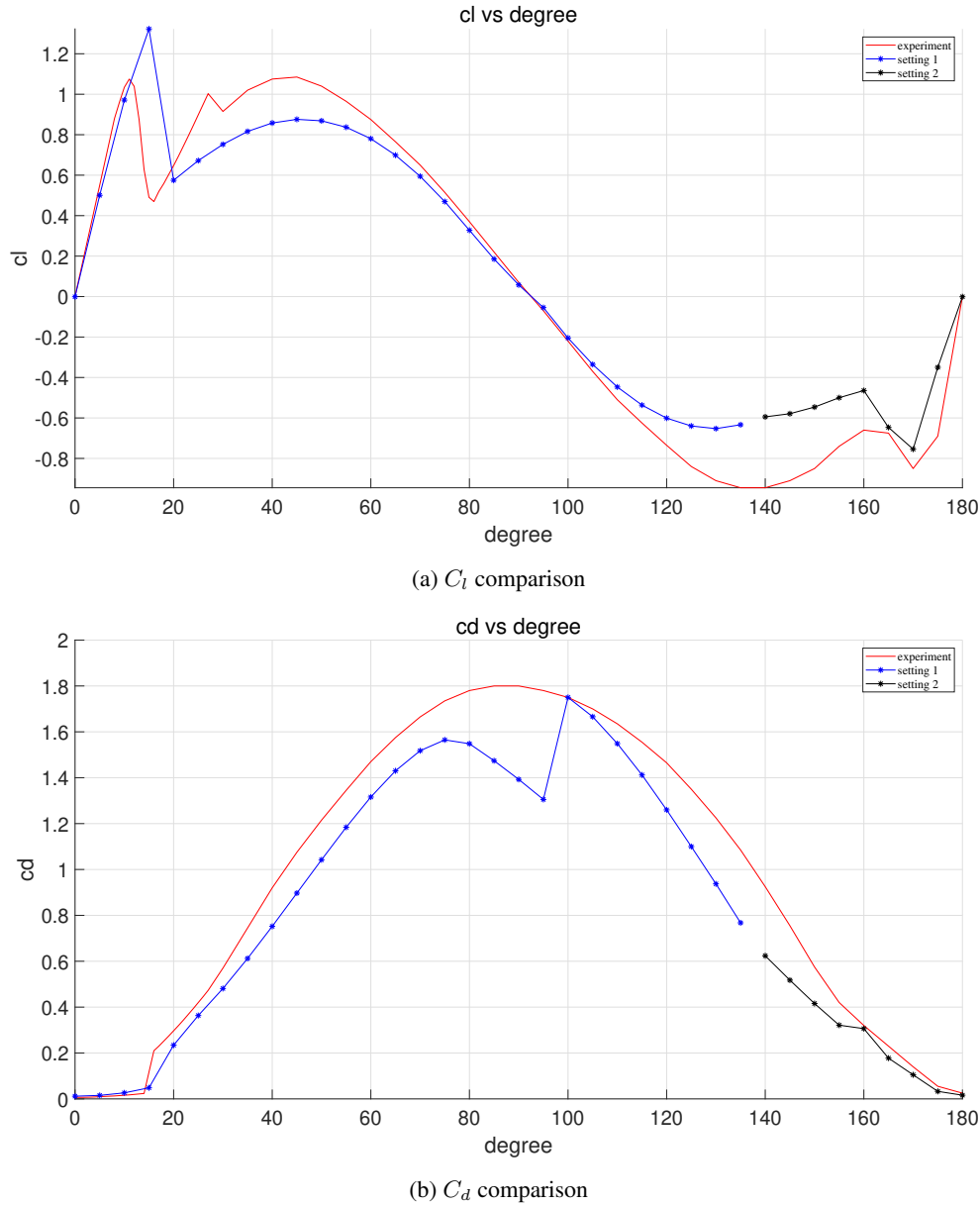


Figure 7: Comparison of the coefficients for experiment data and monosail

3. Theoretical analysis

3.1. Improved Deduction Section

The sailboat can not only work in the direction of the wind but can also work against the wind. When sailing against the wind, the sail can be considered as a foil with an Angle of attack. The driving force is produced by lift force and drag force, while other forces are balanced by the keel under the sailboat.

The working principle of the sailboat when sailing against the wind is shown in Figure 8:

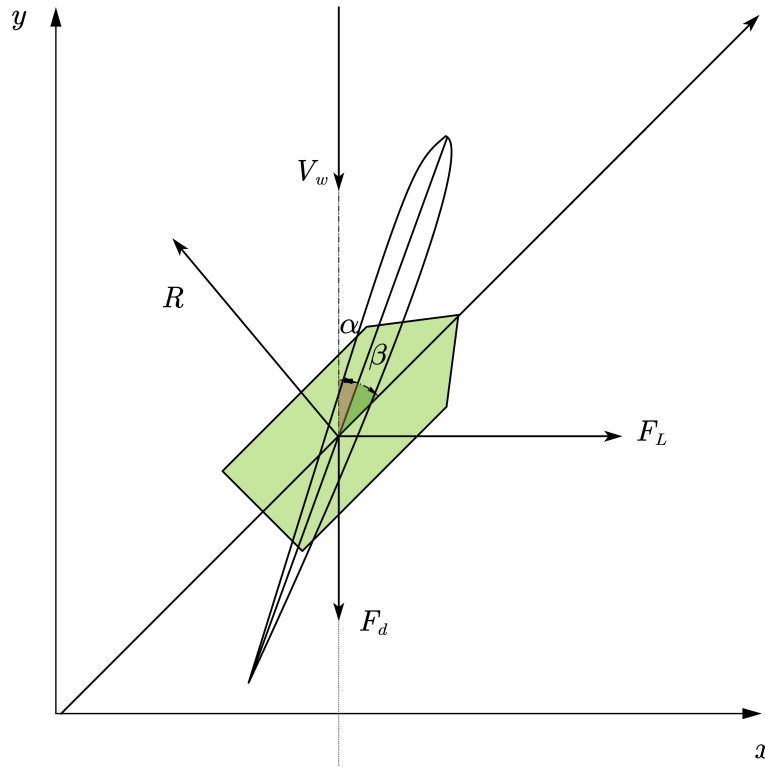


Figure 8: Sketch of a sailboat and the sail

- F_L is the lift
- F_D is the drag
- R is the resistance exerted by the keel
- α is the angle of attack of the sail
- β is the angle between the wind and the direction of the boat
- C_L is the lift coefficient
- C_D is the drag coefficient
- ρ is the air density
- F_t is thrust force

The thrust force F_t which is positive in the direction of travel of the boat can be calculated using the following formulas:

For $0^\circ < \beta < 180^\circ$:

$$F_t = F_l \sin(\beta) - F_d \cos(\beta) \quad (4)$$

$$F_t = \frac{1}{2} \rho v^2 A \sqrt{(C_l^2 + C_d^2)} \cdot \left[\sin(\beta) - \tan^{-1} \left(\frac{C_d}{C_l} \right) \right] \quad (5)$$

When $\beta = 90^\circ$, meaning the sailboat is driving perpendicular to the wind, the lift force aligns with the direction of the driving force, and the sailboat reaches its maximum resultant force when C_l reaches its maximum:

Special case when $\beta = 45^\circ$:

$$F_t = \frac{1}{2} \rho v^2 A (C_l - C_d) \quad (6)$$

In this case, the formula simplifies to the above form. When $C_l - C_d$ reaches its maximum, the resultant force F_t also reaches its maximum.

4. Results

4.1. The lift and drag coefficient of bisail

The lift and drag coefficients attained by the monosail 57k mesh, bisail 57k mesh from 0 to 180 degrees (with the step of 5 degrees), and the single airfoil experimental data are compared in Figure 9. It can be seen that the absolute value of the lift coefficient and the value of the drag coefficient of the bisail are both lower than that of the monosail for most AoAs.

The simulation of the monosail is inaccurate at certain angles. Since the bisail and monosail share a similar mesh and settings, the results of bisail are probably inaccurate in the similar angle ranges, which are at 15 degrees, from 25 to 60 degrees as well as from 120 to 160 degrees for lift coefficient, and from 75 to 95 for drag coefficient. It is obvious that in bisail results, 15 degrees AoA can also give the highest lift coefficient.

4.2. Aerodynamic performance for monosail and bisail

The parameter used in this research to compare the aerodynamic performance is the thrust coefficient C_t which is also one of the parameters used to compare the performance in the papers of [9] and [10]. This coefficient is calculated by the thrust divided by the dynamic pressure and the sail area. The equation for C_t is given by Equation 7

$$C_t = C_l \sin \beta - C_d \cos \beta \quad (7)$$

A Python program was developed to find out the maximum thrust coefficient and the corresponding AoA α for each β in which the α varies from -180 to 180 degrees. As for the data from -180 to 0 degrees, they were obtained by simply time -1 to all the lift coefficients and copy the drag coefficient for the reversed angle. The choosing of β is from 0 to 180 degrees with a step of 5 degrees.

The optimized AoAs for each β to gain the maximum thrust coefficient for single airfoil experiment data, and monosail as well as bisail simulation are shown in Figure 10. It can be seen that for the experiment data, from 5 to 85 degrees, the optimized AoA is 11 degrees at which the result of the lift coefficient is the highest. From 90 degree to 180, the optimized angle increase steady from 45 to 85 degree.

However, for the data of monosail simulation, since the AoA that obtains the highest lift coefficient is 15 degrees and its coefficient value is much higher than other AoAs in the simulations, the straight line with the optimized AoA of 15 degrees extended further, from 5 to 110 degrees. In addition, because of the drop of the drag coefficient between 75 to 90 degrees in the simulation, the optimized AoA changes to -100 or 100 degrees for the range of β where the optimized AoA is 75 to 90 in the airfoil experiment data figure 10(a). Moreover, the optimized AoA is 0 when β is 0, which indicate that the boat is not able to move forward when sailing exactly against the wing.

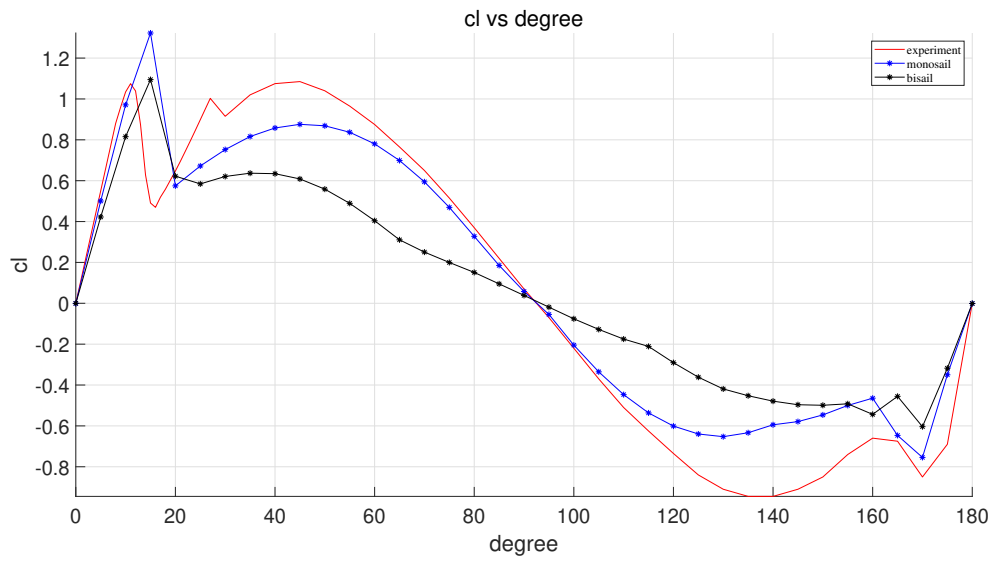
The figure of the bisail 10(c) behave in a similar manor as the monosail figure 10(b) due to the similar tendencies for the figure of the coefficients. According to the results from the monosail simulation, the coefficients of bisail are expected to experience an inaccurate simulation in the similar AoA

region which is around 90 degrees and at 15 degrees. As a result, the optimized AoA figure of the bisail also has a flat line of 15 degrees extended into large angles, and in the second part of the figure, the optimized AoA also increased to the AoA which can generate the maximum drag coefficient.

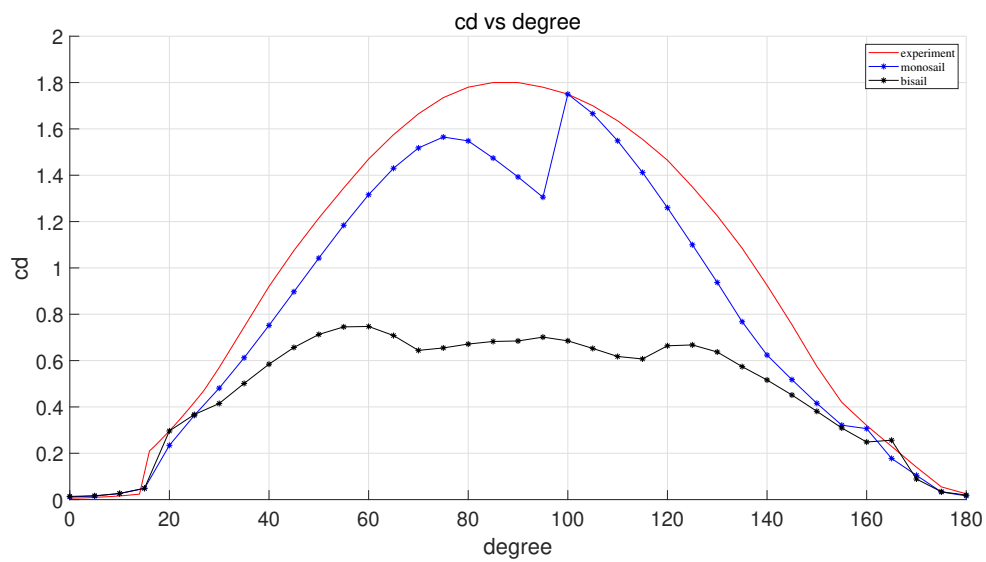
In summary, in relatively small angles of β the optimized angle largely depends on the AoA that generates the highest lift coefficient, while in the larger angles of β , the optimized AoA depends on the range of AoA that can generate high drag coefficient.

The principle above is also demonstrated in the comparison of the thrust coefficient. Figure 11 shows that the thrust coefficient of the simulation of monosail is generally higher than that of the airfoil experiment in a relatively small β angle. This is due to the higher lift coefficient obtained from AoA 15 degrees. In addition, the thrust coefficient of the simulation of monosail is generally lower than that of the airfoil experiment in a larger β angle. This is caused by the drop of the drag coefficient around the AoA 90 degrees.

The thrust coefficients gained from the simulation of the bisail are likely to have similar issues. Therefore, only the results from the simulation result of monosail can be compared with that of the bisail. The comparison provides a crucial conclusion that the thrust coefficient of the current bisail configuration and design is lower than the thrust coefficient of the monosail. Furthermore, the difference of the results become larger when increase the β , since the result of the bisail begins to decrease while the result of the monosail start to increase in the larger angle region. This implies that two smaller sails are not as good as a larger sail in terms of generating drag in the AoA range of around 90 degrees. Additionally, the lift-generating ability of the bisail also cannot reach that of the monosail.



(a) C_l comparison



(b) C_d comparison

Figure 9: Comparison between the coefficients for experiment data, bisail, and monosail

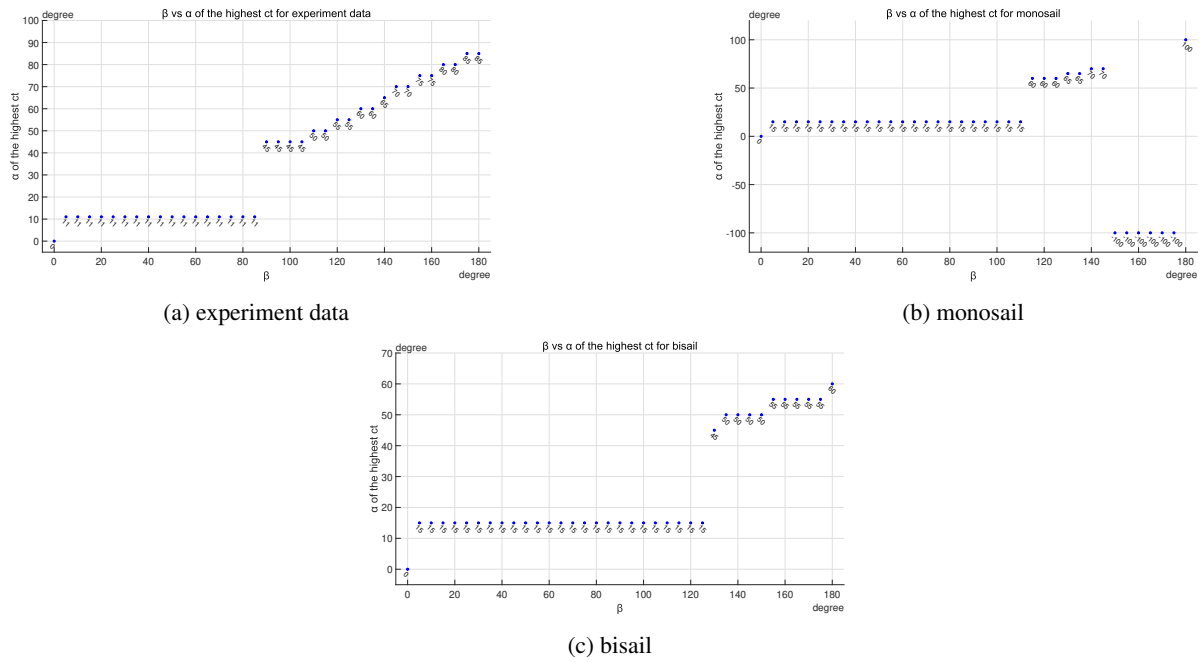


Figure 10: The optimized AoA α of the highest c_t for experiment data, bisail, and monosail vs β

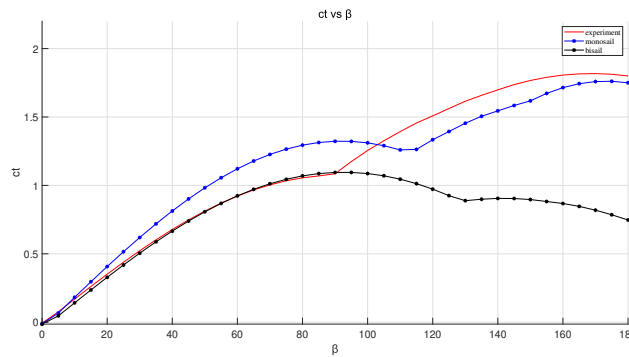


Figure 11: c_t for experiment data, bisail, and monosail vs β

5. Discussion

5.1. Discussion in simulation

In this research, in order to find the optimized mesh, a thorough cell number convergent test was conducted by using 10 different cell numbers for quadrilateral monosail mesh, and 6 triangular monosail mesh. After obtaining the 57k quadrilateral mesh from the convergent test, a validation was then conducted together with the comparison between papers that used other simulation models. Therefore, the 57k quadrilateral mesh obtained from all these studies can not only provide relatively accurate results, but also save the calculation time and power. The 57k quadrilateral mesh was then applied in the cases of bisail, and 6 cell numbers for quadrilateral bisail meshes were also employed to prove

the convergence of the 57k quadrilateral mesh. In addition, two triangular bisail meshes were used to increase the confidence in the bisail results and provide potential self-validation of the results.

However, in the simulation part, the accuracy should be considered more, due to the limitations of the simulation model, the vortex in the simulation cannot be captured well, so the accuracy of C_l and C_d are not well during deep stall.

The limitation also lies in the drawing of the bisail mesh, which is complex and hard to avoid generating the mesh with a small region where the mesh is unstructured and not symmetric. This limitation may also influence the accuracy.

5.2. Discussion in theoretical analysis

After obtaining the lift and drag coefficients of both monosail and bisail from the selected mesh, the theoretical analysis was conducted in order to explain how to figure out the parameter to compare the aerodynamic performance–thrust coefficient. The comparison of monosail and bisail drew some important results. The achieved results include the optimized AoA at a different angle of wind direction, and the conclusion that the current bisail does not perform better than the monosail.

However, for the theoretical analysis part, there seemed to be some limitations, in this part, the sail is assumed to be only affected by the lift and drag force provided by the sail, and the keel can cancel out the force in the direction perpendicular to the driving direction. The optimized angle of attack(α) has a strange result that in the domain 0 to 90 degrees, except the exact 0 and 90 degrees, the best angle of attack is always 11 degrees, in the domain 90 to 180 degree, the best AoA for the sailboats is increasing from 45 degrees to 85 degrees gradually. This means under most conditions when against the wind, the sailboat can keep the AoA of exactly 11 degrees and only change the direction of the sailboats, that conclusion can give rise to two more limitations. The first limitation is the exclusion of the relative wind velocity that generated by the motion of the boat, which can be added to the original wind velocity to form the true wind velocity experienced by the boat and sail. The second limitation is the keel may not cancel out all the forces perpendicular to the driving direction. So, the negligible forces acting on the boat would influence the answer.

In the part of the accuracy test, there is a small drop in the reference that we work as the standard data. To improve the data, the new graph is drawn in the method of interpolation, which make the graph more smooth but cannot ensure the accuracy of the new graph.

5.3. Future work

In the research, the way of sailboat working follow and against the wind are be determined, the monosail NACA0012 with a chord length of 1 m is compared to bisail NACA0012 chord length of both 0.5 m and with a separation of 0.5 m in the condition of 700k Reynolds number. Through the simulation, we know that the bisail does not work well in this case as the monosail. However, only testing one kind of bisail is far from enough. So, future research is discussed. According to Figure 12, for the region between two sails, especially the region at the rear of the upper sail, the low-pressure region of the lower sail reduces the pressure in the high-pressure region of the upper sail. That is because of the interaction between two sails. So, the lift is not used in an efficient way. In this case, the separation between the two sails, stagger, and size of to sail can be considered to change in future research. For the separation between sails, it can be increased to reduce the interaction of the two sails. For the stagger, the lower sail can be moved forward to move the low-pressure region forward. A third sail can also be added for symmetric. For the size of the sails, two small sails with a larger

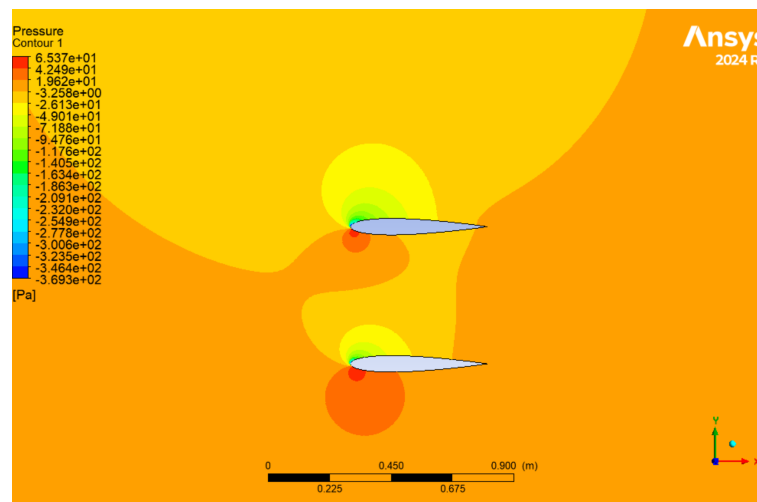


Figure 12: Pressure contour of 479k bisail mesh 12 degrees

sail in the middle, which are all aligned with the leading edge may have a potential to decrease the low-pressure region. All of these are intended to form a higher C_l

The simulation can also be improved in the following research. The vortex is a significant uncertainty and greatly hinders the accuracy of the results. Future work may be to improve the simulation pattern to better consider the vortex. However, instead of focusing on simulations, the research in a wind tunnel can be conducted with some bisail 3D models and accurate force sensors.

6. Conclusion

In this research, the aerodynamic performance of monosail and bisail was compared. The comparison was conducted between a monosail with a chord length of 1m and a pair of bisail with a chord length and separation of 0.5m. A thorough study of mesh cell number convergent test was conducted for both quadrilateral and triangular mesh of monosail. The convergent test implied that the quadrilateral mesh with 57k cell number is the optimized mesh. The validation was conducted after the cell number convergent test to examine the accuracy of the simulation results. Although the results have relatively large errors in certain regions, other advanced simulation models also encounter a similar problem due to the failure to capture the vortex and the error for other regions is small. Therefore, the mesh passed the validation, and the 57k quadrilateral mesh was introduced to bisail. The result of this research shows the optimized AoA for each angle of the wind. However, because of the inaccurate results obtained by the simulation, the result of optimized AoA in some regions also may not be correct. Lastly, by comparing the thrust coefficient obtained from simulation for monosail and bisail, it indicates that the performance of the current bisail is not better than that of the monosail. In addition, the difference of thrust coefficient increases when the angle between wind direction and boat sailing direction increases.

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