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Study of Gurney Flap as Passive Flow Control Method on NACA 4418

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Abstract

Global problems related to the greenhouse effect and global warming have pushed research towards clean energy sources. One of the technologies of concern is wind turbines, whose performance is highly dependent on the aerodynamics of the airfoils used. This study aims to analyze the effect of input speed variation on the aerodynamic performance of NACA 4418 airfoil using gurney flap as a passive flow method. In this study, the Reynolds Averaged Navier-Stokes (RANS) method was used to calculate aerodynamic parameters, by varying the height of the gurney flap on the trailing edge of the airfoil. The results showed that the use of gurney flaps with flap height variations of 1%, 2%, and 3% of chord length was able to significantly increase the lift coefficient, with the highest increase at the flap height of 3% c. In addition, this passive method has proven to be efficient in improving aerodynamic performance without the addition of an active control system. In conclusion, variations in input speed and flap height can improve the aerodynamic performance of NACA 4418 airfoils, making this method feasible to apply to wind turbines.

Introduction

The emergence of problems related to the greenhouse effect and global warming is one of the biggest reasons to switch to cleaner energy sources. In this case, most of the electrical energy sources used still rely on fossil fuels. Therefore, research and development related to new and renewable energy is needed to support the need for a cleaner supply of electrical energy (Omer, 2008). One of the renewable energies that is currently being developed in both research and manufacturing is massive, is wind turbines. In general, wind turbines are divided into two types, namely horizontal wind turbines and vertical wind turbines (Basta et al., 2020). There is one important component in a wind turbine, namely the airfoil (Rayhan Fariansyah Billad et al., 2024). The performance of a wind turbine also depends rather than aerodynamics on the airfoil used as blades. Various flow control methods have been used to improve the aerodynamic performance value of an airfoil. One of the commonly used flow control methods is the active flow control method.

According to Lu et al. (2020) and Kougias et al. (2019) that the active flow control method is considered the most ideal because it can be controlled according to actual conditions. However, this method requires larger capital, such as the addition of power supplies, controllers, and air systems, which makes the application of this method limited. On the other hand, the passive flow control method focuses more on adding or modifying the shape of the airfoil body. The passive flow control method is considered more practical because of its lower level of complexity than active flow control, and is considered more affordable to apply financially (González-Salcedo et al., 2020). Therefore, in terms of improving the aerodynamic

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performance of the airfoil, the passive flow control method is preferred. One of the commonly used passive flow control methods because of its ease and good ability to improve aerodynamic performance is the gurney flap (Manerikar et al., 2021).

Many studies have been conducted in applying gurney flaps to airfoils as a passive flow control method. Such as research conducted by J. Alber et al. The study conducted a wind tunnel experiment on several types of airfoils to determine the difference in aerodynamic performance in the form of coefficient of lift and coefficient of drag between clean base airfoil and airfoil with a gurney flap on the trailing edge side.

The types of airfoils used include DU 98W180 with Reynold number and gurney flap height of 2.5%c, DU 93W210 with Reynold number and gurney flap height of 2%c, DU91 W2-250 with Reynold number and gurney flap height of 2%c, DU97 W300 with Reynold number and gurney flap height of 1.67%c, NACA 633618 with Reynold number and gurney flap height of 1.33%c, NACA 4412 with Reynold number and gurney flap height of 0.5%c, NACA 0012 with Reynold number and gurney flap height of 0.5%c, HQ17-14.38 with Reynold number and gurney flap height of 1.66%c, AH93 W174 with Reynold number and gurney flap height of 1%c. Based on the experimental results carried out in the study, quite positive results were obtained in all types of airfoils that were tested, which resulted in an average increase in cl value of 3% in each type of airfoil and an increase in cd value of 6%. In addition, this study also concluded that the use of gurney flap as an $(1{,}3.10)^6$ $(2.10)^6$ $(2.10)^6$ $(1{,}3.10)^6$ $(1{,}3.10)^6$ $(2.10)^6$ $(2{,}1.10)^6$ $(1.10)^6$ $(1.10)^6$ elevator device can increase annual electricity production by 0.8% (Alber et al., 2017).

Chen et al in their research entitled "Aerodynamic Enhancement of Vertical-Axis Wind Turbine Using Plain and Serrated Gurney Flaps". They conducted a test on NACA 0021 airfoil by applying plain gurney flaps and serrated gurney flaps on the trailing edge side of the airfoil. The study was conducted on NACA 0021 airfoil with Reynolds number and variations in gurney flaps height of 1.5%c, 3%c, 6%c. In the study, the results were obtained in the form of when the height of the gurney flap was 6%c, the maximum value of cl in each type of gurney flap, both plain gurney flap and serrated gurney flap, increased by 89.9% and 65.6%. In addition, the effective aerodynamic performance of the airfoil depends on the specified flap height. The lift to drag ratio on plain gurney flaps has a greater value than serrated gurney flaps at flap heights of less than 6% c $(1{,}6.10)^5$ (Chen et al., 2023).

The research entitled "Effect of Gurney Flap Geometry on a S809 Airfoil" conducted by Li et al examined the effect of applying the geometric shape of the gurney flap. They examined the effect of applying rectangular and triangular shapes to flaps attached to the trailing edge side of the airfoil. In addition, they also examined the effect of flap width variations on the aerodynamic performance of airfoils. The study was conducted on Reynolds' number and flap height of 2%c. The variations in the applied flap widths were 0.2%c, 0.6%c, and 1%c. In the simulation results, it was found that the rectangular flap with a flap width of 0.2%c, 0.6%c, and 1%c at the angle of attack experienced an increase in Cl values of 102.33%, 91.79%, 89.23%, respectively. Meanwhile, in the angle of attack, the Cl value increased by 28.33%, 26.97%, and 23.36%, respectively. Meanwhile, in the triangular flap for the angle of attack, there was an increase in Cl values by 100.86%, 108.52%, 114.81%. And in the angle of attack, there was an increase in Cl values by 31.73%, 34.57%, and 36.25%. In this case$(1.10)^6$ (1,03) (7,1) (1,03) (7,1), the triangular flap shape has better performance than the rectangular flap, in addition to that, it is also concluded that the gurney flap can increase the value of the lift to drag ratio at low attack angles (Hao & Gao, 2019).

The research conducted by He et al is entitled "Numerical Simulation of Gurney Flaps on a Low Reynolds Number Aifroil". The study tested the variation in gurney flap height between 0.25%c, 0.5%c, 1%c, 1.5%c, 2%c, 3%c with a Reynolds number set as. In the simulation

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results, data was obtained that the Reynolds flap number with a height of 3%c has better performance when compared to other height variations that have been set. This is supported by the data on the maximum Cl value which has increased by 25% from clean airfoil (3.10)[5] (3.10)[5] (He et al., 2017).

The next research was conducted by Graham et al entitled "Experimental Study on the Effect of Gurney Flap Thickness on Airfoil Performance". The study was conducted on the SD7062 airfoil with the air condition parameter set at the Reynolds number or 27m/s. The variations in the height of the gurney flap used are 1%c, 2%c, and 4%c. Based on the test data of the experimental results, it was obtained that the flap with a height of 4%c has a maximum value of Cl that is about 29% greater than that of clean airfoil (1,5.10)[5] (Graham et al., 2018).

Julian et al. (2023) conducted a study on the effect of the use of gurney flaps on the aerodynamic performance of NACA 4415 airfoils. The research was conducted using a CFD computational approach. The parameter applied to the study was in the form of a Reynolds number set at 1 x 10^6. In addition, the flap heights used are 0.5% c, 1% c, and 2% c of chord length. The test yielded quite good results, where at a flap height of 0.5% c there was an increase in Cl value by 12%, while for a height of 1% c of 23%, and a height of 2% c of 37%. The results were also followed by an increase in the value of Cd. Which for a flap height of 0.5% c increased by 2%, for a height of 1% c by 4%, and for a height of 2% c by 6% (James Julian et al., 2024).

Based on previous studies that have been simulated and tested directly by empirical, there has been no specific study that discusses the effect of variations in the input of Reynolds number parameters. In these papers, Reynolds' number parameters are not varied, while the parameters that are varied are in the form of height and width of the flap. This is not like the conditions in the field directly where each aerodynamic device, both wind turbines, operates at different fluid speeds (Julian et al., 2023). This study aims to analyze the effect of the application of input speed variation on aerodynamic performance while also using gurney flap as a passive flow method. NACA 4418 airfoil was used in this study because of its fairly wide application, especially in wind turbines. In addition, because there have not been many studies that have applied NACA 44xx as a research subject, further research is needed to enrich the findings.

Methods

Gurney Flap

A gurney flap is a small device that is mounted vertically on the trailing edge of an airfoil. The device was first introduced by an American race car engineer, Dan Gurney in 1971. The gurney flap works by disrupting the airflow around the trailing edge which creates a swirl behind it. This affects the pressure distribution above and below the airfoil, resulting in increased lift and decreased drag. Then in this way the gurney flap can improve the aerodynamic performance of the wing or blade providing more lifting force. Gurney flap is a passive fluid control flow method. The optimal value of the recommended gurney flap height is between 1% c - 5% c (Li et al., 2002).

Governing Equations Formula

This study uses the Reynolds Averaged Navier-Stokes equation as a calculation method. In the RANS method there are two foundation equations, namely the quantity equation and the momentum equation. This RANS equation is written in the form of a mathematical model in equations 1 and 2 (Aftab et al., 2016).

$$\frac{d\rho}{dt} + \frac{d}{dx_i}(\rho u_i) = 0 \qquad (1)$$

$$\frac{d}{dt}(\rho u_i) + \frac{d}{dx_i}(\rho u_i u_j) = \qquad (2)$$

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$$\frac{dp}{dx_i} + \frac{d}{dx_j}\left[\mu\left(\frac{du_i}{dx_j} + \frac{du_j}{dx_i} - \frac{2}{3}\delta_{ij}\frac{du_i}{dx_i}\right)\right] + \frac{d}{dx_i}(-\rho)\overline{u_i'u_j'}$$

In this study, the convergence model used is k-ε because of its fairly good ability in fluid flow calculation accuracy (Douvi C. Eleni, 2012). This convergence model is written in mathematical equations 3 and 4 (Lew et al., 2001).

$$\frac{D}{D_t}(\rho k) = \frac{d}{dx_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{dk}{dx_j}\right] + G_k - \rho\varepsilon \qquad (3)$$

$$\frac{D}{D_t}(\rho\varepsilon) = \frac{d}{dx_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{d\varepsilon}{dx_j}\right]$$

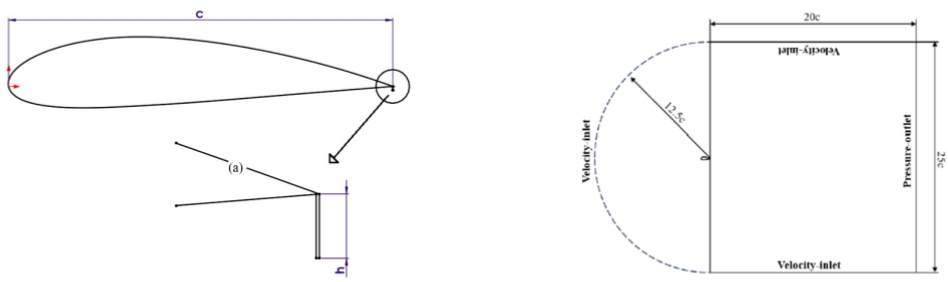
$$+C_{el}\frac{\varepsilon}{k}G_k - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \qquad (4)$$

NACA 4418

NACA 4418 airfoil is a type of naca type asymmetrical airfoil, where the first digit shows a camber value of 4% and the second digit shows a maximum camber value of 40%. While the third and fourth digits show a thickness-to-chord length ratio of 18% (Mahato et al., 2023). Asymmetrical airfoils are able to produce lift at zero angle of attack and are able to reduce drag which results in a larger lift-to-drag ratio (Airfoils in General, 2017). The chord length (c) used in this study is 1 meter, while the width of the flap is 0.05%c (Lukiano et al., 2023).

Fluid Domain

This study calculates 4 types of geometry, the first design is NACA 4418 airfoil without using a gurney flap, the second design is NACA 4418 airfoil using a gurney flap of 1% c, the third calculation is on NACA 4418 airfoil with a gurney flap of 2% c, and the last calculation is on NACA 4418 airfoil using a gurney flap of 3% c. In this case, the fluid domain aims to make calculations more accurate and more convincing, which is one of its roles to capture the phenomena that occur around the airfoil. The fluid domain used is type c, where it has a radius configuration of 12.5 times the chord length and 20 times the length and width of the chord length and 25 times the chord length, respectively (Parluhutan et al., 2024). Details regarding the geometry and fluid domain are shown in figure 1.



(a) (b)

Figure 1. Detail Geometry and Fluid Domain, (a) NACA 4418 Airfoil with Gurney Flap, (b) Fluid Domain

Results and Discussion

Mesh Independence Test

Mesh independence test is a crucial stage where in this stage the fluid domain will be divided into small partitions or called elements (Ansari et al., 2019). At this stage, the fluid domain will be divided into three mesh segments, namely coarse mesh, medium mesh, and fine mesh. Each mesh segment has a total of 25000 elements for coarse mesh, 50000 elements for medium mesh, and 100000 elements for fine mesh. The type of mesh used in this study is a

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mesh structure with the shape of rectangular elements (Liang et al., 2020; Gao et al., 2019). In the area around the airfoil, the number of elements tends to be more and the distance is tighter (Nakhchi et al., 2021). This aims to be able to produce more accurate calculation values so that relatively small calculation errors will be obtained. More details regarding the mesh segment are found in figure 2.

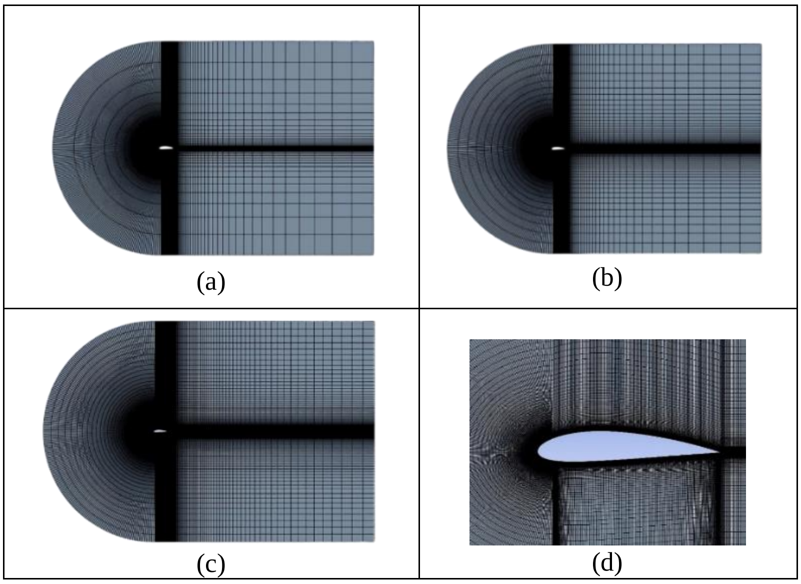

Figure 2. Detail Mesh in Current Study, Coarse Mesh (a), Medium Mesh (b), Fine Mesh (c), Around Airfoil (d)

The next stage is to verify the meshing that has been made with a mesh independence test, the goal is that the mesh that has been generated has a small error value and can be used as a computational model. In this study, the mesh independence test method used refers to Richardson's extrapolation method (Boache, 1994). Each mesh segment will be subjected to a computational process with specific reference points that have been determined (Lukiano et al., 2023). In the first step, determine the variation ratio using equation 5. The next step is to calculate the order value using equation 6. After calculating the order value, one of the other most important stages is calculating the Grid Convergence Index (GCI).

Equation 7 is the GCI coarse formula, which is the equation for calculating the error between the coarse mesh segment and the medium mesh. While the fine GCI in equation 8 is to calculate the error between the fine mesh segment and the medium mesh. Once the calculation process is complete, the next step is to verify the calculations with equations 9 and 10 to consider that the mesh variations used have been appropriate so that they can be applied to this study. The details of the results of the mesh independence test calculation have been shown in table 1.

$$r = \frac{h_2}{h_1} \quad (5)$$

$$\overline{p} = \frac{\ln\left(\frac{f_{fine}-f_{medium}}{f_{medium}-f_{coarse}}\right)}{\ln(r)} \quad (6)$$

$$GCI_{coarse} = \frac{F_s|\epsilon_{coarse}|r^{\overline{p}}}{(r^{\overline{p}}-1)} \quad (7)$$

$$GCI_{fine} = \frac{F_s|\epsilon_{fine}|r^{\overline{p}}}{(r^{\overline{p}}-1)} \quad (8)$$

$$\frac{GCI_{fine}}{GCI_{coarse}r^{\overline{p}}} \approx 1 \quad (9)$$

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$$f_{rh=0} = f_{fine} + \frac{(f_{fine} - f_{medium})}{(r^{\overline{p}} - 1)} \qquad (10)$$

Table 1. The result of mesh independence test

Variation	Coarse	Medium	Fine
Velocity	58.2164	58.2725	58.2805
$f_{rh=0}$	-	58.2818	-
r	-	2	-
p	-	2.81	-
GCI_{coarse}	-	0.02%	-
GCI_{fine}	-	0.003%	-
Results	-	1	-
Mesh error	0.1123%	0.016%	0.0023%

Validation

Data validation is carried out to ensure that the results obtained from the simulation are close enough to the results in the actual test. This data validation is carried out by comparing the results of experiments on NACA 4418 airfoil with Reynolds number. Coefficient lift and coefficient drag are taken into consideration in this data validation process. The result of the value and has been shown in figure 3. In the simulation process using CFD, when the airfoil has experienced a trend stall, the curve tends to be wider compared to the experimental results. This is due to the limitations of computing software to capture fluid phenomena during post-stall conditions. In general, the curve obtained in the simulation and experiment results provides a fairly consistent trend, but in the results of the experiment the stall angle occurs 2 degrees earlier than the simulation results, namely at AoA = . However, the calculation results can be considered valid based on the set data obtained on the coefficient of lift and coefficient of drag results.$3 \times 10^6 C_l C_d 15^0$.

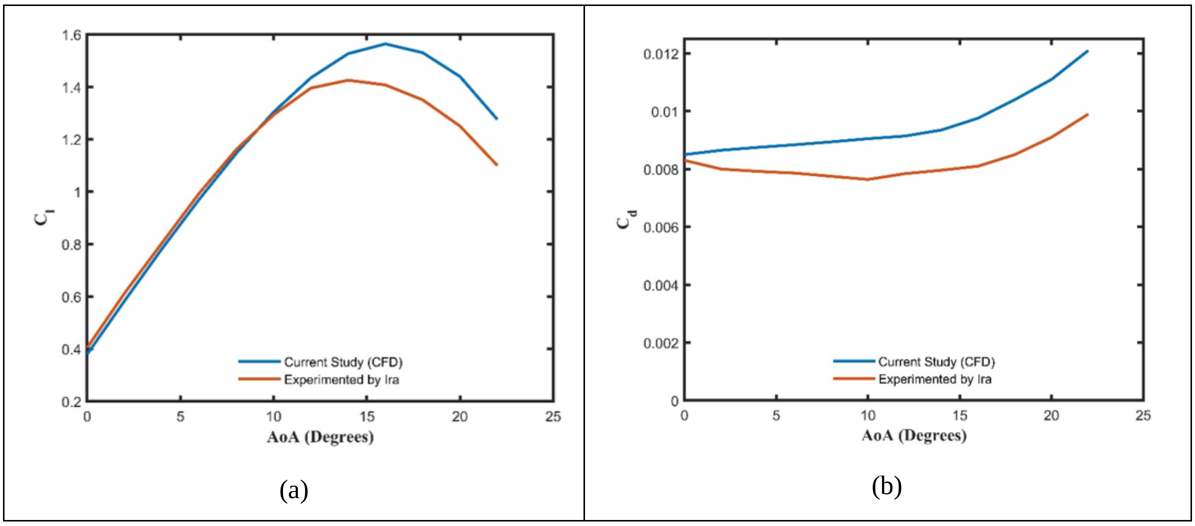

Figure 3. Plot of Validation Result, Plot of C_l Result Againt AoA (a), Plot of C_d Result Againt AoA (b)

Analysis

The test was carried out with 4 different geometries and each geometry varied the value of the Reynolds number parameter. Clean base NACA 4418 airfoil with Reynold number variation and, NACA 4418 airfoil with 1% c gurney flap with Reynold number variation and, NACA 4418 airfoil with 2% c gurney flap with Reynold number variation and , and the last NACA 4418 airfoil with 3% c gurney flap with Reynold number variation and Figure 4 shows that the gurney flap as a passive control method can significantly increase the value. NACA

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4418 with flap height 1% c experienced a maximum value increase of 15.33% in Reynold's number and a maximum increase of 15.53% in Reynold's number. In addition, NACA 4418 with a flap height of 2% c experienced a maximum value increase of 21.72% in Reynold's number and a maximum increase of 22.4% in Reynold's number. As for the flap height of 3% c, the maximum increase in value is 26.54% in the Reynolds number and the maximum increase is 27.47% in the Reynolds number. NACA 4418 with the use of gurney flap experiences stall first from the clean base airfoil at the average AoA = , while the stall angle on the clean base airfoil occurs when AoA = $5 \times 10^5 10^6 5 \times 10^5 10^6 5 \times 10^5 10^6 5 \times 10^5 10^6 C_l C_l 10^6 5 \times 10^5 C_l 10^6 5 \times 10^5 C_l 10^6 5 \times 10^5 13^0 15^0$.

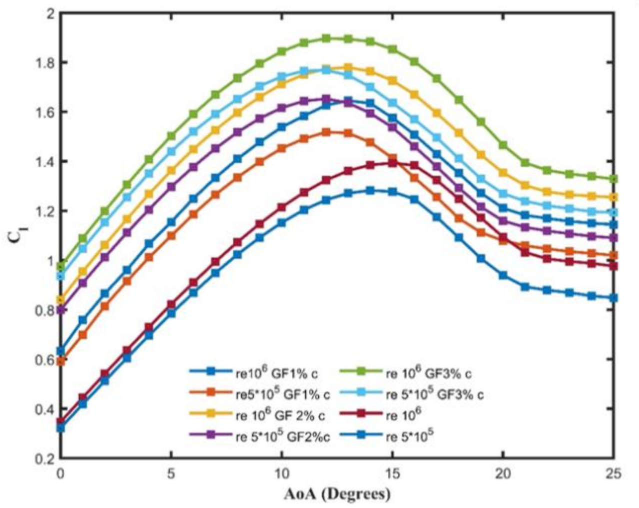

Figure 4. Plot the Simulation Result of C_l Againt AoA.

The use of gurney flap as a passive control method also increases the value of that. As shown in figure 5 where at a flap height of 1% c there is an increase in value of 10.06% in Reynold's number and an increase in value of 10.7% in Reynold's number. In addition, at a flap height of 2% c, the value increases by 7.62% in the Reynolds number and by 7.03% in the Reynolds number. Meanwhile, at flap height 3% c the value increases to 16.34% in Reynold's number and by 15% in Reynold's number $C_d C_d 10^6 C_d 5 \times 10^5 C_d 10^6 5 \times 10^5 C_d 10^6 5 \times 10^5$.

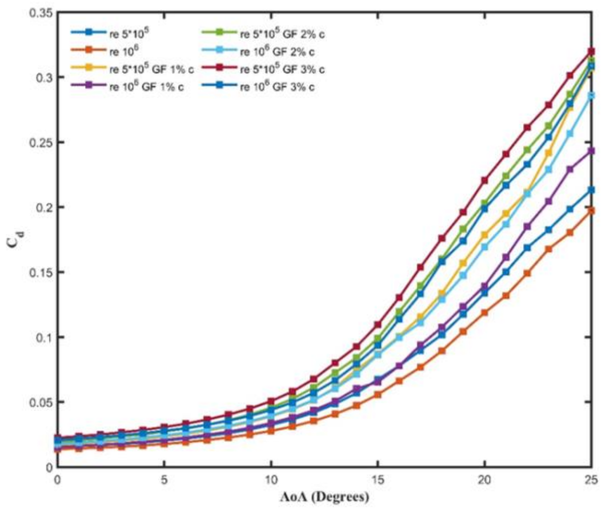

Figure 5. Plot the Simulation Result of C_d Againt AoA

In Figure 6, the ratio of / is shown, the results of the plot show that the highest ratio value occurs in NACA 4418 with a flap height of 2% c in the Reynolds number. Then followed by a flap height of 1% c by saying Reynold. While the last on the flap height is 3% c with the Reynolds number.$C_l C_d 10^6 10^6 10^6$

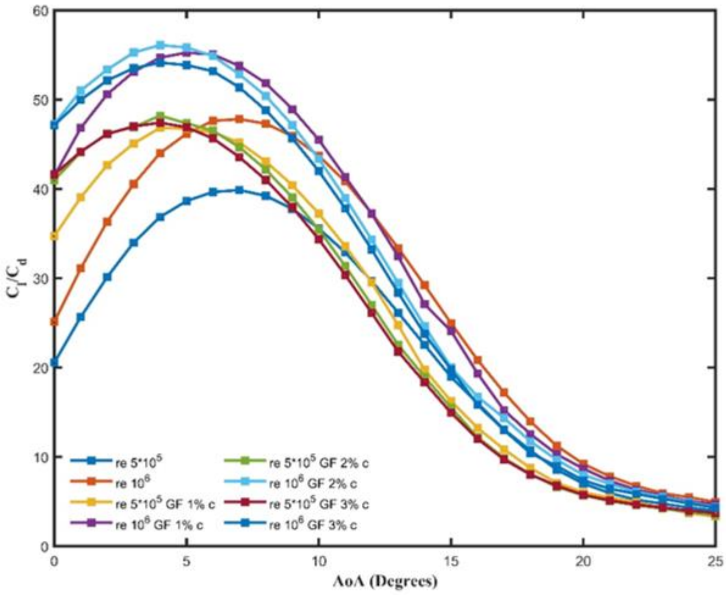

Figure 6. Plot the Simulation Result of the Ratio $\frac{C_l}{C_d}$ Againt AoA

Conclusion

This study aims to analyze the influence of the use of gurney flap as a passive control method on NACA 4418 airfoil. In this study, Reynold's number was also varied as a test parameter. The results obtained were quite positive, airfoils with flap height of 3% c on Reynold's number had the highest lift coefficient value. In addition, airfoils with flap height of 3% c in Reynold's number have a higher coefficient of lift value than airfoils with flap height of 1% c both in Reynold's number and in Reynold's number. Meanwhile, on the coefficient side of drag flap height 2% c has a lower increase in value compared to flap height 1% c and 3% c. This is a good result because by using a flap height of 2% c on the NACA 4418 airfoil, it can improve aerodynamic performance in the form of a coefficient of lift value without causing a significant increase in coefficient of drag 10^6 5×10^5 10^6 5×10^5 C_d.

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