Aerodynamic Analysis of Active Trailing-Edge Flaps and Passive Surface Roughness on NACA 4412 Airfoil

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Abstract. The focus of this study is to understand the effect of the flow control mechanism on NACA 4412 airfoil. Two configuration of flow control method is used in this investigation. The first configuration is, airfoil with only the trailing-edge flap. This is the active flow control method. The trailing-edge flap can be deflected to various angle accordingly. The second configuration is a combination of, active trailing-edge flap with a passive surface roughness at the leading-edge of the airfoil. The surface roughness is expected to reduce the flow separation at the leading-edge of the airfoil. This is expected to enhance the aerodynamic performance of the airfoil. Both configuration 1 and configuration 2 was simulated and the results compared with the base airfoil without any flow control mechanism. Based on the results, airfoil with configuration 1 performed better compared to the base airfoil. Airfoil with configuration 2, performed well but not better than the airfoil with configuration 1. Upon further analysis, key patterns emphasise airfoil with configuration 2 could perform better if the roughness element parameters further optimised. This airfoil to be used for wind turbine applications.

1. Introduction
Surge of 4 percent in electricity consumption globally, from the year 2017 to 2018 was recorded [1]. This is most obvious in Southeast Asian countries, as most are considered as developing nations and require more energy due to industrialization [2]. As most power plant uses fossil fuels, increase in greenhouse gases raises environmental concerns. Countries such as Malaysia, Indonesia, Vietnam and Thailand have extensive coastlines which makes it suitable for wind energy utilization by erecting wind turbines. This can help in decarbonizing the generation of electricity. Optimized wind turbines can improve reliability of utilizing wind energy. To improve wind turbines performances, optimization of airfoil is required as it will help to generate a greater lift coefficient which is crucial to wind turbine blade characteristics [3].This paper aims to investigate the effect of active flow control method (configuration 1) and a combination of active with passive flow control method (configuration 2) on NACA 4412.

1.1 Flow Control Methods.
Trailing-edge flaps, a common component used as an active-flow control mechanism. Adjusting flaps on turbine blades to a sinusoidal cycle per revolution eliminates cyclic loading acting on wind turbines [4]. Flaps can also be used to reduce vortex down-wash which causes drag, by employing a morphed trailing-edge flap with an extended radial length [5]. As to improve lift to drag coefficient ratio, high chambered flap profile with a high deflection angle can be used [6]. Lift coefficient can also be improved by increasing the exposed surface area by employing extrados flexible trailing-edge flaps [7].
Passive flow control method is usually designed on the surface of an airfoil to reduce the flow separation that occurs at high angle of attack (AOA). Air slots, a common passive flow control feature. An airfoil with an air slot wind inlet at the leading-edge and outlet at the trailing-edge respectively improves the lift coefficient [8]. Without optimization of air slot feature, undesired drop in lift coefficient is produced [9]. Surface roughness element near the leading-edge of an airfoil is another passive flow control feature. This feature reduces the flow separation of an airfoil despite showing a reduction of lift force coefficient due to increase in skin friction [10]. By optimizing the roughness element’s height and location near the leading-edge of the airfoil, an increase in the lift to drag coefficient ratio as well as reduction of flow separation on the airfoil was attained [11]. Another passive feature is attachment of oscillating micro-cylinders at the leading-edge. By optimizing oscillating frequency, improvement of lift coefficient is recorded [12].

Based on observation, a study of both this flow control method combined on an airfoil is insufficient. Therefore, this paper adapts the surface roughness element near the leading-edge of the airfoil as the passive flow control element and a simple trailing-edge flap as the active flow control mechanism. The surface roughness element is expected to reduce the flow separation that would occur in an airfoil at high angle of attacks. The simple trailing-edge flap is attached to increase the surface area. The flow around the airfoil and lift to drag ratio is analyzed.

2. Methodology

This section explains the selection of the airfoils, physical parameters used in this investigation, computational methodology, governing equation applied, airfoil modelling, simulation domain and boundary condition as well as the mesh generation.

2.1. Airfoil Selection

The airfoil selected as the base for the study is NACA 4412 airfoil. The airfoil has a chord length of 175mm and a width of 100mm. Plot of NACA 4412 is shown in figure 1. For the trailing-edge flap, NACA 64-008A airfoil was selected. The airfoil had a chord length of 6.25% of the base airfoil length. A plot of NACA 64-008 A is depicted in figure 2.

![Figure 1. NACA 4412 airfoil.](image)

2.2. Physical Parameters

The surface roughness element used at the leading-edge of the NACA 4412 airfoil is based on a previously optimised value [11]. Therefore, the ratio of height of the surface roughness element to airfoil chord length (k/C) is 0.003, making the roughness height 0.51mm. The location of surface roughness element on the airfoil is at 15% from the leading-edge up to 25% of the chord length. Other conditions are as summarised in the table 1 below.
Table 1. Physical parameters used for investigation.

| Features                        | Values                  |
|---------------------------------|-------------------------|
| Angle of attacks (AOA)          | 0°, 5°, 10°, 15°        |
| Inlet wind speed                | 6 m/s, 12 m/s, 18 m/s   |
| Deflection of trailing-edge flaps| 0°, 5°, 10°, 15°        |

2.3. Computational Methodology
This investigation is carried out using computational fluid dynamic (CFD) approach. In Star-CCM+, a three-dimensional analysis using the Unsteady Reynold’s-Averaged Naiver Strokes (U-RANS) model was created. A three-dimensional setup is necessary to provide an accurate result. This is due to the introduction of the roughness element on the surface of the airfoil. To understand the flow of near wall condition, SST $k – \omega$ turbulence model was selected for this investigation. Star-CCM+ solver was utilized in solving the governing equation of mass and momentum conservation.

2.4. Governing Equation.
Following equations applied to solve airflow problems around the airfoil. The main equation consists of continuity of flow equation and momentum equation.

**Continuity equation:**

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0$$

**Momentum equation:**

$$\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial (\rho U_i U_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial (\tau_{ij} - \rho U_i U_j)}{\partial x}$$

Where, the viscous tensor is expressed as:

$$\tau_{ij} = \mu \left( \frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial U_l}{\partial x_l} \right)$$

**Transport equation for turbulent kinetic energy (k):**

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_i k)}{\partial x_i} = P_k + D_k + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right]$$

Specific dissipation rate ($\omega$):
\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho \bar{u}_i \omega)}{\partial x_i} = P_\omega + D_\omega + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right]
\]

Where the production terms:
\[
P_k = \mu_t \bar{S}^2 - \frac{2}{3} \rho k \left( \frac{\partial (\bar{u}_i)}{\partial x_i} \right) - \frac{2}{3} \mu_t \left( \frac{\partial (\bar{u}_i)}{\partial x_i} \right)^2
\]
\[
P_{\omega} = \rho \gamma \bar{S}^2 - \frac{2}{3} \rho \gamma \omega \left( \frac{\partial (\bar{u}_i)}{\partial x_i} \right) - \frac{2}{3} \rho \gamma \left( \frac{\partial (\bar{u}_i)}{\partial x_i} \right)^2
\]

Where the term
\[
\bar{S}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)
\]

Destruction terms:
\[
D_k = -\rho \beta^* k \omega
\]
\[
D_\omega = -\rho \beta \omega^2
\]

Model coefficients are \(\sigma_k\), \(\sigma_\omega\), \(\beta^*\) and \(\beta\). Where, \(\mu\) is the dynamic viscosity of the fluid.

2.5. Airfoil Modelling.

The airfoil was modelled using SolidWorks software. A three-dimensional model of the base airfoil, airfoil with trailing-edge flap (configuration 1) and airfoil with combined trailing-edge flap with surface roughness (configuration 2) is modelled as depicted in figures 3, 4 and 5. The angle of deflection of the trailing-edge flap in this investigation is calculated relative to the chord line of the NACA 4412 airfoil as shown in figure 7.

Figure 3. Base NACA 4412 airfoil.

Figure 4. Configuration 1: trailing-edge flap.
2.6. Simulation Domain and Boundary Condition.

The domain was created in Star-CCM+. The wind inlet is 900mm away from the leading-edge of the airfoil. The wind outlet is 1800mm away from the trailing-edge of the airfoil. The height of the domain 2440mm and the width of the domain is 500mm. The wind inlet condition set to be velocity inlet and the wind outlet condition to pressure outlet. Both sides of the domain wall set to be interference with periodic translational to define a confined space. The domain was setup to be sufficiently large to avoid disturbance of flow over the airfoil from the induced inlet speed and remove confinement effects.
2.7. Mesh Generation.

A polyhedral mesh is used in this investigation with a wall \( y^+ \) value close to 1. The mesh had a base value of 10mm and volume of refinement of 5mm. The mesh around the airfoil, refined to value of 3.1mm minimum size and 4.0mm target size. The mesh near the trailing-edge flap, refined to minimum value of 0.05mm and a target value of 4.0mm. Finally, to accurately capture the flow changes near the surface roughness element, mesh around the surface roughness was set to be the finest with a minimum value of 0.05mm and a target size of 1.0mm. The number of prism layer used in this investigation is 17 with a stretching factor of 1.2mm for the first layer and 0.5mm for the subsequent layers.

2.8. Validation.

The validation study is initially conducted to ensure the computational setup is accurate and able to mimic the results of a published paper [7]. This would provide confidence to the results obtained later in this investigation. The obtained result is very close to a published result. Slight variation in the results is acceptable. Thus, this validates the simulation setup used for the investigation to be adequate.

3. Results

3.1. Configuration 1.
From AOA of 0° up to 4°, it is observed that airfoil with flap with a deflection angle of 15° has the highest lift to drag coefficient ratio. Beyond AOA of 5°, a drop in lift to drag coefficient ratio is recorded and significantly reduces at angle of attack of 15°. At AOA of 0°, lift to drag coefficient ratio of 36.57
percent higher than the base airfoil is generated a significant increase in airfoil performance. But the value dropped below to 10.22 percent lower than of the base airfoil at a higher AOA of 15°.

Figure 13. Validation of CFD Results with results obtained from Beyhaghi and Amano [7].

For airfoil with flap of 10° deflection angle, a lower lift to drag coefficient ratio is generated compared to the airfoil with flap of 15° deflection angle in a lower AOA of 0° up to 4°. Beyond an AOA of 4°, this airfoil generated a higher lift to drag coefficient ratio compared to the airfoil with flap deflection angle of 15°. At AOA of 0°, this airfoil generated lift to drag coefficient ratio higher compared to the base airfoil by 23.25%.

For airfoil with flap 5° deflection angle, lift to drag coefficient ratio higher than the base airfoil for a longer AOA from 0° up to 7° was generated. At the AOA of 6°, this airfoil managed to obtain the highest lift to drag coefficient ratio.

For airfoil with trailing-edge flap of 0° deflection angle, from an AOA of 0° up to 8° it had generated the lowest lift to drag coefficient ratio compared to the base airfoil and airfoil with other flap deflection angles. As the AOA is increased, lift to drag coefficient ratio generated became close to the value generated by the base airfoil. It can be summarised that, for airfoil with configuration 1 flow control mechanism the higher flap deflection angle performed well in a lower AOA. Airfoil with lower deflection angle performed better at higher AOA. The values of lift to drag coefficient ratio of airfoil with different flap angles in different angle of attack is plotted as shown in figure 14.

Figure 14. Lift to drag coefficient ratio for configuration 1.
3.2. Configuration 2.
For airfoil with a trailing-edge flap of 15° deflection angle, highest lift to drag coefficient ratio was obtained at lower AOA of 0° up to 4°. Drop in the lift to drag coefficient ratio was noticed beyond the AOA of 4°. The lift to drag coefficient ratio of 29.25 percent higher than the base airfoil recorded for the AOA of 0°.

For airfoil flap angle of 10°, it displayed a similar pattern of lift to drag coefficient ratio when plotted against the AOA. At lower AOA of 0° up to 4° it generated a lift to drag coefficient ratio higher than the base airfoil. Lift to drag coefficient ratio of 18.48 percent higher than the base airfoil was obtained for the AOA of 0°. At AOA of 4°, the lift to drag coefficient value begins to reduce. The lift to drag coefficient ratio continues to drop as the AOA is continuously increased.

For airfoil with flap angle of 5°, lift to drag coefficient ratio with small difference than that of the base airfoil was generated. Lift to drag coefficient ratio of 0.53 percent lower than the base airfoil was obtained at 0° AOA. This value is insignificant difference compared to the base airfoil value and can be said to have similar or a close aerodynamic performance of the base airfoil.

For airfoil with flap of 0°, the lowest lift to drag coefficient ratio was obtained. Lift to drag coefficient ratio of 24.62 percent lower than the base airfoil was obtained at 0° AOA and this is the lowest value generated by an airfoil studied in this investigation for configuration 2. Increment in the AOA showed that the lift to drag coefficient value gets closer to the value generated by the base airfoil.

To summarise the data obtained for configuration 2, it shows a similar pattern as the airfoil in configuration 1. This is because, as the deflection angle of the flap is increased it performs better in a lower AOA. Lower deflection angle of the flap has a better performance at high AOA. Although, the airfoil in configuration 1 and 2 has the same pattern when comparing the data of lift to drag coefficient at various AOA, configuration 2 had generated a lower lift to drag coefficient ratio compared to the airfoil in configuration 1. The lift to drag coefficient ratio against AOA is shown in figure 15.

![Figure 15. Lift to drag coefficient ratio for configuration 2.](image)

3.3. Comparison Between Configuration 1 and Configuration 2.

Table 2 shows the value of lift to drag coefficient ratio obtained by airfoil with configuration 1 and 2 relative to the base airfoil in terms of percentage. The (+) symbolize the lift to drag coefficient ratio is higher than the base airfoil, where the (-) symbolize the lift to drag coefficient ratio is lower than the base airfoil.
In table 2, observing the difference between airfoil with configuration 1 and configuration 2, the airfoil with only active flow control method used for this investigation performed better in terms of aerodynamic efficiency.

**Table 2.** Comparison of Cl/Cd for airfoil with configuration 1 and 2.

| AOA | Airfoil with configuration 1. (Cl/Cd) % | Airfoil with configuration 2. (Cl/Cd) % |
|-----|---------------------------------------|---------------------------------------|
|     |                                       |                                       |
|     | Flap 0°                               |                                       |
| 0   | -23.1 %                               | -24.62 %                              |
| 5   | -3.0 %                                 | -5.99 %                               |
| 10  | -0.32 %                                | -3.20 %                               |
| 15  | -0.3 %                                 | -2.45 %                               |
|     | Flap 5°                               |                                       |
| 0   | + 4.84 %                               | -0.53 %                               |
| 5   | + 1.81 %                               | -1.88 %                               |
| 10  | -2.06 %                                | -4.40 %                               |
| 15  | -3.28 %                                | -4.89 %                               |
|     | Flap 10°                              |                                       |
| 0   | + 23.25 %                              | + 18.48 %                             |
| 5   | + 2.31 %                               | -1.38 %                               |
| 10  | -5.05 %                                | -7.55 %                               |
| 15  | -6.58 %                                | -7.88 %                               |
|     | Flap 15°                              |                                       |
| 0   | + 36.57 %                              | + 29.25 %                             |
| 5   | + 0.6 %                                | -2.11 %                               |
| 10  | -8.78 %                                | -10.63 %                              |
| 15  | -10.22 %                               | -10.83 %                              |

4. Conclusion.
This paper investigated the effect of using both active and passive flow control method on NACA 4412 airfoil. It was observed that, a reduction of lift to drag coefficient ratio was observed for configuration 2. It was also observed that for airfoil with configuration 1, the lift to drag coefficient value improved relative to the base airfoil. With further optimisation of roughness element on NACA 4412, the lift to drag coefficient ratio can further improve along with its aerodynamic performance.

Based on the results obtained, it can be observed that the flow separation was high for the airfoil with configuration 2. This is due to the parameters related to the roughness element in the leading-edge of the airfoil. But, the drop in the lift to drag coefficient ratio in the airfoil with configuration 2 is not too far from the values obtained by the airfoil with configuration 1. To achieve a better lift to drag coefficient ratio for the airfoil with configuration 2, optimisation of the roughness element for the airfoil is required. With a proper optimisation of the roughness element, drag coefficient generated by the airfoil is expected to reduce.

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