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Modification of Horizontal Wind Turbine Blade: A Finite Element Analysis

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Abstract. Turbines are efficient power generators. Because wind energy is a clean fuel source, it is widely utilized in some regions. One of the major factors affecting wind turbine performance is the angle of attack of the blade. The aerodynamics and efficiency can be improved by improvising the lift-to-drag ratio CL/CD to get the best design for wind turbine blades. There are many factors affecting the efficiency of horizontal wind turbine blades such as the angle of attack of the blade. Therefore, this study investigated the effect of the angle of attack on coefficients and forces, particularly on a blade with NACA 4412 airfoil in a horizontal axis wind turbine. The length, thickness, and chord length of the blade were 3m, 0.36m, and 0.12 m respectively. Computational Fluid Dynamics was used to develop to obtain lift and drag coefficients in a horizontal wind turbine blade. In addition, the correlation between different angles of attack, lift, and drag forces were studied and validated. The results demonstrated that the lift and drag coefficients increase as the angle of attack increases. Furthermore, the optimal angle of attack for this study was 0° because it has the highest lift-to-drag ratio, resulting in the greatest efficiency. The results demonstrated that it is possible to have a different lift and drag coefficient for the same angles of attack at a similar airfoil.

Keywords: Angle of attack; Energy; Horizontal wind turbine; Lift-to-drag ratio

1. Introduction

Globally, renewable energy is now more cost-effective than fossil fuels (Sudarsono, Susastriawan, and Sugianto, 2019). Renewable energy is of great importance nowadays. It provides reliable power supplies and fuel diversity, which leads to energy security and lower fuel demand. There are various renewable energy sources. The wind is one of the elements. Horizontal-axis turbines and vertical-axis turbines are the two main types of wind turbines. The rotating axis of a wind turbine is horizontal, or parallel to the ground if it has a horizontal axis. The turbine's rotational axis is vertical or perpendicular to the ground in vertical-axis wind turbines. In comparison to the vertical design, the horizontal one is more common as it produces more power, causing it the most common machine design in use today.

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The blade is designed as an aerodynamic geometry with nonlinear chord and twist angle distributions to convert wind energy into mechanical power (Tang, 2012). Because numerous disciplines are involved, such as aerodynamics, construction, materials, and economics, wind turbine blade design is a multi-objective optimization process. The three main models that represent the design process are an aerodynamic model, a structural model, and an economic model (cost model). These three elements form the foundation of wind turbine design. The aerodynamics model is crucial in the design of wind turbine rotor blades and other components. Furthermore, the initial concern in the wind turbine design process is an accurate aerodynamic model. The structural design of a wind turbine blade includes defining the wind turbine loads, selecting an appropriate material, building a structural model, and solving the model using the finite element method. This process will be repeated several times until a final design is achieved (Kasem, 2020). Cost of materials, labor and cycle durations, and virtual factory are the three key processes that make up the cost model for horizontal wind turbines.

First, the bill cost of materials is estimated, then labor and cycle time for a vacuum-assisted resin transfer molding process. This data is used to create a virtual blade. It calculates the costs per blade for labor, utilities, buildings, tools, equipment, maintenance, overhead, and capital. (Bortolotti *et al.*, 2019).

Based on blade element momentum theory, Chaudhary and Roy (2015) reported on the design and optimization of rotor blade performance for a 400-W compact wind turbine at lower operating wind speeds (BEM). The main focus was the link between solidity, pitch angle, tip speed ratio, and maximum power coefficient. For a number of blades of 3, 5, and 7, the maximum power coefficient was found for solidity in the range of 3% to 12% (Chaudhary and Roy, 2015). Yavuz *et al.* conducted an in-depth analysis of wind turbine blades' design and performance evaluation and the outcome (Yavuz *et al.*, 2015). Turbines are efficient power generators. The turbine will not operate and produce power efficiently if the speed is lower than the range. According to Yavuz *et al.*, the greatest lift coefficient occurs when the attack angle is approximately 12 °, and the minimum velocity required to generate power is calculated to be 7 m/s (Yavuz *et al.*, 2015). Chang *et al.* devised a method that incorporates design goals such as airfoil lift, drag coefficients, and lift-drag ratio to produce an analytical expression that results in a highly smooth airfoil for wind turbine applications. According to the study, airfoils created using the proposed technology showed delayed flow separation and excellent airfoil performance (Chang, *et al.*, 2014).

Additionally, Johansen *et al.* also developed a three-blade wind turbine rotor design that maximizes the mechanical power coefficient (CP) in operating circumstances. A free-wake lifting line approach and a three-dimensional Navier-Stokes Solver were utilized to validate the model, which was created using an actuator disc. The study found that CP = 0.51 and that it grows and reduces as you get closer to the root and tip (Johansen *et al.*, 2009).

One of the most challenging aspects in assessing the efficiency of a wind turbine blade is the drag throughout its length, which attempts to stop its movement. Drag is caused by the friction of air against the blade surface. It runs parallel to the lift and in the same direction as the airflow across the blade surface. Bending or twisting the blade, as well as tapering it throughout its length, can reduce drag, resulting in the most efficient wind turbine blade design. To enhance the efficiency of wind turbine blades, the rotor blades require an aerodynamic profile to create lift and rotate the turbine (Woofenden, 2013). The angle of attack (AOA) of an airfoil is a 2D concept defined as the angle between its chord and the undisturbed streamlines far upstream. Furthermore, it is the variation between lift and drags with its direction of travel through a fluid. The determination of the angle of attack is necessary in order to calculate lift and drag forces over the blade, develop accurate aeroelastic models, or establish a control tool (Soto-Valle *et al.*, 2020).

Various factors affect the efficiency of horizontal wind turbine blades includingthe angle of attack of the blade. The angle of attack of the blade is one of the most dominating parameters for wind turbine control and blade design (Wen *et al.*, 2018). Ravi, Madhukeshwara, and Kumarappa (2015) presented a study on NACA 4412 airfoil to compare wind tunnel test experimental results of lift and drag coefficients with two different modeling approaches, namely the k-ω model and the Spalart-Allmaras model (Ravi, Madhukeshwara, and Kumarappa, 2015). These comparisons revealed that the two models provided close predictions of the experimental outcomes. It is concluded that the K-ω SST turbulence model with transition capabilities gives a close prediction of lift and drag coefficient both in the pre-stall and post-stall region.

This study investigates the effect of the angle of attack on coefficients and forces, specifically on a blade with NACA 4412 airfoil in a horizontal axis wind turbine. The length, thickness, and chord length of the blade were 3m, 0.36m, and 0.12m respectively. To accomplish these objectives, a method was developed to model the horizontal wind turbine blade, generate meshes, and perform Computational Fluid Dynamics (CFD) of horizontal axis wind turbine blades to find lift and drag coefficients. CFD assists in determining whether or not the turbine can operate because, if the turbine fails in CFD, it will probably fail empirically. In addition, the correlation between different angles of attack, lift, and drag forces have been investigated in this study. Lastly, an attempt was made to compare the efficiency with other results by modeling horizontal axis wind turbine blades in real dimensions. The real-size simulation, which is suitable for the climate of the city, can be a significant reference for comparing data between smaller and real sizes. Due to their high complexity, air-fluid and aerodynamic calculations can generate strange and extraordinary results in different dimensions. This type of analysis can be useful for improving wind turbine blades in specific cities and may assist other researchers to achieve more accurate results.

2. Methods

One of the most commonly used is NACA 4412 airfoil because it has a high cl/cd ratio. (Lololau *et al.*, 2021). For instance, the NACA 4412 wing section has a 4% camber at 0.4 chords from the leading edge and a 12% thickness. Teak is utilized as the blade material because of its ease of production, availability, and affordability (Sekhar, Kumar, and Reddy, 2014). Furthermore, the use of teak wood blades were chosen due to their light weight and ability to withstand fatigue testing (Maldhure and Kharde, 2013). It was agreed that SolidWorks software would be utilized for the project's modeling work.

Figure 1 depicts the forces and angles of relative wind (p) and angle of attack (a) acting on blade sections, where TN and TQ are normal (thrust) and tangential (torque) forces, respectively, and both forces are generated by lift (L) and drag (D) forces.

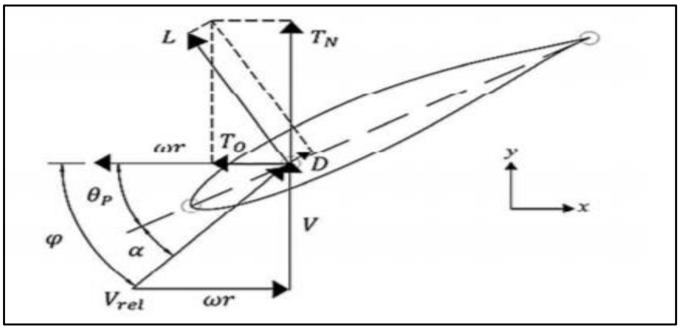


Figure 1 Diagram of the angles and forces on one of the sections of the HAWT blade

The Drag force is a rearward, retarding force caused by disruption of airflow by the wing, rotor, fuselage, and other protruding objects. The coefficient of drag is defined by the equation (1) below:

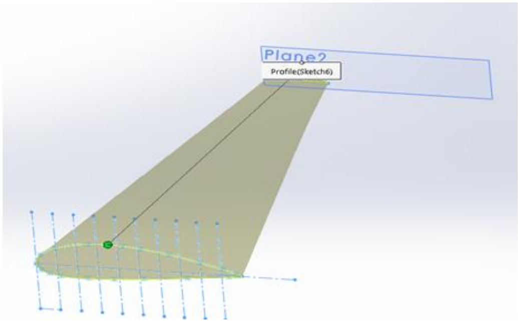
$$C_d = \frac{D}{0.5\rho V_\gamma^2 l} \tag{1}$$

Where: D is the drag force, ρ density of the air (kg/m^3), *Vr* relative velocity when air flowed through the airfoil (m/s), and *l* is the chord length (m). The Lift force is a force that opposes the downward force of weight. It is produced by the dynamic effect of the air acting on the airfoil and acts perpendicular to the flightpath through the center of the lift. The coefficient of lift is defined by following equation:

$$C_l = \frac{L}{0.5\rho V_\gamma^2 l} \tag{2}$$

Where: L is the drag force, ρ density of the air (kg/m^3), *Vr* relative velocity when air flowed through the airfoil (m/s), and *l* is the chord length (m).

In this study, the modeling process was initiated by creating the blade curve at the front plane using (curves through xyz points) from the Curves menu from the Features panel. As a reference for the blade length, the front plane was 3 m away from the original curve and 0.36 m thick, while the chord length was 0.12 m. The airfoil curves are then converted to a sketch on their respective reference planes and twisted about their aerodynamic center. The new plane was used to scale the original curve into a smaller entity with a ratio of 0.26 smaller than the original curve. The scaled entity was given a 10-degree twist in the direction denoted by the negative sign, which refers to the direction of the twist. Additionally, a lofted base boss was made between the two planes which consist of the original curve and the scaled entity, as depicted in Figure 2. After lofting the two planes, a new sketch was created using the front plane to draw a 250 mm-diameter circle and a construction line at the first quarter of the chord length. Moreover, a new sketch was created at the front plane by drawing a line connecting the blade and the circle. At the right side of the blade, a spline was sketched to shape the blade.



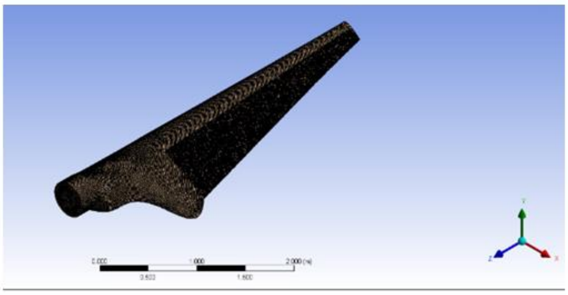


Figure 2 Left: Lofted Boss Base; Right: The CAD model after meshing

A horizontal-axis wind turbine blade with a Naca 4412 airfoil was modeled and analyzed in this study. The blade measured 3 meters in length, 0.36 meters in thickness, and 0.12 meters in chord length. The blade was analyzed in the simulated wind tunnel using Ansys software. The blade was placed horizontally and connected to the left wall from the root in the direction of the X-axis in the mentioned wind tunnel; it was located at the end of the first third of the wind tunnel. The entrance surface of the tunnel had a curved projection. Hence, the wind entering the tunnel would be proportional to its speed, Reynolds number, and disturbances. The X-axis or transverse axis of the wind tunnel should be used when adjusting the angle of attack. This angular change was done without displacement in the depth of the wind tunnel. The depth of the wind tunnel was three times the length of the blade. Air entered the blade from the front of the wind tunnel at a speed of 6.9 m/s. In this study, the Reynolds number was determined based on the kinematic viscosity value which is $1.5 \times 10^{-5}\ m^2$/s, air velocity of 6.9 m/s, and air density of 1.225 kg^3/m. The air velocity was estimated to be around 6.9 m/s as it's the average wind speed in Oman and the chord length is 1 m. The Reynolds number selected in this study was 563,500.

The mesh generating process was conducted using ANSYS Workbench Project Schematic and double-click on the Mesh cell in the elbow fluid flows analysis system as shown in Figure 2. Generating a mesh manually can be time-consuming and error-prone. Mesh size is a key factor in an effective simulation. Mesh refining techniques should be used to optimize mesh sensitivity to produce a mesh of excellent quality. Mesh convergence was done in this study. A blade was modeled and meshed with eight different sizes ranging from 0.5 mm to 5.5 mm. Both lift and drag were obtained. It was observed that the outcomes are approximately the same with a 2-mm mesh size. Hence, convergence was reached when there was no qualitative change in the result of less than 1% in the blade. Therefore, a mesh size of 2 mm was chosen for the whole study.

Despite the fact that ANSYS CFD is an industry-standard modeling software, it is important to ensure that the results produced are logical and valid. The results produced from the blade using ANSYS were compared with XFLR5 software. XFLR5 is a user-friendly design and analysis program for airfoils and bodies. The program analyzes the aerodynamic performance of two-dimensional airfoils using XFOIL codes. The program is capable of calculating lift, drag, pitching moment, and pressure coefficients of airfoils in two-dimension by using a fully coupled viscous/non viscous interaction method with a high-order panel method (GÜZELBEY, Eraslan and Dogru, 2018). The results obtained from ANSYS Fluent were compared with XFLR5 software to guarantee the accuracy of the results.

3. Results and Discussion

Several parameters influence the efficiency of horizontal wind turbine blades, including the blade's angle of attack. One of the most important criteria for wind turbine control and blade design is the angle of attack of the blade (Wen *et al.*, 2018). The effect of the angle of attack on lift and drag coefficients and forces of NACA 4412 is studied insufficiently. This research will investigate this correlation to increase the efficiency of horizontal wind turbines. Therefore,, the focus of this research is on the alteration of horizontal wind turbine blades. To accomplish these goals, a methodology for modeling a horizontal wind turbine blade, creating meshes, and performing computations were created.

Figure 3 compares the outcomes of previous studies conducted to determine the lift coefficient for NACA 4412 with the outcomes of the current study. Figures 3.1, 3.2, and 3.3 are the results of the previous studies conducted on the relation between the angle of attack and lift coefficient, while Figure 3.4 is the result of the current study. In all the studies, the lift coefficient is observed to increases as the angle of attack increases. Also observed in the previous study is that after 16°**,** the lift coefficient starts to decrease as the blade stalls, and the lift decreases once more. Nevertheless, the results of the present study indicated that the lift coefficient continued to increase until it reached 20°.

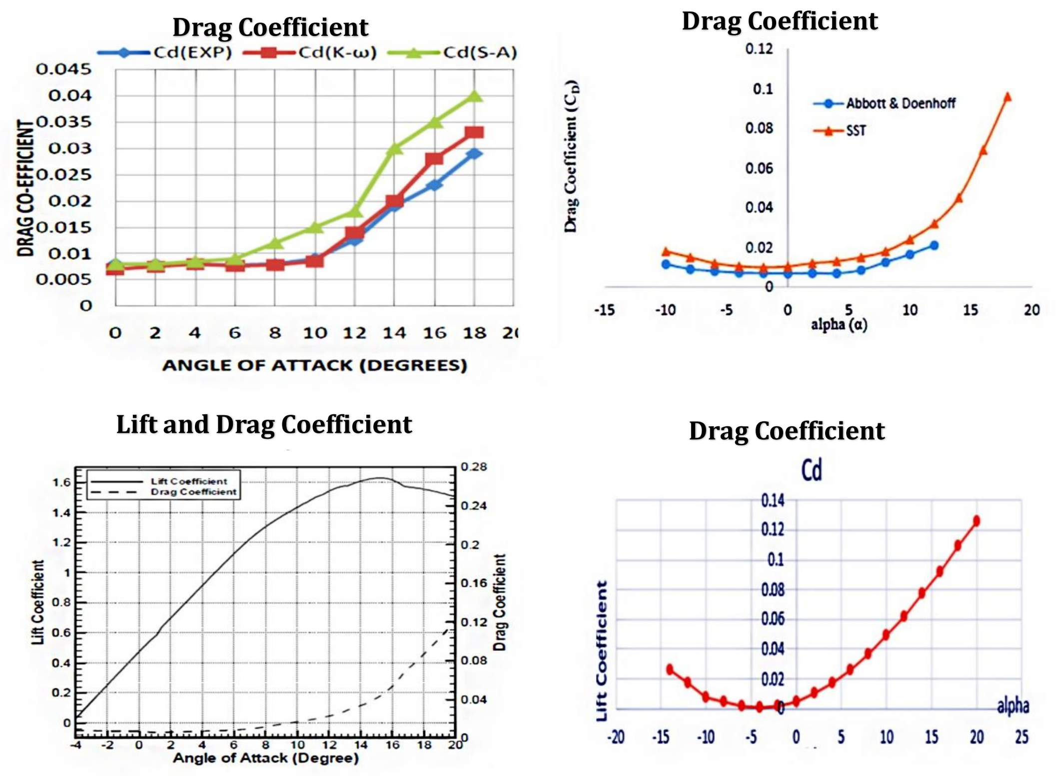


Figure 3 Comparison between different graphs to obtain Cl; (a): Ravi, Madhukeshwara, and Kumarappa, (b): Petinrin and Onoja, (c): Khaled, (d): current study

The results obtained from this study were relatively similar to the results of previous studies conducted to find the drag coefficient. Table 1 displays the results of a study conducted by Ravi utilizing the book "theory of wing sections" by Abbott with two different modeling approaches, namely the k-ω model and Spalart-Allmaras, and the results of the current study from 0°-18°. This indicates that the Spalart-Allmaras has the highest matching with the current study results of Cd.

Figure 4 shows a comparison between the results from the previous studies conducted to find the drag coefficient for NACA 4412 in addition to the results obtained from this study. It is observed that in all the studies the drag coefficient increases with the increase in the angle of attack. Also, the drag coefficient starts to decrease after 16°. However, the results obtained from this study indicated that the lift coefficient kept increasing until 20°.

Table 1 Comparison between Ravi, Madhukeshwara, and Kumarappa's study to obtain Cd

AOA	Current Cd Results	Spalart-Allmaras Cd results	K-ω model Cd results	Wind Tunnel Test Cd results
0	0.005	0.008	0.007	0.008
2	0.01	0.008	0.0075	0.008
4	0.017	0.0085	0.008	0.0079
6	0.026	0.009	0.0076	0.0078
8	0.037	0.012	0.0078	0.008
10	0.049	0.015	0.0085	0.009
12	0.062	0.018	0.014	0.0125
14	0.077	0.03	0.02	0.019
16	0.092	0.035	0.028	0.023
18	0.109	0.04	0.033	0.029

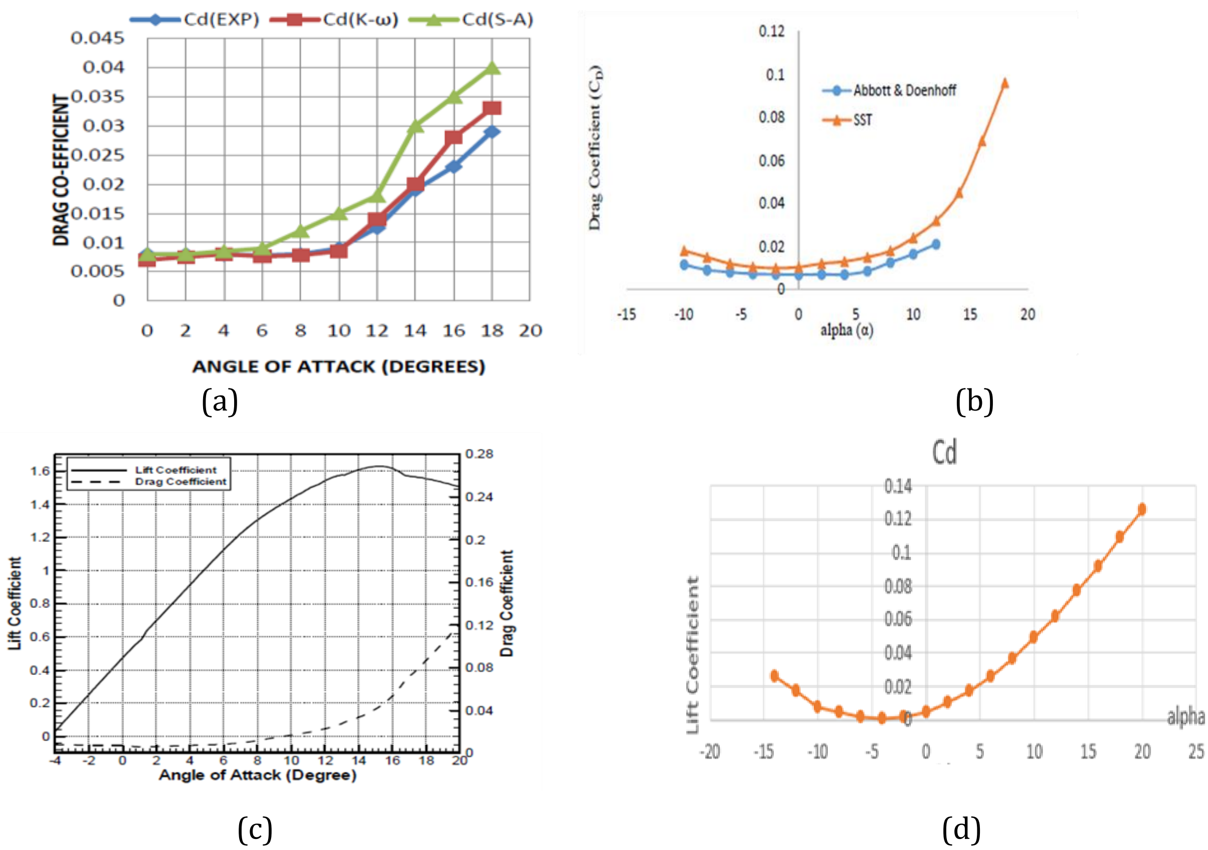
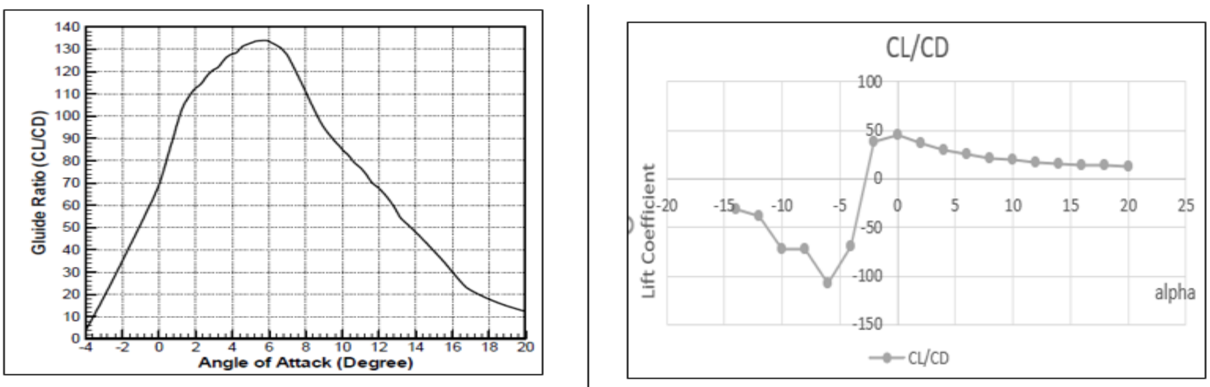


Figure 4 Comparison between different graphs to obtain Cd; (a): Ravi, Madhukeshwara, and Kumarappa, (b): Petinrin and Onoja, (c): Khaled study, (d): the current study

Figure 5 shows a comparison between the results from the previous studies conducted to find a lift-to-drag ratio for NACA 4412 in addition to the results obtained from this study. Khaled's previous research demonstrated that the efficient attack angle for an airfoil is 6 °, after which the efficiency of the airfoil decreases. The current study indicated that the most efficient attack angle is 0°. This experiment was conducted at angles ranging from -14° to 20°. The expectations for angles above 20° are likely to have an increment in lift force and drag force. Consequently, both the lift and drag coefficients will rise.



(a) (b)

Figure 5 Comparison between different graphs to obtain Cl/Cd; (a): Khaled study, (b): the current study

This project is modifying the horizontal wind turbine blade design by studying the effect of blade angle of attack on efficiency. In 2019, lift and drag are the key factors affecting wind turbine efficiency. The project was conducted by selecting an appropriate airfoil, selecting appropriate software, modeling a horizontal wind turbine blade using SolidWorks, transferring CAD files into Ansys, running models and investigating CFD results, and validating the obtained results. CFD investigation was conducted on an attack angle ranging from -14° to 20°.

The negative lift coefficient only occurs at small angles of attack, which corresponds to laminar separation without flow transition and reattachment. It also implies that the lift is acting in the opposite direction of the body (Pranesh, *et al*, 2019). It was determined that the lift coefficient increased as the angle of attack increased because the angle between the chord line and relative wind increased. Furthermore, it is also observed that the drag coefficient decreased until it reached to 0°, then it increased as the lift coefficient increased. As the angle of attack increases, the lift coefficient increases which affects in the amount of the induced drag. This effect is known as “induced drag” or “drag due to lift.” Induced drag increases as the angle of attack of the blade increase. As a result of increasing the drag coefficient, the drag force increased too. Positive drag force indicates that the airfoil is decelerating; thus, the values obtained experimentally indicate that the drag is causing the wind turbine blade to slow. Furthermore, the lift-to-drag ratio is used to express the relation between lift and drag and is determined by dividing the lift coefficient by the drag coefficient. This ratio indicates the airfoil’s efficiency; the higher the ratio the more efficient is the airfoil.

The findings of this research were close to the previous studies conducted to find lift coefficients. In the literature, it has been demonstrated that a higher Reynolds number results in a higher lift coefficient; thus, the difference in lift coefficient results can be attributed to the use of various Reynolds numbers. The current study used a Reynolds number of 563,500, whereas the previous study used a Reynolds number of 3 million.

4. Conclusions

The angle of attack is a significant factor that affects the efficiency of the blade. Furthermore, it is very important to determine the ideal attack angle for the airfoil selected to guarantee the best performance and efficiency. This project aimed to investigate the impact of the relationship between angle attack and efficiency by determining the optimal angle of attack to increase the efficiency of the horizontal axis wind turbine blade. Therefore, an analysis was conducted on the blade to find the lift coefficient, drag coefficient, and lift and lift-to-drag coefficient ratio. Furthermore, the lift and drag force affecting the blade was determined and calculated. This study concluded that the most efficient attack angle for NACA 4412 is 0° and the highest lift and drag coefficient occurred at 20°. The results demonstrated that an identical airfoil have different lift and drag coefficients at the same angle of attack. This study was conducted by modeling a full blade and performing dynamic analysis on the blade to produce results, which may cause a source of errors due to modeling errors. However, this problem can be overcome by using an airfoil curve instead of the entire blade for the analysis.

Acknowledgments

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