Numerical analysis dynamomometer (water brake) using computational fluid dynamic software

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Numerical analysis of the effect of free-stream turbulence on aerodynamic performance of wind turbine airfoil NACA 4415

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Abstract. The aerodynamic performance of airfoils is essential for the design and analysis of wind turbines. The purpose of the study was to obtain the free stream turbulence effect on the aerodynamic performance of wind turbine airfoil NACA 4415. The study was conducted by varying the turbulence intensity from 1% to 10% at Reynolds number of 216,000, and the angle of attack from -4 to 24 degrees. The airfoil had a chord length of 0.153 m. Two-dimensional finite volume method was employed in this study, and the aerodynamic performance of the airfoil was analyzed. It was found that the free-stream turbulence reduced the values of C_D, C_D, C_P, and C_L/C_D, but had no significant effect on the wake area behind the airfoil. The decreased in airfoil efficiency was caused by disruption of the boundary layer flow, which resulted in a decreased in the total pressure coefficient of the airfoil surface. The turbulence intensity could suppress the boundary layer thickness, which results in a reduction of the airfoil shear stress. It is concluded that the free-stream turbulence has a significant effect on airfoil performance, where the effect will increase and decrease the airfoil performance.

1. Introduction

The wind is a renewable energy that is currently widely used to generate electricity, replacing non-renewable energy sources. The electricity generation cost of wind energy shows a declining trend compared to coal [1]. Therefore, the construction of the wind power plant also showed a significant increase. One of the wind turbine performance indicators is efficiency or performance coefficient (Cp). In designing wind turbine blades, the critical parameters are wind speed distribution and turbulence intensity [2]. The effect of wind speed on power and pressure coefficient has long been understood. Nevertheless, the influence of the turbulence intensity (TI) on the wind turbine performance is still being studied. Bardal [3] showed that there is a 50% annual power difference when including the effect of free-stream turbulence. Cao [4] showed that the TI could increase the generated power of the airfoil. Colman [5] studied the effect of turbulence intensity and length scales on the performance of an airfoil and found that the performance is independent of the scales of the incoming turbulence.

Several other studies discussed the airfoil efficiency, boundary layer separation, vortex, and the effects of free-stream turbulence. Maldonado [6] concluded that an increase in turbulent intensity could increase the ratio of lift forces to drag forces (C_L/C_D), and delayed flow separation at high attack angles. An increase in turbulent intensity could delay stall conditions, increase the maximum value of the lift coefficient, and increase the resistance of the boundary layer to flow separation [7]. Kim and Xie [8] found that the intensity of high turbulence resulted in a reduction in separation bubbles, which ultimately increased the C_L/C_D value on static airfoils. Yao [9] conducted a numerical study by comparing several turbulence models, namely k-ε, RNG k-ε, SST4, and Reynolds stress models. It was found that the lift coefficient obtained from numerical simulations, for all turbulence models, was in good agreement with experimental data.

In the present study, the influence of free-stream turbulence intensity on the performance of a two-dimensional (2D) NACA 4415 airfoil at Reynolds number 216,000 has been studied numerically. This study is a fundamental part of research on the optimum design of wind turbines by considering the free flow turbulence factor in laminar, transition, and turbulent flow, to be applied to an onshore wind farm. The simulation used a one equation turbulence model, namely Spalart-Allmaras. The calculated parameters are C_L, C_D, C_L/C_D, C_P, and separation positions. The results of this study are expected to provide clear and detail information for conducting a numerical study on the effect of the free-stream turbulence intensity of a three-dimensional wind turbine for various types of airfoils.

2. Materials and methods

2.1 Numerical methods

In this study, the method used was a computational fluid dynamics (CFD) approach, namely the finite volume method. In the finite volume method, unknown variables are explained using a specific point on the nodal points. In CFD, Reynolds Average Navier-Stokes (RANS) is the most widely used turbulence modeling approach. In this approach, the Navier Stokes equations are split into mean and fluctuating components. Generally, the necessary steps for solving problems using the finite volume method are as follows: estimating the value of unknown flow variables using a simple function; make a discretization equation by entering the estimation into the general equation of flow; doing the mathematical manipulation; and finally, solve the algebraic equations of the problem.

2.2 Geometry and flow condition

In this simulation, a NACA 4115 airfoil was used with a chord length of 145 mm. The airfoil was placed in the free air, where the speed and intensity of turbulence and other flow conditions were varied. Wall effects, which were experienced in a real wind tunnel testing, were eliminated by using a fairly extensive calculation domain around the airfoil. The velocity inlet boundary condition was placed in the front and two sides of the airfoil, which had a distance of 12 times the airfoil chord length. At the back, there was a pressure outlet boundary condition which had a distance of 21 times of the chord length. Wall with no-slip boundary condition was applied at the airfoil wall. Setting the angle of attack was done by adjusting the direction of speed according to the angle of attack. In this simulation, the surface roughness of the airfoil is smooth, and the angle of attack (AOA) was varied between -4 and 24 degrees. The free-stream turbulence intensity were 0.1%, 3%, 7% and 10%.

2.3 Turbulence models

The simulation was taken away at a speed of v = 22.56 m/s that was calculated based on frontal and tangential wind speed, which was experienced by a real wind turbine blades. By using the chord length as the characteristic length and this speed, the Reynolds number was 216,000. Therefore, the flow regime is turbulent with a low Reynolds number. For such flow conditions, turbulent models that are quite well are Spalart-Allmaras and k-ω SST [9 and 10]. Based on argumentation in [10], for this study, the Spalart-Allmaras turbulence model was selected. This model is very suitable for flow that has a positive pressure gradient, does not require wall function, requires relatively few cell numbers, and is more easily converged in a relatively time fast. However, the cell size must meet the condition where the value of Y_{plus} (wall distance dimension) should be less than 1.

3. Results and Discussion

3.1. Grid independence test

Based on the Y_{plus} value, the first stage number of cells was 62,540. The computation of the drag coefficient for the airfoil was tested with the number of cells as much as 79,616, 88,022, 104,828, and 138,434. The criterion of the relative error produced in the simulation was less than 2%. Based on this value and computational time, in this study, the optimal number of cells was chosen as 88,202. The Y_{plus} value of this grid in all simulations was less the 0.25. The mesh generation of the calculation domain and near the airfoil is depicted in figure 1.

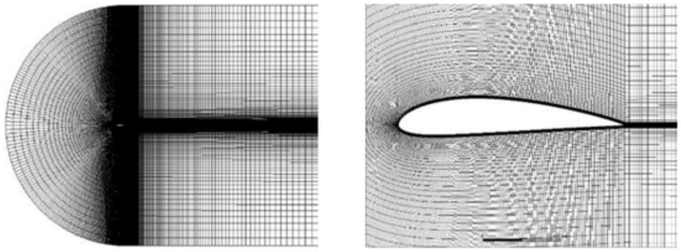


Figure 1. Mesh generation of calculation domain and near the airfoil wall

3.2. Selection of convergence criteria

In this study, the convergence criteria for flow equations and turbulence equations were considered as well. The residual values tested were 10^{-3}, 10^{-4}, and 10^{-5}. The test results evidenced that a decrease in residue would increase accuracy by up to 1%. However, in most of the simulations tested, the use of residual of 10^{-5} gives non-convergent results. Thus, in this study, the convergence criteria were chosen as 10^{-4}.

3.3. Validation

The standard airfoil data of NACA 4115 [11] and Aftab [10] were used to validate the calculation results. The results of the validation of the C_L values indicated that the calculations performed reasonably good results, with an error of about 12% based on NACA data and 15% for the other one. For AOT = 12 degrees, the validation results showed an error of approximately 8%. Based on these results, it can be verified that the calculation at Re = 216,000 gave quite a proper validation.

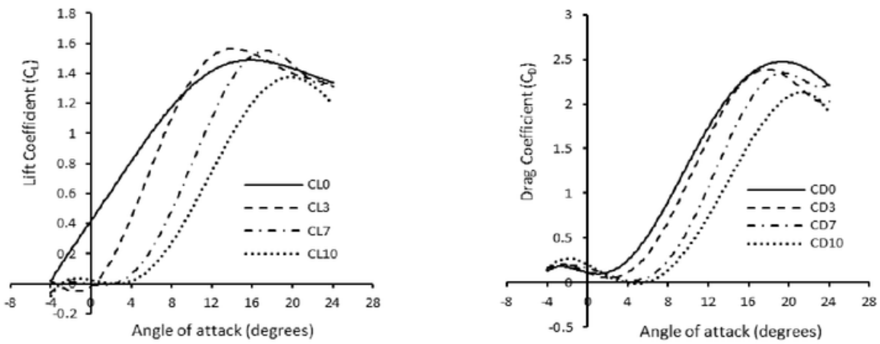
3.4. Airfoil performance

Figure 2 shows the results of the C_L and C_D for various AOT and turbulence intensity. The reference value used to calculate the C_D and C_L is at a speed of 22.56 m/s with a span area of 0.1453 m^2, and a cross-sectional frontal area of 0.0225 m^2. Figure 3a shows the C_L/C_D values for various TI.

3.4.1 Effect of turbulence intensity on C_L and C_D. It can be seen in figure 2a, that the effect of TI is quite clear and significant at various AOT. The CL0, CL3, CL7, and CL10 means that the TI is 0%, 3%, 7%, and 10%, respectively. At AOT = 8 to 12 degrees, the effect of TI is decreasing the C_L value. The higher the TI, the lower the C_L. At higher AOT, the reduction of the C_L value is more significant. The gradient of the C_L to AOT is getting lower with the increasing value of TI. However, it also shows that the maximum value of C_L changes upon the value of TI. At TI = 7% and 10%, there is an increase in this value, while at TI = 3% the CL decrease. The position of the maximum C_L value also shifts to the right with increasing the TI. In figure 2b, it can also be seen clearly that the TI has a significant effect on the drag coefficient. The higher the value of TI, the lower the drag coefficient. This certainly has a positive impact both on torque and the power produced by the airfoil. Likewise, the maximum C_D decreases with increasing TI, and the maximum position of the C_D will shift to a larger AOT.

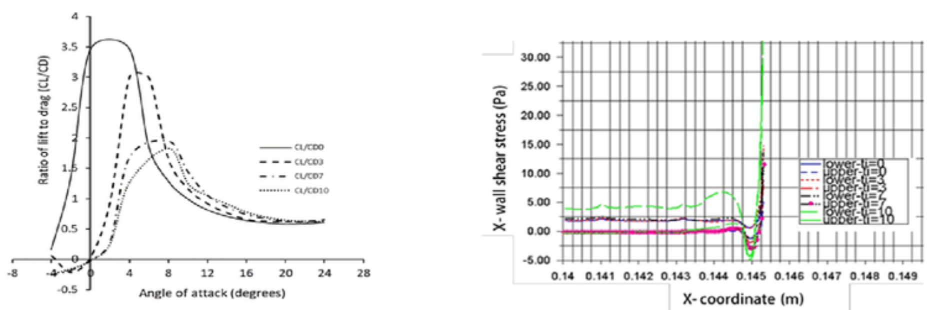
The C_L/C_D can be considered as a measure of airfoil efficiency. The effect of turbulence intensity on the airfoil efficiency can be seen clearly in figure 3a. The separation position can be estimated from the shear stress distribution in the flow, as shown in figure 3b. The first effect is that the turbulence intensity reduces the distribution of C_L/C_D in almost the entire AOT range. The C_L/C_D tends to decrease with increasing value of TI, both before and after the maximum value. The second effect is a shift in the value of the maximum C_L/C_D. In this case, if TI is getting higher, the maximum position of C_L/C_D will shift towards a larger AOT. With these results, it can be concluded that the free-stream turbulence has a negative effect on the efficiency of wind turbine airfoils.

3.4.2. Effect of turbulence intensity on pressure coefficient (Cp). Figure 4 shows the distribution of pressure coefficients on the upper and lower airfoil surfaces, for AOT 8 and 12 degrees, at various turbulence intensity. It can be seen that the Cp for the upper airfoil is below the lower airfoil. This indicates that in both AOT values, the airfoil has a positive lift or upward force. This is in accordance with the distribution of C_L values in figure 2a, which shows a positive value. Furthermore, the picture also shows that the turbulence intensity also has a significant impact on the distribution of Cp values. Increasing the intensity of turbulence will reduce the distribution of Cp values on the upper airfoil, both at AOT = 8 and 12 degrees. However, the distribution of the Cp value also decreases with increasing value of TI. Since Cp decrease in the upper part of the bottom is higher, with an increase in the value of TI, the result is a decrease in the value of C_L. This condition applies to AOT = 8 or 12 degrees, but the value is different. At AOT = 8 degrees, the influence of TI is stronger compared to AOT at 12 degrees. This can be confirmed from the C_L and C_L/C_D values in figures 2a and 3, respectively.



(a) (b)

Figure 2. Effect of turbulence intensity on the lift (a) and drag coefficient (b)



(a) (b)

Figure 3. Effect of turbulence intensity on airfoil efficiency (a) and separation point (b)

3.5. Discussion

Comparing the results of this study with the previous one is not so easy, because there are no similar results, based on the NACA 4415 airfoil, both experimental and computational. However, the simulation results mentioned above are still in accordance with the results of a study [3], which carried out turbine power comparisons, which were calculated based on TI = 0, on power in the field, which had a high turbulence intensity. In these measurements, there was a power difference of 50% lower than the power measured by assumptions without turbulence intensity. Also, the results obtained by Li [12] on the NACA 0012 symmetry airfoil, which concluded that the turbulence intensity had a significant effect on airfoil performance, especially on boundary layer and separated shear flow.

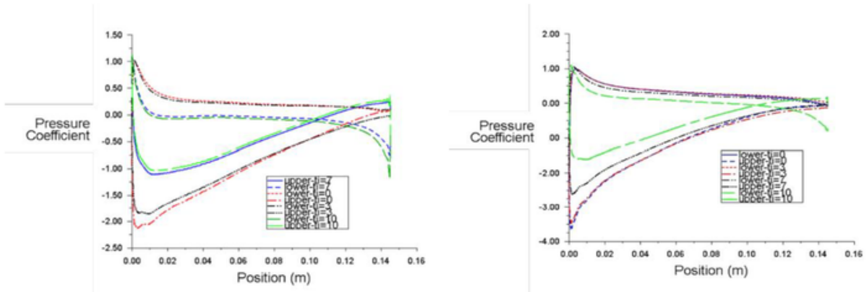


Figure 4. Distribution of Cp on an airfoil at AOT of 8 degrees (a) and 12 degrees (b)

Based on the measurement by Mikkelsen [13], the free flow turbulence had a positive and negative impact on power generation in the wind turbine. This fact might be the reason why the maximum power produced was reduced by only around 2.4% when applying free-stream turbulence in the test. So, by increasing the turbulence intensity could increase the drag force, which inevitably reduced the power produced by the turbine. However, at the same time, the increase in turbulence intensity increased the relative speed of the turbine blades, which had an impact on the increase in kinetic energy and the power produced by the turbine. In the present study, the effect of increasing the turbulence intensity is reducing the C_L value, which is higher than the decrease in C_D. This condition will decrease the power produced by the turbine. The result is consistent with the results obtained by Maldonado [6], Amandolese [7], and Li [12].

The NACA 4415 airfoil is widely used as a wind turbine blade. This airfoil, despite delivering a low maximum C_D value, its profile has the advantage to use in low Reynolds numbers. The shape of the airfoil profile is quite streamlined so that the boundary layer does not have a laminar separation bubble at the front area of the airfoil. It seems that the effect of turbulence intensity does not change the separation position. This is in accordance with the results of the simulation, where the laminar bubble separation phenomenon was not found. The boundary layer, ranging from laminar to turbulent, developed without bubble separation. The separation took place near the trailing edge that produced a narrow wake area. Such an airfoil character is not sensitive to the freestream turbulence intensity. In this study, turbulence intensity affects the thickness of the boundary layer, where the higher the intensity of the turbulence, the thinner the boundary layer, which results in a decrease in skin shear stress. However, pressure distribution on the surface is disturbed, so that the distribution of the pressure coefficient will decrease, resulting in a higher drop of lifting force coupled with the decline of the frictional force. The final effect is that C_L /C_D values will decrease, so the airfoil performance will also decrease.

4. Conclusions

Some conclusions can be drawn from the study of the effects of free-stream turbulence on the performance of this NACA 4415 airfoil. The first general conclusion is that the numerical methods can be used to investigate and analyze in detail the flow around the airfoil. Secondly, the free-stream turbulence has a significant effect on airfoil performance, where the effect can increase and decrease the performance. The other conclusions produced from this study are as follows:

- The free-stream turbulence intensity can reduce the values of C_D, C_L, C_P, and C_L/C_D.
- The free-stream turbulence intensity does not significantly affect the wake area behind the airfoil.
- The reduction in airfoil efficiency is caused by disruption of the boundary layer flow, which decreases the total pressure coefficient of the airfoil surface.
- The intensity of turbulence can attenuate the thickness of the boundary layer, which decreases shear stress along the surface of the airfoil.

5. Future works

Based on the discussion above, it is suggested to do further research on the effects of free-stream turbulence experimentally and numerically, using more precise setups and measuring instruments, ranging from laminar to turbulent flow. Also, it is necessary to study the effects of laminar flow, which is influenced by the free-stream turbulence intensity. This research needs to be done given the phenomenon that is still mysterious in the transition area, and there are still various scientific questions about the onset of turbulent flow. The study of numerical methods is also developed further, involving the latest turbulence models.

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