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Research Article

Wind Turbine Blade Design with Computational Fluid Dynamics Analysis[#]

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Wind turbine
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Blade element momentum theory (BEM Theory)
Computational fluid dynamics (CFD)

Abstract: Although there are many blade profile have been improved for use in aviation and energy sector, there is still needed blade profiles which have higher performance especially the commercial horizontal axis wind turbine efficiency is taken into account. The purpose of this study is to obtain the new blade profiles which have higher lift (CL) and drag (CD) coefficients for wind turbine making geometric modifications on several NACA wing profile systematically. For this purpose, the performance of NACA and developed new profiles have been compared with each other using computational fluid dynamics analysis and it is seen that the new developed profiles have higher performance than NACA profiles. Later on, according to the Blade Element Momentum Theory (BEM Theory) turbine blades are designed with developed new profiles and 3-dimensional CFD analyses are performed. Increase in torque in the wind turbine is determined.

1. Introduction

One of the natural, renewable and clean alternative energy sources is wind power plants. Nowadays, the electricity demand is increasing rapidly due to advancing technology. It seems the demand will continue to increase in the future.

In literature search, it is seen that studies are mostly concentrated in performance development and it's optimum usage of the main equipment that make up the wind power plant to increase the annual electric energy produced. The main structural element of power plant is the wind turbine which converts the kinetic energy of air to the mechanical energy. For this reason, improving the performance of the wind turbine will directly increase the efficiency of the wind power plant. Some of the researchers have been trying to improve of the plant performance with a new turbine blade design, while the others investigate the optimum conditions for existing wings. M.Y. Maalawi and M.T.S. Badawy [1] tried to improve of the blade performance obtaining the optimum beam width and turning angle analytically in their study. A. Erisen and M. Bakirci [2] produced new profiles from NACA-0012 and NACA-4412 profiles making some mainline changes on it's profiles and they determined that the lift force increases depending on changes with the blade profile analyzing aerodynamic admittance using the Computational Fluid Dynamics (CFD) method. M. Jureczko et all. [3], developed a software package for the design of the wing which gives the best performance taking into account a lot of parameters such as dynamic and mechanical properties of the material used, from sizing of turbine blades to production. W. Xudong et. all [4] tried to design of optimum wind turbine blade which has maximum performance taking the beam width, the rotation angle and the thickness into account in their study. A. Varol et. all [5] investigated the effects of the number of blade, the distance between the blades and the blade slope to the wind turbine efficiency. M.M. Doquette and K.D. Visser [6] determined that in their study, power factor in other words the power of turbine can be increased with the more number of blades for small-scale wind turbines. E. Benini and A. Toffolo [7] investigated optimum turbine design which has the minimum cost and the maximum production of energy. L. Xiong et. all [8] made a blade optimization for the purpose of the maximum annual energy production taking into account the wind speed distribution in a particular area for horizontal axis wind turbine. K. Kishinami et. all [9] have found the optimum operating conditions of the aerodynamic performance for the horizontal axis wind turbines which have variety of blade types in their theoretical and experimental study. The performance of the blade profiles with different geometries in the high Reynolds number and the low angle of attack were investigated by K.M. Güleren and S. Demir [10]. They determined the optimal blade profile for the operating conditions with CFD approach. The aerodynamic behavior of wind turbine blade especially the angles of attack where the torque is low in turbulent flow has been affected quite a lot by the level of turbulence was determined by P.H. Devinant et all [11] in their experimental study. The properties of time-dependent aerodynamic behavior of horizontal axis 3 blade wind turbine were investigated with CFD method by L. Bermudez et. all [12].

In this study, a new blade profile which has higher performance has been developed changing the front and the back flatness of the NACA-0012 profile. For this purpose, lift-to-drag ratios depending on the angle of attack were obtained after developed the profile by performed 2 dimensional CFD analysis. Based on the blade element momentum theory, a new design blade has been proposed using the coefficients which are obtained from the developed profile and the results of the 2D CFD analysis. Thereafter, increasing in the blade performance was determined by performing 3 dimensional CFD analysis.

2. 2D Numerical Model

A 2D model is developed to simulate air flow over modified blade profile to obtain better lift-to-drag ratio value than NACA-0012 profile, and numerical computations are performed using Ansys/Fluent Software [13]. Continuity, momentum and turbulence equations are solved for air flow. The turbulence air flow model uses one equation in the Spalart-Allmaras model which was improved for air flow on solid surface. Turbulent intensity and hydraulic diameter method is used for the turbulent specification method.

Boundary conditions and the grid mesh for the computational domain are shown in Fig. 1. Turbine surface is defined as “wall”. Computational domain of the input and the output are defined as “velocity inlet” and “pressure outlet” boundary conditions, respectively. An independent mesh structure is created, where the density of the nodes increased up to the result of computational study is no longer changed with additional grid refinement. Mesh grid is occurred about 55000 nodes and elements and the skewness value is around 0,69. Suitable grid refinement on the blade surface is necessary to obtained sufficient wall interaction event and computational stability. Therefore, a weight factor used to concentrate the mesh structure on the domain, which is near the blade surface with high pressure gradient.

3. Findings

Naca 0012 profile and modified profiles are shown in Fig. 2. Positive percentage change expresses increase of the back flatness of the profile for A and decrease of the front flatness of the profile for B. CFD analysis have been performed for the modified profiles from Naca 0012 and lift-to-drag coefficients have been obtained.

Increasing of the drag as well as the lift coefficients with the increase of the front flatness for modified profile A are observed in the Fig. 3. On the other hand, decreasing of the back flatness for modified profile B increases the lift coefficient whereas it decreases the drag coefficient after 0.2% change. The decrease of the drag coefficient while the lift coefficient is increased will cause the lift-to-drag coefficient to increase remarkably.

Lift-to-drag coefficient is a very important parameter for the wind turbine blade design. It is preferred that it’s value is at least over 20 at the optimum angle of attack for a wing to be designed [14]. Figure 4 shows the lift-to-drag coefficients of the modified wing profiles at 5 degree of angle of attack. Decrease of the front flatness in spite of the increasing the back flatness leads to higher lift-to-drag coefficients especially after 0.2% change. Drag and lift coefficients of modified blade profile which is depending on angle of attack are given in Fig. 5 for different Reynolds number. Both the drag and the lift coefficients which are depending on the increase in Reynolds number are increasing. On the other side, while the drag coefficient increases with the increase in the angle of attack, the angle of attacks at the low lift coefficient, at first there is driblet increment then starting to decrease with depending on the increment of the angle of attack.

According to the official website of the general directorate of renewable energy in December 2015 [15], the effective wind speed is approximately 7 m/s at approximately 67% of the wind energy plant installation area in Turkey. This means 7 m/s is equal to 700k Reynolds number under simulation conditions. In cases which the Reynolds number is 700k, it is necessary to determine the angle of attack which is highest in the lift-to-drag coefficient which is an important parameter of the wing design although the highest lift coefficient seems to be occurred at about 5 degree angle of attack.

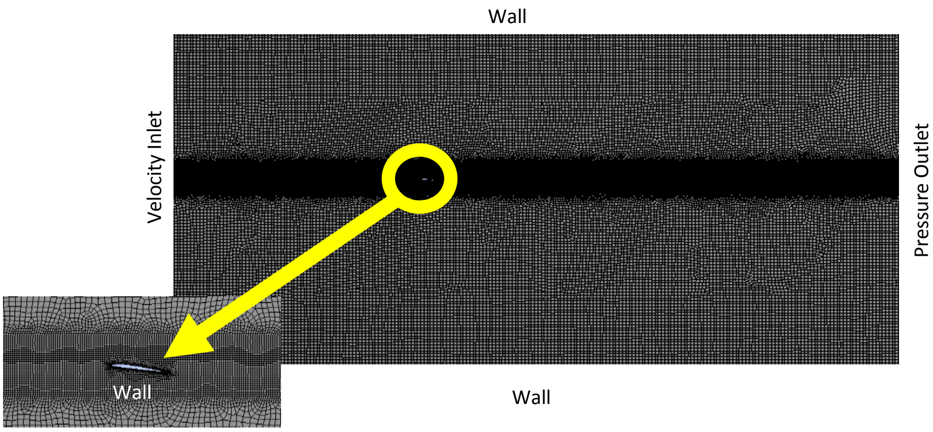

Figure 1. *Boundary conditions and mesh grid of the model.*

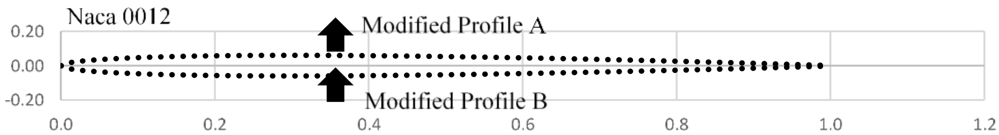

Figure 2. *Blade profiles.*

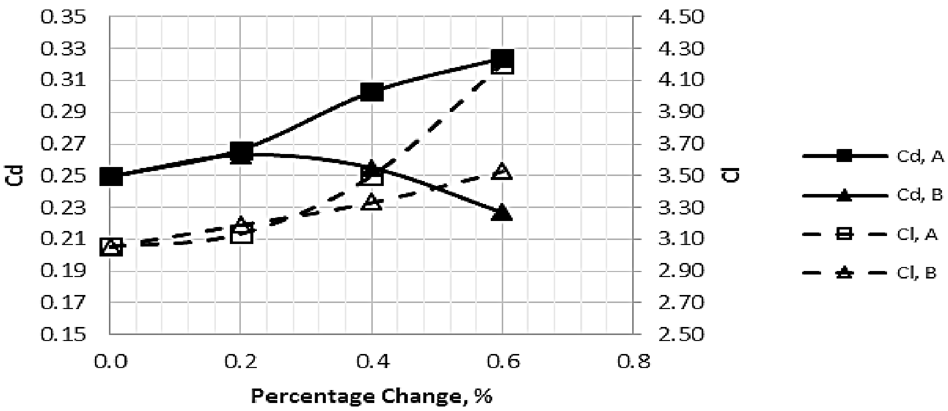

Figure 3. *Cd and Cl coefficients depending on the flatness*

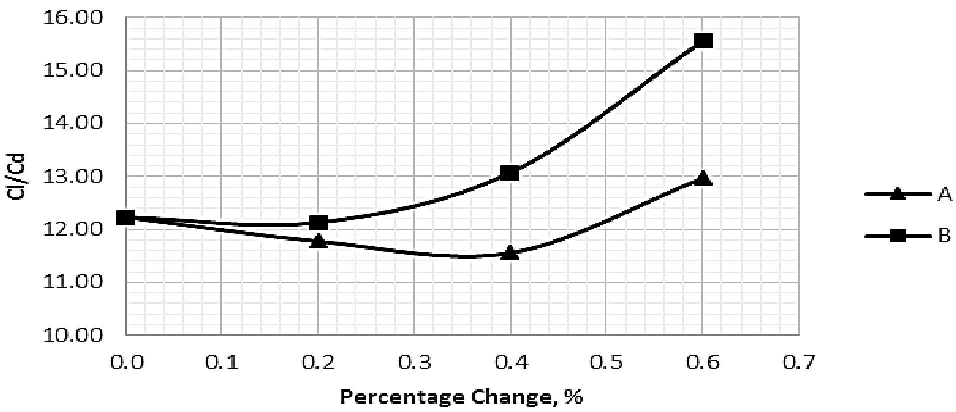

Figure 4. *Lift-to-Drag coefficient versus percentage change of the front and back flatness*

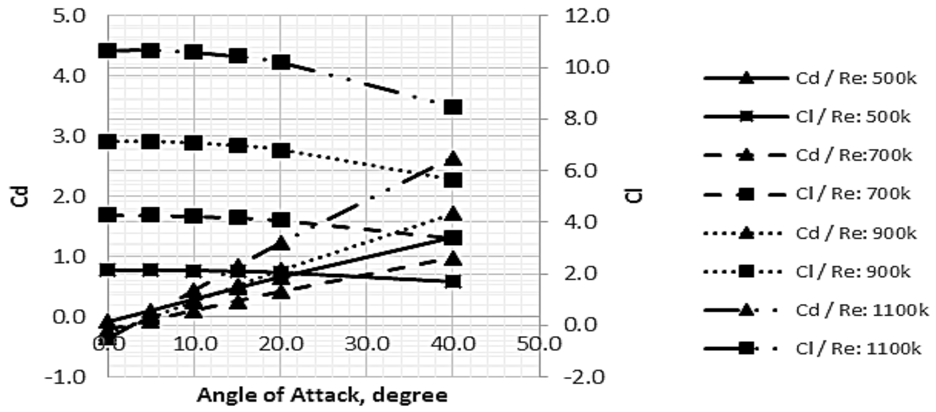

Figure 5. *Lift and drag coefficients depending on the angle of attack.*

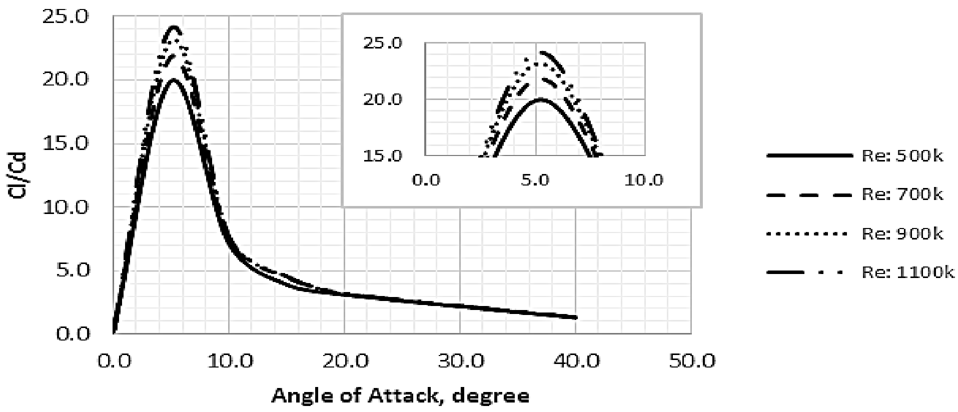

Figure 6. *Lift-to-drag coefficient depending on the angle of attack.*

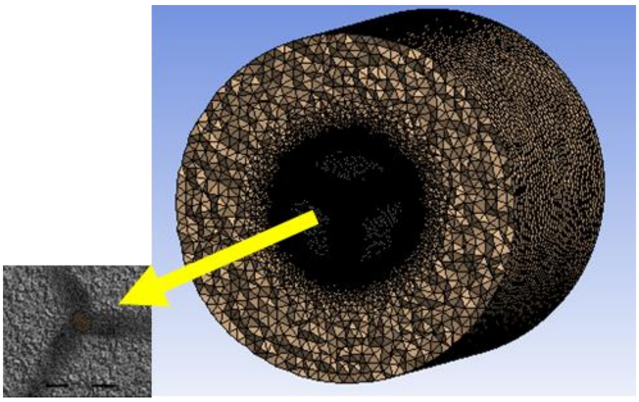

Figure 7. *Mesh grid of the model*

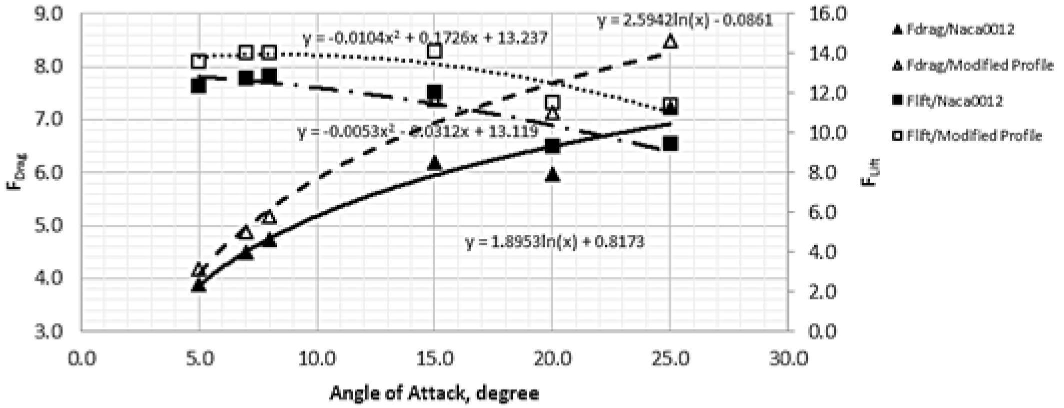

Figure 8. *Lift and drag forces depending on the angle of attack.*

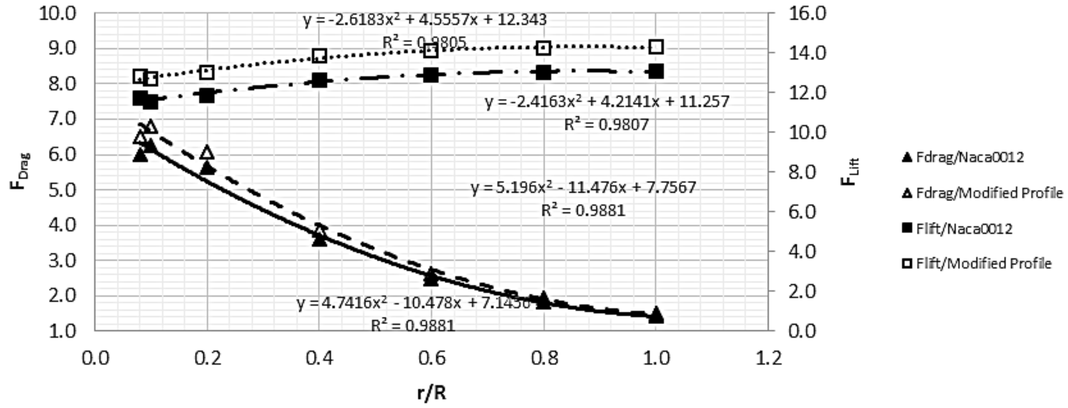

Figure 9. *Lift and drag forces along the wing.*

Figure 6 shows the lift-to-drag coefficients for various Reynolds numbers depending on the angle of attack. The highest lift-to-drag coefficient for the 700k Reynolds number was determined to be 21.82 at 7 degrees. In this angle of attack, the lift coefficient is found about 4.27 and the drag coefficient is found about 0.19. Under these findings, 1m length and 3-blade wind turbine which has in the range of 5 to 8 value of tip speed ratio is selected and it is designed based on blade element momentum theory and modelled using Ansys/Design Modeler as 3D.

4. 3D Numerical Model

A 3D model which is used pressure based solver and implicit formulation is developed to bring out the aerodynamic behavior of the modified blade profile. Computational calculation domain which is consist of wind turbine and air surrounding the blade is generated as cylindrical shape. When the Mach number, which is lower than 0.02, is taken into consideration, the calculation region is sized to the optimum dimensions. Thus, air behavior over the blade surface should not been affected boundary conditions. The standard wall function was applied to blade surface, a constant velocity is defined in the velocity inlet boundary condition. Ambient conditions are defined in the pressure outlet boundary conditions where is applied at the output of the computational domain.

The mesh grid is concentrated for close region of the turbine blade in the calculation domain, because of the computational accuracy. The mesh grid of the 3D model is shown in Fig. 7. Mesh structure has tetrahedron elements is occurred about 1M nodes and 6M elements and maximum skewness value is around 0,89 which has been acceptable in literature. The independent mesh structure is obtained with approximately 6 million elements. Spalart-Allmaras turbulence model is preferred as a viscous model for the air flow over the wind turbine. y+ values on the blade surface is preferred to be almost 1 with Spalart-Allmaras model to obtain reliable results [13]. In this study y+ values are between 4 and 8, which are close to 1. Continuity, momentum, turbulence equations are solved for the air flow over the wind turbine. Flow, velocity and pressure areas were obtained as the results of analysis. The model was initialized as hybrid to obtain the initial conditions, and then it as solved as second order upwind to get the final results.

5. Results and Discussions

The CFD results which were obtained from the Naca 0012 and modified profile are given in Fig. 8. At low angle of attacks, while the lift force shows a tendency to increase with the angle of attack, at high angle of attacks, the lift force is decreasing with depending on the increment of the angle of attack. The drag force has the minimum value at the low angle of attacks and it is decreasing with increase in the angle of attack. As a result of analysis, higher lift and drag forces were obtained from modified profile than Naca 0012. In figure 9 shows lift and drag force changes from the root to tip of blade. Since the chord length is larger at the root than at the wing tip, drag force is high at the root of the wing and it decreases towards the tip. As to the lift force increases from the root to tip of blade. This can be explained with changing in tip speed ratio.

6. Conclusion

In the present study, the performance of a new blade profile which is modified from the Naca 0012 profile has been studied using CFD analysis method. The results obtained can be summarized as follows.

1. While increasing the back flatness of the profile (modified profile A) provides approximately 5% performance increment compared to the decreasing the front flatness of the profile (modified profile B), there is also an increase of approximately 15% in the drag coefficient. This has a negative effect on the lift-to-drag coefficient. Taking into account increase in the front flatness of the profile reduces the drag coefficient in 0.2% change, modified profile B which lift-to-drag coefficient is 21.82 was preferred for the turbine blade design.
2. Naca 0012 profile and modified profile B were compared. An increase between 7.76% and 9.51% in the drag force at low angle of attack was obtained for modified profile B. Also there is an increase between 9.48% and 10.01% in the lift force was obtained. Thus, 1.5% - 2% average increase of lift-to-drag ratio was achieved at low attack angle along the wing.
3. Since the tip speed ratio at the wing tip (r/R=1) is 12.5 times greater than at the wing root (r/R=0.08), the lift force increases about 13.08% along the wing root to wing tip. On the other side, since the chord length at the wing root is 36.37% greater than wing tip, the drag force occurred on the wing root is about 3.48 times that of the wing tip.

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