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Improving the Horizontal Axis Wind Turbine Blade Profiles

Cemil Yiğit^{*1}

Abstract

Due to greenhouse gases, we feel the effects of global warming more and more every day, so we need far more efficient Horizontal Axis Wind Turbines (HAWTs). This study was carried out to develop turbine blades with higher momentum coefficient (C_m) for the HAWTs. For this purpose, the blade profile that has higher performance was improved using Taguchi and Computational Fluid Dynamics (CFD) methods. With reference to the NACA 0012 profile, changing the upper and lower cambers of the profile derived the new blade profiles. Using the Taguchi method, the optimum blade profile with a maximum C_m coefficient was obtained. After the profile to be used on the turbine blades is determined, the blades are designed with the Blade Element Momentum (BEM) theory. A 3-dimensional model for the HAWTs is developed using ANSYSv.16.2/Fluent Software. CFD analyses were performed using a sliding mesh approach to get more realistic and reliable results and to gain more knowledge of the performance. Numerical analysis results show that power coefficient (C_p) of the optimum profile is increased by 7.42% according to the NACA 0012 profile.

Keywords: Horizontal Axis Wind Turbine (HAWTs), Blade design, Taguchi Method, Computational Fluid Dynamics (CFD), Sliding Mesh

1. INTRODUCTION

Wind power plants which are the natural, the renewable and the clean alternative energy source are gaining increasing significance due to the effects of global warming. We need far more efficient Horizontal Axis Wind Turbines (HAWTs) because we feel the effects of global warming more and more every day. Nowadays, the electricity demand increases with the developing technology. In the literature research, it is seen that studies are mostly concentrated on improving performance in order to increase the electrical energy produced. The turbine, where the first energy conversion begins, is the primary element of the power plant. Therefore, when the performance of the wind turbine is improved, the efficiency of the plant will also increase directly.

If we take a look at the literature, on the one hand, while trying to recover turbine performance with the new blade profile developed, on the other hand, the best conditions for the existing blade profiles are being investigated. Cayiroglu and Kilic have optimized the aerodynamics of the wing by using the genetic algorithm and CFD approach [1]. Maalawi and Badawy [2] have improved the blade performance by analytically obtaining the optimum chord and attack angle in his work. Wang et al [3] studied on the vertical axis wind turbines that have different thicknesses and different cambers. Erisen and Bakirci [4] using NACA 0012 and 4412 airfoils produced the new profile, and they found that the changes they made on the profile increased the lift force. Qamar and Janajreh [5] studied the effect of the cambered blades on Darrieus Vertical Axis Wind Turbine (VAWTs). In their study, cambered blades are investigated using high fidelity CFD

* Corresponding Author

¹ Sakarya University Engineering Faculty Mechanical Engineering Department, cyigit@sakarya.edu.tr

modeling under unsteady, turbulent regimes using arbitrary Eulerian and Lagrangian approaches with sliding mesh configuration. The study reveals that VAWTs with cambered blades is at higher Coefficient of performance (C_p) compared to symmetrical bladed turbines. The software was developed to design turbine blade that gives the highest efficiency considering dynamic and mechanical properties of the materials by Jureczko et al [6]. Fernandez et al [7] conducted a comprehensive analysis to investigate the performance of the straight-bladed VAWTs taking into account parameters such as solidity, Reynolds number, and profile of the blade. Xudong et al [8] designed the optimal turbine blades that have maximum performance considering parameters like rotation angle, thickness, and chord. A powerful multipurpose wind turbine blade is presented design using the CFD approach by Liang et al [9]. The solution obtained with the suggested approach is better over to the gradient-based optimization method. Moreover, the computational cost is agreeable. Varol et al [10] examined the effects of some parameters such as camber and number of the blade on the turbine efficiency. Hughes et al [11] have proposed an isogeometric analysis concept. It is claimed that isogeometric analysis concept is a suitable alternative for polynomial-based, standard, and finite element analysis in addition to having many advantages. Benini and Toffolo [12] studied on the wind turbine which can produce high energy at low cost. Xiong et al [13] investigated optimum blade design that has maximum energy production considering the wind speed distribution in a specific area for HAWTs. Kishinami et al [14] conducted an experimental and theoretical study to determine the optimum operating conditions for the HAWTs that have different blade types. Guleren and Demir [15] have determined the optimal wing profile by CFD approach in their study of the effects of different profile geometries on wing performance at low attack angle and high Reynolds number. Bermudez et al [16] conducted numerical method to investigate the time-dependent aerodynamic behavior of the HAWTs that have three blades.

In the study carried, a new blade profile that has higher efficiency has been developed. For this purpose, the upper and the lower camber of the NACA-0012 airfoil are systematically changed depending on a numerical matrix using Taguchi method. The CFD models which have 10.5 m/s air velocity, 78-rpm rotation speed and a rotor diameter of about 17 m were created in the

computer environment. After that, a final optimization study was carried out with the CFD model using sliding mesh approach.

2. NUMERICAL METHODOLOGIES

To determine the aerodynamic performance of the HAWTs a 3D model was developed at 10.5 m/s air velocity, 8.16 rad/s angular velocity environmental conditions and 8 m turbine blade length by using ANSYSv16.2/Fluent Software. The pressure-based solver and transient formulation were used for simulation. Turbulence, momentum and continuity equations are solved for the airflow on the blades. The k-epsilon RNG turbulence model was used in the analyses. Thus, the low-Reynolds-number effects can be determined with the model that is derived from the momentarily Navier-Stokes equations using a mathematical technique called "renormalization group" (RNG). The turbulence viscosity ratio and intensity are used as the turbulent specification method.

Since the Mach number has a small value of approximately 0.03, there is no need for a large calculation area. As shown in Figure 1, a cylindrical calculation area was created for the flow develop. The size of the area was determined to be five times the blade length on the front side, ten times on the rear side and six times the tunnel diameter. The rotating wall function was applied to the blade surface and to the rotor. A fixed airspeed and ambient conditions were defined velocity inlet and pressure outlet boundary conditions, respectively. The air is assumed to be at atmospheric conditions.

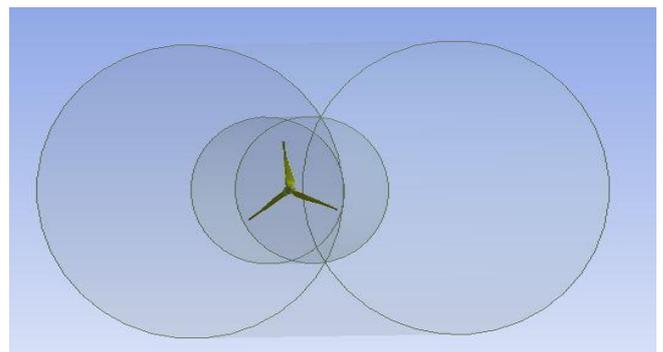


Figure 1. 3D model and boundary conditions

The mesh structure of the numerical model is shown in Figure 2. The density of the nodes was increased till the results that obtained from CFD model is not change. After about three million elements the results no longer changed with the additional grid refinement, which is

essential for computational stability. Mesh structure contains tetrahedron elements have occurred about 1 million nodes and 3.3 million parts, and the skewness is around 0.65 that is an acceptable value in the literature. It is required that grid increments to capture the sufficient wall interaction with the air stream, so the mesh grid is intensified at the near zone of the turbine blade in the computational domain and also inflation mesh is used for the wall interaction region. The performed CFD analyzes, the y^+ value varies from 2 to 7 on the blade surface that is close to 1.

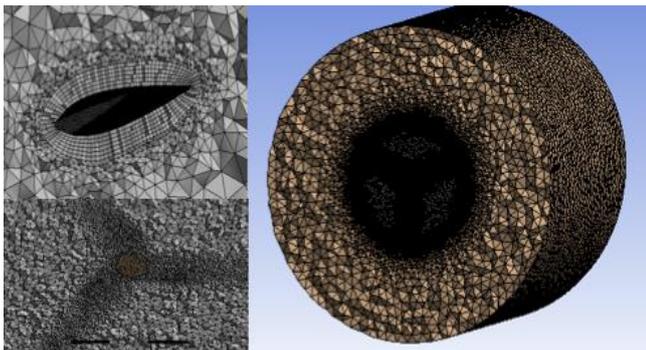


Figure 2. Mesh structure

3. RESULTS AND DISCUSSION

Medium-sized HAWTs, about 8 meters turbine blade length, produce approximately 50 kW of power at an air velocity of 10.5 m/s and an angular velocity of 8.17 rad/s [17]. The power value obtained from the 3D model with NACA-0012 blade profile is approximately 48 kW. This shows that the numerical model has a good compliance and is validated with 4% error.

The upper and lower cambers of the NACA 0012 airfoil were systematically changed by taking the chord (c) length as a parameter. In other words, a new profile was produced by shifting the upper camber of the airfoil points by a certain percentage of the chord (c) length. The same process was carried out for lower camber of the NACA-0012 airfoil. In this way, the NACA 0012 airfoil was modified to produce new profiles. The blade profile is shown in Figure 3.

Average moment coefficients (C_m) for each profile were obtained by using CFD analyzes. To get more realistic and reliable results, the number of time step was chosen as long as the blade would take 10 turns. The time step (Δt) was calculated as the function of the blade speed (v), blade length (R) and tip speed ratio (λ).

$$\Delta t = \frac{2\pi}{360} \left(\frac{\lambda R}{v} \right) \quad (1)$$

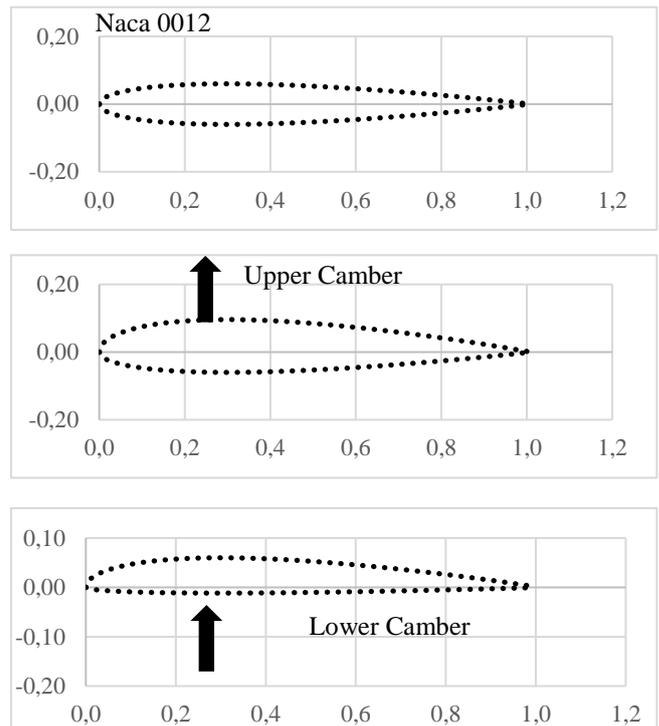


Figure 3. Blade profiles

The average torque was obtained with the equation as below using the average of the C_m values taken over 10 turns.

$$T_{avg} = \frac{1}{2} \rho C_{m,avg} v_{\infty}^2 c A \quad (2)$$

Here, ρ ; density of the air, v_{∞} ; air velocity, A ; area of the turbine, c ; chord length. The average power coefficient of the wind turbine was obtained by taking the average torque produced in the turbine and the power carried by the wind. It is shown in Figure 4 that only the effect of the upper camber on the average C_p .

In Figure 4, the average C_p value obtained from the NACA 0012 profile is shown as a dashed line. The power coefficient was increased by 2.28% when the upper camber increased to 6c%. When the camber continues to be increased, the power coefficient starts to decrease. When the airflow cannot hold onto the surface, the reverse pressure gradients behind the blade come into play, in which case the drag force increases considerably, and the lift force decreases. So that blade performance drops dramatically. This event is called the stall effect.

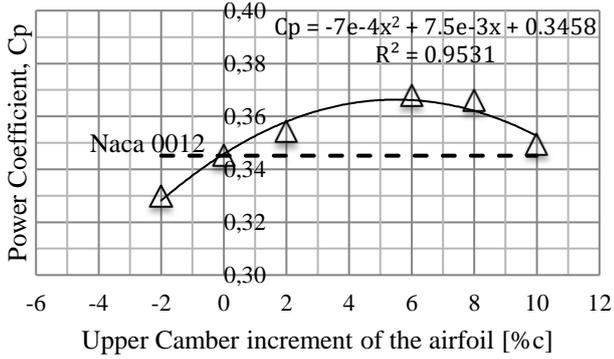


Figure 4. Power Coefficient (Cp) Values Depending on the Upper Camber

It is shown in Figure 5 that only the effect of the lower camber on the mean Cp. When the amount of reduction in the lower camber is 6c%, the maximum power coefficient value is reached 0.3579 with an increase of 1.28%. In both of the upper and lower camber graphs, the power coefficient increases by 6c% in the same way and starts to decrease at this point. The reduction of the performance is due to the flow separation behind the blade.

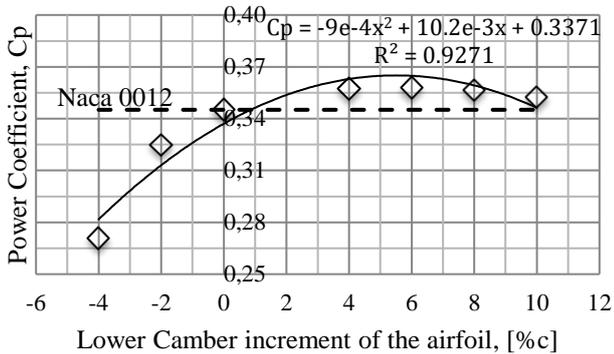


Figure 5. Power Coefficient (Cp) Values Depending on the Lower Camber

The Taguchi method was used to investigate the together effect of the upper and lower cambers on the power coefficient. The-higher-the-better signal-to-noise (S/N) ratio analyze was used in this study. A orthogonal array OA (N, p, s, t) as a function of the design parameters (p) which are the upper camber and the lower camber, parameter levels (s) which are -6, -4, -2, 0, 2, 4, 6 levels, effect values (t) and minimum model number was determined using the following equation [18].

$$N \geq \sum_{i=1}^u \left[\begin{matrix} k \\ i \end{matrix} \right] [s - i]^i, \quad t = 2u, \quad u > 0 \quad (3)$$

The Taguchi method recommends optimization with at least 12 models instead of 128 models depending on 2 parameters and 7 degrees of freedom. The L14 orthogonal array, which is shown in Table 1, is created for optimization.

Table 1. Orthogonal Array

Model No	Upper Camber	Lower Camber	Test_avg	(S/N) ratio
1	-6	-6	3276.2874	70.3076
2	-6	-4	3992.8121	72.0256
3	-4	-2	4908.6700	73.8193
4	-4	0	5665.5038	75.0648
5	-2	2	6222.5480	75.8794
6	-2	4	6136.9683	75.7591
7	0	6	4646.5673	73.3426
8	0	-6	5988.6773	75.5466
9	2	-4	6081.2498	75.6799
10	2	-2	6350.6574	76.0564
11	4	0	6430.2479	76.1646
12	4	2	6653.2100	76.4606
13	6	4	6875.9876	76.7467
14	6	6	7198.2363	77.1445

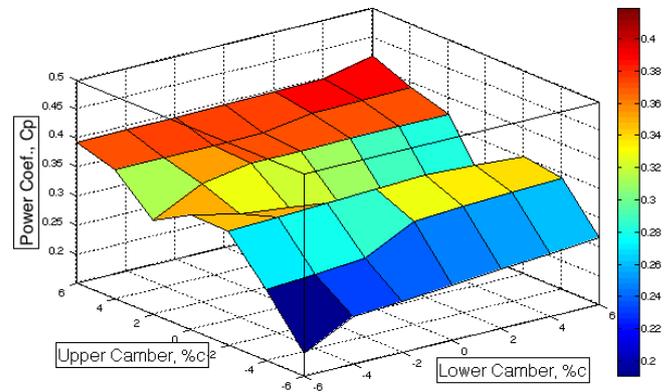


Figure 6. Effect of the upper and lower cambers on the power coefficient

The maximum power coefficient was obtained as 0.4193 at 6c% change on the upper camber and the lower camber. This corresponds to an increase of approximately 7.42% in the power coefficient.

Using the-higher-the-better approach, the highest torque value expected in optimum conditions was calculated using the following expression.

$$Y_{opt} = \sqrt{\frac{1}{10^{((S/N)_{opt}/-10)}}} \quad (4)$$

4. CONCLUSION

In the current study, the performance of the new turbine blade that is obtained from the NACA-0012 airfoil investigated using CFD model and optimized with Taguchi method. The results can be summarized as shown below;

- The power coefficient increases by approximately 2.28% with the rise in the upper camber. And also a rise of 1.28% in power coefficient was achieved when the lower camber was reduced.
- Taken the increases of the upper camber and reduces of the lower camber of the profile together into account, a 7.42% increase in the power coefficient was obtained with a change of 6c%.
- When over 6c% increases both the upper camber and the lower camber, the power coefficient starts to decrease. This is because of the stall effect.

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