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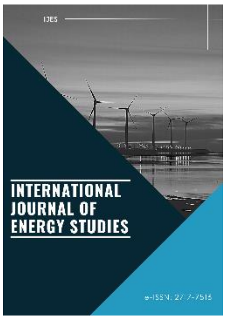

Research Article

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Hybrid axis wind turbine profile design

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Highlights

- The wind turbine types identified.
- A new airfoil designed including both horizontal and vertical axis.
- Hybrid axis airfoil electric generation efficacy investigated.

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ABSTRACT

Wind offers vast opportunities in terms of energy potential. Previous studies have shown that wind power can meet all the world's energy needs by using effective wind turbines. However, the efficiency of wind turbines is not at the expected level, and they are not widely used due to various reasons. In this sense, it is substantial to yield airfoils with better aerodynamic properties. Geometrically, wind turbines are divided into two types as horizontal and vertical axes. Within the scope of this study, it was aimed to design a modified airfoil including both horizontal and vertical axes properties. Accordingly, a hybrid design was made in terms of the airfoil axis obtained by the modification of the NACA4412 profile. In terms of the method of the study, the electric generation efficiency of hybrid airfoils with different inclinations was measured under constant distance and air flow. As a result of the study, it was attained that the modified airfoil curved at an angle of 30° was about 12% more efficient in terms of electricity generation than the unmodified one.

Keywords: Wind turbine, Airfoil, Hybrid, NACA

1. INTRODUCTION

Wind is accepted as a clean, environmental-friendly, competitive and sustainable energy source that gradually enables it to become more widespread [1]. The limited availability of fossil sources and the ecological issues direct the global demand to use renewable sources more [2]. Moreover, the theoretical evaluations imply that even 4% of wind energy can compensate for the energy needs of the whole world [3]. Today, developed economies allocate a significant source of their budget to wind energy (Table 1).

Table 1. Installed wind energy power of countries [4]

No	Country	Update	Installed Power (MW) 2022	Installed Power (MW) 2023
1	China	December 2023	328.973	450.000
2	USA	December 2023	132.738	152.000
3	Germany	December 2023	63.760	69.000
4	India	December 2023	40.067	45.000
5	Spain	December 2023	27.497	30.500
6	UK	December 2023	27.130	30.500
7	Brazil	December 2023	21.161	29.253
8	France	December 2023	18.676	26.500
9	Canada	December 2023	14.304	16.849
10	Sweden	December 2023	12.080	16.328
11	Turkey	December 2023	10.886	15.000
12	Italy	December 2023	11.276	12.300
13	Austria	December 2023	8.951	11.500

Historically, the first wind turbines were produced in the 1700s and were produced for pumping water or grinding grain, and their geometry was vertical axis wind turbines [5]. It is known that it was built in Denmark in 1891 by Paul la Cour, an important aerodynamic engineer, for electricity production [6]. These turbines were later followed by horizontal axis turbines, which developed in the 1900s. Today, commonly used industrial wind turbines have horizontal axis [3]. These turbines are differentiated according to the number of blades, degree of torsion or blade angle. Apart from geometry, there are various types of wind turbines according to their rotation speed, type of generator and power (Figure 1). This study was carried out on the geometric properties of turbines.

Airfoil geometry is an important variable that adjust the efficiency of wind turbines. Vertical axis airfoils have been produced in many different shapes throughout history, trying to use this geometry effectively. Vertical axis turbines were generally small-scale, high-frequency, and could operate under low wind speed [7]. These turbines are mainly classified as Savonius, Darrieus, H type and other types of wind turbines. The general geometric feature of these turbines is that they have elliptical designs and take the wind from all angles. In this way, they require lower rotation diameter and wind power [8]. They are quite suitable for home applications.

Another type of wind turbine is horizontal wind turbines. Achieving the best design for these airfoils, which are positioned perpendicularly according to the wind angle of attack, is significant in terms of energy efficiency. There are different types depending on the degree of twist, the given angle , and the number of airfoils. Industrial production of horizontal axis airfoils gained momentum in the 1900s. Airfoils were first studied mathematically by Albert Betz [9]. Later, various aviation academies characterized these models.There are some fundemental variables that affect energy efficiency in these models. These are wind speed, number of airfoils and aerodynamic structure of the airfoil. In addition, blade strength, noise level, cost and operating speed are also crucial variables in blade selection. Many effective variables on the efficiency of horizontal airfoils were examined simultaneously, including the number of blades, were determined. Today, three-blade horizontal axis turbines are among the widely used profiles [10]. However, certain limitations of using wind turbines are a significant obstacle to the widespread use of this technology. In this sense, developing systems that use wind power more effectively will allow this energy to be used more widely. Current studies are carried out, especially on using airfoil aerodynamics more effectively. In this sense, airfoil efficiency can be defined in 3 stages: parameterization, evaluation, and optimization. Methods such as Bézier, CFD-based methods, FFD-based methods, PARSEC and B-spline are commonly used for the parameterization process. Surfaces simulated with such methods create a virtual spectrum within certain variables. This spectrum is scanned with gradient-based methods to obtain the optimum shape. In this way, serious time and energy savings are achieved. However, having unlimited points and gradients still makes it impossible to reach a single optimum surface [11].

Nowadays, for further evaluation and optimization processes, deep learning-based airfoil designs developed for the production of high lift and better viscous forces airfoils [12] to evaluate multiple sets of airfoils geometries more practically by set of training data in three dimentional space. Today lots of deep learning tools are utilized to map the gradients for optimum surface shape [13], [14]. Additionally, large-scale topology optimization studies [11], and computer-aided design (CAD) [15] enhance the efficiency of the wind habitat through a more comprehensive perspective.

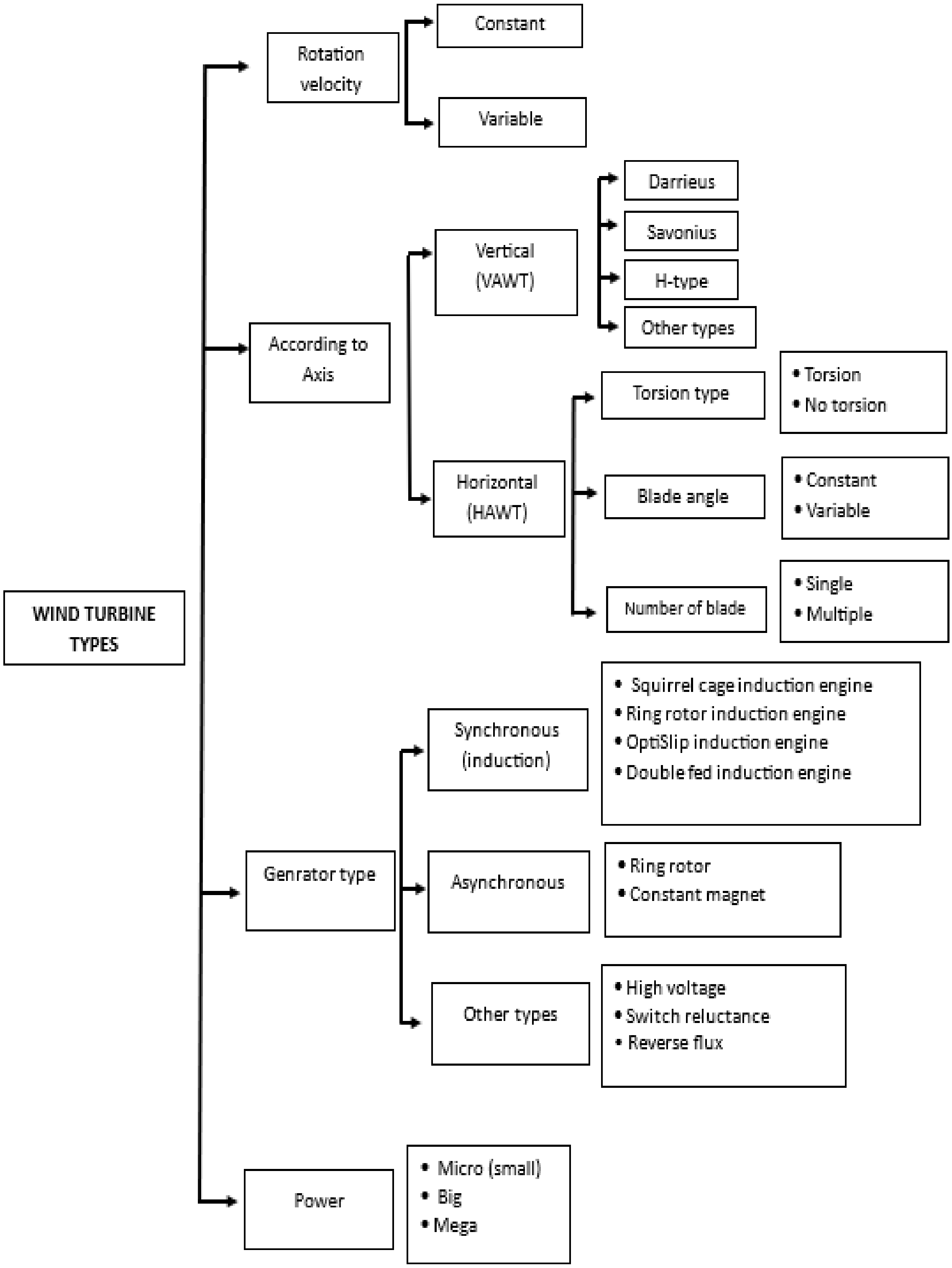

Figure 1. Wind turbine types [29, 19, 17, 5, 20, 21, 22, 23, 24]

The effect of airfoil surface shapes [16], [17] and the correlation between airfoil parameters [18] are also intensively carried out to enhance performance.

In general terms, despite all the studies, airfoil airdynamics is still being studied as an important variable in terms of energy performance. This area has been seriously examined with the simulations produced. However, an approach in which vertical and horizontal axis airfoils are designed together has not yet become widespread. These types have serious advantages and disadvantages against each other. Therefore, such hybrid approaches have the potential to make significant contributions to this field.

In this paper, a hybrid airfoil design for geometry optimization by using a modified NACA profile to upgrade the surface pattern was presented. The previous optimization tools primarily focus on a single geometry among HAWT or VAWT types to parameterize the potential optimal design. In this study, the effect of hybrid type as a more efficient design on energy efficiency was examined.

2. MATERIALS AND METHOD

In this section, a possible efficient design by following the process in four steps; 2D drawing, 3D design, creating a model with a 3D printer and measuring the energy efficacy were presented.

2.1. Study Design

The study consists of four stages as modifying the existing airfoil, representing the 2D and 3D modified models, printing airfoils with a 3D printer, and finally investigating the electricity generation efficacy of each airfoil. The airfoils produced for industrial purposes have different cross-sectional areas and different curvature radii. The physical dimensions of industrial airfoils vary between 50-120 m, and towards the tip of the airfoil, a thinner structure was designed to increase the airfoil durability [25]. Within the scope of this study, the airfoil sections are defined based on the airfoil geometries determined by the US National Advisory Committee for Aeronautics (NACA). The profited NACA 4412 airfoil is a low-speed, non-symmetrical airfoil in the transonic flow regime. In this context, NACA4412 aerofoil was preferred, which is one of the commonly used for industrial purposes. The first two digits represent the maximum chamber percentage and the distance of chamber to the edge. The last two digits of this four-digit aerofoil informs that a 12% maximum thickness of the chord. That is , 4412 represent that airfoil has a maximum camber of 4% located 40% (0.4 chords) from the edge with a maximum thickness of 12% of the chord.

NACA has different airfoil geometries and utilizes the aerodynamic performance on lifting effect and viscous forces of the wind effectively. The aerodynamic surface structure is optimized in these airfoils. The most significant part of the study is to make a design that will increase and optimize aerodynamic efficiency in the light of existing airfoil models. For this purpose, For this purpose, the determined airfoil design was implemented and its measurements were carried out.

The wind speed at a certain distance for the wind power applied to the airfoil was measured. Apart from this, other variables such as angular speed, torque, airfoil strength and noise level were not considered. The main reason is that the study aims to measure only the electricity production value of airfoils under a certain wind speed.

To print the profile with a 3D printer, different curvature radii were given to the 4412 profiles with the "bend" tab in the 3ds Max program. It was reduced to dimensions that could be printed in one go with a 3D printer. Tinkercad is an application developed for students that can provide 3D applications. Zaxe desktop 3D printer with a 300x300mm working area was used as the printer.

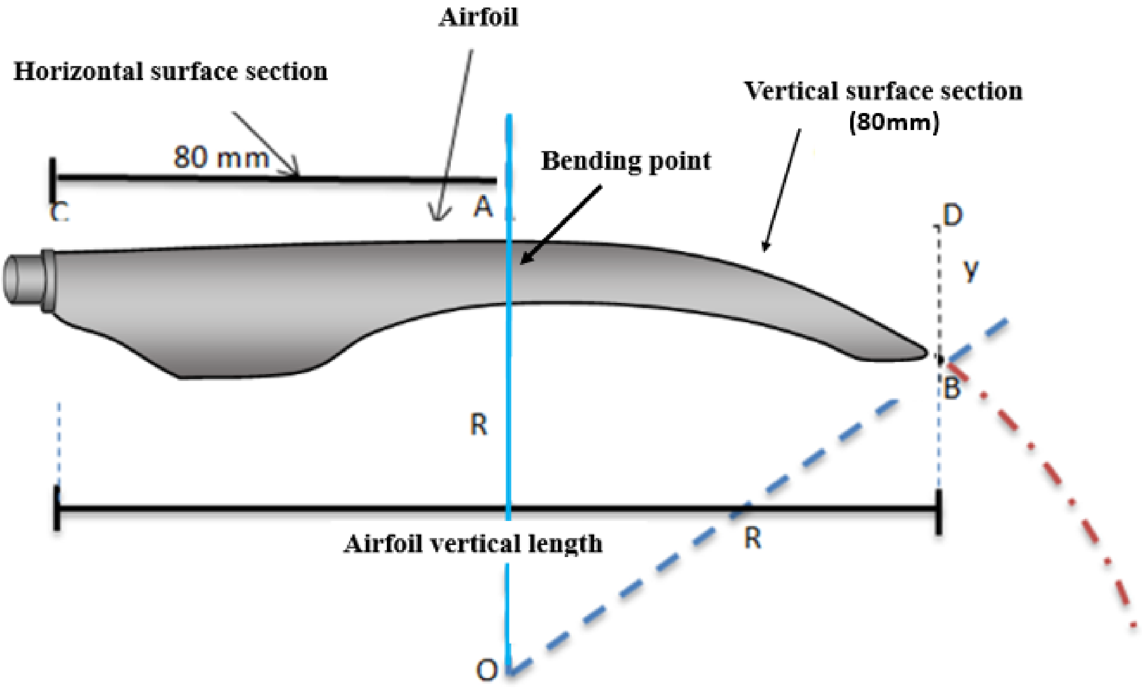

Figure 2. Two-dimensional perspective of the hybrid airfoil

2D and 3D drawings of the determined models were provided. Microsoft Word was utilized for 2D representation (Figure 2), and to ensure the aerodynamic structure of the existing model, 3ds Max simulation and Tinkercad were utilized. Finally, models were printed by a 3D printer. Later mean voltage and mean frequency values were measured.

2.2. Airfoils

2.2.1. NACA4412 airfoil

NACA4412 airfoil was used in this study (Figure 3). In this profile, the lower and upper curvature radii of the airfoil are yielded in different proportions for Bernoulli's principle. The size and radius of curvature of each section are different, and the surface becomes smaller as you move towards the airfoil tip. This curvature is defined as "humpback" for the airfoil [27]. These surfaces can also be provided in different shapes with torsion or non-torsion, variable, or constant slope, with different number of airfoils and different wind sweeping areas, and they are designed according to the durability of the airfoil, the location in which it is used, and the wind map. On the NACA side, the impact of these variables was determined and simulated.

Figure 3. NACA4412 airfoil details [28]

The study purpose is to configurate a hybrid design by modifying a professional horizontal airfoil model. The airfoil length was defined as 160 mm, and the maximum height was 20 mm. Since "bending" cannot be performed in Tinkercad, it was implemented through 3ds Max and use stl. for size editing and output operations. Exported with file. Arrangements were made via Tinkercad (Figure 4).

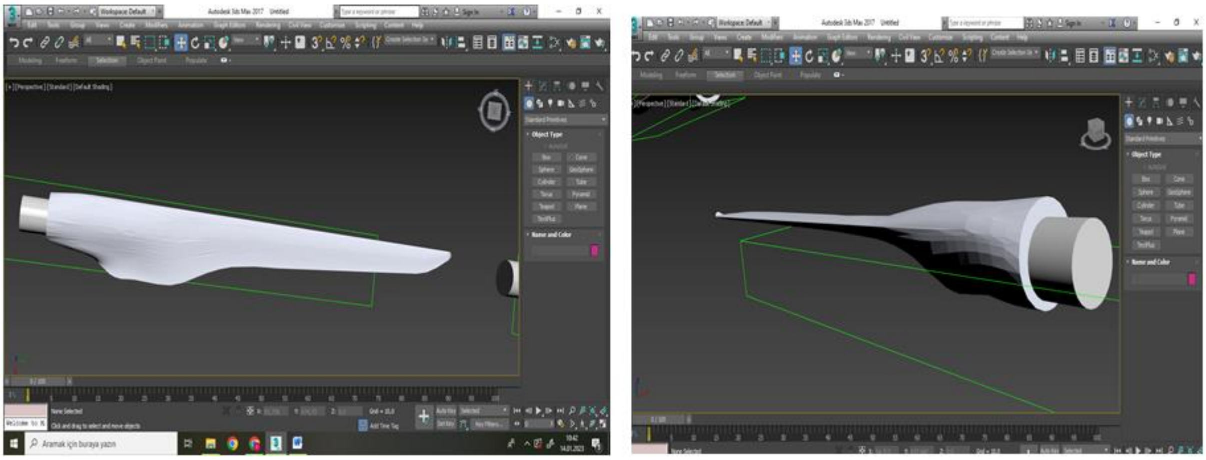

Figure 4. Unmodified NACA4412 airfoil [26]

2.2.2. Modeling for 15°

A 15° bend was applied from the midpoint of the model by "bend modifier". This allows the airfoil to yield a 15° radius of curvature between its midpoint and tip. The airfoil length and airfoil aerodynamic properties were kept constant. The total length was fixed at 80 mm and a circular surface was provided 15° angle from the midpoint of the airfoil. The amount of deviation between the tip of the airfoil and the horizontal surface are described at Figure 5. The degree of deviation increases in lineer section of curvature radii of the predefined circular section. This arc draws a curve tangent to the airfoil and scans a 15° angle of the circle with radius 306 mm. The degree of deviation was measured approximately 10.4 mm. The deviation value and the circular surface here are depicted in Figure 5.

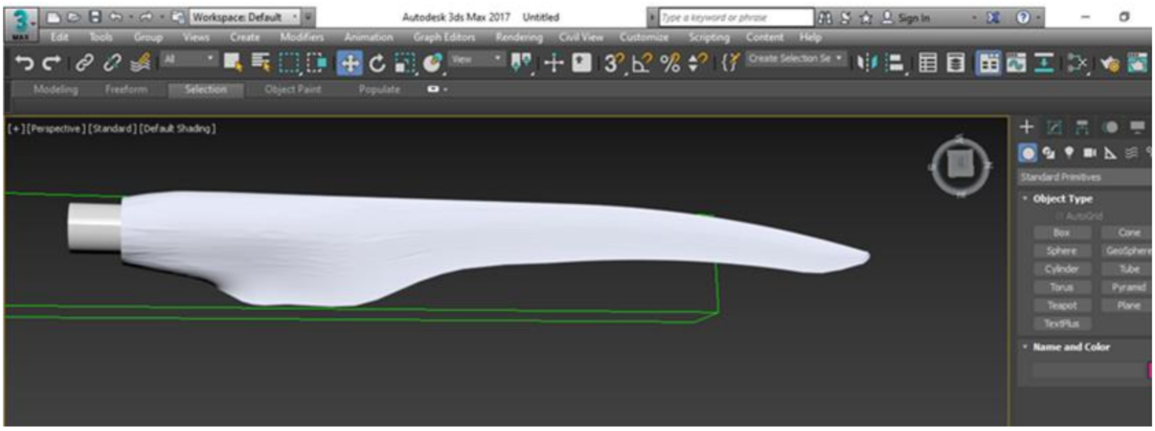

Figure 5. Modeling for 15°

2.2.3. Modeling for 30°

In this model, a deviation of 20.5 mm occurs at the tip of the airfoil. After this value was determined on the program, α angle and R radius values are used. This airfoil draws a slope on the circular arc created and scans the 30° angle of the circle with a radius of 153 mm. The degree of deviation was determined to be approximately 20.5 mm. The 3D drawing of this design can be seen in Figure 6.

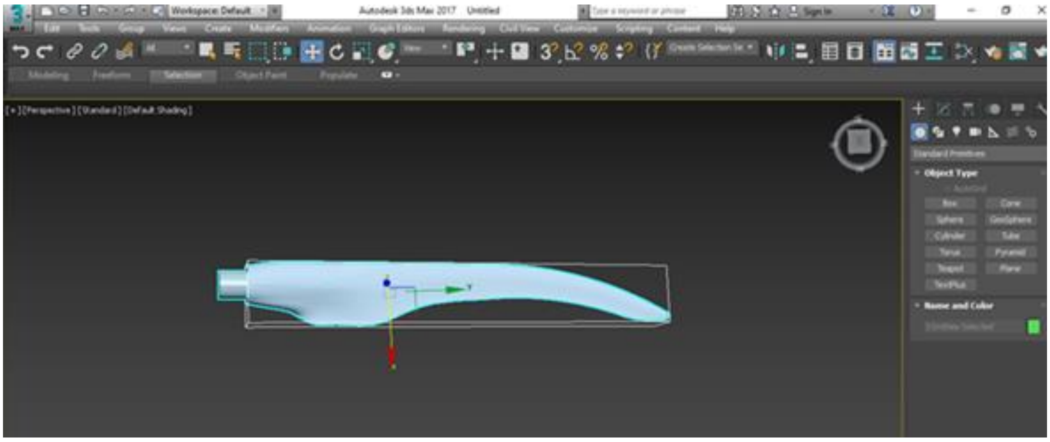

Figure 6. Modeling for 30°

2.2.4. Modeling for 45°

There is a deflection degree of 29.8 mm at the tip of the airfoil and the arc length is 80 mm. It draws a slope on this arc and scans the 45° angle of the circle with radius of the arc 102 mm (Figure 7). The degree of deviation is approximately 29.8 mm.

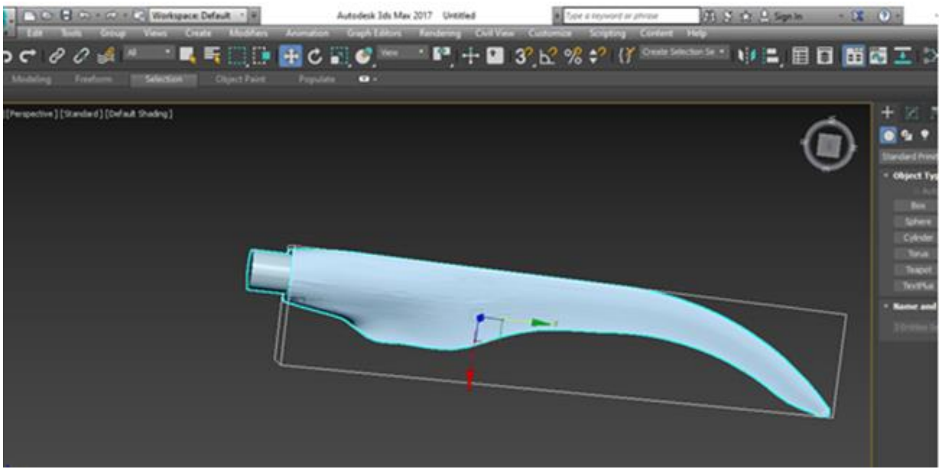

Figure 7. Modeling for 45°

The airfoil printing arrangement process implemented by 3ds Max and Tinkercad (Figure 8). In the last step, it was necessary to place the obtained airfoils into the wind turbine and measure mean voltage. The mean voltage values were measured using the Nova experiment set (Figure 9).

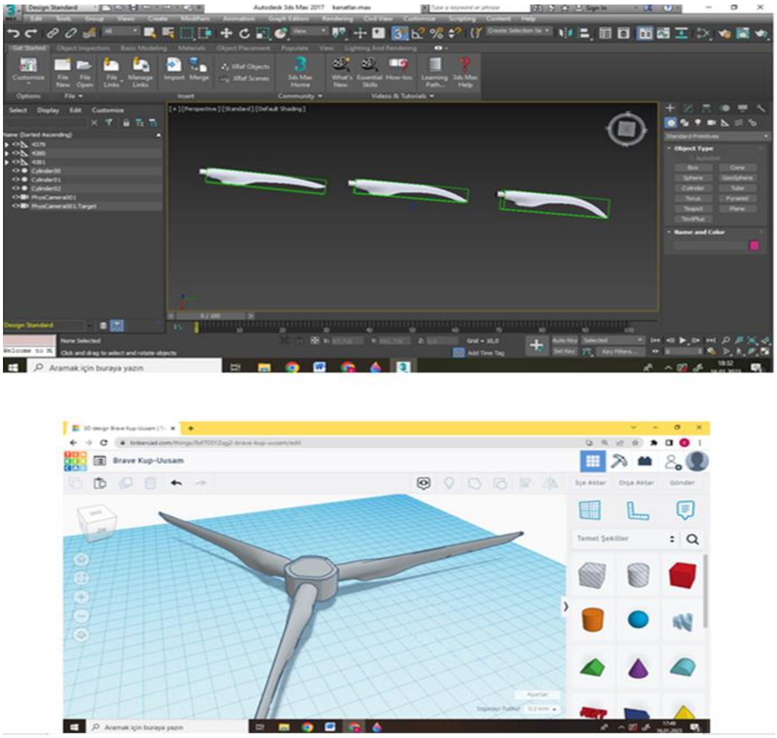

Figure 8. Printing process for airfoils

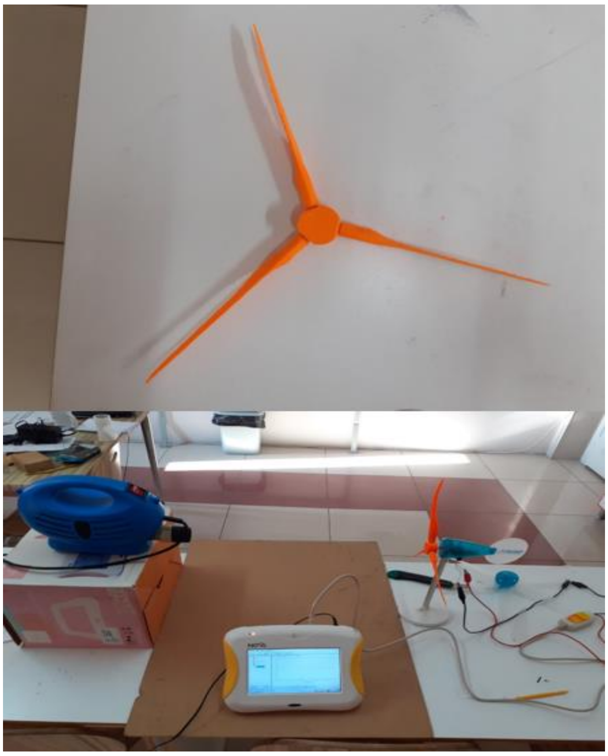

Figure 9. Measurement process

3. RESULTS AND DISCUSSION

In this section, the descriptive data about the airfoils and wind speed, the visual representations of the airfoils and the comparison of the mean voltage of the models are included. In this way, the effectiveness of the modified airfoils was try to be addressed.

3.1. Mean Voltage Measurements

According to the obtained data for the profile in which the NACA4412 profile, without any slope process, was used as a model, the voltage values produced by the wind turbine were measured as 2.01V on average (Table 2). It was thought that the mean voltage yielded by the airfoil is closely related to the airfoil rotation frequency. In other words, it is an indirect measurement of the rotational force applied to the airfoils because of the airfoil aerodynamic performance. In addition to this rotation effect, the moment of inertia of the profile varies the rotation frequency of the airfoils. A high moment of inertia leads an increase necessary wind power that should be applied to the airfoils to ensure rotation at the same frequency.

The data obtained for the unmodified straight airfoil was represented in Table 2. The mean voltage was measured as 2.01V. The weight of each airfoil is 5.5g and the distance from the airfoil center of mass to the pivot point is 43 mm. In line with these data, the moment of inertia was calculated as 495 g.cm^2.

Table 2. Data for original airfoil

Mean voltage (V)	2.01
Max. wind velocity (m/s)	23.6
Mean wind velocity (m/s)	12.68
Number of blades	3
Blade weight (g)	5.5
Max. airfoil tip speed (m/s)	34.18
Profile rotation diameter(mm)	350
Moment of inertia (g.cm^2)	495
Max. rotation frequency (Hz)	34
Max. angular velocity (rad/s)	213.6
Distance of the center of blade mass to pivot point (mm)	43

According to the data obtained from the 15° airfoil, mean voltage was measured as 2.11 V (Table 3). The rotation frequency of the airfoil increases, and the moment of inertia decreases compared to the straight airfoil. In addition, although the angle of attack decreases, a positive total effect was observed.

Table 3. Data for 15° airfoil

Mean voltage (V)	2.11
Max. wind velocity (m/s)	23.5
Mean wind velocity (m/s)	12.60
Number of blades	3
Blade weight (g)	5.5
Max. airfoil tip speed (m/s)	36.26
Profile rotation diameter(mm)	348
Moment of inertia (g.cm^2)	462
Max. rotation frequency (Hz)	37
Max. angular velocity (rad/s)	232.48
Distance of the center of blade mass to pivot point (mm)	42.2

According to the data obtained from the 30° airfoil, the mean voltage was measured as 2.25V on average (Table 4). This airfoil provided higher energy efficiency than the other three airfoils. As expected, the moment of inertia is lower than the other airfoils.

Table 4. Data for 30° airfoil

Mean voltage (V)	2.25
Max. wind velocity (m/s)	23.7
Mean wind velocity (m/s)	12.68
Number of blades	3
Blade weight (g)	5.5
Max. airfoil tip speed (m/s)	37.48
Profile rotation diameter(mm)	336
Moment of inertia (g.cm^2)	453
Max. rotation frequency (Hz)	39
Max. angular velocity (rad/s)	245
Distance of the center of blade mass to pivot point (mm)	41.6

Finally, it was measured that the 45° airfoil produced an average of 1.93V voltage (Table 5). Both the rotation frequency and the moment of inertia are reduced compared to other profiles. The total mass of the airfoil is constant. The total effect appears to be negative. In other words, the sloped surface section at the airfoil tip significantly reduced the wind sweep area of the airfoil. While this effect reduces the total wind power on the airfoil, it was also thought to reduce the rotation frequency of the airfoil.

Table 5. Data for 45° airfoil

Mean voltage (V)	1.93
Max. wind velocity (m/s)	23.8
Mean wind velocity (m/s)	12.7
Number of blades	3
Blade weight (g)	5.5
Max. airfoil tip speed (m/s)	29.41
Profile rotation diameter(mm)	332
Moment of inertia (g.cm^2)	441
Max. rotation frequency (Hz)	31
Max. angular velocity (rad/s)	194.78
Distance of the center of blade mass to pivot point (mm)	41.2

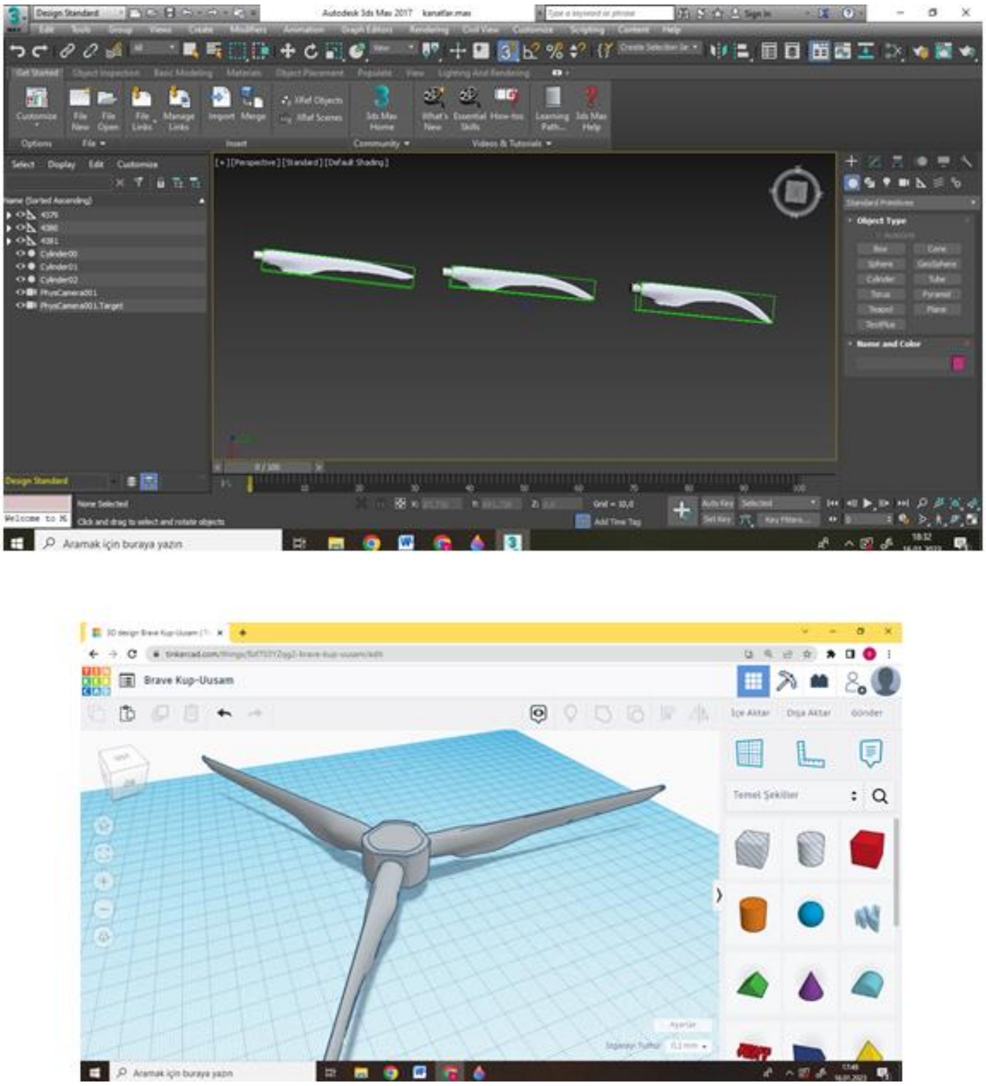

Figure 10. Profiles made on 3ds Max and Tinkercad

3.2. Printing and Comparison of Airfoils

The airfoils that scan radial angles for the center of curvature of 0°, 15°, 30° and 45° and whose curvature radii are 306mm, 153mm and 102mm, were respectively utilized (Figure 10). Airfoils with certain radii of curvature are frequently used in vertical wind turbines such as H-type. From this perspective, it can be yielded that the modified airfoils are hybrid models that reflect the features of both vertical and horizontal types. The curvature values with the bending module are provided by the "bend" tab in the 3ds Max program and it is possible to adjust these values to more optimal degree to provide remarkable improvements.

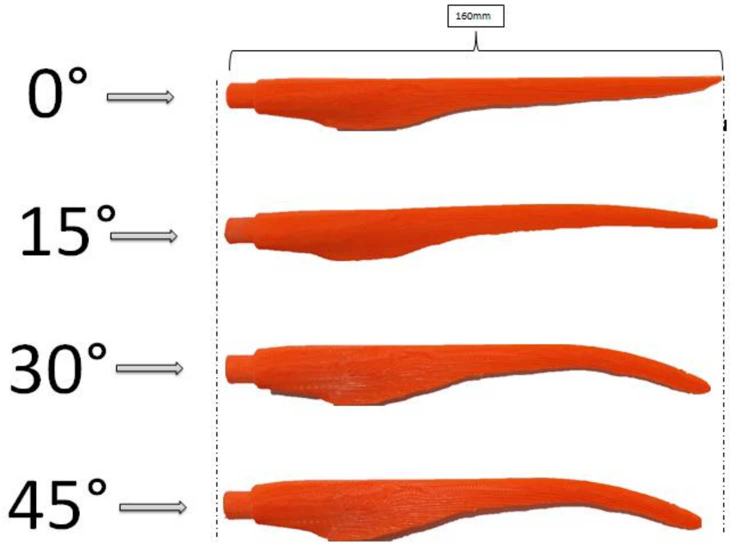

Figure 11. Modified airfoils

Zaxe desktop professional 3D printer was used to print the models in three dimensions. This printer can print 300x300mm with 1mm precision. The average writing time for an airfoil under specified conditions is around four hours. The average of 100 data taken from the Nova 5000 tablet test set was used for mean voltage measurement. Nova experiment set Marvell PXA320 is a laboratory set with a 624 MHz processor, where many data are obtained with the help of external sensors. With this set, it is possible to receive and process data such as voltage, current, light, sound, pressure, frequency, vibration, oxygen level, pH values via the Windows 5 operating system. A Vernier anemometer was used to measure the speed of the wind sent to the profile. An anemometer designed for professional laboratory applications that provides instant graphic and data flow information. Its features are given as follows;

Measurement limit: 0.5-30 m/s

Sensitivity:1.2×10-2m/s

The tension values and applied wind power of each airfoil designed and printed with a 3D printer were measured. Using these profiles, a relationship between the degree of angle scanned and the average electrical power values were observed (Table 6).

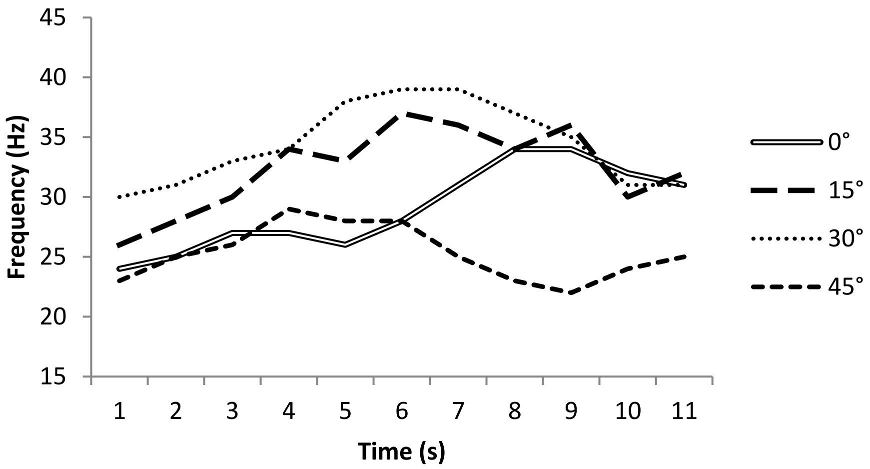

Figure 12. Airfoil type-frequency graph

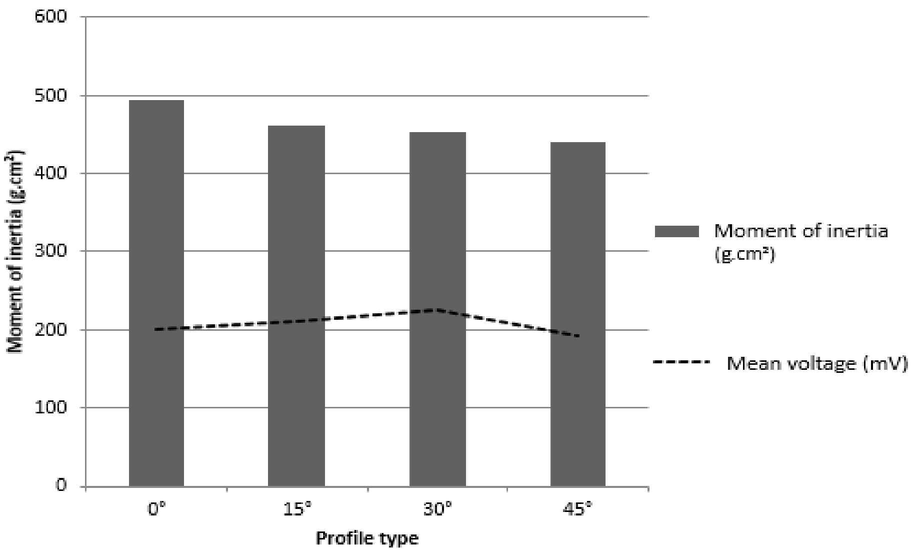

Figure 13. Comparison of moments of inertia and mean voltage for profiles

According to the obtained data, the mean voltage, frequency and angular speed of the airfoil at 30° slope angle are higher than the other profiles (Figure 13). It was observed that this effect was stem from the aerodynamic properties of the airfoils and their rotational inertia (Figure 14). Nevertheless the angle of attack of the wind coming to the airfoil changes with the inclination of the airfoils in that lead to reduce the distance of the airfoils perpendicular to the wind. Thus the total wind sweep area of the profile decreases with increasing angle.

The decreasing wind sweep area has a total stress-reducing effect on the 45° model. This effect is also a result of the changing aerodynamic structure of the airfoil. In this sense, the low wind sweeping area effect of vertical profiles that provide rotation at high frequency is more evident in this model. As a result, the mean voltage produced by this profile, which scans a 45° angle and has a smaller radius of curvature and moment of inertia than other profiles, is also low.

Table 6. Descriptive values of airfoils

Airfoils (Slope degree)	Radius of curvature (mm)	Airfoil length (mm)	Vertical length (mm)	Airfoil weight (g)	Mean voltage (V)
0	-	160	160	5.8	2.01
15	306	160	156	5.8	2.11
30	153	160	153	5.8	2.25
45	102	160	151	5.8	1.93

In this study, a study on the voltage efficiency of a hybrid airfoil obtained by modification of the NACA 4412 airfoil was conducted. The main purpose was to optimize the electrical voltage value that the original profile (0°) can produce for the same dimensions and aerodynamic structure. It was intended to eliminate the low electrical generation problem of the original profile by giving a semi-vertical shape with different curvature radii from the midpoint to the tip of the airfoils, thus moving the center of gravity to a closer to the rotation point. Thus, it was tried to reduce the rotational inertia energy. This enabled the profile to rotate at a higher frequency with the constant wind power coming to the airfoils.

In this sense, the highest mean voltage was yielde by the 30° airfoil. As a result, it was attained that the modified airfoil curved at an angle of 30° was about 12% more efficient in terms of electricity generation than the unmodified one. While the increase in the “bend” degree used in the airfoils brings the center of mass of the profile closer to the rotation point, the mass of the profile does not change. This situation reduced the rotational moment of inertia of the profile and reduced the necessary wind power for rotation. In this way, the rotational inertia energy of the profile is lower than that of totally horizontal geometry. However, in circular hybrid geometry, the decrease in the inertia torque may have caused the rotation speed to increase, but as the slope of the airfoil increases, the wind sweep area decreases and the angle of attack of the wind changes, reducing this effect. At high slope, this effect negatively affects the measured mean voltage values. For this reason, a rapid decrease is noticeable at a high slope bending such as 45 degrees. As a result, it was observed that hybrid geometry increases the rotation frequency of the airfoil at smaller angles (large curvature radii), optimizes the electrical voltage produced and uses the incoming wind power more efficiently. However, as the bending angle increases (decreases in the radius of curvature), the voltage values decrease after a while and negatively affects the total efficacy.

4. RECOMMENDATIONS

As a recommendation, to observe the above-mentioned effects more reliably, consistent models should be created and examined for each slope. Secondly, printing larger sizes of the airfoils that can produce more energy will provide more reliable data. These profiles should also be used with better generators.

However, using different airfoils can significantly change the results. To create better models, airfoils should be designed in which both the curvature of the airfoil and surfaces are defined simultaneously.

NOMENCLATURE

NACA: National Advisory Committee for Aeronautics

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DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Çağatay Paçacı: Performed the whole processes.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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