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Design and Calculation of The NACA 4412 Horizontal Wind Turbine Blades with Variations in Angle of Attack Using Blade-element Momentum (BEM) Simulation

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Abstract: The need for electricity in Indonesia becoming increasingly part of people's needs. Fossil fuels such as oil and coal used as the main material for producing electrical energy the more limited availability, especially in its use of fossil fuels that pollute the environment. Wind energy is a renewable energy source that could potentially be developed. Wind energy is clean and does not pollute the environment in utilization into mechanical or electrical energy. The conversion of wind energy into electrical energy by converting this energy into mechanical rotation. In the wind energy utilization process made a tool to convert wind energy into electrical energy, that is wind turbines. Wind turbine or windmill is a tool for converting wind energy. Wind turbines transform kinetic energy into mechanical energy in the form of a round shaft. Shaft speed is then used to rotate the dynamo or a generator which produces electricity. The research was carried out on a horizontal axis wind turbine NACA 4412, diameter 1 m, the number of blades 3 pieces and variations in wind speed 2-8 m / s. Results showed the greatest lift (CL) at 14o angle of attack with a value of 1.583. The driving force of the smallest (CD) at an angle of attack -4o to 2o with a value of 0.008. Value CL / CD was found in the angle of attack of 6o with a value of 93.057. The maximum power generated by 484.63 Watt. Wind speed, the number of blades, angle of attack and the election of the airfoil effect on the generated power.

Keywords: wind energy, wind turbines, blade-element momentum, airfoil, NACA 4412

1. Introduction

The need for energy, especially electrical energy in Indonesia is increasingly developing into an inseparable part of the daily needs of society. Fossil fuels such as petroleum and coal used as the main ingredients to produce electrical energy are increasingly scarce (limited availability), moreover in their utilization these fossil fuels produce pollution for the environment.

Wind energy is one of the renewable energy sources that has the potential to be developed. This wind energy is clean and does not pollute the environment in its utilization into electrical or mechanical energy [3].

Wind turbine is a tool to convert wind energy. Turbines convert kinetic energy into mechanical energy in the form of shaft rotation. The shaft rotation is then used to rotate the dynamo or generator which ultimately produces electrical energy [4].

Therefore, this research was conducted to see the potential of wind power in Tegineneng village, Limau kec. Limau, Tanggamus district and design the most optimal wind turbine blades. Tests were carried out on a horizontal axis wind turbine NACA 4412, 1 m in diameter, the number of blades 3 pieces and variations in wind speed 2 - 8 m/s.

The objectives of this research are as follows: to analyzing aerodynamic characteristics including lift force (CL), thrust force (CD) and comparison of lift force and thrust force (CL/CD), the optimal power coefficient (CP) with different wind speed variables, and finding the optimum airfoil angle of attack to produce the most maximum power. Also, it will analyzing the effect of wind speed to produce the most maximum power.

1.2. Literature Review

1.2.1 Horizontal Shaft Wind Turbine

Horizontal shaft wind turbines are wind turbines consisting of a tower at the top of which there is an electric generator and a propeller that functions as a rotor and faces the wind direction. Small turbines are directed by a simple wind vane (weather vane), while large turbines generally use a wind sensor coupled to a servo motor. Most have a gearbox that converts the slow rotation of the wheel into a faster rotation. Since a tower generates turbulence behind it, the turbine is usually directed downwind of the tower.

1.2.3. NACA (National Advisory Committee for Aeronautics)

NACA airfoil is a form of geometry that has been determined by NACA and is a standard in the design of an airfoil. Actually, the use of NACA airfoil itself is commonly used in the world of aeronautics as an airplane wing. The more developed world of technology today the use of NACA airfoil is applied in making geometry in the world of generation [2]. The standard geometry of NACA 4412 is presented in the figure 1 below [3].

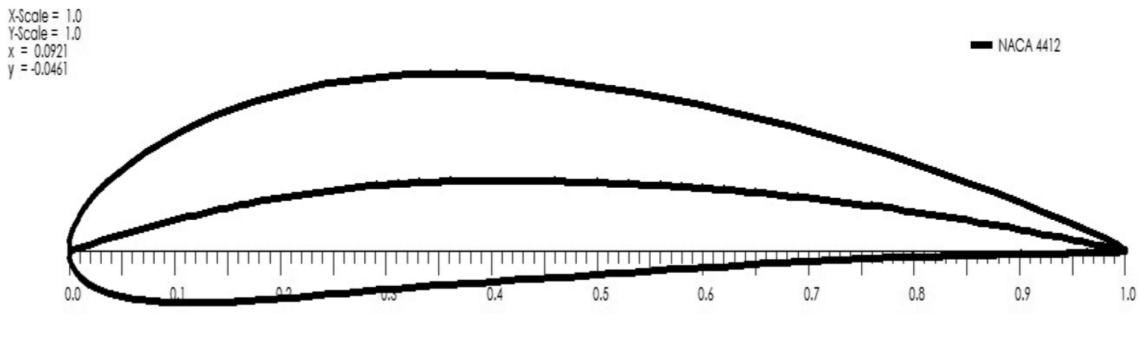

Figure 1. The Aerodynamic Profile of NACA 4412 [3]

The Blade Element Momentum (BEM) method is a popular technique for simulating the aerodynamics of rotating blades, such as those on wind turbines or propellers. It combines two key concepts: blade element theory (which divides the blade into small sections or elements) and momentum theory (which applies conservation of momentum to the flow around the rotor). In naming and numbering models from the series on the airfoil. NACA has a predetermined coding standard such as 1 number, 2 number, 4 number, and 5 number series. As the selection of NACA 4412 airfoil is symmetrical, the meaning is as follows:

1. The first number is the maximum chamber on the chord line in hundredths of a chord.
2. The second number is the maximum position of the chamber on the chord line in tenths of a chord from the leading edge.
3. The last two numbers are the maximum thickness values in hundredths of a chord.

1.3. Characteristics of Wind Turbines

1.3.1. Tip speed ratio

Tip speed ratio is a very important factor in wind turbine design, which is defined as the ratio of the tangential velocity at the blade tip to the actual wind speed [1].

$$TSR = \frac{\pi \cdot D \cdot n}{v}$$

Where,
D = turbine diameter (m)
v = wind speed (m/s)
n = turbine rotation (rpm)

The diagram airfoil's geometry as well as the force on stationary rotor blade in airflow is based on the previous studied and presented on Figure 2 and Figure 3 below.

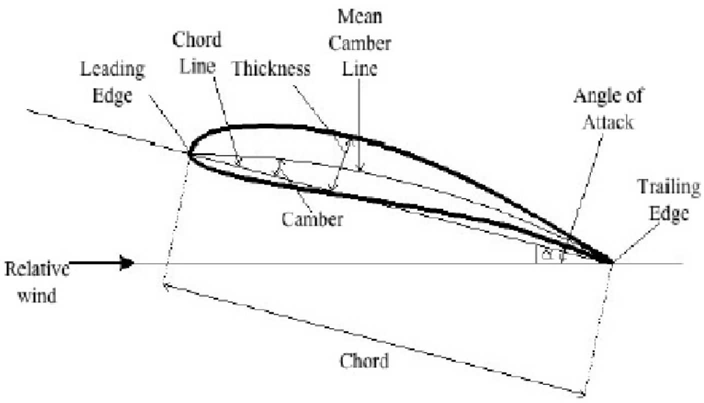

Figure 2. The Standard of NACA 4412 Airfoils' Geometry [4]

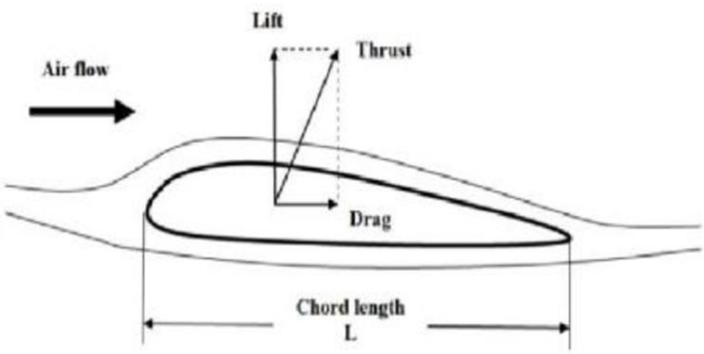

Figure 3. The Forces on a stationary rotor blade in airflow of NACA 4412 [4]

1.3.2. Power Coefficient (CP)

The coefficient of moment (CM) value is related to the determination of wind turbine power which can be obtained from the power coefficient (CP) value. The output power of a wind turbine changes with the rotational speed of the turbine so that the rotor performance is usually shown by a graph between the power coefficient and the tip speed ratio. However, it can also be shown with a graph of the moment coefficient against the tip speed ratio.

1.3.3. Blade element momentum (BEM) theory

Blade element momentum (BEM) theory to calculate thrust, power, and power coefficient (CP) with different parameters of air speed, rotational speed, and pitch angle of wind turbine blades can use Blade Element Momentum (BEM) theory [5].

2. Materials and Methods

2.1. XFoil Direct Analysis

Xfoil direct analysis is to simulate variations in the angle of attack of horizontal turbine blades. This simulation is carried out to obtain the value of the largest lift force (CL), the smallest thrust force (CD) and the largest lift and thrust force ratio (CL/CD).

2.2. Rotor BEM Simulation

BEM (blade element momentum) simulates the momentum of each element on the blade. The result of the BEM simulation is to obtain the torque value, tip speed ratio and mechanical power. The NACA 4412 is a commonly used airfoil shape, known for its moderate camber and thickness, making it suitable for various applications, including rotor blades in wind turbines or propellers.

To simulate the performance of the NACA 4412 airfoil using the BEM method, there will be some steps that need to be done, they are including:

a. divide the rotor blade into several radial elements (sections) along its length, each with a specific radius and spanwise location,
b. define the operating conditions of the rotor, such as wind speed, rotational speed, and angle of attack at each radial station,
c. calculate the aerodynamic forces for each blade element using airfoil data (e.g., lift and drag coefficients) for the NACA 4412 at the given angles of attack. These can be obtained from experimental data or through airfoil analysis tools,
d. apply the momentum theory to compute the induced velocity and pressure at each element. This involves solving the conservation of momentum in the axial and tangential directions,
e. and then iterate to find the equilibrium conditions for the rotor, adjusting for the balance between aerodynamic forces, centrifugal forces, and induced velocities.

3. Results and Discussion

The results of BEM simulation of each element on the attack angle variations blade of NACA 4412 is presented on Table 1, while the calculation of the Turbine Torque, CP and Power Simulation is presented on Table 2 below.

Table 2. Simulation of Attack Angle Variations

A (O)	C_L	C_D	C_L/C_D
-8	-0.338	0.027	-12.558
-7	-0.235	0.026	-8.959
-6	-0.131	0.025	-5.143
-5	-0.06	0.009	-6.586
-4	0.042	0.008	5.095
-3	0.148	0.008	18.686
-2	0.257	0.008	33.862
-1	0.364	0.008	46.706
0	0.474	0.008	60.744
1	0.582	0.008	73.402
2	0.69	0.008	86.35
3	0.789	0.009	87.664
4	0.885	0.009	93.887
5	0.98	0.011	92.679
6	1.08	0.012	93.057
7	1.17	0.013	87.542
8	1.273	0.014	92.646
9	1.359	0.015	90.295
10	1.429	0.017	84.385
11	1.48	0.019	76.066
12	1.533	0.022	68.447
13	1.577	0.027	59.466
14	1.583	0.034	46.525
15	1.568	0.046	34.32
16	1.524	0.062	24.674
18	1.358	0.133	12.057
19	1.358	0.143	8.826

Analysis of Aerodynamic Characteristics of Lift Coefficient (CL), Thrust Coefficient (-CD) and CL/CD Comparison. By simulating the NACA 4412 airfoil, the largest CL value is obtained at α = 14o with a value of 1.583. The smallest CD value is obtained at α = -4 to 2o with the smallest value of 0.008. The largest CL/CD value is found at α = 6o with a value of 93.057. Lift and drag forces are vector quantities, where negative numbers only indicate the direction of the force. The simulation results are plotted into graphs, namely the angle of attack graph α vs CL, α vs CD, α vs CL/CD. The CL value increases and will be maximized at α = 14o which is 1.583. At α = 16o to 19o the CL value decreases to 1.524 and 1.358. This occurs in the stall state. The stall effect occurs when the flow passing through the airfoil does not continue.

Table 3. Turbine Torque, CP and Power Simulation

Speed (m/s)	Rotational speed (rpm)	Turbine Power (Watt)	Cp	Torque (Nm)
2	102	7,58	0,47	0,71
3	153	25,57	0,47	1,6
4	204	60,57	0,47	2,84
5	255	118,33	0,47	4,43
6	306	204,45	0,47	6,39
7	357	324,67	0,47	8,68
8	408	484,63	0,47	11,35

The higher the CL value indicates better airfoil performance, but in addition to the onset of lift force, drag force will also arise. For the highest CL value occurs at α = 14o which is 1.583 but the CD produced is also large, namely 0.034 so this causes the CL / CD value to be smaller, namely 46.525 when compared to the CL / CD value at α = 6o with a value of 93.057. This is because at α = 6o the air continues to pass through the airfoil even though the CL value is smaller at 1.08 but the CD value is smaller at 0.012.

The smallest CD value occurs at an angle of attack α = -4o to 2o which is 0.008. The smaller the CD value, the better the airfoil performance. On the airfoil there are 2 kinds of forces that work, namely lift and thrust. Airfoil performance is related to the ratio of CL to CD which is called the glide ratio. The lift and drag coefficients are very important values as a consideration of the performance of the airfoil to be designed. Simulation of the best angle of attack variation to produce the most maximum power is at an angle of attack of 6o because the air flow continues through the airfoil.

4. Conclusions

After analyzing, the largest lift force (CL) value was obtained at an angle of attack of 14o with a value of 1.583. At an angle of attack of -8o to 14o the lift value increases significantly because the wind flow continues through the airfoil. The smallest thrust force (CD) value is at an angle of attack of -4o to 2o with a value of 0.008. The largest CL/CD value is obtained at an angle of attack of 6o with a value of 93.057. After analyzing, the most optimal power coefficient value is 0.47. The maximum power generated is 484.63 Watt at an angle of attack of 6o because at an angle of attack of 6o the air flow continues through the airfoil. Influential parameters in generating power include wind speed, torque, angle of attack and number of blades.

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