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Design, Fabrication and Performance Test of Helical-Blade Vertical-Axis Wind Turbine at Low Tip Speed Ratio

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Abstract: ***A helical-blade vertical-axis wind turbine was designed and tested ina wind tunnel. A relatively low tip-speed ratio of 1 was targeted for usage in an urban environmentat a rated wind speed of 8m/s and a rotational speed of 160 rpm.The power coefficient and torque coefficient was calculated by a mathematical model. TheAerodynamic performance and the lift and drag of the blade with respect to the angleof attack during rotation were calculated using 2D computational fluid dynamics (CFD) simulationto take into account stall region. The average power output calculated by the model was 95W.The manufactured wind turbine was tested in a largeclosed-circuit wind tunnel, and the power outputs were measured for given wind speeds. At thedesign condition, the measured power output was 101.7 W, which is 5.9% higher than that of themathematical model. This result validates the proposed design method and power estimation by themathematical model.***

Keywords: Vertical Axis Wind Turbine, Low Tip Speed Ratio, Helical Blade, Wind Tunnel Test

1. Introduction

The consumption of fossil fuels has increased, resulting in high CO2 emissions and serious climatechange. Research on renewable energy is actively under way to solve these environmental problemsand in anticipation of the depletion of fossil fuels. Wind energy is an environmentally friendlyrenewable energy source that does not cause environmental pollution, and its use is rapidly spreadingaround the world. Research on wind power generation has therefore been actively pursued. At first, research onmiddle-size and large horizontal wind turbine generators was the main focus. However, due to factorsaffecting the environment such as **noise**, such wind turbines are difficult to install near residences andhave negative effects on the ecosystem. A wind turbine generator can have a vertical or horizontal rotation axis. A vertical-axis windpower generator is advantageous for installation in city centers because it is not affected by thedirection of the wind as much as a horizontal-axis wind power generator. It is easy to maintain becauseit does not need complicated structure such as yawing devices .In the case of horizontal-axis windturbines, the angle of attack due to the rotation of the wind turbine is constant. Many studies havebeen conducted on the prediction of the blades' aerodynamic characteristics, However, in the case of vertical-axis wind turbines,the angle of attack due to the rotation of the wind turbine changes continuously.Therefore, it is essential to develop an output verification process for a vertical-axis wind turbine. The most obvious method of verification is experimentation. However, due to spatial limitations, this method is limited to very small wind turbines.Darrius proposed the concept of a vertical-axis wind turbine in 1931. The first simplifiedapproach is the single-stream-tube numerical model proposed by Templin. The characteristics ofthe airfoil were calculated using blade element theory. The output of the whole rotor is the same asthe performance of a single blade with the chord length of the entire rotor blades. This approach allowsus to predict the performance of the rotor in terms of the average torque per revolution of the rotor.

Islam et al. compared and analyzed three mechanical models to design aDarrius wind turbine with straight blades and predict the performance. The DMST model, free vortexmodel, and cascade model were compared. Sutherland et al. proposed a stream-tube model and a vortex model that can analyze theaerodynamic response of a vertical-axis wind turbine using a mathematical model.

Brusca et al. analyzed the relationship between the aspect ratio of avertical-axis wind turbine with straight blades using a calculation code based on a multiple-stream-tube model. They concluded that a low aspect ratio has some advantages over a high aspect ratioand emphasized that the power factor was affected by the solidity and Reynolds number of the rotor. Field tests or wind tunnel tests have also been conducted to verify the performance of wind turbines. Shel dahl conducted a field test on a Darrius-type vertical-axis wind turbine with a NACA 0012 airfoiland compared it with the results of an ideal wind tunnel test.

Bedon et al. reported field test resultsfor a 1-m-diameter helical blade with a NACA 0018 airfoil. Recently, Cheng et al. performed a 2Dflow field simulation of a helical VAWT with four blades by means of a large eddy simulation (LES).They showed that the variation of angle of attack (AOA) and blade-wake interaction under differenttip speed ratio conditions are the two main reasons for the power output of the helical VAWT [24].In this study, a wind turbine was designed based on a lift-type vertical-axis wind turbine.The initial design output is 100W, and the target tip speed ratio is 1.1, which is smaller than the ratio of4–6 of a conventional vertical-axis wind turbines. For the conventional tip speed ratio, the maximumand minimum angles of attack are reduced. Therefore, the angle of attack does not reach the stallregion, so that the lift and drag coefficients can be easily predicted and the conventional DMST modelcan be used.

2. Design of Helical Blade Vertical-Axis Wind Turbine

In the case of a horizontal-axis wind turbine, a large number of devices are required, such asa yawing device and a pitching device. While the generation efficiency is relatively high, the bladeshape is complicated. There is also a disadvantage in that the wind direction is limited. In the case ofa vertical-axis wind turbine, the structure is simple, and it is advantageous for installation in a citycenter because there is no restriction of the wind direction. Typical blade types of vertical-axis wind turbines are Darrieus, gyro-mill, Savonius, and helical blades. The helical type is advantageous in that the fluctuation range of the output is smaller than that of the conventional Darrius or gyro-mill blades, and the self-starting performance is better. It also has less mechanical load and less noise than a Savonius rotor, which is a drag-type rotor.

Figure 1 shows a basic schematic for the aerodynamic design of a vertical-axis wind turbine.

Equation (1) represents the power of the wind flowing wind turbine rotor

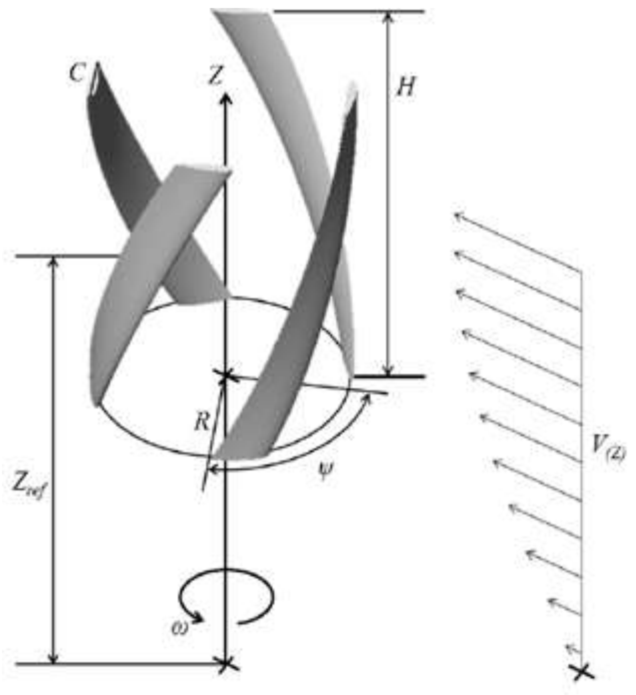

Figure 1. Basic design parameters of the vertical wind turbine.

$$P = 1/2 r A_w V^3 \quad (1)$$

Equation (2) is the mechanical power output generated by the rotation of the wind turbine rotor.

$$P = Tw \quad (2)$$

The ratio of the power converted from the rotor power to the wind power flowing is called thepower coefficient, which is a concept of aerodynamic energy conversion efficiency. Theoretically, the maximum value of the power coefficient is 0.593 in a horizontal axis wind turbine, which is knownas the Betz limit. The Betz limit is derived from actuator disk momentum theory and is the theoreticalmaximum assuming that the flow is steady-state The Darrius turbine is a typical lift-type vertical-axis wind turbine and has a maximum power coefficient of about 0.4 at a tip speed ratio of 5.

Equation (3) shows the power output (P) of the wind turbine considering the power coefficient (C_P) and power transmission efficiency (*h*). A_w is the rotor swept area

$$P = 1/2 r A_w V^3 H c_p \quad (3)$$

The tip speed ratio (*l*) is closely related to the power coefficient. The tip speed ratio is defined as the ratio of the blade tip speed and the wind speed at which the blade tip moves with rotation

$$l = Rw/v \quad (4)$$

All wind turbine rotors have an optimum tip speed ratio with maximum power. The optimal ratio is related to the change of the incoming wind speed. The rotor swept area (A_w) is determined bythe radius and height of the wind turbine.

$$A_w = 2RH \quad (5)$$

The wind swept area should consider the height of the rotor (H) and the aspect ratio with respect to the radius (R). The longer the rotor radius, the higher the generated torque, but the longer the strutlength, the lower the structural stability. However, when the rotor height is greater, the generatedtorque is lower, and the rotational speed of the rotor should be increased to obtain the same poweroutput. The aspect ratio (AR) can be expressed as

$$A = H/2R\text{-}H = AR\ x2R \quad (6)$$

Solidity (*s*) is an important variable that determines the performance of wind turbines. Solidity isdefined as the ratio of the total projected area (NC) of the rotor blade to the rotational area of the windturbine rotor. The projected area is the projection in the vertical section of the rotating shaft and can be expressed as

$$s = NC/2pR \quad (7)$$

The blade chord length (C) can be calculated using the solidity. The chord length is the length ofthe airfoil and is an important design variable because the generated torque changes according to thechord length.

Wind shear is considered, and the velocity profile (V(Z)) is shown in Equation (8)

$$V(Z) V_{ref} (Z/Z_{ref})^a \quad (8)$$

Blade Specifications
Rotor type -Helical
Rated power output -95W
Rated wind speed -8 m/s
Power coefficient- 0.15
swept area- 1.57 m^2
Aspect ratio- 1.3
Rotor radius- 0.55 m
Rotor Height- 1.43 m
Rotational speed- 160 rpm
Solidity -0.3
Chord length -0.25 m
Number of blades- 4
Airfoil- NACA0018

The design equation for the vertical-axis wind turbine does not reflect the factors for the blade airfoil, so an additional prediction of the power output is needed. In this study, the aerodynamic power of the wind turbine rotor was investigated by applying a NACA 0018 airfoil and a mathematicalmodel using the lift and drag forces of the airfoil according to the angle of attack. Unlike the bladeof a horizontal-axis wind turbine, which has a fixed angle of attack, the angle of attack varies for avertical-axis wind turbine depending on the rotation angle of the rotor . Figure 2 presents thetip velocity vector and the lift and the drag vectors generated by the rotation of the turbine blade.The angle of attack changes with the blade tip velocity vector and the influx wind velocity vector The vector sum (W) of the tip velocity vector and incoming wind velocity vector (V) is calculated byEquation (10). The maximum value occurs at q = 0_, and the minimum value occurs at q = 180

$$W = \sqrt{V^2\left[(\lambda - \sin^2\theta)^2 + \cos^2\theta\right]} = V\sqrt{1 + 2\lambda\cos\theta + \lambda^2}$$

The normal coefficient (C_N) and the tangential coefficient (C_T) are generated from the blade by using the lift coefficient and the drag coefficient and calculated using Equations (9) and (10).

$C = C_L \cos a + C_D \sin a(9)C_T = C_L \sin a$ □$C_D \cos a$ (10)

The normal force (F_N) and tangential force (F_T) of the blade can be calculated through the normal and tangential coefficients using Equations (11) and (12).

$F_N(q = 1/2\, rcHW^2 C_N$ (11)

$F_T(q = 1/2\, rcHW^2 C_T$ (12)

The power output can finally be calculated using the blade torque (Equation (13)) and the angular
velocity using the tangential force:

$T(q = 1/2\, rcHW^2 C_T R$ (13)

The instantaneous and average power output of the designed rotor are given by Equations (14)

$P(q) = T(q) \times w$ (14)

3. Wind Tunnel Test

A helical vertical-axis wind turbine rotor was fabricated based on the design dimensionsThe rotors, hubs, and struts con were designed and are structurally stable according to IEC61400-2. The axis of rotation connects the upper and lower hubs and is designed to withstand bendingcaused by wind. A carbon steel pipe (50A _ Sch. 40) with an outer diameter of 60.5 mm was used forpressure piping. The strut is an important part for connecting a blade to the hub. It is one of the componentsthat receives the largest load. The strut bears the weight of the rotor and the centrifugal force fromthe rotation of the blades. The design was made while considering the position of the blade and theposition of the hub. The hub is a part that fixes the rotating shaft and the strut. When the rotor isrotated, the strut is designed so that it does not move in the rotating direction. Finally, helical bladeswere manufactured using FRP material, which has excellent formability. All the parts were designed
for manufacturability.

The rotational speed of the wind turbine can be estimated through the three-phase frequency (f_e) of the generator

$f_e = N_m N_P/120 - N_m = 120 f_e/N_P$
where N_p is the number of generator poles.

The wind tunnel test is divided into the starting wind speed measurement and the power generation measurement. The starting wind speed is the wind speed at which the vertical-axis wind turbine is moving from standstill and is measured without electrical resistance. The starting wind speed is measured with a gradual increase of the wind speed with intervals of 0.5 m/s and kept for 5 min for stabilization at each wind speed. At each wind speed, the voltage, current, and three-phase frequency generated by the generator of the wind turbine were measured. Using a multi-meter and an oscilloscope, the voltage and current curves over time were all measured, and the output as calculated. The measured frequency was used to obtain the rotational speed of the wind turbine.

The test was conducted with increases in wind speed of 1 m/s from the starting wind speed. In each section of wind speed, the test was performed while changing the duty ratio of the controller. The output range including the maximum power point at a given wind speed was examined. When all conditions were changed, the results were recorded after obtaining a stabilized state. Table 5 provides a brief description of the test conditions.

4. Results and Discussion

During the rotation of the blades, the torque generated was obtained using Equation (18), as shownin Figure 8. The maximum torque occurred between rotation angles of 50 and 70_. After angle of70_, the angle of attack reaches stall region followed by rapidly decrease of torque. Over 90_ of angle,which means backward flow, torque value is almost zero, and the blade does not create any lift force.The final output value calculated from Equations (19) and (20) is 108.34 W, and the power coefficient is0.154, which shows a discrepancy of 8.34% from the design value but is higher than the target output.

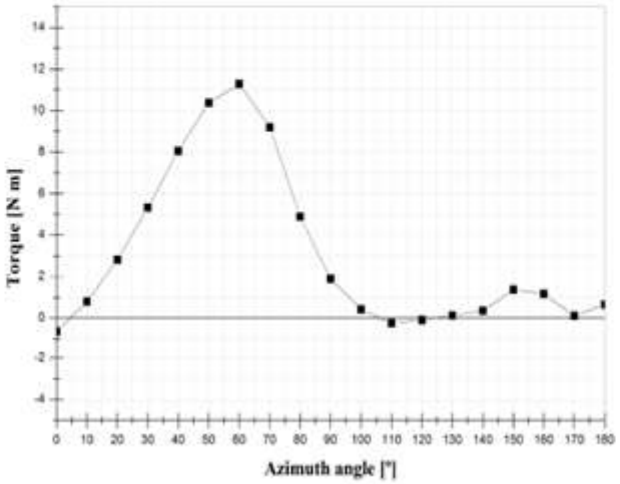

Figure 4: Torque variation of a blade for revolution

wind turbine rotors have maximum output points at each wind speed, and the maximum power point tracking (MPPT) method is used to control the maximum wind power at each wind speed. This method minimizes the performance loss of the wind turbine. The maximum output point rises steeply as the wind speed increases because the output increases in proportion to the cube ofthe wind speed, as shown in Equation (1). Due to structural stability, the test was not performed atoperating conditions above 260 rpm. The constructed VAWT is designed to have power outputat a wind speed of 8 m/s at a rotor speed of 170 rpm (TSR = 1).

Wind Velocity	*Rotation Speed*	*Power output*	c_p	*Remark*
4	24.6	0.03	0.001	velocity =3.5 m/s
5	110	10.44	0.087	-
6	131	26.30	0.127	-
7	161	55.74	0.137	-
8	182	99.72	0.146	94.7w
9	215	158.3	0.235	114.7w
10	255	250	0.238	135.8w
11	258	302.4	0.236	156.7w

The vertical-axis wind turbine starts at 3.5 m/s, and the power output increases as the wind speedincreases. From 8 m/s, the maximum output is generated while exceeding the design rotation speed of170 rpm. The maximum output at the design wind speed of 9 m/s is 160.2W, and the rotation speedis 215 rpm. When the load is controlled at 170 rpm, the output is 114.7 W, which is higher than thetarget output. The design power coefficient of the wind turbine is 0.15, and the output is higher thanEnergies **2018**, 11, 1517 15 of 17 the designed power coefficient beginning at 7 m/s. When the wind turbine is operated at 9 m/s and 170 rpm, the power coefficient is 0.163, which is larger than the design value of 0.15. Table 7 compares the output power of the wind turbine predicted by the mathematical model with the measured power output from the wind tunnel experiment. At the design condition, the measuredpower output was 114.7 W, which is 5.9% higher than that of the mathematical model. This resultvalidates the proposed design method and power estimation by the mathematical model can be usefulto design a low speed VAWT with a reasonable accuracy. The higher power output of the wind tunneltest could be a result of the confinement effect due to wind tunnel walls.

Table 7: Power output and power coefficient obtained from the mathematical model and wind tunnel test

Method	Power	c_p
Mathematical Model	95w	0.146
Wind Tunnel test	101.7	0.235

The size of the blade was determined through Equations (1)–(9), but it is impossible to design thechange of the airfoil and the twist angle of the blade. In the power output estimation process throughthe mathematical model, the output can be predicted by reflecting the lift and drag of the airfoil. However, it is impossible to consider the output change due to the wake occurring in the range after180 degrees of azimuth. Further studies should be done to investigate the flow structures associatedwith the rotating helical blade

5. Conclusions

The basic design formula yielded the wind turbine rotor dimensions with an aerodynamic powerof 100Wat a rated wind speed of 9 m/s and a tip speed ratio of 1.1. The torque due to rotor rotation can be calculated by applying the lift and drag forces derived from the 2D CFD results. The averageoutput was calculated as 108.34 W, and the target output of 100 W was satisfied. The designed turbinewas fabricated, and a wind tunnel test was performed. The output variation according to the rotorspeed was measured at each wind speed. When the incoming wind speed is 9 m/s at the rotationalspeed of 170 rpm, the measured power output was 114.7 W, and the design method was validated.However, the design method cannot predict the power output variation due to the number of blades,the twist angle of the helical blade, the pitch angle, and the position of the strut. Further researchshould be carried out for different geometry details of the helical rotor.

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