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A Study on Design of A High Efficiency Vertical Axis Wind Turbine Blade Using Composite Materials

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Abstract: This work is to design a high efficiency 500W class composite VAWT blade which is applicable to relatively low speed region. In the aerodynamic design of blade, the parametric studies are carried out to decide an optimal aerodynamic configuration. The aerodynamic efficiency and performance of the designed VAWT is confirmed by the CFD analysis. The structural design is performed by the load case study, the initial sizing using the netting rule and the rule of mixture, the structural analysis using FEM, the fatigue life estimation and the structural test. The prototype blade is manufactured by the hand lay-up and the matched die molding. The experimental structural test results are compared with the FEM analysis results. Finally, to evaluate the prototype VAWT including designed blades, the performance test is performed using a truck to simulate the various range wind speeds and some measuring equipments. According to the performance evaluation result, the estimated performance is well agreed with the experimental test result in all operating ranges.

Keywords: Vertical Axis Wind Turbine Blade, composite materials, FEM Analysis

1 Introduction

Since the energy crisis and the environmental issue have been focused due to excessive fossil fuel consumption, the wind power has been considered as an important renewable energy source. Recently, several MW class large scale wind turbine systems have been developed in some countries. Even though the large scale wind turbine can effectively produce the electrical power, the small scale wind turbines have been continuously developed due some advantages, for instance, it can be easily built by low cost without any limitation of location, i.e. even in city. In case of small scale wind turbines, the vertical axis wind turbine (VAWT) is used in city

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having frequent wind direction change, even though it has a bit lower efficient than the horizontal axis wind turbine. Furthermore, most small scale wind turbine systems have been designed at the rated wind speed of around $12m/s$, but they have a great reduction of aerodynamic efficiency in low wind speed region [Kong (n.d., 2006, 2011)].

This work is to design a high efficiency $500W$ class composite VAWT blade which is applicable to relatively low speed region. In this work an aerodynamic and structural design procedure is proposed to design the vertical wind turbine using the skin-spar-foam core sandwich structure having Glass/Epoxy skin and spar and Polyurethane foam core.

2 Aerodynamic design

The aerodynamic design of Darrieus type rotor including H-type vertical wind turbine follows R. J. Templin's theory [Templin (1974); Eggleston (1987); Solum, Bernhoff, and Leijon (2008)].

An in-house aerodynamic design program based on the theory above is newly coded. The program is coded using Visual Basic. If the wind speed and design parameters are given as an input data, the program can calculate the tip speed ratio, power coefficient and power considering Reynold's Number. Here the look-up table of the local Reynold's Number of each airfoil is obtained by the CFD analysis.

In order to validate the proposed aerodynamic design program, it is applied to comparing with test results the Uppsala University H-type vertical axis wind turbine which can produce the power of 12 kW with 3 blades have NACA0021 airfoil, the blade length of $5m$, the turbine radius of 3m and the chord length of $0.25m$ at the rated wind speed of $12m/s$ [Lee (2010)]. Through this comparison, it is confirmed that the proposed program is well agreed with the test results.

The optimal aerodynamic design of the $500W$ class H-type vertical wind turbine rotor is carried out by the proposed in-house program through the parametric study. In the parametric study, it is performed to find an optimal aerodynamic configuration having high efficiency in both low and high wind speed regions with the following design parameters such as number of blades, solidity, airfoil, height to radius ratio, etc. Figure 1 shows the optimal aerodynamic design results and the designed configuration using the parametric case study.

Prior to getting the performance test the designed wind turbine is numerically analyzed using a commercial CFD code, ANSYS, CFX. Figure 2 shows the flow pattern obtained by CFD analysis using this code. In the analysis, input data as an operating condition are the rotational velocity of 167RPM and the rated wind speed of 8m/s at sea level. In order to consider the rotating position of the blade, the dynamic moving mesh method is applied. Separate disconnecting zones are used for expressing the rotating and stationary regions. The SST(Shear Stress Transport) turbulence model based on $\kappa - \omega$ model is used. The analysis result shows that the calculation power of 663 W meets closely to the design target rated output of $600W$.

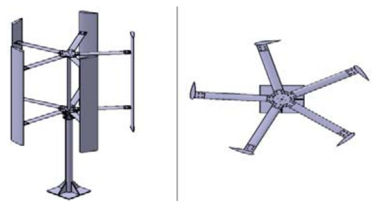

Figure 1: Designed $500W$ VAWT configuration

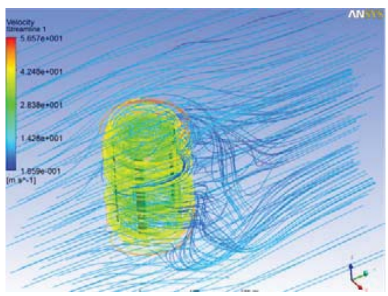

Figure 2: Stream line distribution for fluid flow analysis using ANSYS

3 Load case analysis and structural design

Main loads acting on the blade are the aerodynamic load and the centrifugal force. The centrifugal force can be simply calculated from rotational speed, and the aerodynamic loads defined as the following expressions can be calculated at several load cases mentioned in Table 1.

The shear forces and the bending moments can be defined by integrating the normal and chordwise aerodynamic force component distributions acting on each section of the blade depending on the wind speed and the incidence angle in various operating conditions.

Table 1 shows the definition of various aerodynamic load cases having gust conditions and centrifugal body forces considered in the structural design. According to load case analysis, the load case 2 is found as the most severe condition. Therefore, the structural design is performed in consideration of the load case 2.

Table 1: Definition of load cases considered in sturctural design

Load case	Case 1	Case 2	Case 3
Reference wind speed	$8m/s$	$20m/s$	$55.0m/s$
Gust condition $\pm(20m/s, 40°)$	Without gust	With gust	Storm
Rotational speed	$167rpm$	$353rpm$	stop

In the structural design, the blade adopts the skin-spar-foam core sandwich structure concept. The glass fabric/epoxy composite material, which is supplied by a domestic company, is used for both skin and spar. The bending force is endured by the spar flange layered with the ply angle of $0°/90°$ and the torsion is endured by the upper and lower skins layered with the ply angle of $\pm 45°$. Figure 3 shows the blade structural design concept with skin-spar-foam core sandwich.

The initial design of the composite blade is performed using the netting rule and the rule of mixture which were used in the previous study [Kong (n.d., 2006, 2011)], and then the designed feature is repeatedly modified by structural analysis results using a FEM tool, NASTRAN. In this analysis, stresses, strains, tip deflections, buckling loads and natural frequencies are found. Skin, spar and core of the blade structure are meshed by 3584 PCOMP 4-node shell elements which can have good composite structural behaviors. The aerodynamic loads are applied on the aerodynamic centers of the span-wise distributed blade airfoils, the boundary condition is assumed as a fixed condition at the joint part between the connection support and blade root. The analysis results show that the highest stresses occurs at the 1st ply of the skin and the 13th ply of the spar, respectively. Figure 4 shows the spanwise (Y-axis) stress contour on the blade illustrated by FEM analysis.

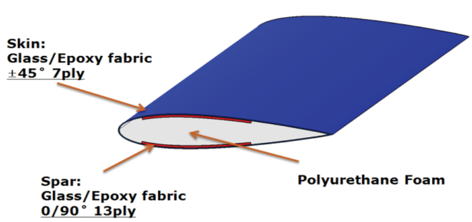

Figure 3: Structural design concept of blade with skin-spar-foam core sandwich

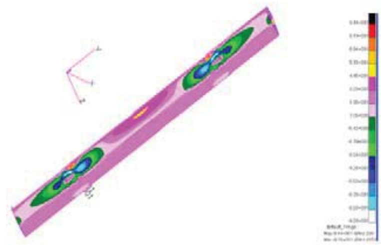

Figure 4: Spanwise(Y-axis) stress contour on the 13th ply of spar for load case 2 (Mpa)

4 Manufacturing of prototype blade and structural test

Manufacturing, the hand lay-up and the matched die molding methods are applied Kong (2011). In the manufacturing process, the Styrofoam mold is firstly manufactured using steel plate templates and hot wires due to economic reason, and then glass fabrics for the second mold are layered-up on the Styrofoam mold with special coating. Again the glass fabrics are layered on the second mold once again for the final mold, and then glass fabrics for the upper and lower surface skins of the blade are layered on the final mold according to the structural design result. The cured upper and lower surface skins are bonded by epoxy, and then the Polyurethane foam is injected into the space between upper and lower skins. After completely curing the blade, the proper coating is applied.

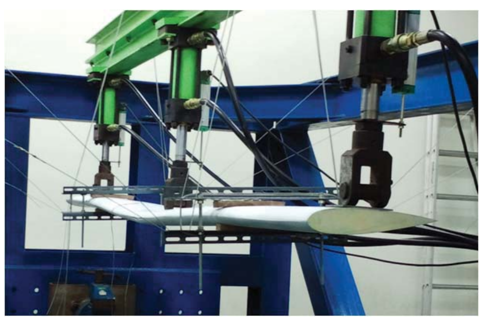

Figure 5: Static structural test of the prototype blade using the 3-points loading

The design loads for the static structural test are simulated by the 3-points loading. The test is performed by the structural test equipment shown in Fig. 5. The test results are compared with FEM structural analysis results. The deflection measured at blade center is 51*mm* and the estimated deflection at the same position is 54*mm*.

And the upper and lower surface spanwise strains measured at 50mm from blade center are 1060$\mu\varepsilon$ and 870$\mu\varepsilon$, respectively. Estimated results at the same locations are 1010$\mu\varepsilon$ and 762$\mu\varepsilon$, respectively. Figure 5 shows static strength test loads simulated by the 3-point loading method.

5 Performance test of prototype small VAWT

To evaluate the target design performance, the performance test of the prototype small VAWT is performed using test purpose tower, generator, electrical loader, performance measuring instruments, etc.

Because the wind tunnel for the aerodynamic test of the full scale wind turbine system is not available, a truck is used for the performance test. In order to simulate various wind speeds, the truck is specially controlled by various speeds. The simulated speed range on the truck is 3 to 11 m/s. However, even though some errors in wind speed are expected due to measurement at the difference location from the wind turbine blades, but it is negligible because of the measuring location is near by the test machine. Figure 6. shows the test setup for performance test of the prototype VAWT. In the test, the wind turbine starts to produce the electrical power from around 3m/s and the power is limited at around 700W due to the limited power of the 500W generator and its power control system. However the developed wind turbine produces the design power of 500W at the rated wind speed of 8m/s.

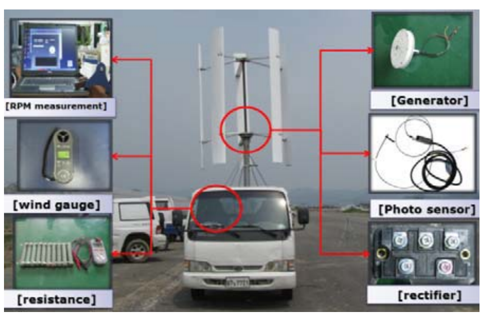

Figure 6: Test setup for performance test of prototype small VAWT

6 Conclusion

In this work, the aerodynamic and structural design procedure of a high efficiency 500W class composite VAWT is proposed. In the aerodynamic design of blade, the parametric studies are carried out to decide an optimal aerodynamic configuration.

The aerodynamic efficiency and performance of the designed VAWT is confirmed by the CFD analysis. The structural design is performed by the load case study, the initial sizing using the netting rule and the rule of mixture, the structural analysis using FEM, the fatigue life estimation and the structural test. The prototype blade is manufactured by the hand lay-up and the matched die molding. The experimental structural test results are compared with the FEM analysis results. Finally, to evaluate the prototype VAWT including designed blades, the performance test is performed using a truck to simulate the various range wind speeds and some measuring equipments. According to the performance evaluation result, the estimated performance is well agreed with the experimental test result in all operating ranges.

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