AERODYNAMIC AND STRUCTURAL DESIGN OF A HIGH EFFICIENCY SMALL SCALE COMPOSITE VERTICAL AXIS WIND TURBINE BLADE

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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 such as 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 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 around 12 m/s, they have a great reduction of aerodynamic efficiency in low wind speed region like Korea.[1][2][3]

This work is to design a high efficiency 500W class composite VAWT blade which is applicable to relatively low speed region like Korea. In this work an aerodynamic and structural design procedure shown as Fig.1. 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 rated wind speed to design the 500W class vertical axis wind turbine system is considered as 8m/s. In the aerodynamic design of blade, the parametric study is carried out to find an optimal aerodynamic configuration having high efficiency in both low and high wind speed region using the proposed design procedure. The aerodynamic design parameters are number of blades, solidity, airfoil, height to radius ratio, etc. For this analysis, the following equations are used, and the calculation flow is coded by a computer program. The power coefficient is defined as the following equation; [4][5]

$$C_p = \frac{2P}{\rho S V_1^3} = \frac{bc}{2\pi S}\int_{-H}^{+H}\int_0^{2\pi} C_t \frac{W_u^2}{V_1^3}\,\omega r dz d\theta \qquad (1)$$

And the mechanical power and the electronic power are calculated as follows;

$$P = M\omega = \frac{bc}{2\pi S}\int_{-H}^{+H}\int_0^{2\pi} C_t \; q r \omega dz d\theta \qquad (2)$$

$$P_e = \eta_g P \qquad (3)$$

Where C_P; wind turbine power coefficient ρ; air density, S; projected frontal area of the vertical axis wind turbine, V_1; uniform wind velocity, b; number of blade, c; blade chord length, H; half-height of blade, C_t; tangential coefficient, W_u; resultant air velocity relative to a blade element, ω; angular velocity, r; local radius, q; $\frac{1}{2}\rho W_u^2$, dz; length of blade element projected on to the leading edge, η_g; generator efficiency. Table 1 and Fig.2 show the aerodynamic design results using the aerodynamic design program developed in this work. To confirm the design results, torque and flow stream lines are found using the CFD tool, CFX.[6] Fig.3 shows power coefficient curve versus tip speed ratio obtained by the aerodynamic design program for the VAWT.

3. Load case analysis and structural design

Main loads acting on the blade are the aerodynamic

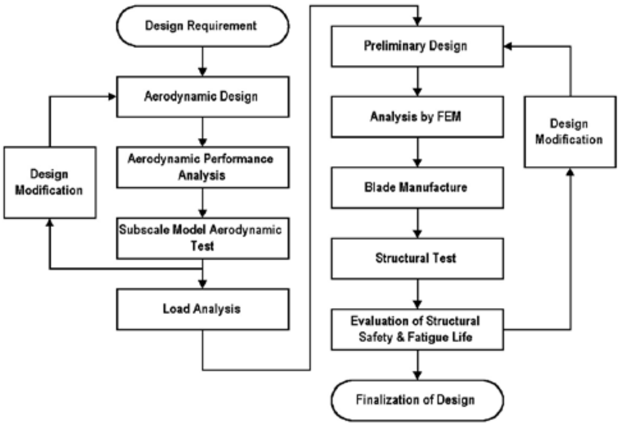

Fig.1. Proposed aerodynamic and structural design Procedure

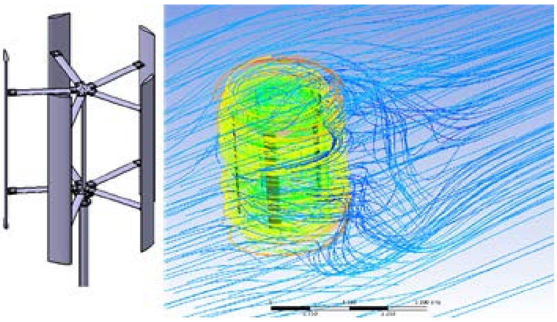

Fig.2. Designed 500W VAWT configuration and str eam line distribution obtained by CFD analysis

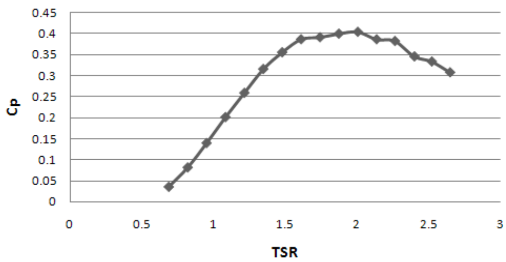

Fig.3. Power coefficient vs. tip speed ratio

load and the centrifugal force. The centrifugal force can be simply calculated from rotational speed, and the aerodynamic load can be calculated by aerodynamic coefficients in several load cases mentioned in Table 2. The shear force and bending loads can be defined by the aerodynamic normal force distribution acting on each section of the blade, and their variations depend on the wind speed and

Table 1 Aerodynamic design results of 500W VAWT

Rated power	500W
Rated wind speed	8m/s
Rated RPM	168
Number of blades	5
Radius	0.9m
Blade length	2.56m
Blade chord length	0.27m
Airfoil	NACA0018

the incidence angle in various operating conditions. 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.

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 ±45°. Fig.4 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 [1][2][3], 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. Fig.5 shows the stress contour on the blade illustrated by FEM analysis. Table 3 shows structural analysis results.

Table 2 Aerodynamic design results of small wind turbine

Load case	Case 1	Case 2	Case 3
Reference wind speed	8m/s	20m/s	55.0m/s
Gust condition ±(20m/s, 40˚)	without gust	with gust	storm
Rotational speed	167rpm	353rpm	stop

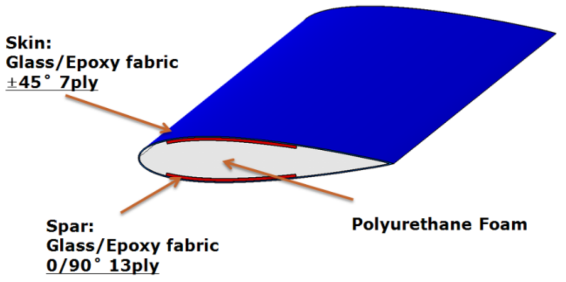

Fig.4. Structural design concept of blade with skin-spar-foam core sandwich

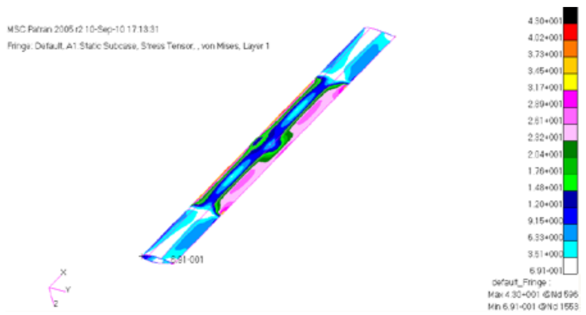

Fig.5. Stress contour on blade illustrated by FEM analysis

Table 3 Stress analysis results of small VAWT blade

Analysis result \ Blade components		Spar	Skin	Connection support
Max. stress [Mpa]	Ten.	12.4	94.4	259
	Comp.	21.1	92.8	
Max. stress failure criterion	Ten.	0.04	0.3	0.91
	Comp.	0.11	0.5	
Tsai-Wu failure criteria		0.23	0.78	

To estimate fatigue life of the designed blade, the wind speed data, which was measured at a particular region during a year, is used to obtain the load spectrum. The wind data is divided into several regions with 1.5 m/s interval. Normal aerodynamic load and centrifugal force at each wind speed region are calculated by the aerodynamic design and load calculation program. And cycles occurred at each region can be simply estimated by the rotational speed calculated at the wind speed. The estimated cycles at all regions are normalized by minimum cycles of 20~40m/s wind speed region. The loads are randomly distributed shown as Fig.6. It is assumed that this spectrum occurs repeatedly during a year.

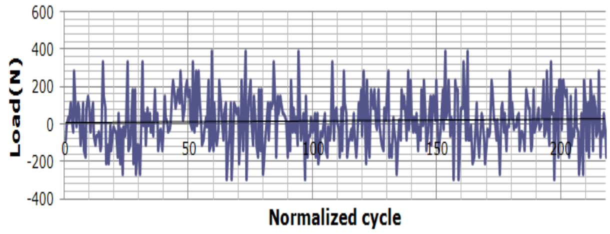

Fig.6. Load spectrum obtained by the developed loa d spectrum estimation program

From stresses calculated by load spectrum and S-N curve of the used materials, fatigue life N_i at constant stress level S_i can be estimated. Finally, from the number of applied load cycles n_i at constan t stress level S_i, the required 20 years fatigue life[7][8] is confirmed using the obtained load spectrum and the modified Miner rule, equation(4) as follows;

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = 0.7 < 1 \tag{4}$$

Where k; total sets of applied load cycles at constant stress level S_i.

4. Manufacturing of prototype blade and structural test

In manufacturing, the hand lay-up and the matched die molding methods are applied.[3] 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. The manufacturing process and the first prototype blade are shown in Fig.7.

Fig.7. Applied manufacturing process and the first prototype blade

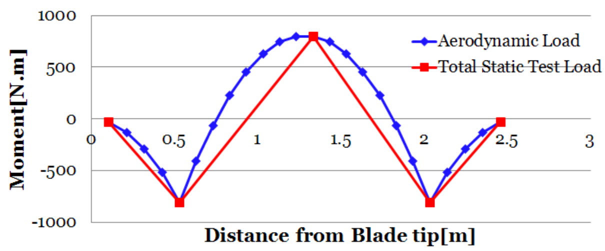

Fig.8. Static strength test loads simulated by the 3-point loading method

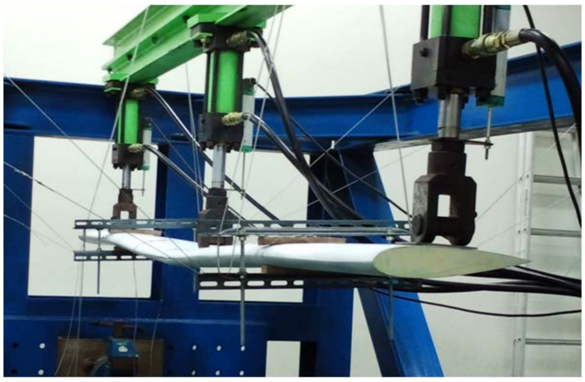

Fig.9. Static structural test of the prototype blade using the 3-points loading

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.9. The test results are compared with FEM structural analysis results. The deflection measured at blade center is 51mm and the estimated deflection at the same position is 54mm. And the upper and lower surface strain measured at 50mm from blade center are 1060 με and 870 με, respectively. Estimated results at the same locations are 1010 με and 762 με, respectively. Fig.8. shows static strength test loads simulated by the 3-point loading method and Fig.9. shows the picture of static structural test using 3-points loading.

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. In order to simulate various wind speeds, a truck is specially used instead of the natural wind condition. The simulated speed range on the truck is 3 to 11 m/s.

To measure the electrical power produced by the wind turbine, a gearless generator 'SYG-A208-600-570'[9], which has some advantages such as simple due to gearless, easy blade mounting and low noise, is used. Additional test devices are a rectifier, resistances for electrical loading, a multi-meter and a photo sensor and an instrument to measure the blade rotational speed. Fig.10. shows the test setup for performance test of the prototype VAWT.

Fig.11. shows comparison between experimental test results and estimation results of electrical power produced by the prototype VAWT. Through the comparison, it is found that the VAWT starts around the wind speed of 4 m/s, and the power increases rapidly at 6 m/s. Here the reason why the tested electrical power is not increased from 600W region is due to use of the 500W generator.

This comparison result reveals that the test result is well agreed with the estimation result in all operating range.

6. Conclusion

In this work, the aerodynamic and structural design procedure of a high efficiency 500W class

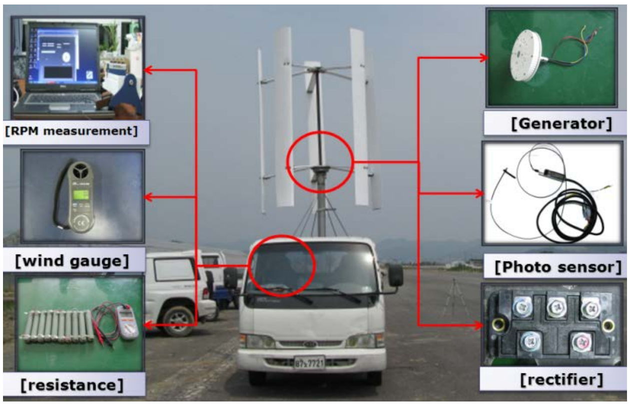

Fig.10. Test setup for performance test of prototype small VAWT

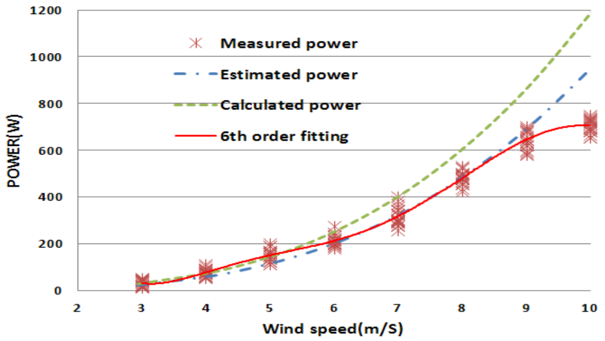

Fig.11. Comparison between test results and estimation results of electrical power produced by prototype small VAWT

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.

References

[1] J. Bang, “A Study on Design and Analysis of Small Wind Turbine System for High Efficiency and Light Weight”, PhD thesis, Chosun University, 2004.

[2] Changduk Kong, et al., Structural Design of Medium Scale Composite Wind Turbine Blade, 13th International Conference on Composite Materials (ICCM-13), pp.561. 2001.

[3] Changduk. Kong, et al.,” Investigation on Design for a 500W Wind Turbine Composite Blade considering Impact Damage”,Advanced Composite Material Vol.20, pp.105-123,2011.

[4] David M. Eggleston, et al., "Wind Turbine Engineering Design", Springer, 1987

[5] Desir Le Gourieres, "Wind Power Plants Theory and Design", Pergamon, 1982

[6] Jong-Wook Lee, et al., “Development of Small Lifting-Type Vertical-Axis Wind Turbine”, Proceedings of 2010-International Symposium, Yanbian University, 2010 .

[7] 2. IEC 1400-1, "Wind Turbine Generator System Part I, Safety Requirement, First Edition”, IEC, 1994.

[8] IEC 61400-02, “Part 2: Design requirements for small wind turbine”, IEC,2006

[9] Seoyoung Tech. http://www.evsmotor.co.kr/kor /afpm /afpm_list1.php