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Investigation on Design for a 500 W Wind Turbine Composite Blade Considering Impact Damage

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Abstract

Recently wind energy has been alternatively used as a renewable energy resource instead of the mostly used fossil fuels due to their increasing scarcity and environmental issues. This work is to propose a structural design and analysis procedure for development of a 500 W class small wind turbine system which will be applicable to domestic use at a relatively low speed region like Korea. Structural analysis including load case study and stress, deformation, buckling, vibration and fatigue estimation was performed. In addition, the blade should be safe from the impact damage due to FOD (foreign object damage) including bird strikes. MSC Dytran was used to analyze the bird strike phenomenon on the blade, and the applied method, Arbitrary Lagrangian–Eulerian, was evaluated by comparison with the previous study results. Finally, the structural test was carried out and its test results were compared with the estimated results for evaluation of the designed structure.

Keywords

Wind turbine blade, sandwich composite, structural and aerodynamic design, bird strike, impact analysis

1. Introduction

Recently, development of alternative energy sources instead of fossil fuels is very intensive. Among them, wind energy is especially a strong candidate due to unlimited natural energy resource that is clean; hence there are many studies on the wind turbine system actively being carried out in many countries. The current development trend of the wind turbine system is mostly in multi MW scales. Large scale wind turbine systems more than several MW need some special requirements, for instance, provision of a large wind turbine site, expensive manufacturing facilities and equipment. However, even though the small scale wind turbine system produces a relatively small amount of electric energy, it has been continuously de-

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veloped due to many advantages, such as easy manufacturing, low cost, relatively easy personnel handling and operation, etc.

Because most recent commercialized small scale wind turbine systems have been designed at the rated wind speed of more than 12 m/s, they show a great reduction of aerodynamic performance in a low wind speed region like Korea [1, 2]. Therefore, the proposed wind turbine system in this study has an appropriate rated wind speed, namely, 8 m/s.

This work shows an aerodynamic and structural design for the 500 W-class wind turbine system with a low noise factor for local area use. Material for this wind blade is the glass/epoxy that has good structural performance, such as long fatigue life and low cost [3]. Prototypes of the designed blades are manufactured by autoclave curing process. The structural test is performed to evaluate the structural design and analysis results with the real structural behaviour [3].

2. Blade Design

In the blade design, aerodynamic design is firstly performed according to design requirements, and its results are evaluated through performance analysis and test. The blade structure is designed according to structural design loads that are found from the load case analysis. For the structure analysis, the finite element method (FEM) is used as a means for investigating stresses, displacements, structural stability, etc. Also, the blade resonance is checked by eigenvalue analysis, which can obtain natural frequencies and modes. Using Spera's empirical equations and the S–N linear damage method [6], the required life-time of more than twenty years is examined. Finally, after manufacturing the prototype wind turbine blade, the structural experimental test is carried out. Figure 1 shows the blade design flow.

2.1. Blade Aerodynamic Design

Table 1 shows the wind turbine system design specification. For electric power generation, the direct drive AFPM (axial flux permanent magnet) generator is used for simplicity. Aerodynamic design results are expressed in Table 2, and blade aerodynamic configuration is shown in Fig. 2.

2.1.1. Blade Performance Analysis

Blade performance analysis is performed for investigation whether the aerodynamic design of blade is acceptable for the design target performance. For this analysis, the following equations are used, and the calculation flow is coded by a computer program. The power coefficient is calculated using the following equation [4]:

$$C_{\mathrm{p}} = \frac{2M \times \lambda_0}{\rho S V_1^2 R} \tag{1}$$

and the mechanical power and the electronic power are calculated as follows:

$$P = \frac{1}{2}\rho C_{\mathrm{p}} S V^3, \tag{2}$$

$$P_{\mathrm{e}} = \eta_{\mathrm{g}} P, \tag{3}$$

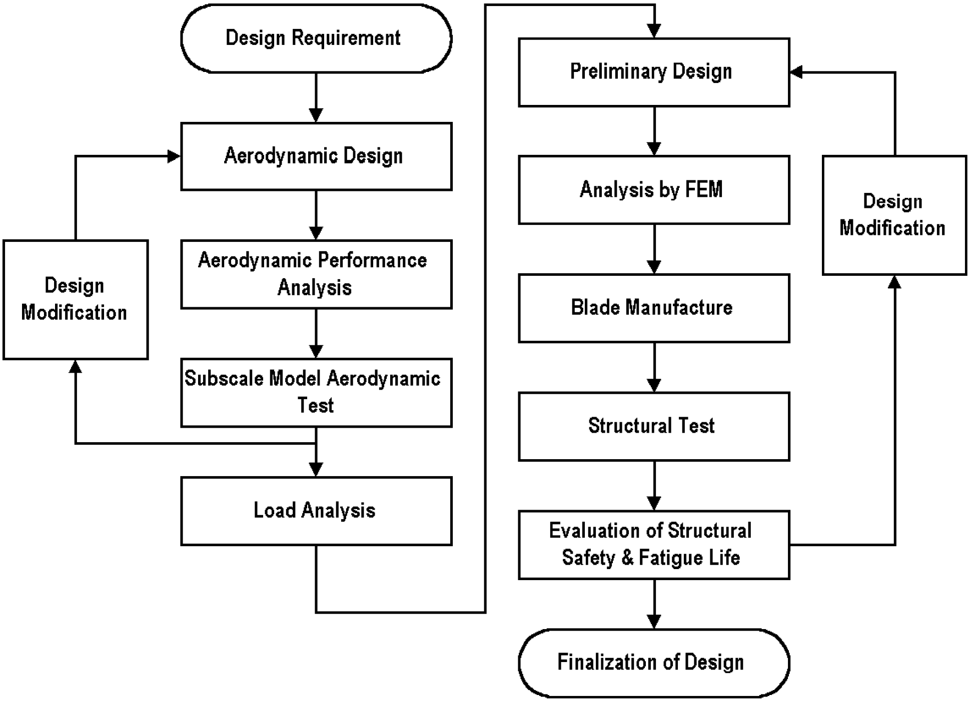

Figure 1. Flow of aerodynamic and structural design.

Table 1.
Design specification of 500 W wind turbine system

Type	Horizontal axis wind turbine system
Target rated power	500 W
Operation condition	Rated wind speed: 8 m/s cut-out wind speed: 20 m/s
Number of blades	Three
Blade material	Glass/epoxy composite

Table 2.
Aerodynamic design results of small wind turbine blade

Rated power	500 W
Rotor diameter	2.47 m
Blade root chord	149.208 mm
Blade tip chord	42.727 mm
Blade total twist	24.353 deg
Airfoil	DU 93-W-210

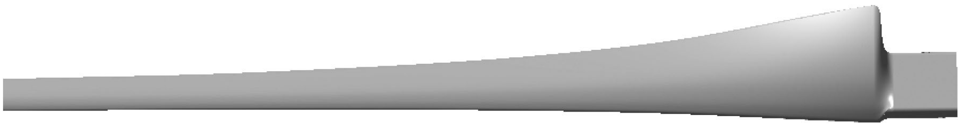

Figure 2. Designed aerodynamic configuration of blade.

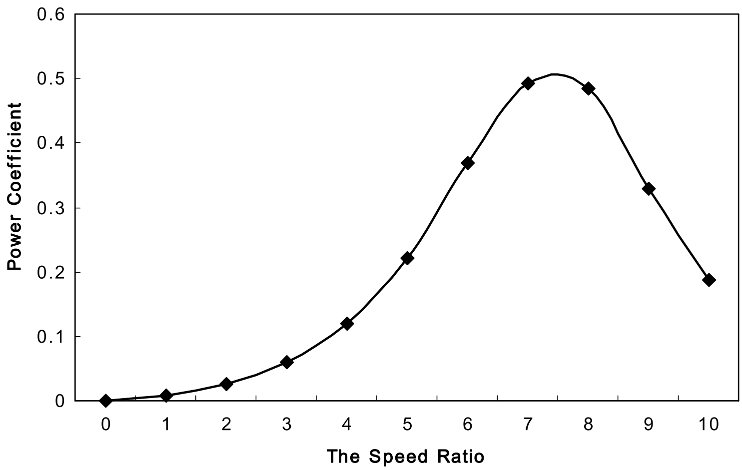

Figure 3. Power coefficient *vs* tip speed ratio.

where M is moment, R is radius, ρ is air density, V_1 is wind speed before passing blade, λ_0 is tip speed ratio and η_g is generator efficiency.

As a result of the performance analysis, the power coefficient for tip speed ratio of 7 is maximum, and it is decreased after tip speed ratio of 7. The power coefficient *versus* the tip speed ratio is shown as Fig. 3, and the calculated power according to wind speeds is shown as Fig. 4. Through this analysis, it is confirmed that the aerodynamic design is acceptable for the target rated performance because the blade power at the rated wind speed of 8 m/s is slightly higher than the target requirement power.

2.2. Blade Structural Design

2.2.1. Structural Design

The aerodynamic loads and the centrifugal forces are mainly acting on the blade. The centrifugal forces can be simply calculated from rotational speed, and the aerodynamic loads are calculated by aerodynamic coefficients in several load cases which are mentioned in Table 3. The shear force and bending loads can be defined by the normal force distribution acting on each section of the blade, and their variations depend on the wind speed and the angle of attack. Therefore, the bending loads must be calculated by consideration of operating conditions. According to the load analysis, the load case 2 is the most severe condition. Hence the structural design was performed on the basis of the load case 2. Figure 5 shows the flapwise

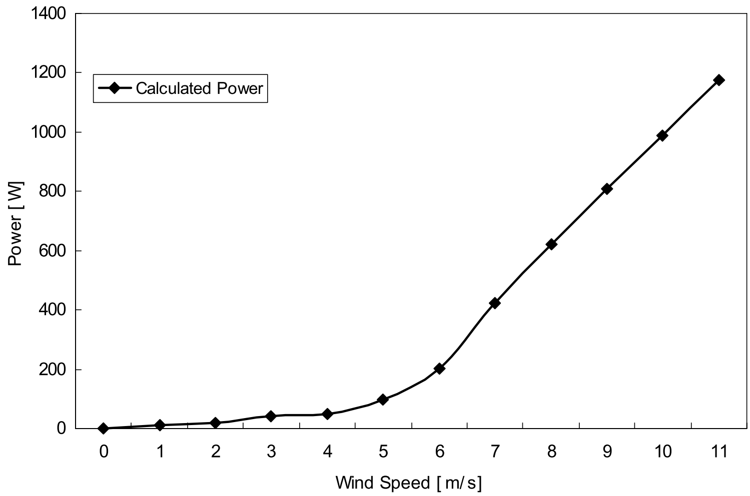

Figure 4. Calculated blade power at various wind speeds.

Table 3.
Design load cases for structural design

Load case	Case 1	Case 2	Case 3
Reference wind speed	8 m/s	20 m/s	55.0 m/s
Gust condition (±20 m/s, ±40°)	Without gust	With gust	Storm
Rotational speed	433 rpm	1069 rpm	Stop

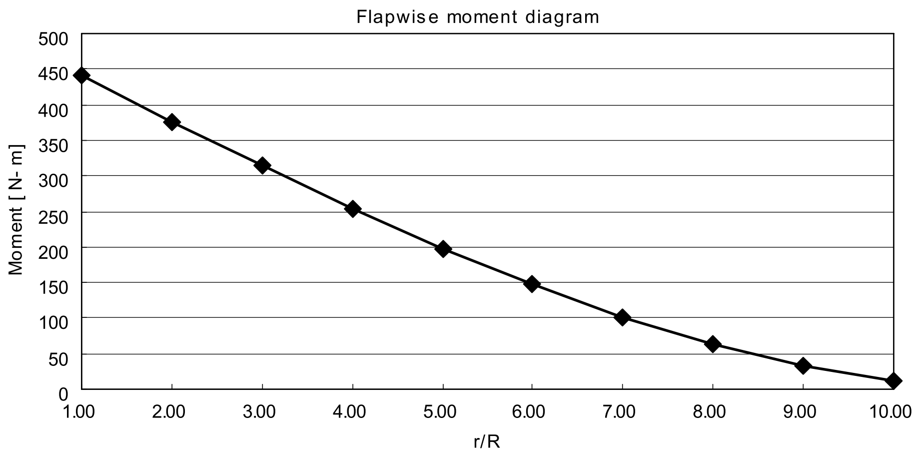

Figure 5. Flapwise bending moment diagram at load case 2.

moment distribution of the design load case 2. The blade adopts the skin/spar/foam sandwich type structure (see Fig. 6) [4].

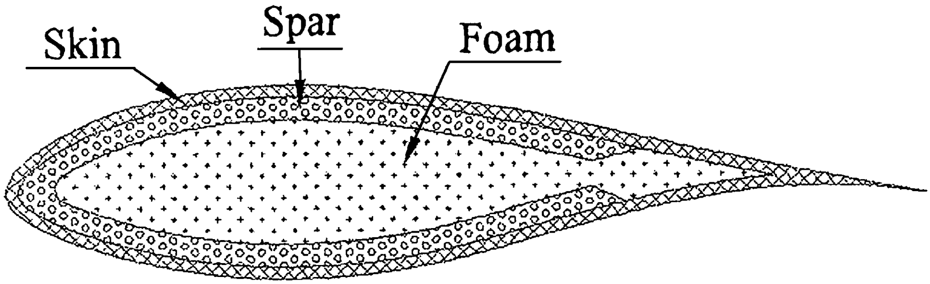

Figure 6. Section design model for blade structure.

Table 4.
Final structural design

Station (r/R)	Thickness (mm)	
	Upper surface	Lower surface
Root ∼0.1	Skin 1 t (4 ply)/spar 6.75 t (27 ply)	Skin 1 t (4 ply)/spar 6.75 t (27 ply)
0.1–0.2	Skin 1 t (4 ply)/spar 2.25 t (9 ply)	Skin 1 t (4 ply)/spar 2.25 t (9 ply)
0.2–0.3	Skin 1 t (4 ply)/spar 2.70 t (11 ply)	Skin 1 t (4 ply)/spar 2.70 t (11 ply)
0.3–0.4	Skin 1 t (4 ply)/spar 3.15 t (13 ply)	Skin 1 t (4 ply)/spar 3.15 t (13 ply)
0.4–0.5	Skin 1 t (4 ply)/spar 3.15 t (13 ply)	Skin 1 t (4 ply)/spar 3.15 t (13 ply)
0.5–0.6	Skin 1 t (4 ply)/spar 3.15 t (13 ply)	Skin 1 t (4 ply)/spar 3.15 t (13 ply)
0.6–0.7	Skin 1 t (4 ply)/spar 3.15 t (13 ply)	Skin 1 t (4 ply)/spar 3.15 t (13 ply)
0.7–0.8	Skin 1 t (4 ply)/spar 1.35 t (6 ply)	Skin 1 t (4 ply)/spar 1.35 t (6 ply)
0.8–0.9	Skin 1 t (4 ply)/spar 0.45 t (2 ply)	Skin 1 t (4 ply)/spar 0.45 t (2 ply)
0.9–1.0	Skin 1 t (4 ply)/spar 0.225 t (1 ply)	Skin 1 t (4 ply)/spar 0.225 t (1 ply)

By the preliminary composite design method, such as the netting rule and the rule of mixture that was proposed at the previous study [2], the initial structural design is carried out, and then the initial design feature is repeatedly modified by structural analysis using the finite element method. The bending force is endured by the spar flange layered by plies angle of 0°/90° and the torsion is endured by the upper and lower skins layered with the angle ply ±45°. Table 4 shows the final structural design results and Table 5 shows mechanical properties of composite materials used in the present blade design.

2.2.2. Structural Analysis

In order to perform the structural analysis, a finite element code, MSC Patran/Nastran, is used. In this analysis, the linear static stress analysis, the eigenvalue analysis and the buckling analysis are carried out. The intra-lamina 'Tsai–Wu' failure criterion is used to find the structural safety [5]. The boundary condition is assumed that the blade root is fixed. Distributed aerodynamic loads were applied on the blade along length direction and centrifugal body force also is applied. According to the analysis results, it is confirmed that the blade is safe from the point of view of strength. The linear static structural analysis results, the natural frequency

Table 5.
Mechanical properties of materials

	Glass/epoxy fabric	Polyurethane foam
E_{11} (N/mm^2)	10 500	60.86
E_{22} (N/mm^2)	10 500	59.86
G_{12} (N/mm^2)	1450	19.18
N	0.27	0.2
X_t (N/mm^2)	283.9	2.63
X_c (N/mm^2)	184.6	1.41
Y_t (N/mm^2)	283.9	2.49
Y_c (N/mm^2)	184.6	1.41
S (N/mm^2)	15.0	0.71
S (N/mm^2)	1.705	0.1197
Ply thickness (mm)	0.25	12.5

Table 6.
Structure analysis results

	Case 2
Max. stress (MPa)	
Ten.	68.7
Com.	25.5
Max. disp. (mm)	166
Natural frequency (Hz) (first flap mode)	22.034
Buckling load factor (first buckling mode)	1.2073

analysis result and buckling analysis result are presented in Table 6. Stress distribution and deformed blade shape at the load case 2 are shown in Figs 7 and 8. In this analysis, it is confirmed that the final structural design feature is safe from the point of view of strength, the deformed blade tip clearance requirement, buckling, resonance possibility and maximum strain requirement for fatigue life [6] (see Fig. 9 and Table 6).

2.2.3. *Fatigue Life Analysis*

Spera proposed empirical equations that were based on a set of test data that were broad enough in scope to include the sizes and types of rotors and towers. Fatigue life was estimated by using the S–N linear damage equation and Spera's empirical formulae [6]. Calculation of dynamic loads with these equations is essentially a process of interpolation rather than extrapolation. The flapwise and chordwise cyclic moments will be calculated. Table 7 shows calculation results for blade flap and chordwise cyclic bending moment (δM_y, δM_z), where n is the number of standard deviation ($n = 0$ for the 50th percentile load, $n = 1$ for the 84th percentile load, $n = 2$ for the 98th percentile load).

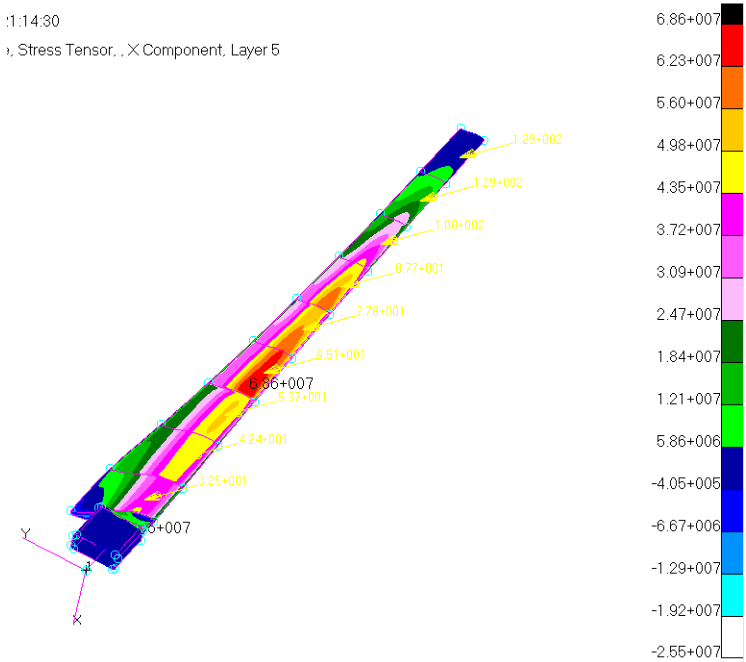

Figure 7. Stress distribution at load case 2. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

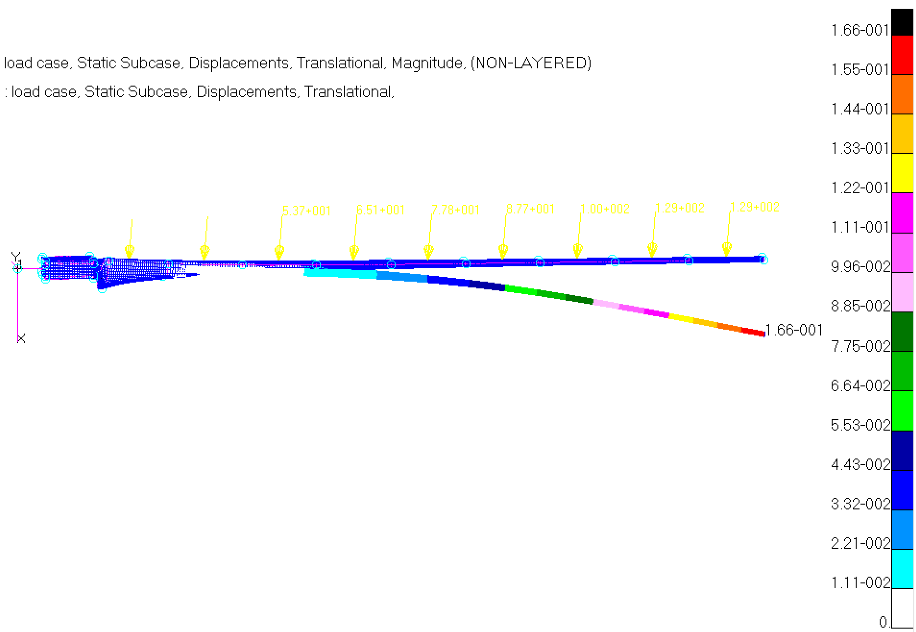

Figure 8. Deformed blade shape at load case 2. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

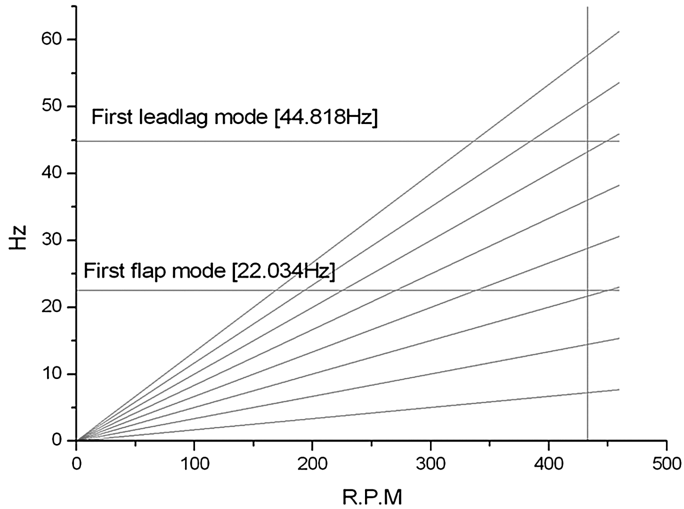

Figure 9. Campbell diagram for load case 2.

Table 7.
Results of fatigue load calculation

n	δM_y (Nm)	δM_z (Nm)
0	17.606	121.215
1	27.378	201.857
2	43.405	348.227

In order to perform comparison between the allowable fatigue stress and the estimated fatigue stress from the Spera's empirical formulae, the calculated maximum flap-wise and chord-wise bending moments in Table 7 are applied to the finite element model of the wind turbine rotor blade. According to the FEM analysis, the maximum tensile and compressive stresses are 39.4 MPa and 23.5 MPa, respectively. Figure 10 shows stress distribution at the spar layer under maximum fatigue load. Therefore, the designed wind turbine blade satisfies the design criteria for the fatigue life of 20 years.

2.2.4. Impact Damage Analysis due to Bird Strike

The fluid–structure interaction analysis has been used as a coupled analysis method for the bird strike impact analysis by most bird strike researchers. The coupled analysis means that considering effect by interaction in case fields are combined. The ALE (Arbitrary Lagrangian–Eulerian) coupling method provided by MSC/Dytran may calculate faster as well as use fewer meshes than other methods. However, the modeling of this method must be simple due to a restriction to share nodes between Euler meshes and Lagrange meshes shown in Fig. 11 [7].

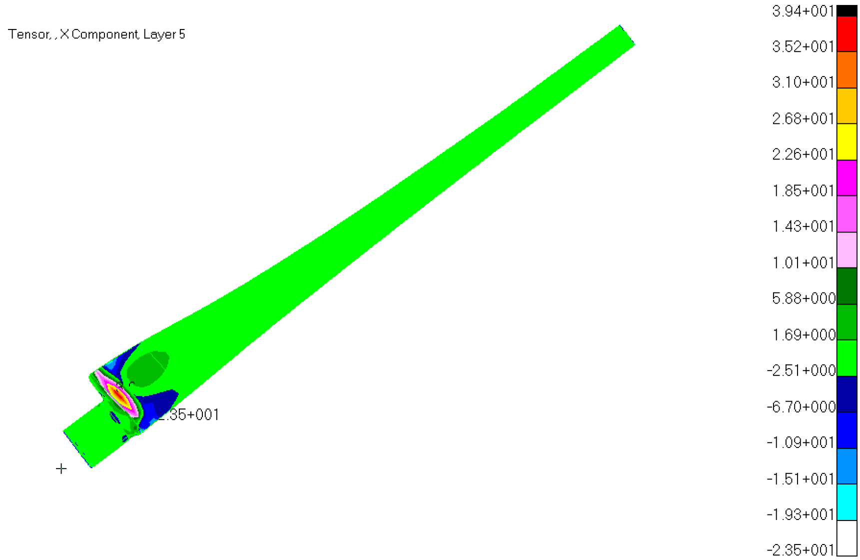

Figure 10. Stress analysis result for cyclic load. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

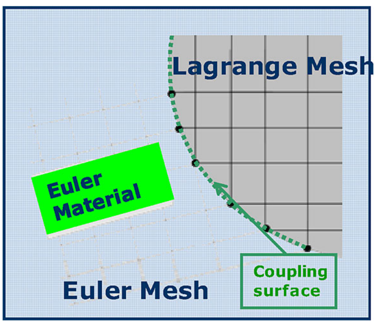

Figure 11. ALE coupling between Euler meshes and Lagrange meshes. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

In order to evaluate the bird strike analysis method using MSC/Dytran, a bird strike analysis example given by ref. [8] is solved using the proposed method. Generally, there are many kinds of birds in nature. However, chickens are mostly used for the bird strike test instead of wild birds because of their easy acquisition. In this work, a sparrow size bird is selected as the bird strike analysis model because the most likely bird strike size that can be expected in operation of the wind turbine blade is that of the sparrow. Figure 12 shows a simulated bird model for the analysis, and its mechanical properties are shown in Table 8 [8]. The hydrodynamic material is applied for the bird modeling, and 8 hex elements are used for Euler meshes. The bird model on a rigid plate has 197 m/s of impact speed, 1.814 kg of mass and 950 kg/m^3 of density.

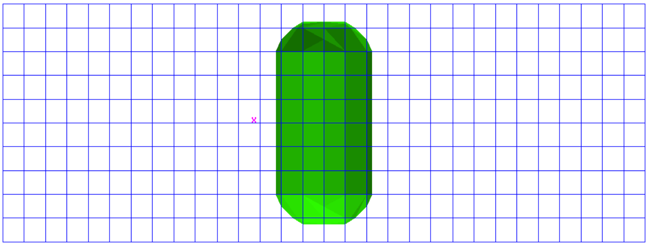

Figure 12. Simulated bird model for analysis. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

Table 8.
Properties of simulated bird

Material properties (bird)	
Density (kg/m^3)	950
Bulk modulus (Pa)	2.2×10^9
Diameter (m)	0.106
Length (m)	0.213
Mass (kg)	1.8144
Initial velocity (m/s)	197

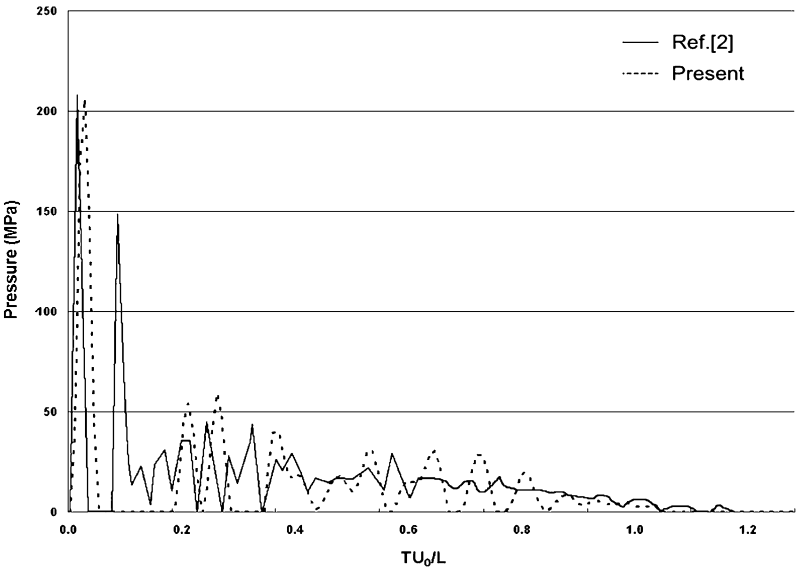

Figure 13. Comparison between present study and reference result [8].

The calculated surface pressure due to the bird impact is shown in Fig. 13. According to the analysis result, the highest pressure is generated at the initial impact moment, and then the pressure decreases greatly and suddenly. After that, the pres-

Table 9.
Properties of the blade and the bird

	Skin	Bird
Density (kg/m^3)	1780	950
Bulk modulus (Pa $\times$ 10^{-9})	6.55–11.14	2.2
Poisson's ratio	0.31–0.46	
Yield stress (Pa)	3.08×10^8	
Thickness (m)	0.00235–0.0085	
Diameter (m)		0.03
Length (m)		0.06
Mass (kg)		0.079
Initial velocity (m/s)		55

Table 10.
Bird strike analysis results

	Normal impact (55 m/s)
Max. stress	113 MPa
Max. displacement	184 mm

sure is sustained at low pressure during a relatively long time period. Through comparison with the reference result, it is confirmed that the results using the proposed method agree well with the reference results.

Hereafter the bird strike problem on the study wind turbine blade will be discussed. The bird strike may occur in rotating operation or at stationary condition in a storm. In this study, the storm condition of the wind speed of 55 m/s is considered for the blade bird strike because it is expected as a much more severe condition. Composite materials are assumed as quasi-isotropic materials for simplification. The material properties of the blade and the bird are considered as shown in Table 9. Table 10 shows the bird strike analysis results. Figures 14 and 15 show finite element models of the blade with Eulerian and Lagrangian meshes under ALE coupling. Blade impact pressure due to the bird strike is shown in Fig. 16, and stress and displacement distributions at the maximum impact pressure are shown in Figs 17 and 18, respectively.

3. Blade Manufacturing and Structural Test

3.1. Blade Manufacturing

In order to manufacture the prototype blade, the autoclave method is adopted. In the manufacturing process, the styrofoam mold is firstly manufactured using steel plate templates and hot wires for economic reasons, and then glass fabrics for the second

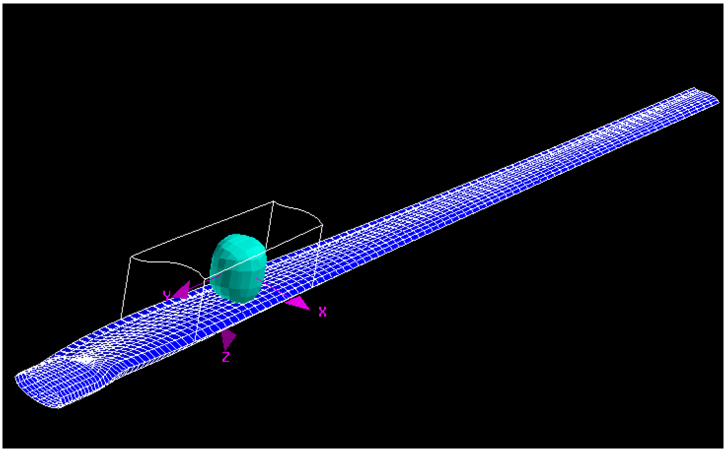

Figure 14. Bird strike modeling using FEM meshes. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

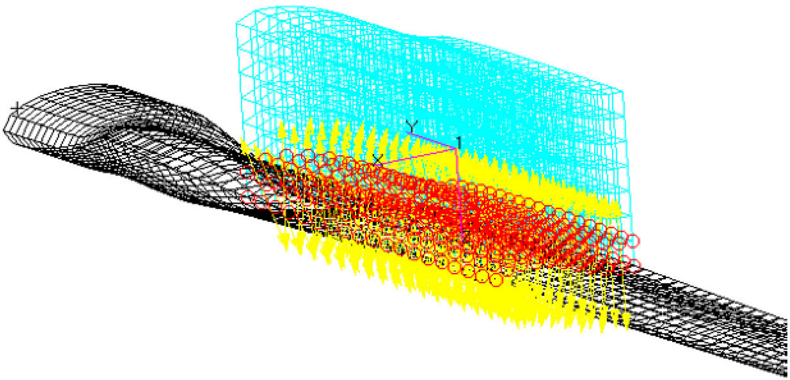

Figure 15. ALE coupling between Euler meshes and Lagrange meshes. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

mold are layered-up on the styrofoam mold with special coating. After that, the glass fabrics are layered-up on the second mold once again for the last mold, and then glass fabrics for the upper and lower surface skins of the blade are layered-up on the last mold according to the structural design result (see Fig. 19). The cured upper and lower surface skins are bonded by epoxy, then the urethane foam is injected into the space between upper and lower skins. After completely curing the blade, the proper coating is applied. The manufactured blade is shown in Fig. 20.

3.2. Structural Test

In order to evaluate the design results, the structural test must be performed, and then the test results must be compared with analysis results. The structural test of the prototype was conducted by the hydraulic structural test equipment which can adjust the applying load and its speed by 3 hydraulic cylinders and a controller. In

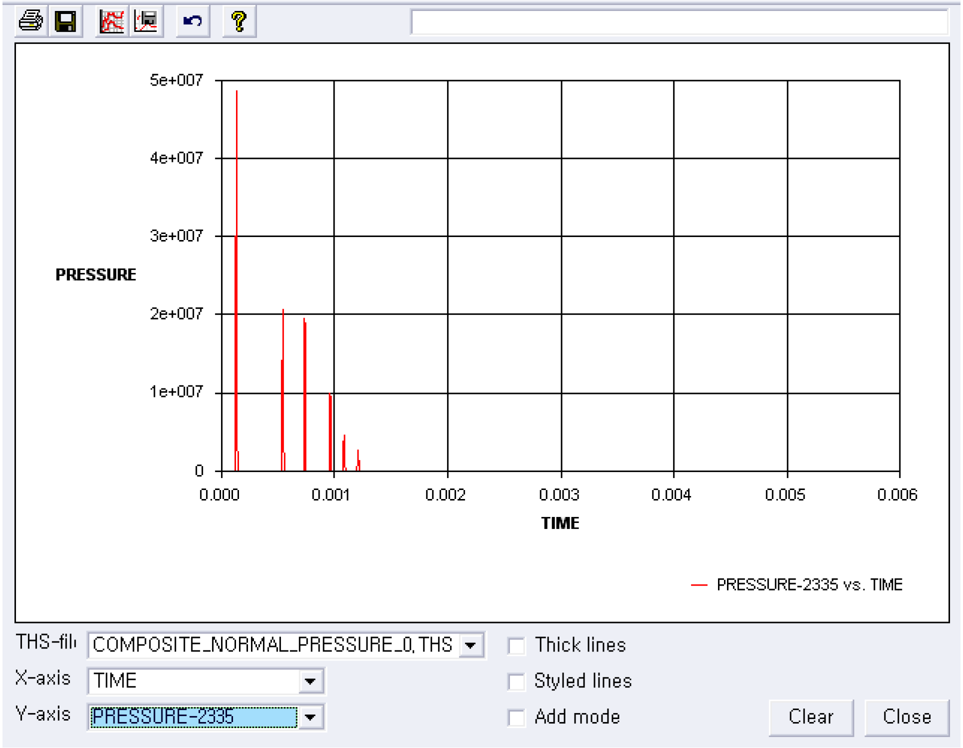

Figure 16. Impact pressure due to bird strike. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

this test, three point loads are applied for simplicity. Figure 21 shows that the blade is tested at the load case 2 by this method. Table 11 shows comparison between the analysis results and the test results. This comparison shows that analysis results are well agreed with the experimental results.

4. Blade Performance Test

In order to evaluate the target design performance, the blade performance test is performed with the test purpose tower. In the performance test, a special truck was used instead of the natural wind condition because the natural wind conditions around the laboratory could not be achieved. The simulated speed of the wind turbine system installed on the truck is from 3 to 11 m/s.

For the designed wind turbine performance test, a gearless generator 'SYG-A208-600-570' was used: this had the advantage of being simple because it was gearless, had easy blade mounting and low noise. Other test equipments are a rectifier, resistances for electrical loading, a multi-meter and a photo sensor and an instrument for measuring the blade rotational speed. Figure 22 shows the wind turbine system during the experimental performance test.

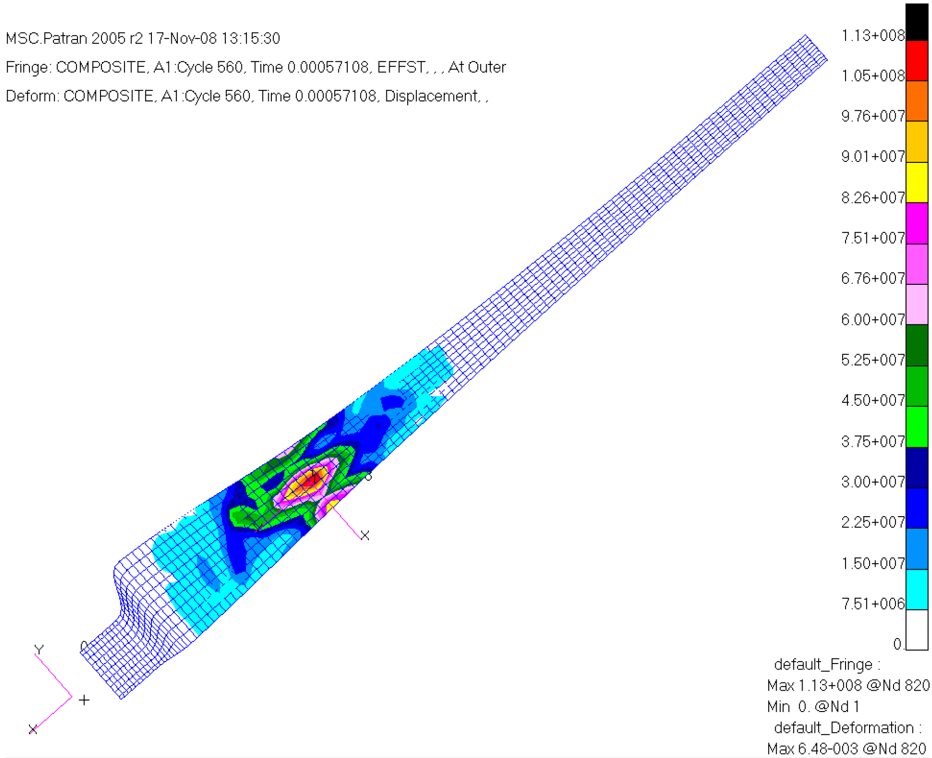

Figure 17. Stress distribution at maximum bird strike impact pressure. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

Figure 23 shows comparison between the estimated power and the experimental result of power. In the graph, it can be found that the wind turbine starts at around the wind speed of 4 m/s, and its power increases rapidly at 6 m/s. This comparison result reveals that the test result is in reasonable agreement with the estimated result in the whole operating range. Table 12 shows comparison between the test result and the analysis result at 8 m/s.

5. Conclusions

In this work, all design activities including aerodynamic and structural design, analysis and test of a 500 W-class wind turbine system were performed. Through the structural analyses, it was confirmed that the final structural design feature is safe from the point of view of strength, the deformed blade tip clearance requirement, buckling, resonance possibility and maximum strain requirement for fatigue life. In addition, it was found that the blade has enough safety to be able to withstand a bird strike in extreme storm conditions.

The prototype of the designed blade was manufactured, and the structural test was performed to evaluate the structural design and analysis results. Through the

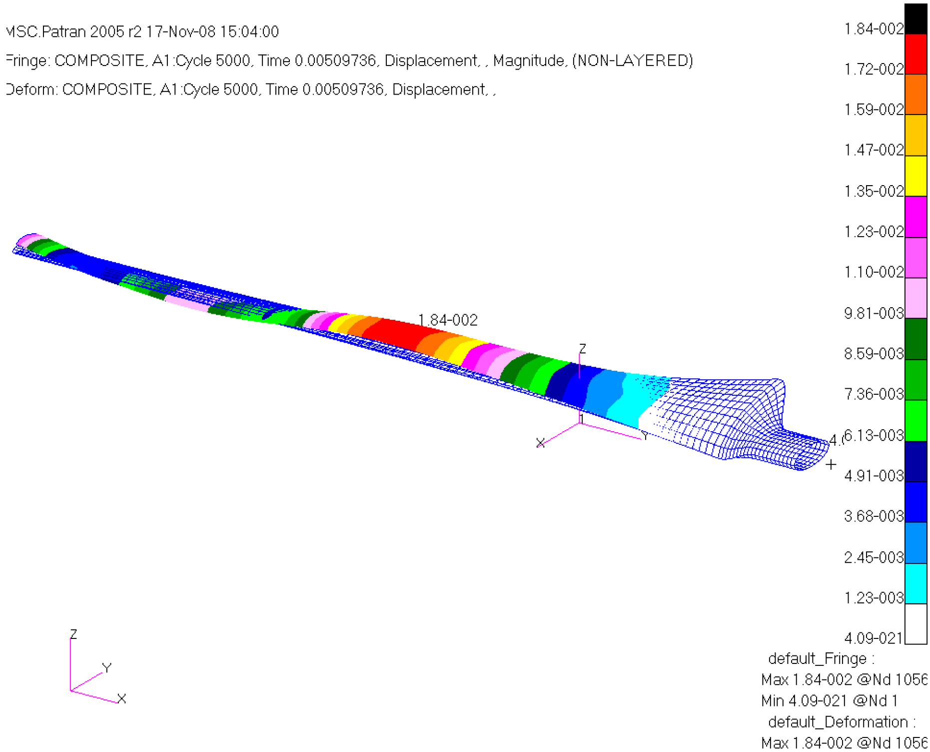

Figure 18. Displacement distribution at maximum bird strike impact pressure. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

Figure 19. Lay-up process on the mold. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

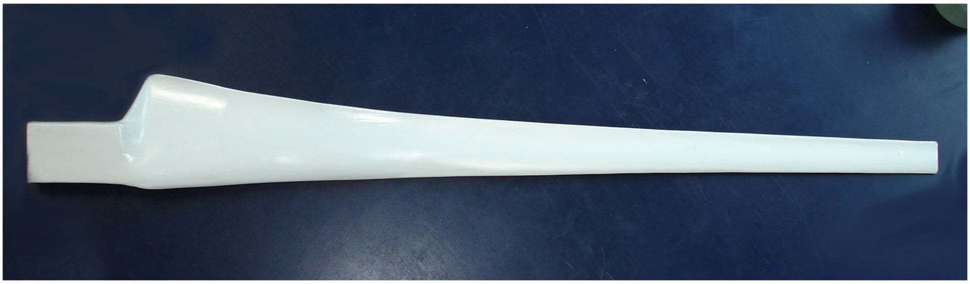

Figure 20. First blade prototype. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

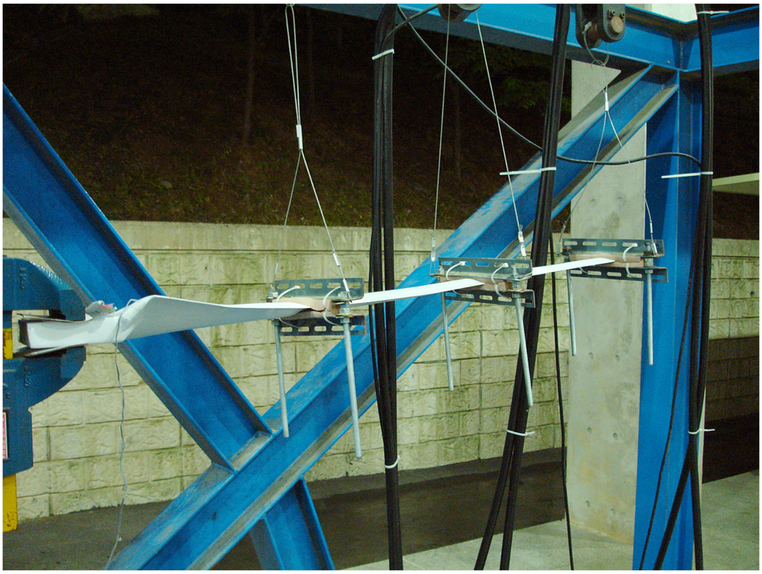

Figure 21. Structural test of prototype blade. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

Table 11.
Comparison between the static analysis results and the test results

Item	Analysis result	Test result
Stress (MPa)	29.1	27.4
Tip deflection (mm)	166	152

evaluation, it was found that structural analysis results agreed well with the experimental results.

Finally, in order to evaluate the wind turbine system including the designed blades and the gearless generator, the performance test was performed using a truck

Figure 22. Wind turbine system during experimental performance test. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

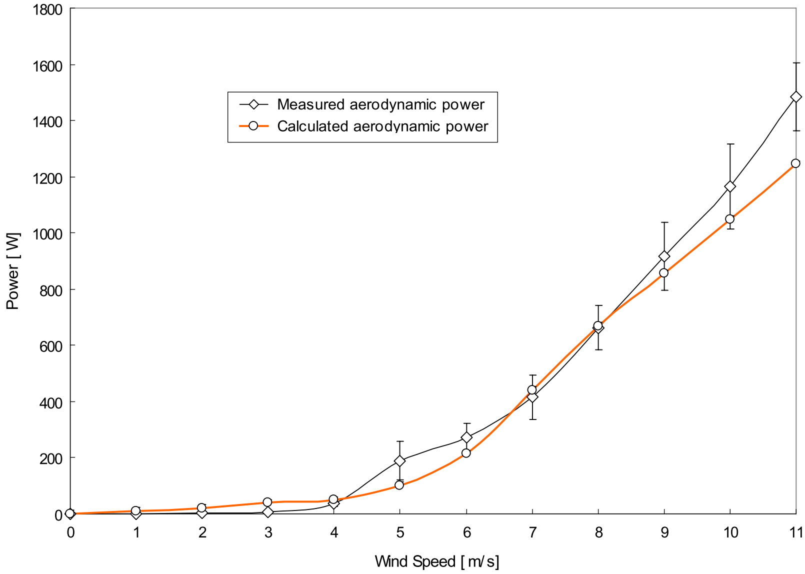

Figure 23. Comparison between estimation and the experimental test result of power. This figure is published in color on http://www.ingentaconnect.com/content/vsp/acm

to simulate the natural wind speed and other measuring equipments. According to the performance evaluation result, the estimated performance agreed well with the experimental test results in all operating ranges.

Table 12.
Comparison between test result and analysis result at 8 m/s

	Analysis result	Test result (average)
Power (at 8 m/s)	669 W	663 W

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