STRUCTURAL DESIGN AND ANALYSIS OF ELLIPTIC CYCLOCOPTER ROTOR BLADES

In Seong Hwang[1], Seung Yong Min[1], Choong Hee Lee[1], Yun Han Lee[1] and Seung Jo Kim[12]
[1]Seoul National University, Korea
[2]Flight Vehicle Research Center, Korea

Keywords: *Cyclocopter, Elliptic blade, Structural design and analysis, Composite rotor blades*

Abstract

A cyclocopter propelled by the cycloidal blade system is a new concept of VTOL vehicle which has excellent hovering characteristics and low speed forward flight capability. The cycloidal blade system, which can be described as a horizontal rotary wing, offers powerful thrust levels and a unique ability to change the direction and the magnitude of the thrust almost instantly. In this paper, rotor blades of unmanned cyclocopter with 4 rotors are designed and structural analysis is carried out. Elliptical blades are fabricated of carbon and glass composite materials to reduce relatively high centrifugal force. Rotor design variables are determined through CFD analysis, and structural analysis by MSC.NASTRAN is carried out for the designed characteristics. Parametric study of composite rotor hub arm is carried out about the dynamic mode behaviors according to the variations of composite lay-up and joint condition.

1 Introduction

Cyclocopter is a new rotary-wing aircraft generating thrust by blades which are rotating about horizontal axis [1]. It has high maneuverability including vertical take-off and landing, hovering and low speed forward flight by cyclic pitch variation of rotating blades that offer a unique ability to change the magnitude and the direction of thrust perpendicular to rotating axis, almost instantly. It has also good characteristics of low noise level because the rotating speed of blade tip is low comparing with helicopter blade.

Figure 1 shows the whole view of designed cyclocopter. Four rotors are located in front and rear and rotate in opposite direction to compensate the anti-torque [2]. Each rotor consists of four elliptical blades and they are supported at mid-position. It is powered by DC brushless motors and Li-Po batteries. Control devices are equipped in each rotor to control the blades pitch angles independently.

In this paper, structural design and analysis of cyclocopter rotor blades are carried out. Cyclocopter rotor blades are subjected to centrifugal and aerodynamic loading, and the relatively high centrifugal force causes bending moment in blades. In blade design, increasing stiffness usually require more weight and increased weight means more centrifugal force, therefore blades need to be manufactured by advanced composite materials that have good strength-to-weight ratio. In addition to static analysis, rotor dynamic analysis is carried out to avoid resonance due to coalescence between modal frequencies and forcing frequencies during rotor rotation [3].

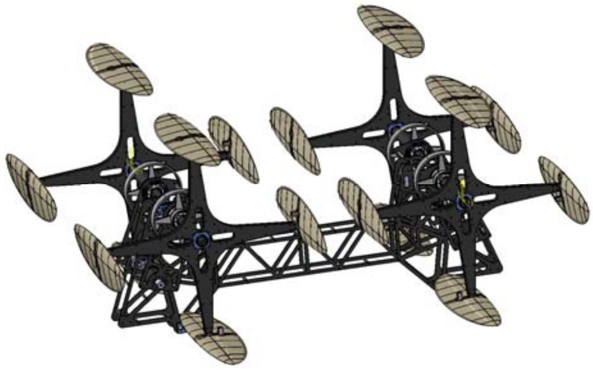

Fig. 1. Designed cyclocopter

2 Rotor Design

Cyclocopter is propelled by the cycloidal blade system. The characteristics of the rotating blades are close to those of fixed wing aircraft, because the blades are parallel to the rotating shaft. Designed cyclocopter shown in Fig. 1 has 16 blades, so it is important to reduce drag of each blade. Therefore elliptic shape blade is adopted based on the Prandtl's classical lifting line theory to minimize the induced drag and to reduce the required power of cyclocopter rotor system [4].

The geometric parameters of cyclocopter rotor blade system are designed through CFD analysis. Design variables are span and chord length, rotating speed, pitch angle, rotor radius, etc. and those are determined through 2D CFD analysis and the results are verified through 3D CFD analysis. The same airfoil and blade surface area are used for 2D and 3D model. Required power of four rotors is limited to 3 hp, and the goal of design for thrust is 15 kgf when total weight of the aircraft is estimated to 11 kg.

For efficient parametric study, PCL (Patran Command Language) of MSC.PATRAN is used to generate CFD mesh [5]. Design variables considered in this mesh generation are rotor radius, blade chord length, rotating speed and maximum pitch angle. The commercial software, STAR-CD is used for CFD analysis, and moving mesh method is adopted to simulate rotor blades which have periodic pitch angle variation [6]. Figure 2 shows generated mesh around the rotor.

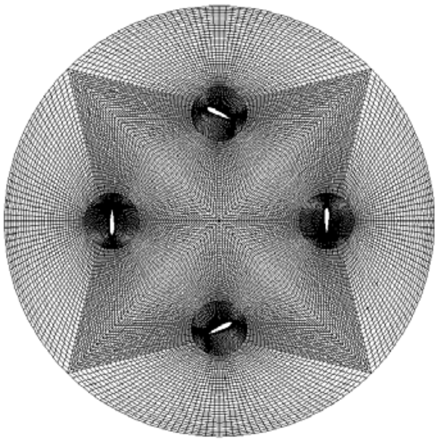

Fig. 2. Generated 2D mesh around the rotor

The elliptical shape of the blade is shown in Fig. 3. The dashed rectangular represents the model used in 2D CFD analysis. The elliptical geometry is determined based on the result of 2D CFD analysis. The ratio of minor axes is 1 to 3 to coincide with 25% point of chord which is the aerodynamic center of NACA0018 airfoil. The span length is 0.5 m and the largest chord length at the central position is 0.105 m.

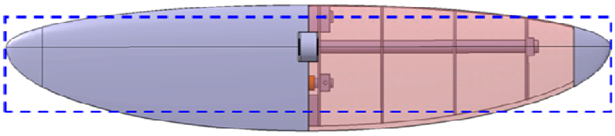

Fig. 3. Planform of the blade

Table 1 shows designed parameters obtained from CFD analysis. When the rotor rotates in 1130 rpm, it produces 16.9 kgf at 3 hp. Figure 4 shows thrust variation according to rotating speed, it is proportional to square value. Figure 5 shows required power variation which is proportional to cube of rotating speed.

Table 1. Designed parameters of cyclocopter rotor

Number of rotors	4
Number of blades (for 1 rotor)	4
Airfoil	NACA0018
Rotor radius	0.25m
Blade span length	0.5m
Blade chord length (largest value)	0.105m
Thrust	16.9 kgf
Required power	3 hp

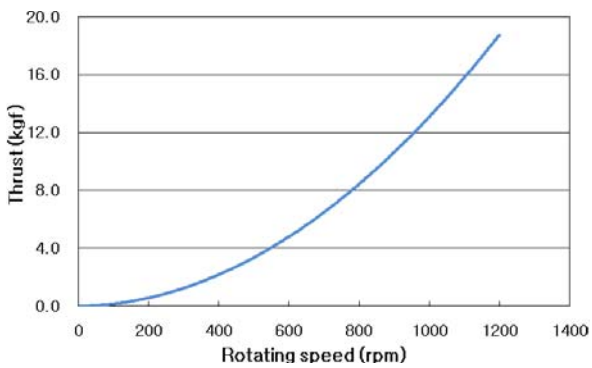

Fig. 4. Thrust variation according to rotating speed

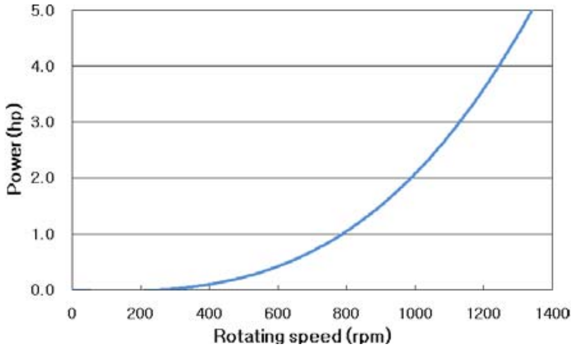

Fig. 5. Power variation according to rotating speed

Figure 6 shows the section view of blade at central position in span direction. The spar is located at 33% position from the leading edge, and the control linkage is connected at 62% position. The center of gravity is coincident with the spar to minimize the force on the control point. Figure 7 shows the assembled picture of rotor blade. The circular spar made in carbon composite material is main structure of supporting loading, and blade shape is formed by skin and rib. Blade is connected to hub arm at pivot point through two ball bearings. The center rib is reinforced by woven glass composite to endure the highest stress value.

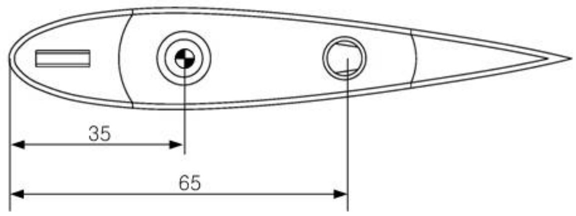

Fig. 6. The section view of blade

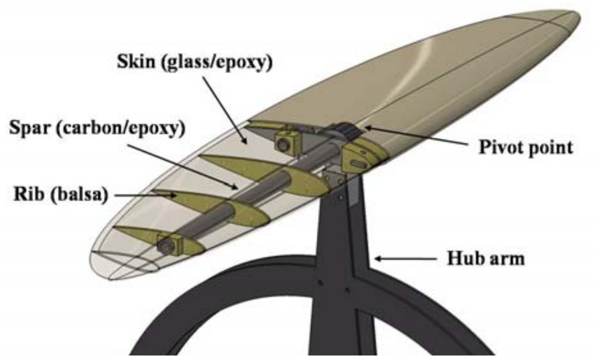

Fig. 7. Assembled picture of rotor blade

3 Structural Analyses of the Rotor Blades

Structural analyses are carried out for the designed cyclocopter rotor system. Cyclocopter rotor blades are loaded by lift, drag and centrifugal force during rotation. Among these loads, centrifugal force is relatively high comparing with other aerodynamic forces, so it should be considered above others. Forces acted on the blades causes bending moment which makes the blades deform and stress concentration could be occurred at the central position of the blade which is connected to the hub arm. Blade deformation makes the aerodynamic performance low, and stress concentration causes blade destruction. Therefore it is important to design the blade of enough strength with light weight. Blades are designed and manufactured in composite material which has good strength-to-weight ratio. MSC.NASTRAN is used for structural analyses of the designed rotor blades system [7].

Figure 8 shows the finite element modeling of the rotor blades. The mesh is generated by MSC.PATRAN. Spar and control linkage are modeled by 1D beam (bar2) element, and other parts are modeled by 2D shell (quad4) element. Boundary condition of pitching motion free is applied to between hub arm and spar and control parts using MPC (Multi Point Constraints).

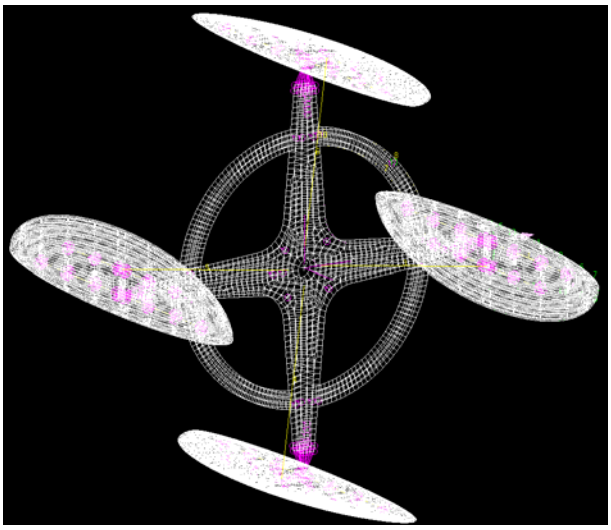

Fig. 8. FE mesh of cyclocopter rotor

Static analysis is carried out for the cyclocopter rotor blades rotating in 1200rpm by nonlinear static solution method (sol 106) of MSC.NASTRAN. Figure 9 shows the analytic results of displacement. The maximum displacement value is 3.26 mm at the blade tip, and circular carbon spar is deformed by

1.48 mm at the same analysis condition. The maximum stress is occurred at the middle position of spar which is connected with hub arm, and that is 115 MPa. At the same condition, the maximum stress on the blade skin is 34.5 MPa. All these values are acceptable, so the designed rotor blade is statically safe.

Cyclocopter rotor blade system is vibrated during rotation, and dynamic instability should be avoided by considering resonance which means the coincidence between the natural frequency and the forcing frequency. Dynamic analysis is carried out, and Fig. 10 shows the 1st mode shape. It is occurred by twist motion between the rigid blade and the rigid hub arm. The lowest four mode shapes are similar to this motion. Especially the 2nd eigenvalue and the 3rd eigenvalue is the same. These mode shapes are caused by one point joint structure connecting the stiff blade with the stiff hub arm. The frequencies are 36.1Hz, 39.0Hz and 41.2Hz. The next four modes are occurred by deformation of hub arm as shown at Fig. 11. The mode frequency of blade deformation is relatively high, so vibration of blade itself does not affect to the dynamic instability.

4 Parametric Analysis of the Rotor Hub Arm

Parametric analysis of cyclocopter rotor vibration mode is carried out. Rotor hub arm consists of carbon composite material, and mode shape and frequency of 15 laminates are calculated according to the lay-up variation. Joint condition of two plates is also analysis parameter. Carbon composite lay-up of $[(0/90)_7/0]$ is applied at the analysis of the former section, and the cases of $[(45/-45)_7/45]$ and [90/0/45/-45/90/45/-45/0/45/-45/90/45/-45/0/90] are added for the analysis. Figure 12 shows joint conditions for the parametric study. The points 1,2 and 6 are selected for the analysis of the former section.

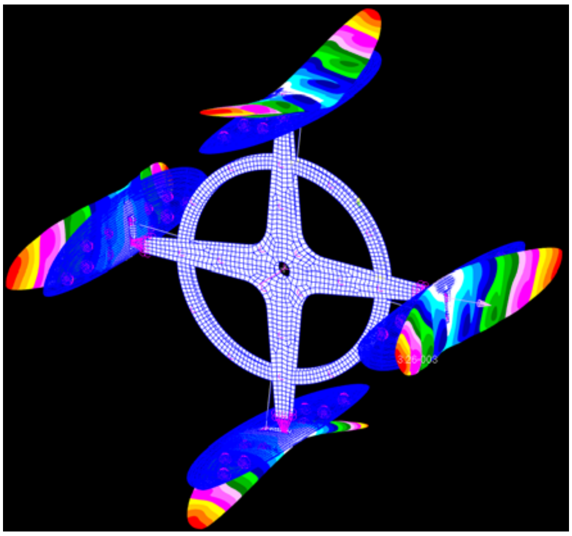

Fig. 9. Displacement distribution

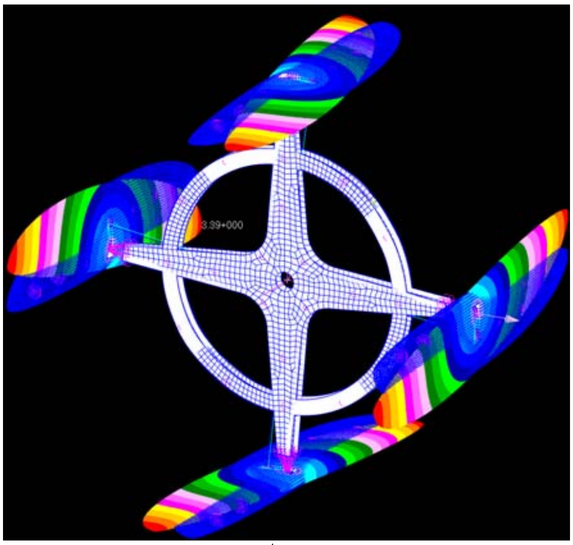

Fig. 10. 1st mode shape

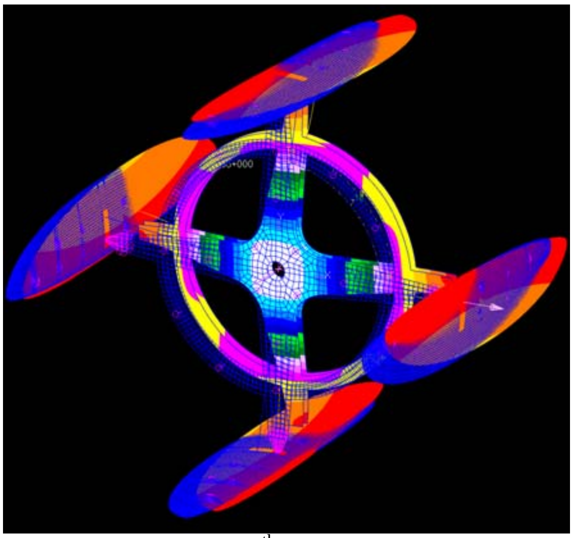

Fig. 11. 4th mode shape

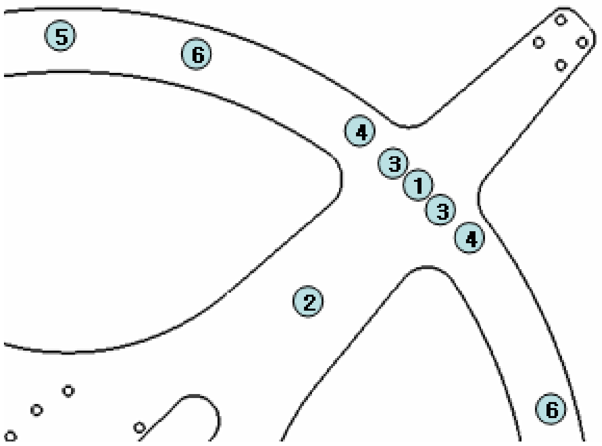

Fig. 12. Joint positions of hub arm

Table 2, 3 and 4 are the results of parametric analysis. Mode a in tables represents the twist motion between the rigid blade and the rigid hub arm as shown at Fig. 10. Mode b is the deformation shape of hub arm as shown at Fig. 11. Mode a/2 and b/2 mean that half of blades or half of hub arm are deformed instead of whole rotor blades deformation mode shapes. In this case, two mode shapes are occurred at the same time, and some cases shows that mode a and b are occurred at the same frequency. The first mode frequencies of mode a and b are also represented in tables.

The results shows that at the same joint conditions of joining 1,2 and 6 positions, the lay-up of the third case has the 1st frequency of 30% higher than that of the former section value. The maximum value is 49.7 Hz by adding the point 4 to the result.

Table 2. Mode analysis of lay-up $[(0/90)_7/0]$

fixed point	st mode freq	mode	a–mode freq.		b–mode freq.	
1,5	31.48	a	31.48	1st	38.598	4th
1,6	34.823	a	34.823	1st	39.664	4th
3,5	33.285	a	33.285	1st	40.973	4th
3,6	36.438	a	36.438	1st	42.181	5th
4,5	34.02	a	34.02	1st	38.408	4th
4,6	35.546	b	40.199	4th	35.546	1st
1,2,5	32.389	a	32.389	1st	47.351	5th
1,2,6	36.041	a	36.041	1st	47.89	5th
2,3,5	33.87	a	33.87	1st	50.191	5th
2,3,6	37.267	a	37.267	1st	50.682	5th
2,4,5	35.199	a	35.199	1st	46.252	5th
2,4,6	37.983	a	37.983	1st	46.75	5th
1,2,4,5	35.762	a	35.762	1st	50.128	5th
1,2,4,6	35.525	a	35.525	1st	50.587	5th

Table 3. Mode analysis of lay-up $[(45/-45)_7/45]$

fixed point	st mode freq	mode	a–mode freq.		b–mode freq.	
1,5	27.2	b	35.344	5th	27.2	1st
1,6	28.083	b	40.446	5th	28.083	1st
3,5	28.38	b	36.195	5th	28.38	1st
3,6	29.042	b	41.263	5th	29.042	1st
4,5	28.378	b	38.727	5th	28.378	1st
4,6	28.908	b	43.936	5th	28.908	1st
1,2,5	32.507	a/2,b/2	33.794	3rd	38.833	5th
1,2,6	32.704	a/2,b/2	41.887	5th	36.999	3rd
2,3,5	33.468	a/2,b/2	34.704	3rd	40.202	5th
2,3,6	33.565	a/2,b/2	42.853	5th	37.991	3rd
2,4,5	33.148	a/2,b/2	36.203	3rd	36.203	3rd
2,4,6	33.25	a/2,b/2	44.761	5th	38.155	3rd
1,2,4,5	34.042	a/2,b/2	36.873	3rd	41.792	5th
1,2,4,6	34.106	a/2,b/2	45.118	5th	39.301	3th

Table 4. Mode analysis of lay-up [90/0/45/-45/90/45/-45/0/45/-45/90/45/-45/0/90]

fixed point	st mode freq	mode	a–mode freq.		b–mode freq.	
1,5	37.545	b	43.779	4th	37.545	1st
1,6	38.516	b	50.605	4th	38.516	1st
3,5	39.819	b	46.179	3rd	39.819	1st
3,6	40.672	b	52.785	4th	40.672	1st
4,5	37.829	b	48.88	4th	37.829	1st
4,6	38.204	b	55.08	4th	38.204	1st
1,2,5	42.157	a	42.157	1st	49.905	3rd
1,2,6	47.079	a,b	47.079	1st	47.079	1st
2,3,5	44.285	a	44.285	1st	52.672	4th
2,3,6	49.274	a,b	49.274	1st	49.274	1st
2,4,5	45.81	a,b	45.81	1st	45.81	1st
2,4,6	47.687	a/2,b/2	56.06	1st	47.821	2nd
1,2,4,5	47.273	a	47.273	1st	53.758	4th
1,2,4,6	49.711	a/2,b/2	57.264	4th	50.414	2nd

5 Blade Manufacturing

Designed blades are manufactured through the process as shown at Fig. 13. All geometric shapes of blade master, mold, rib, skin and assembly are modeled by CATIA. Aluminum molds, MC-nylon assembling jigs and balsa ribs are made by CNC milling machine. Especially blade molds which are the most important parts of blade manufacturing are manufactured through three phase process. After waxing for easy separation between the blade skin and the mold, urethane paint is sprayed on the mold for the blade skin laminate. Two kinds of glass/epoxy composite are laminated on the painted mold, and this skin is assembled with balsa rib, carbon spar and glass roving to complete a blade. Figure 14 shows the manufacturing and assembling steps and a completed blade.

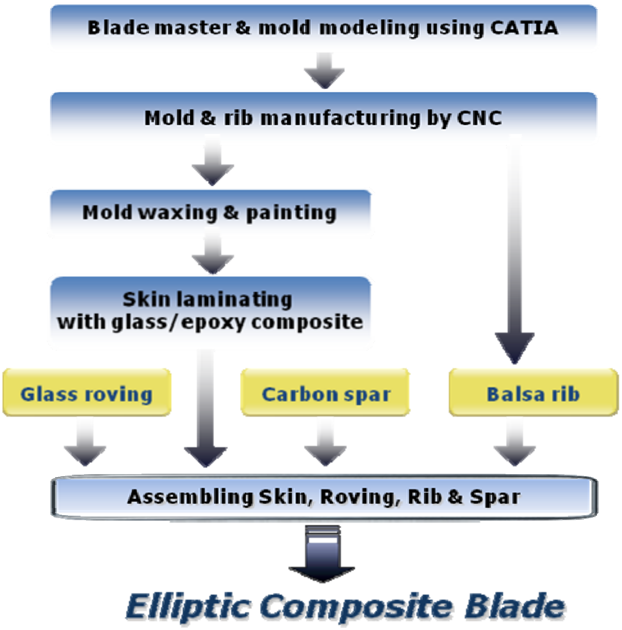

Fig. 13. Blade manufacturing process

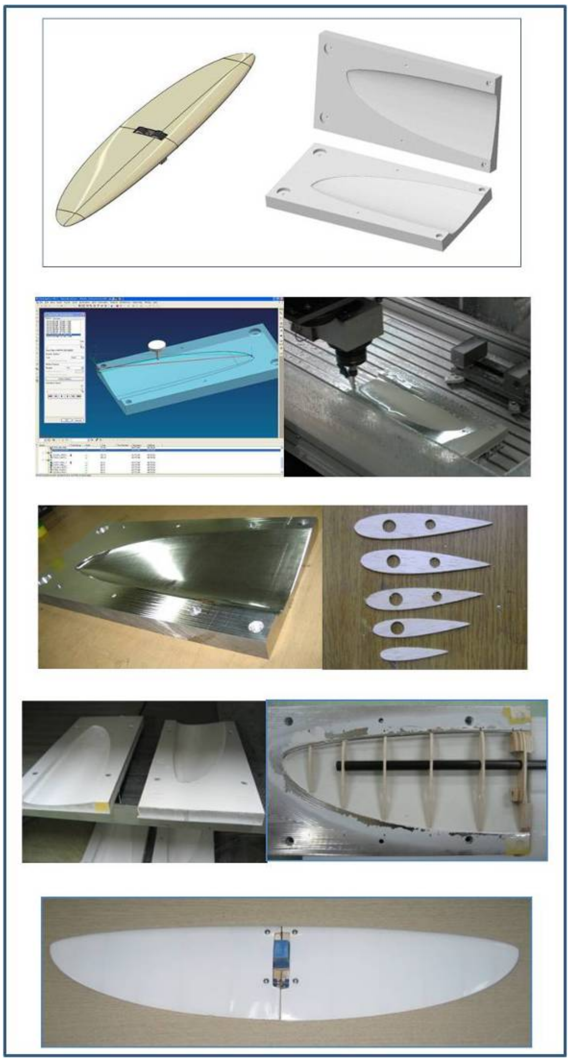

Fig. 14. Blade manufacturing pictures

6 Conclusions

This paper investigates structural design and analysis of cyclocopter rotor blades system. Elliptic blades and hub arms are manufactured in carbon and glass composite materials. Static and dynamic analyses by MSC.NASTRAN are carried out for the designed rotor. Maximum displacement and stress of blade are acceptable values. Dynamic mode frequencies and shapes are obtained for the composite rotor blades, and parametric study of composite rotor hub arm is carried out about the dynamic mode behaviors according to the variations of composite lay-up and joint condition. Elliptic composite blade is manufactured using CATIA, CNC milling machine and composite lay-up.

Acknowledgements

This research is partially supported by the Brain Korea 21 Project in 2007 and the National Research Laboratory Program.

References

[1] Yun C.Y., “*A New Vertical Take-off and Landing Air craft with Cycloidal Blades System: Cyclocopter*,” Ph. D thesis, Seoul National University, 2004.

[2] Hwang I.S., Hwang C.S., Min S.Y., Jeong I.O., Lee C.H., Lee Y.H. and Kim S.J., “Design and Testing of VTOL UAV Cyclocopter with 4 Rotors”, *American Helicopter Society 62nd Annual Forum*, Phoenix, AZ, May 9-11, 2006.

[3] Newman S., “*The Foundations of Helicopter Flight*,” Edward Arnold, 1994.

[4] Anderson, J.D., “*Fundamentals of Aerodynamics*,” 2nd ed. McGraw-Hill, 1991.

[5] MSC.PATRAN 2003 PCL Reference Guide, MSC Software

[6] STAR-CD Version 3.20 User Guide, CD-adapco group, 2004.

[7] MSC.NASTRAN User’s Manual, MSC Software