Efficiency Improvement of a New Vertical Axis Wind Turbine by Individual Active Control of Blade Motion

In Seong Hwang, Seung Yong Min, In Oh Jeong, Yun Han Lee and Seung Jo Kim*

School of Mechanical & Aerospace Engineering, Seoul National University
San 56-1, Sillim-dong, Gwanak-gu, Seoul, 151-742, Korea.

ABSTRACT

In this paper, a research for the performance improvement of the straight-bladed vertical axis wind turbine is described. To improve the performance of the power generation system, which consists of several blades rotating about axis in parallel direction, the cycloidal blade system and the individual active blade control system are adopted, respectively. Both methods are variable pitch system. For cycloidal wind turbine, aerodynamic analysis is carried out by changing pitch angle and phase angle based on the cycloidal motion according to the change of wind speed and wind direction, and control mechanism using the cycloidal blade system is realized for 1kw class wind turbine. By this method, electrical power is generated about 30% higher than wind turbine using fixed pitch angle method. And for more efficient wind turbine, individual pitch angle control of each blade is studied. By maximizing the tangential force in each rotating blade at the specific rotating position, optimal pitch angle variation is obtained. And several airfoil shapes of NACA 4-digit and NACA 6-series are studied. Aerodynamic analysis shows performance improvement of 60%. To realize this motion, sensing and actuating system is designed.

Keyword: Vertical Axis Wind Turbine, Individual active control, Cycloidal blade system, Straight blade

INTRODUCTION

The need for development of renewable energy has been increasing because of the continuing oil crisis and environmental pollution, and one of these resources is wind energy. The survey on demand in USA and Europe showed that about 12% of the global power generation will be substituted with wind power by 2020. In Denmark, wind power covers almost 20% of their power consumption. In China, wind energy occupies only 0.1% now, but they are developing commercial wind power system by cooperation with advanced countries such as Spain. They are also developing small scale home use wind power system for the people in the western regions that are insufficient in electrical energy. Figure 1 shows the growing world wind capacity released by the Global Wind Energy Council – GWEC.

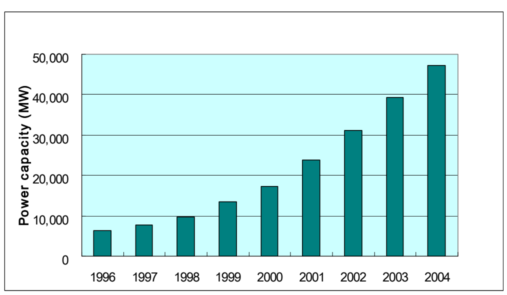


Fig. 1 Global wind power capacity

* Professor, Corresponding author, e-mail: sjkim@snu.ac.kr; phone: +82-2-880-7388; fax: +82-2-887-2662
Director, Flight Vehicle Research Center

Figure 2 shows two kinds of wind turbine according to the type of rotating axis: HAWT (Horizontal Axis Wind Turbine) and VAWT (Vertical Axis Wind Turbine). HAWT has a rotating axis parallel to the wind direction, and it is more popular these days than VAWT. On the other hand, VAWT's rotating axis is vertical to the wind direction, and there are two types of VAWT: Savonius type using drag force and Darrieus type using lift force. VAWT is independent of wind direction, easy to maintain, and has low noise level. Some VAWTs adopted variable pitch system to improve efficiency [1].

Fig. 2 Classification of wind turbine according to rotating axis type

In this paper, new VAWT that actively responds to the change of wind direction and wind speed is presented. It has straight blades which are easy to manufacturing. The cycloidal blade system is used for the mechanism of variable pitch angle, and then individual pitch angle variation method is adopted for better performance.

CYCLOIDAL WIND TURBINE

VAWT USING CYCLOIDAL BLADE SYSTEM

CWT (Cycloidal Wind Turbine) introduces the cycloidal blade system to the classical VAWT [2, 3]. Figure 3 shows the cycloidal blade system that has been studied at the University of Washington, NACA, etc. since the early 1900s [4-7]. It produces thrust by varying the cyclic pitch angle of several blades rotating in the direction parallel to the rotating axis. CWT differs from the classical Darrieus rotor, which use a blade of fixed pitch angle. It maintains efficient power generation by active blade control according to the change of wind direction and wind speed. Pitch angle and phase angle can be controlled in the cycloidal blade system. This paper describes the research for the development of the 1 kW class wind turbine. Figure 4 shows a whole picture of developed system, and Table 1 shows some specifications.

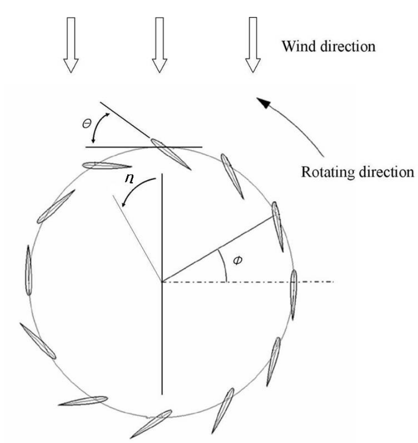


Fig. 3 Cycloidal blade system

Fig. 4 Cycloidal wind turbine

Table 1 Geometric characteristics of cycloidal wind turbine

Parameter	Value
Number of blades	4
Airfoil	NACA0018
Radius of rotor	1.0 m
Span length of blade	1.0 m
Chord length of blade	0.22 m

In Figure 3, when the wind direction is upper part to lower part, the rotor rotates in the counter clockwise direction. Pitch angle θ is the angle between the tangent line and the camber line of blade. It is varied periodically and maximized when the angle φ is 90^{o} and 270^{o} at the setting of Figure 3. At this position, maximum pitch angle is defined. η is the phase angle and defined as the angle between the wind direction and the line connecting the two positions of the maximum pitch angle. It is increased in the counter clockwise direction. Figure 5 shows the basic concept of the control mechanism. The magnitude of eccentricity e is defined as the distance from the center of rotation O to the point of the eccentricity point P, as shown in Figure 5. The phase angle of eccentricity ε is defined as the angle between the line OP and the vertical line. The magnitude and the phase angle of the eccentricity are used to adjust the magnitude and direction of the rotor. Figure 6 shows pitch angle variation according to azimuth angle when the maximum pitch angle is 10^{o}.

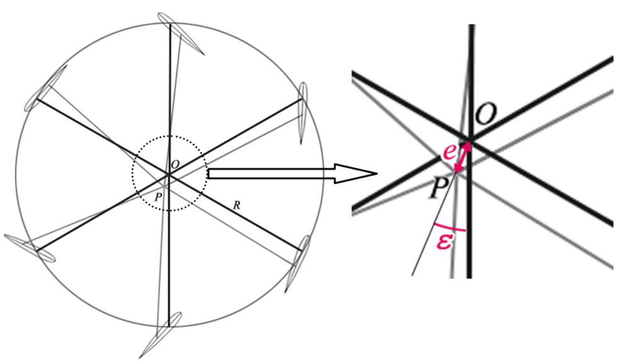


Fig. 5 Basic concept of CWT control mechanism

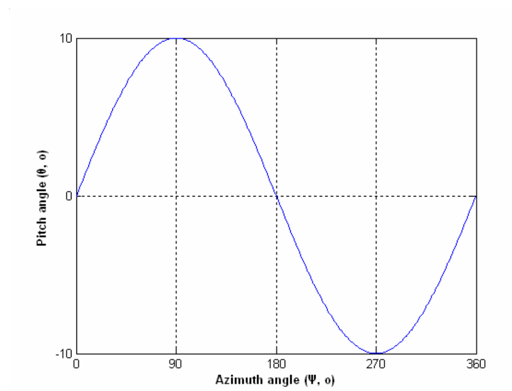


Fig. 6 Pitch angle variation of CWT

AERODYNAMIC PERFORMANCE ANALYSIS OF CWT

To calculate the power generation of CWT according to the change of wind direction and wind speed, STAR-CD, a commercial CFD program, is used. Moving mesh method is applied for the simulation of rotor rotation and periodic blade pitch variation.

Figure 7 shows power generation according to TSR (Tip Speed Ratio: the ratio of the blade-tip speed and the free-stream wind speed) for 4 pitch angles when wind speed is 13 m/s. The more rotating speed of rotor increases, the more power generates, and then power generation is decreased after peak point. The maximum value is produced at pitch angle 8^{o} and TSR 2.2. The maximum power is generated at large pitch angle when the rotor rotating speed is low, and this means that large torque can be obtained by large pitch angle at the starting condition.

Figure 8 shows power generation according to pitch angle and phase angle at TSR 2.2. The maximum output is generated at pitch angle 8^{o} and phase angle 10^{o}, and optimal pitch angle is different by phase angle change.

Figure 9 shows the tangential force of each blade at wind speed 13 m/s, pitch angle 8^{o} and phase angle 10^{o} for CWT and fixed pitch condition. Generally, upwind region that azimuth angle is from 0^{o} to 180^{o} has large values. In VAWT, wind speed at downwind region is reduced to almost half of upwind region, and power generation is proportional to the cube of wind speed, so output values of downwind region are much smaller than those of upwind region, and they are even negative values at some positions. Overall force of CWT is larger than that of fixed pitch system, and the performance is improved about 30% at all wind speed region as shown at Figure 10.

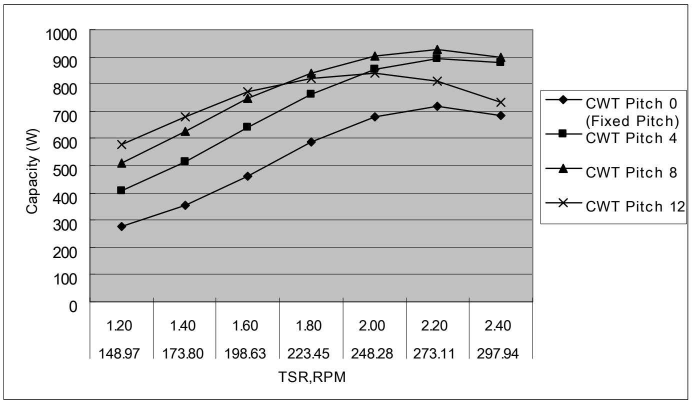


Fig. 7 Power generation according to TSR

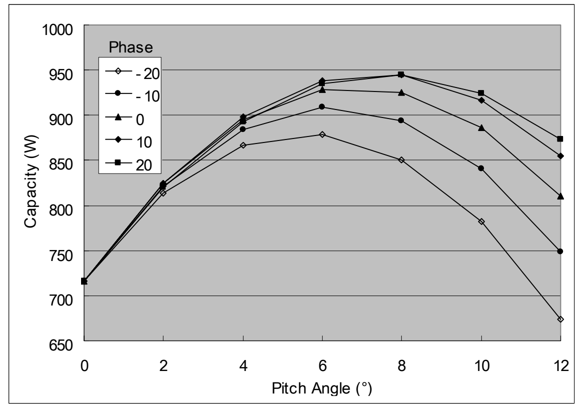


Fig. 8 Power generation according to pitch & phase angle

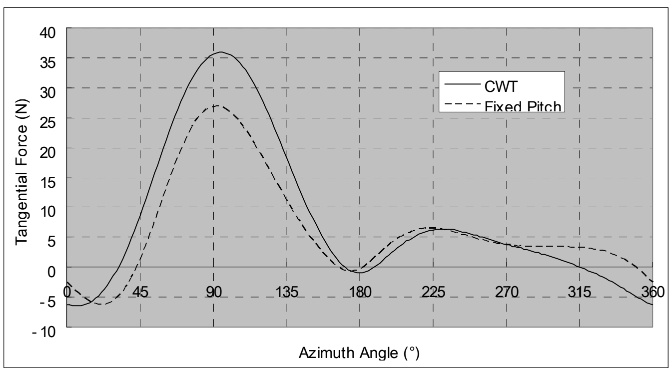


Fig. 9 Tangential force of each blade

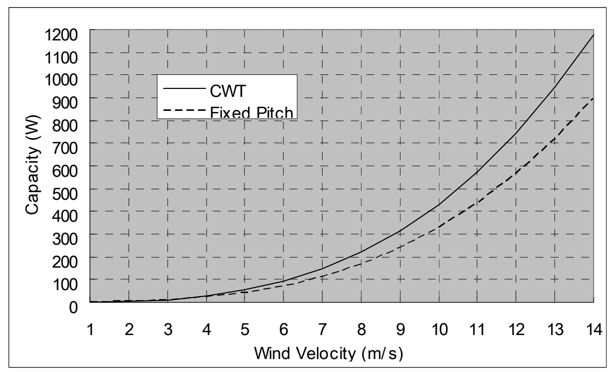


Fig. 10 Power generation according to wind speed

CONTROL MECHANISM OF CWT

To realize cycloidal motion, the mechanism that actively controls pitch angle and phase angle according to the change of wind direction and wind speed is needed. Figure 11 shows a diagram of control mechanism that consists of sensing part, control part and actuating part. Figure 12 shows the realized control devices of CWT. The wind indicator and the anemometer send their sensing information in analog voltage and pulse type. The microcontroller calculates appropriate pitch angle and phase angle from the sensed data and makes PWM signal. Pitch control device is located at top of the main shaft, and servo motor moves the eccentricity point to change the maximum pitch angle. Phase control device is located at bottom of the main shaft, and connected with pitch angle control part through the inner shaft. The shaft and the phase angle control servo motor are connected by a belt-pulley system, to change ε in Figure 5.

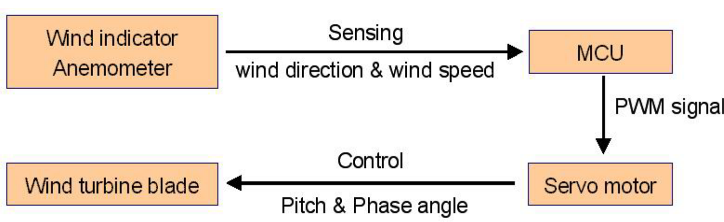


Fig. 11 Control mechanism diagram

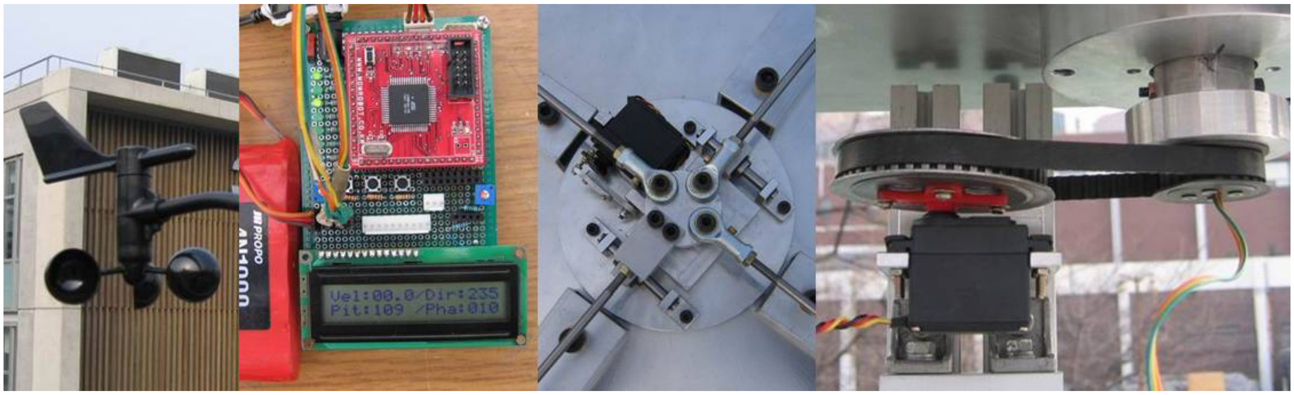


Fig. 12 Control devices of CWT

VAWT WITH INDIVIDUAL BLADE CONTROL

PROCEDURE FOR OPTIMAL PITCH ANGLE

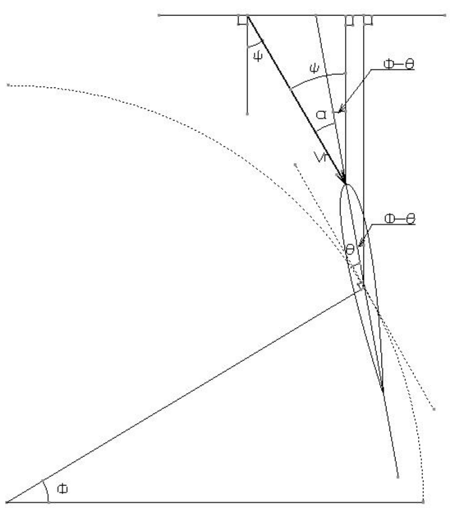
CWT is based on the cycloidal blade system, and it shows higher power generation than fixed pitch system. But it is not the most optimal mechanism for VAWT. The cycloidal blade system makes mechanical connection for rotating blades that follows the cycloidal motion, and the tangential force in each blade is not the optimal value at their position. If each blade can be controlled individually, it is possible to make maximum tangential force by all blades. By this concept, the path for optimal pitch angle is obtained through next procedure.

Force data of one blade is obtained according to the change of wind direction and wind speed. In this step, wind direction is from -30^{o} to 30^{o} and wind speed is from 0 to 60 m/s. Figure 13 shows variables around airfoil. V_r in Figure 13 is the velocity of the blade relative to the surrounding air. From these relations, angle of attack of blade is determined like this:

$$\alpha = \psi - (\varphi - \theta)$$

When wind speed and the angle ψ are determined, maximum tangential force at the specific blade position φ can be calculated from force data, and the optimal pitch angle is

$$\theta = \alpha - \psi + \varphi$$



α : angle of attack

φ : azimuth angle

θ : pitch angle

ψ : angle between wind direction and V_r

Fig. 13 Vector diagram of blade

AERODYNAMIC PERFORMANCE ANALYSIS

The optimal pitch angles can be determined through the above procedure. Figure 14 shows pitch angle variation of CWT and optimal path at wind speed 13 m/s and TSR 2.2. The power generated by this way is 1114 W that is about 20% higher output than CWT.

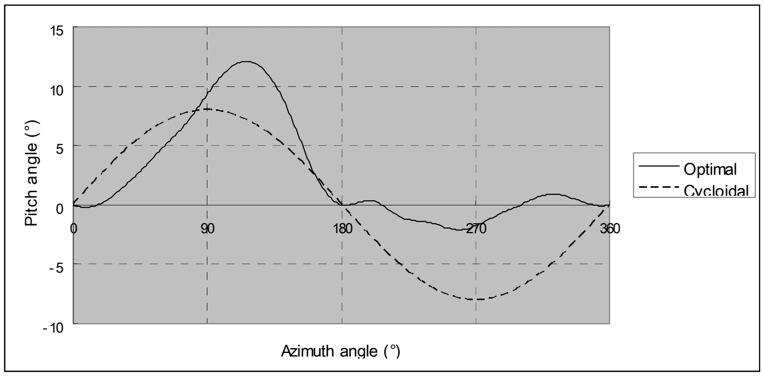


Fig. 14 Pitch angle variation of CWT and optimal path

Optimal pitch angles are calculated for several airfoils in addition to NACA0018. Figure 15 shows airfoils used in this study [8]. Four NACA 4-digit airfoils and four NACA 6-series airfoils are used, and all airfoils have the same thickness of 18%. Figure 16 shows the results by their own optimal paths of each airfoil. In NACA 4-digit airfoils, power generated is decreased as the camber increases, and it is maximized at TSR 2.2 for all airfoils. In NACA 6-series airfoils, all airfoils show better outputs comparing with NACA 4-digit airfoils except NACA 63_3-618. The maximum value is about 1150 W of NACA 63_3-018 and NACA 63_3-218.

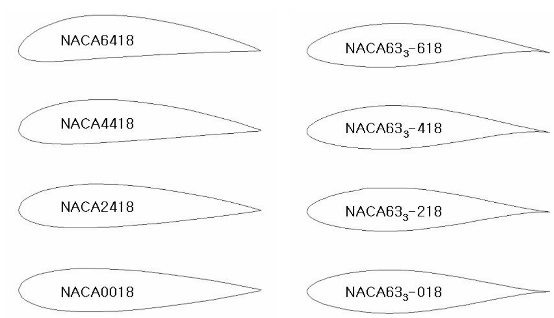


Fig. 15 Airfoil sections of NACA 4-digit and NACA 6-series

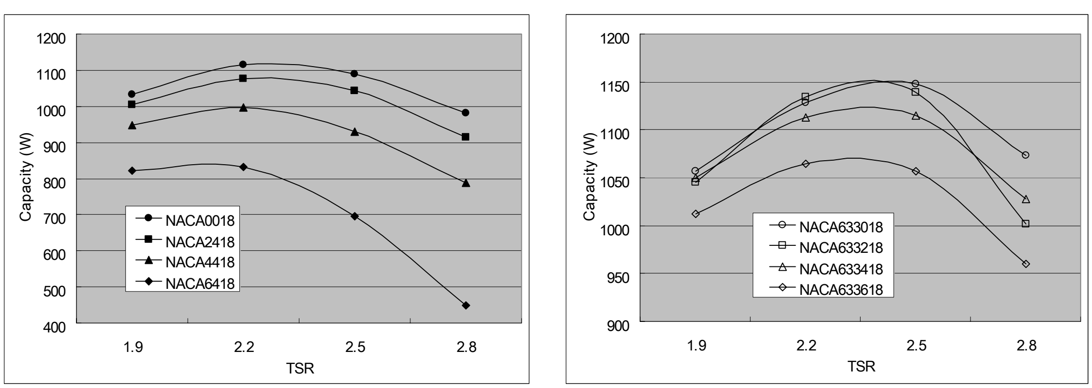


Fig. 16 Power generation of NACA 4-digit and NACA 6-series airfoils

CONTROL MECHANISM

Individual control mechanism is similar to that of CWT as shown at Figure 17. The different thing is an addition of the rotary encoder to sensing part for measuring of rotating angle of rotor. This enables control unit to sense the azimuth angle for obtaining optimal pitch angle at the position. At every time step, microcontroller receives the position of each blade from rotary encoder and wind data from the wind indicator and the anemometer, and calculates optimal pitch angle to send PWM signal to the actuator.

Figure 18 shows actuating part consists of four servo motors. The control device of CWT has phase angle control unit, but individual control system does not need the phase angle controller, so each blade has its own servo motor to control pitch angle. Servo motor can transmit its rotating force directly to blade by linkage, and changing ratio of blade pitch angle can be increased by reducing the length of linkage. This simple setting makes it possible to response rapidly at the high speed rotation of rotor.

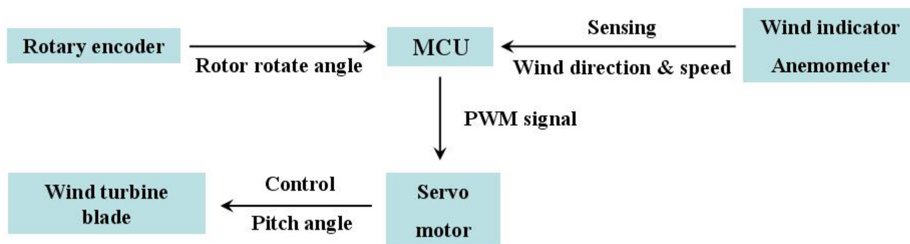


Fig. 17 Control mechanism diagram

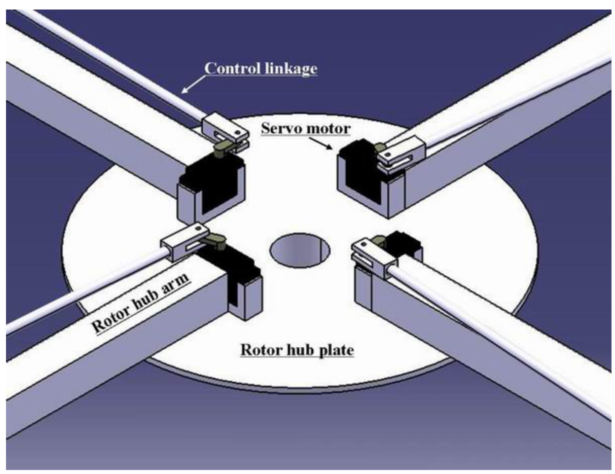


Fig. 18 Conceptual design of individual control mechanism

CONCLUDING REMARKS

In this paper, for the performance improvement of a vertical axis wind turbine, aerodynamic analysis, control mechanism design and its realization of 1kw class model are carried out. 4 straight blades of 1m span length are used and rotor radius is fixed to 1m. For this model, the cycloidal blade system and the individual active blade control system are applied respectively to improve its performance. The aerodynamic analysis shows that the cycloidal wind turbine is possible to generate more power than fixed pitch type VAWT by changing its pitch angle and phase angle according to wind direction and wind speed. The appropriate control mechanism to realize the cycloidal motion is designed and developed, and the whole power generation system of 1kw class is also developed as shown at the above picture. To develop the more advanced system, the individual active blade control system is applied instead of the cycloidal blade system. Optimal pitch angle variation is obtained by maximizing the tangential force of each blade at the specific rotating position, and several airfoils such as NACA 4-digit and NACA 6-series are studied in addition to a symmetric airfoil. By this method, the power output is improved about 60% comparing with VAWT using fixed pitch and symmetric airfoil. And the control mechanism is designed by some sensing and actuating devices. If more optimal airfoil were used, more power would be generated, and other aerodynamic, structural and electrical variables could be considered for better power generation in addition to aerodynamic variables studied in this paper.

ACKNOWLEDGEMENT

This research is partially supported by the Brain Korea 21 Project in 2005.

REFERENCES

(1) Kirke, B.K. "Evaluation of self-starting vertical axis wind turbines for stand-alone applications," Ph.D thesis, Griffith University, Australia, 1998.

(2) Hwang, I.S., Hwang, C.S., Min, S.Y., Jeong, I.O., Lee, Y.H. and Kim, S.J. "Efficiency Improvement of Cycloidal Wind Turbine by Active Control of Blade Motion," 16th International Conference on Adaptive Structures and Technologies, Paris, France, 9-12 October 2005.

(3) Ham, N.D., Soohoo, P., Noll, R.B. and Drees, H.M. "Analytical and Experimental Evaluation of Cycloturbine Aerodynamic Performance," Terrestrial Energy Systems Conference, Orlando, Fla, 1979.

(4) Yun, C.Y. "A New Vertical Take-off and Landing Aircraft with Cycloidal Blades System: Cyclocopter," Ph.D thesis, Seoul National University, Korea, 2004.

(5) Wheatley, J.B. "Simplified Aerodynamic Analysis of the Cyclogiro Rotating-wing System," Technical Notes NACA No.467, 1933.

(6) Kirsten, F.K. "Cycloidal propulsion in air," Bulletin No. 79, Engineering Experiment Station Series, University of Washington, 1935.

(7) Boschma, J.H. "Modern Aviation Applications for Cycloidal Propulsion," AIAA, Aircraft, Technology Integration and Operations Forum, Los Angeles, CA, 2001.

(8) Migliore, P.G. "Comparison of NACA 6-Series and 4-Digit Airfoils for Darrieus Wind Turbines," Journal of Energy, Vol. 7, No. 4, 1983.