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Improving the Self-starting Performance of a VAWT

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수직축 풍차의 자기동 성능 개선

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ABSTRACT

The inherent problem of a Darrieus wind turbine is its inability to self-start. Usually, a motor is used to provide angular acceleration until lift forces are produced in the airfoil blades or up until the turbine can already sustain its speed on its own. This paper describes a method of improving the self-starting of an H-type Darrieus vertical axis wind turbine (VAWT) by incorporating a helical Savonius turbine thus utilizing a drag-lift combination. The effect of each turbine in the combination relative to each other is investigated by testing a prototype windmill consisting of three NACA 0015 airfoil blades combined with a Savonius rotor with a helix angle of 180 degrees and whose swept area equals 30% of the entire turbine.

Key Words : Windmill, Helical Savonius Rotor, VAWT, Tip Speed Ratio, Self-starting, Helix Angle, Darrieus Wind Turbine

1. Introduction

Interest in renewable and environment friendly sources of energy had been increasing recently because of uncertainties in the supply and price of oil and other fossil fuels. Furthermore, pursuant to the provisions of the Kyoto Protocol to the United Nations Framework Convention on Climate Change requiring reduced green house gas emissions, wind energy remains one of the viable choices in meeting these goals.

There are two major classification of wind turbines based on the orientation of its axis of rotation. These are: the Horizontal Axis Wind Turbines (HAWT) and the Vertical Axis Wind Turbine (VAWT). There are two kinds of VAWT depending on how they extract power from the wind. These are: the drag type which is literally being push by the wind, and the lift type which uses pressure difference between faces of an airfoil blade to extract power. Fig. 1 shows some of the existing wind turbines based on classification.

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(a) (b) (c)

Fig. 1 Classification of wind turbines.

(a) HAWT

(b) Darrieus turbine - lift type VAWT

(c) Savonius wind turbine - drag type VAWT

Wind energy production had been dominated by HAWTs mainly because it has a higher tip speed ratio (TSR) and consequently a much higher coefficient of performance (Cp) as against VAWTs. TSR is the ratio of the linear velocity at the tip of the turbine blade to the average wind velocity while Cp is the efficiency of a wind turbine measured as a percentage of the available kinetic energy of the wind that is converted to mechanical energy.

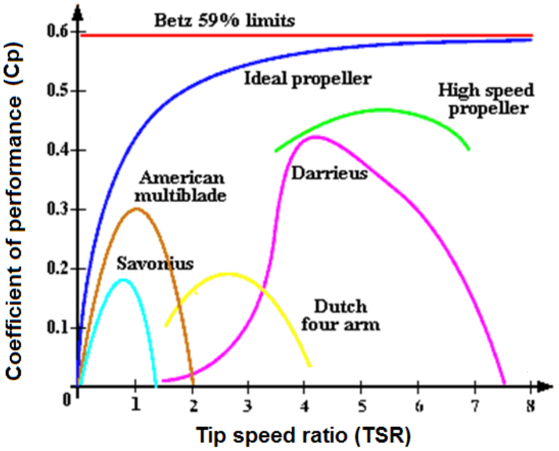


Fig. 2 Approximate relationship of the Tip Speed Ratio (TSR) to the Coefficient of Performance (Cp) of a wind turbines

Fig. 2 shows an approximate relationship of TSR and coefficient of performance for most kinds of wind turbines. It can be seen from Fig. 2 that Darrieus wind turbines can approach the efficiency of high speed propellers (the most common HAWT) except for one major drawback, i.e., it cannot self-start or accelerate from rest up to a region of high TSR (notice the slope of the curve between TSR 0 to 2). This is because no lift forces are available during starting and an external power source is needed to accelerate the turbine. It can be noted that Darrieus turbines have a much higher Cp compared to other HAWT which includes the American multiblade and the Dutch four arm windmill.

VAWTs possess some notable advantages over HAWT in the field of construction, installation and operation which are all superceded by the latter because of its superior efficiency. However, given that a Darrieus turbine could self-start, it can become the windmill of choice for some applications.

This paper aims to explore a method of improving the self-starting of VAWT by utilizing drag forces in providing the starting torque for the Darrieus turbine. The drag forces was provided by a helical Savonius rotor designed so as not to disrupt the flow of air in the airfoil blades. Savonius rotors are characterized by its high torque production which is essential for self-starting. The effectiveness of this combination was tested in a wind tunnel and likewise involved the operation of the two turbines running separately which formed the benchmark for comparison.

2. VAWT Design

Fig. 3 shows the prototype design of a self-starting VAWT. The design features a helical Savonius rotor 200mm wide and 370mm high with a helix angle of 180 degrees. This is constructed by stacking 6mm thick acrylic S-shape plates as described by Cheong, et al.[1]. The swept area of this rotor comprises 30% of the entire wind turbine combination. The helical configuration is expected to increase the torque produced during starting and steadily accelerate the VAWT. The increase in inertia is expected to be handled by the drag forces generated by this rotor. On the other hand Darrieus rotor selected for the design is composed of three straight airfoil blades of the NACA 0015 configuration with a height of 440mm supported by 350mm radial arm on both ends. NACA 00xx symmetric airfoil series, specifically 0012, 0015 and 0018 are well studied airfoil blades for windmill applications. The 0015 is selected because it behaves well even for small Reynolds number and because it is thinner than 0018, thereby reducing the overall weight. The 90mm chord length of the airfoil is computed based on solidity of 0.4 as suggested by Kirke [2] for near maximum peak performance. Three airfoil blades where selected as against two for a more sound structure and to minimize vibration.

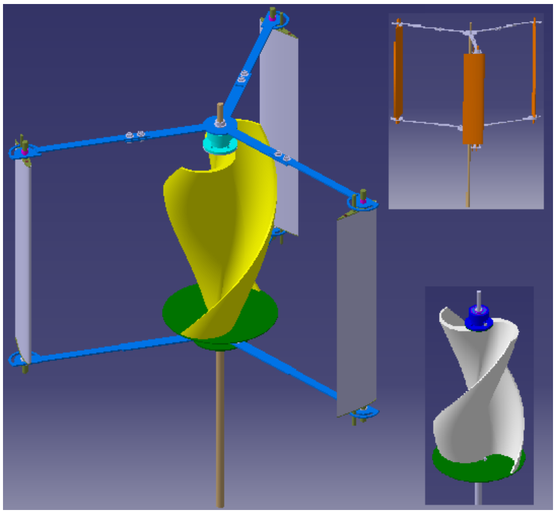


Fig. 3 Design of the self-starting VAWT, combining a helical Savonius and Darrieus turbines

Furthermore, a mechanism for changing the angle of attack of the blades was included so as to allow the investigation of its effect on the overall performance. The overall dimensions of the prototype were based on the size of the available wind tunnel enclosure whose cross-section is 1000mm x 550mm. At a total swept area $0.31m^2$, it is expected to produce 75 watts at its rated speed of 10m/s.

3. Computational Fluid Dynamics(CFD) Simulation

In order to predict the behavior of a helical Savonius rotor when tested in a wind tunnel, as well as to visualize the flow around the rotor, CFD analysis on a stationary helical Savonius rotor was performed.

There had been many studies conducted to investigate the flow around a Savonius rotor which is closely related to the torque and power performance of the rotor, Fujikawa [3]. However, since a helical Savonius rotor's profile is an extrusion along a helical path, as against a straight extrusion for an ordinary rotor, flow fields in most Savonius rotor studies does not apply.

CFD simulation was accomplished utilizing the following methodology. First, design model from CATIA V5 was exported to ANSYS DesignModeler hosted within the ANSYS Workbench environment. Next, a wind tunnel enclosure was added and the resulting void filled to represent the domain of the fluid (air). ANSYS Workbench was also used to generate a hybrid unstructured CFX-mesh for the simulation. An inflation layer was added to the wind tunnel walls and to the helical Savonius surfaces in order to have a good resolution at the boundary layers. In this analysis, the rotor surfaces are considered walls. For the turbulence model, the shear stress transport(SST) turbulence model with automatic wall function treatment was used because of its highly accurate predictions of flow separation according to CFX-5 Solver Theory User's Guide [4]. Table below shows the mesh statistics and other simulation parameters and Fig. 4 shows a slice plane projection 100mm above the base of the helical Savonius turbine cutting through the elements to reveal the mesh.

Table 1 CFD Simulation Parameters

Number of elements	253,382
Tetrahedra	196,622
Wedges	56272
Pyramids	288
Inlet boundary condition	mass flow 4 kg/s

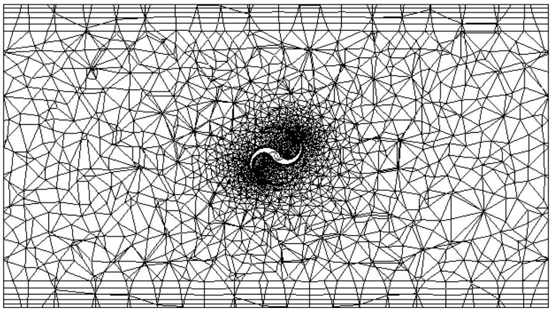


Fig. 4 Slice plane projection of the mesh taken 100 mm from the bottom of the helical Savonius turbine.

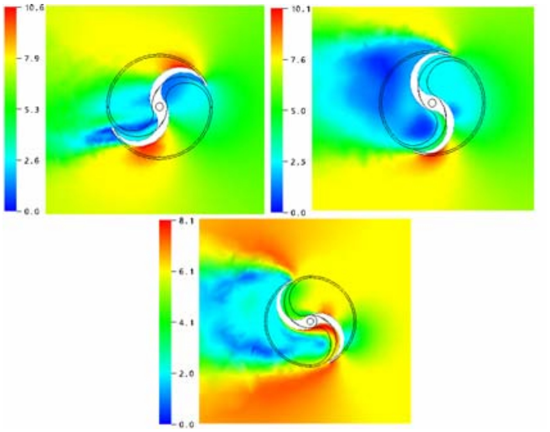


Fig. 5 Velocity distribution along a cut plane 50 mm from the bottom of the rotor for different positions (0, 45, 90 degrees respectively)

Results of the CFD simulation showing velocity distribution and flow pattern at selected locations and regions near the rotor are taken and shown in Figs. 5-7.

The velocity distribution for all the stationary position of the turbine (representing an entire revolution) can be visualized by moving a cutting plane vertically from the bottom.

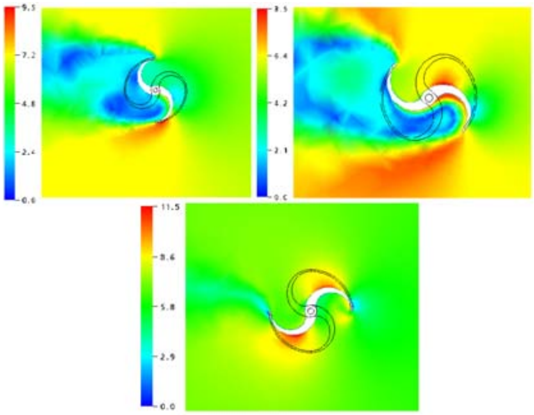


Fig. 6 Velocity distribution along a cut plane in the middle of the rotor for different positions (0, 45, 90 degrees respectively)

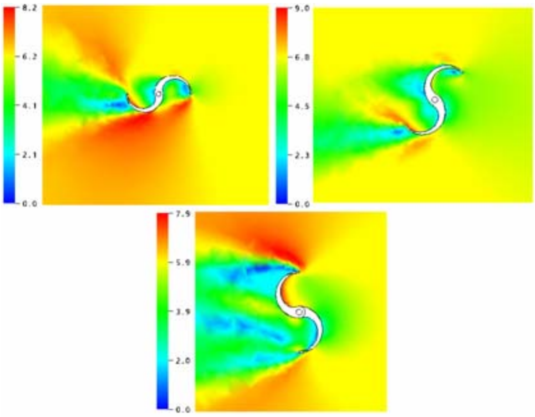
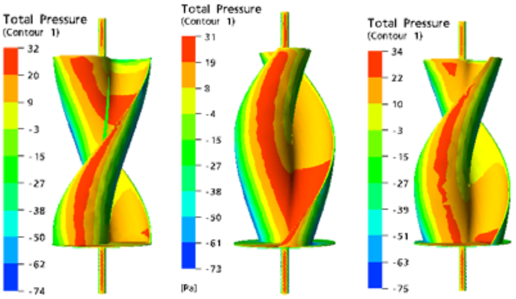


Fig. 7 Velocity distribution along a cut plane near the top of the rotor for different positions (0, 45, 90 degrees respectively)

CFD results illustrate the flow variation throughout the entire height of a helical Savonius turbine which is different from that of an ordinary Savonius (which usually have the save velocity distribution along its height). In essence, it can be deduced that positive toque is generated at nearly all subsequent positions of the turbine. This is significant in the reduction of the negative torque acting on the downwind side of an ordinary Savonius thus allowing the production of more torque which is required for the self-starting of a Darrieus turbine. Pressure distribution contour plot along the surface of the rotor positioned at 0, 45 and 90 degrees as shown in Fig. 8 likewise suggest positive torque generation. The helical Savonius turbine is oriented facing the wind direction in Fig. 8.



(a) (b) (c)

Fig. 8 Pressure contour on the surface of the helical Savonius turbine at the following positions: (a) 0 degrees, (b) 45 degrees and (c) 90 degrees.

4. Experimental Details

The prototype self-starting VAWT was tested under controlled conditions inside a wind tunnel to determine its ability to accelerate from rest and achieve a significantly high tip speed ratio. A benchmark for comparison is obtained by operating and testing the helical Savonius and the Darrieus wind turbines separately. Finally, the two turbines were combined and tested, varying its relative orientations with respect to each other as well as the angle of attack of the airfoil blades.

Fig. 9 illustrates the experiment set-up and the monitoring and control instruments. A 15,000m^3/hr capacity turbo fan unit provides the wind flow required in the test. Wind speed is varied via the fan's vector inverter to provide wind velocities between 5 to 10m/s. A manometer with an attached pitot tube positioned

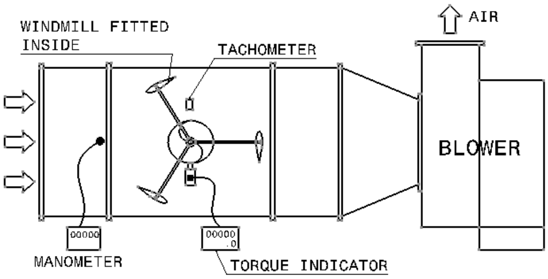


Fig. 9 Experiment set-up for the self-starting VAWT

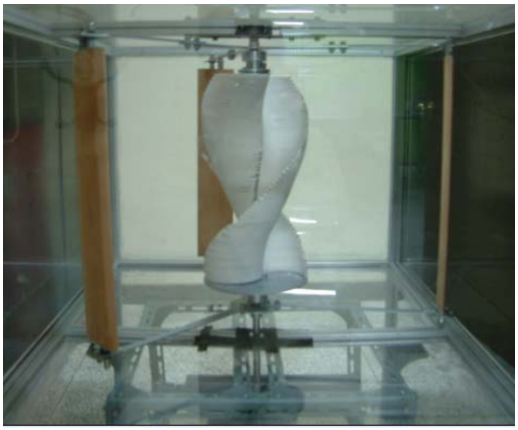


Fig. 10 Combined helical Savonius and Darrieus turbines fitted inside the wind tunnel

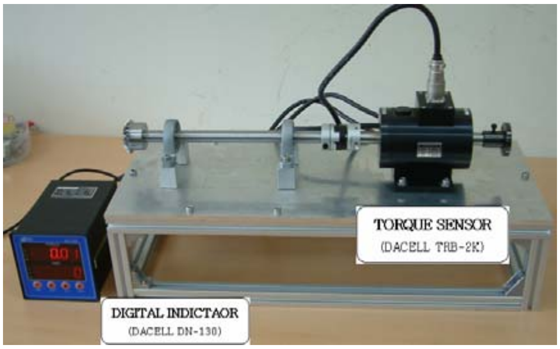


Fig. 11 Torque sensor and indicator setup

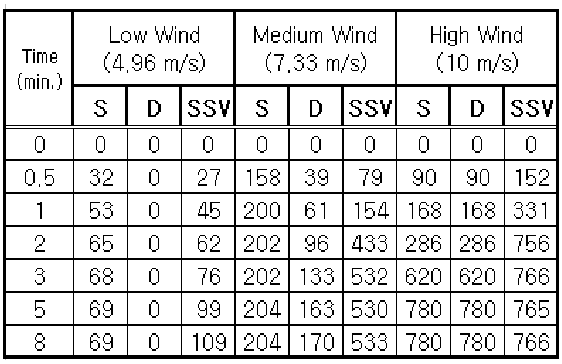
near the turbine measures the approaching wind velocity. Torque sensor installed on the lower end of the turbine shaft measures the corresponding torque. A separate photo-tachometer positioned at the lower end of the wind turbine's shaft measures the rpm at a predetermined interval.

5. Results and Discussion

5.1 Experiment Results

The inability of Darrieus wind turbine to accelerate past the dead band, i.e., the period of low or negative torque specially at low wind velocity was evident during the course of the experiment. Table 2 shows that the Darrieus turbine failed to rotate at low wind velocity. At medium and high wind velocity however, the turbine accelerates and shows evidence of self-starting brought about by the drag forces acting on the NACA 0015 airfoil blades. This acceleration is slow and is vulnerable to changes in wind velocities (usually the case in field installations). On the other hand, the helical Savonius rotor exhibited consistent operating performance for all the test. Low TSR common to drag type VAWTs was obtained for this rotor as can be seen in Fig. 12. High inertia of the rotor affects its acceleration in low winds.

Table 2 RPM of the turbines



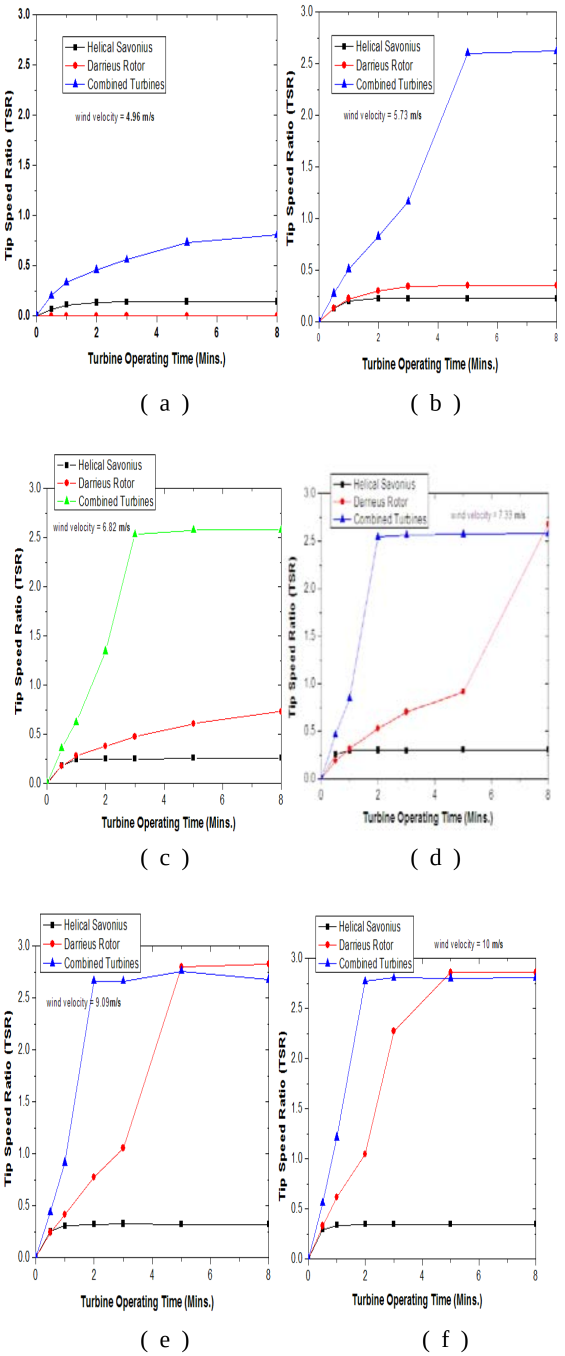
Time (min.)	Low Wind (4.96 m/s)			Medium Wind (7.33 m/s)			High Wind (10 m/s)		
	S	D	SSV	S	D	SSV	S	D	SSV
0	0	0	0	0	0	0	0	0	0
0.5	32	0	27	158	39	79	90	90	152
1	53	0	45	200	61	154	168	168	331
2	65	0	62	202	96	433	286	286	756
3	68	0	76	202	133	532	620	620	766
5	69	0	99	204	163	530	780	780	765
8	69	0	109	204	170	533	780	780	766

S=Savonius, D=Darrieus and SSV=self-starting VAWT

A significant increase in acceleration is observed when the helical Savonius turbine is incorporated to the Darrieus turbine. Fig. 12 illustrates a dramatic increase in TSR and acceleration (notice the slope of the curve). The self-starting of Darrieus wind turbine using symmetric airfoil blades depended on the drag forces available on the blades during starting. Some designs involved the pitching of the turbine blades to maximize drag. Kirke[2] demonstrated a self-acting variable pitch VAWT intended for this purpose. Increasing the available drag forces by means of a helical Savonius demonstrated self-starting. However, drag forces are parasitic when the Darrieus turbine is already operating utilizing lift forces. The effect of the drag forces acting the helical Savonius turbine on the peak operating speed of the combined VAWT proved to be minimal as can be seen Fig. 12 (e) and (f) which shows slight drop on the TSR of the combined turbines compared to a Darrieus turbine operating independently. On extreme cases, severe effects on the overall performance of the combination by parasitic drag in the Savonius rotor can be solved by introducing a decoupling mechanism which can be installed to disengage the helical Savonius. This is unnecessary in this particular case however.

5.2 Factor Affecting Over-all Performance of the Self-Starting VAWT Prototype

The angle of attack or pitching of the airfoil blades affects the ability of combined turbines to self start and operate at high TSR and high performance. Negative angle of attack (the angle between the trailing edge and radial arm is less than 90 degrees) produces negative torque and prevents the turbine from accelerating even with helical Savonius rotor in place. Positive angle of attack promotes self-starting and higher TSR. However, pitching the blade more than 5 degrees decreases the TSR and much larger values produces negative torque. Fig. 13 shows the effect of the angle of attack to the speed of the self-starting VAWT.



(a) (b)

(c) (d)

(e) (f)

Fig. 12 TSR of the helical Savonius, Darrieus and the combination measured as the turbines accelerate from rest

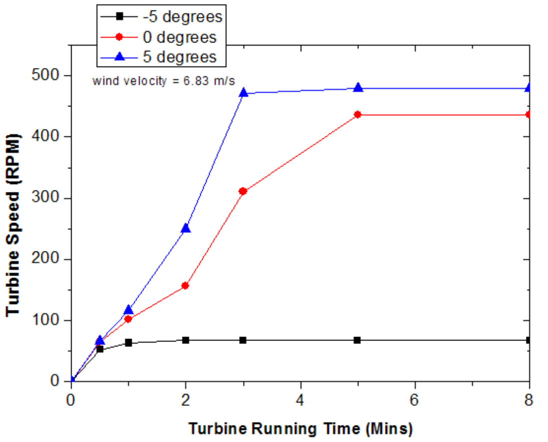


Fig. 13 Speed of the combined turbines at different airfoil blade angle of attack.

6. Conclusion

This work aims to improve the self-starting of a vertical axis wind turbine, specifically, an H-type Darrieus windmill with three NACA 0015 airfoil blades.

Experimental results and computer simulation validates the suitability of a helical Savonius rotor with a helix angle of 180 degrees in improving the self-starting of the mentioned VAWT. It is important that the flow of air in the airfoil blades are not affected by the Savonius turbine. A swept of not more than 30% proved appropriate in increasing the drag forces necessary to start and provide the angular acceleration to the Darrieus H-type rotors. Performance of the combined helical Savonius turbine and Darrieus wind turbines is affected by the pitch or angle of attack of the NACA 0015 blades. Pitching the symmetric airfoil blades produces virtual cambers and likewise affects the direction of the resulting lift. An angle of attack equal to 5 degrees (angle between the airfoil trailing edge and the blade's radial arm is 95 degrees) provided the highest TSR for the prototype.

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References

1. Cheong S.H., Choi S.D., Mag-isa A.E., Choi M.S., “Optimum Design of Helix Angle for Self-starting VAWT's,” KSMPE Autumn Conference, Kumoh National University of Technology, pp. 110-113, 2005.
2. Kirke B. K., “Evaluation of Self-starting Vertical Axis Wind Turbines for Stand-alone Applications,” Ph. D thesis, Griffith University, Australia, 1998.
3. Fujisawa N., “Velocity Measurement and Numerical Calculation of Flow Fields in and around Savonius Rotors,” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 59, pp. 39-50, 1996.
4. ANSYS Inc.., CFX-5 Solver Guide, Solver Theory, pp. 60.
5. Hwang, I. S., Hwang, C. S., Min, S. Y., Jeong, I. O., Lee, Y. H., Kim, S. J., “Efficiency Improvement of Cycloidal Wind Turbine by Active Control of Blade Motion,” Seoul National University, 2005.