

Effects of setting angle on performance of fish-bionic wind wheel

G S Li, Z X Yang¹, L Song, Q Chen, Y B Li and W Chen

Institute of Systems Science and Engineering, Henan Engineering Laboratory of Wind Power Systems
Henan University of Science and Technology, No.48 Xiyuan Road, Luoyang 471003, China

Email: zxyang@haust.edu.cn

Abstract. With the energy crisis and the increasing environmental pollution more and more efforts have been made about wind power development. In this paper, a new type of vertical axis named the fish-bionic wind wheel was proposed, and the outline of wind wheel was constructed by curve of Fourier fitting and polynomial equations. This paper attempted to research the relationship between the setting angle and the wind turbine characteristics by computational fluid dynamics (CFD) simulation. The results showed that the setting angle of the fish-bionic wind wheel has some significant effects on the efficiency of the wind turbine, Within the range of wind speed from 13m/s to 15m/s, wind wheel achieves the maximum efficiency when the setting angle is at 37 degree. The conclusion will work as a guideline for the improvement of wind turbine design.

1. Introduction

Being clean and renewable, wind energy has great reserves in nature, and it has great potential as a new energy with good prospects for development [1-9]. In China, the demand for energy is increasing rapidly with the development of economy. The traditional oil and coal has caused serious environmental pollution, while renewable wind energy can provide complement to modern society without pollution. Therefore more and more countries have recognized the importance of wind energy[1, 3, 6, 8, 9]. Wind power is the most important way to use wind energy, and its wattage is increasing year by year.

The structure of wind turbines is very simple, but the aerodynamic characteristics of the work is extremely complex. At present, we have two main methods to research wind turbine flow field characteristics: numerical analysis and wind tunnel testing [10, 11].

There are many types of wind turbines which can be divided into horizontal axis wind turbine [12-15] and vertical axis wind turbine [16-23] depending on the wind direction and the axis direction.

Compared with the traditional horizontal axis wind turbine, the vertical axis wind turbine has the advantage of advanced design methods, high wind power utilization, low starting wind speed, low noise, and broad market

¹ Address for correspondence: Z X Yang, Institute of Systems Science and Engineering, Henan Engineering Laboratory of Wind Power Systems Henan University of Science and Technology, No.48 Xiyuan Road, Luoyang 471003, China. E-mail: zxyang@haust.edu.cn.



prospects [14, 24-26]. Vertical axis wind turbine includes Savonius type[24, 27], Darrieus type[28, 29], and H-type vertical axis wind turbine[30, 31].

This paper introduces a new type of fish-bionic wind wheel, and researches into the relationship between the setting angle and the wind turbine characteristics by CFD.

2. Structure and principle of fish- bionic wind wheel

The proposed wind wheel is come from the contour of fish, and the geometry is a combination of Fourier fitting, polynomial equations and peripheral curve. At both ends of the rotor blades, the rotor is provided with two threaded holes in the height direction respectively, and connected to the upper and lower cover with certain setting angle. Fish-bionic wind wheel structure is shown in Figure 1 and Figure 2.

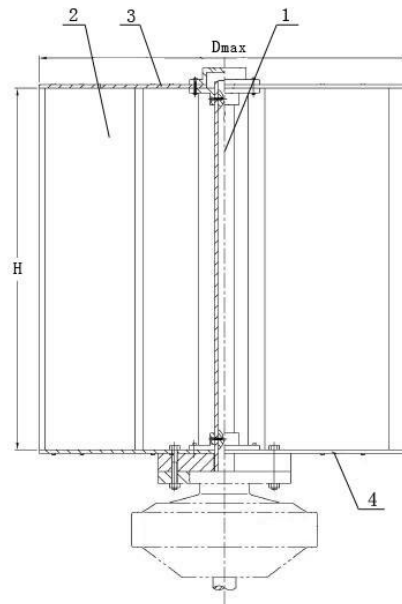


Figure 1. Front view of fish-bionic wind wheel.

In Figure 1, (1) is wind wheel center axis, (2) is wind turbine blade, (3) is wind wheel upper cover, (4) is wind wheel lower cover.

Upper cover and lower cover need to be installed in parallel, and perpendicular to the central axis of the wind turbine. Wind turbine blades are curved structures, where three blades must be the same bending direction, and it should install at least three blades in order to double the use of wind energy effectively. H is the distance between the upper cover and lower cover, and the ratio between the H and $D_{\max}$ is between 1 to 3.

In Figure 2, (5) is wind wheel front edge point, (6) is wind wheel rear edge point. $D_{\max}$ is diameter of circle which is composed by the front edge points of three blades. $D_{\min}$ is diameter of circle which is composed by the rear edge points of three blades. The length between the front edge point of blade and rear edge point of blade is chord. The ratio between the chord length and $D_{\max}$ is 0.5. 40 degree is the setting angle of the wind turbine, which is the angle between the connecting line of front edge and the rear edge point and the connecting line of front edge and the center axis, and setting angle will affect the performance of wind turbines.

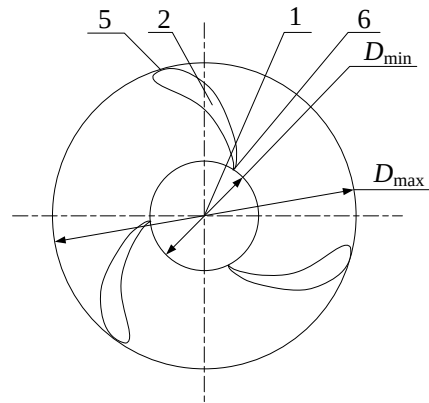


Figure 2. Plan view of fish-bionic wind wheel (without upper cover).

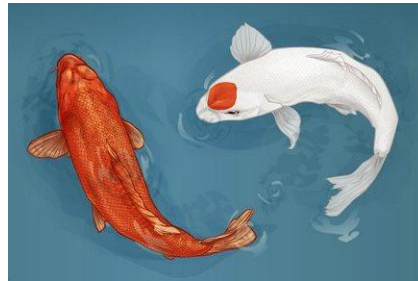


Figure 3. Fish swimming in the water.

As is shown in Figure 3, fish swimming in the water is similar to air flowing through something since fish tail swing generates driving force. According to the principle of bionics, the paper improves the utilization of wind energy by optimizing the end of the blade, changing the number of blades and the installation angle.

We get wind wheel rotor blades sample from bionics, and use an approximate equations to describe sample by curve fitting, then the polynomial equations of intersection line between upper cover and inner surface is:

$$f(x) = 13.22x^7 - 51.08x^6 + 79.58x^5 - 65.14x^4 + 30x^3 - 7.95x^2 + 1.135x + 0.007948 \quad (1)$$

The Fourier fitting of intersection line between upper cover and outer surface is:

$$f(x) = 48.51 - 54.53\cos(1.571x) - 56.82\sin(1.571x) - 1.339\cos(3.142x) + 40.82\sin(3.142x) + 8.975\cos(4.713x) - 8.37\sin(4.713x) - 1.619\cos(6.284x) - 0.05546\sin(6.284x) \quad (2)$$

Where the x is in the range [0-1].

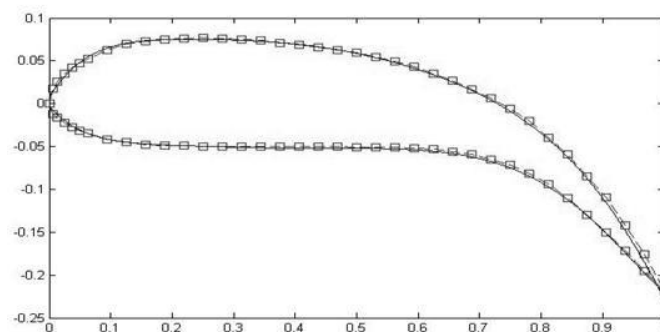


Figure 4. Sample points and approximate curve fitting of fish-bionic wind wheel.

According to the results of curve fitting, we have designed the rotor blades shown in Figure 4 and Figure 5.

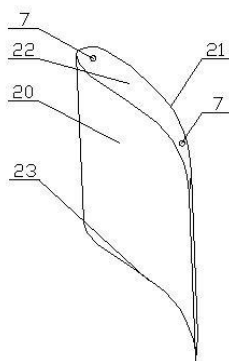


Figure 5. Wind turbine blade structure.

In Figure 5, (7) are threaded holes, the two threaded holes play a role in fixing the upper and lower cover. Both are located on the chord length. (20) is inner surface, (21) is outer surface, (22) is upper cover, (23) is lower cover, the upper cover and lower cover are parallel to each other and the projection of the covers are coincident, and inside surface and outside surface are perpendicular to the upper cover and lower cover, the thickness of the blade reduces gradually and intersects at a point from the front edge point to the rear edge point.

Wind wheel will work by the pressure which is different between the inside and outside surfaces of head. This will produce a pressure that will differentially push the rotating wind wheel, due to the asymmetrical circular surface of the head when the wind flows from the inlet into the wind wheel.

The front half of wind wheel is a lift-typed wind turbine because that has different crown of the shape at the two sides. The rear half of wind wheel is a resistance-typed wind turbine because the concave is located at the windward side of the wind. Traditionally, the lift-typed wind turbines have poor starting performance, and the resistance-typed wind turbines have lower speeds, but the special structure of fish-bionic wind wheel overcomes the above mentioned shortcomings.

3. CFD model

Computational fluid dynamics use discrete mathematical methods, and it can simulate the running state of model in theory, and uses powerful computing capability of computer to solve various issues of hydrodynamics calculations. CFD software simulations can greatly reduce the use of pre-investment projects, save time and improve work efficiency, thus it has become an important modern engineering software tool.

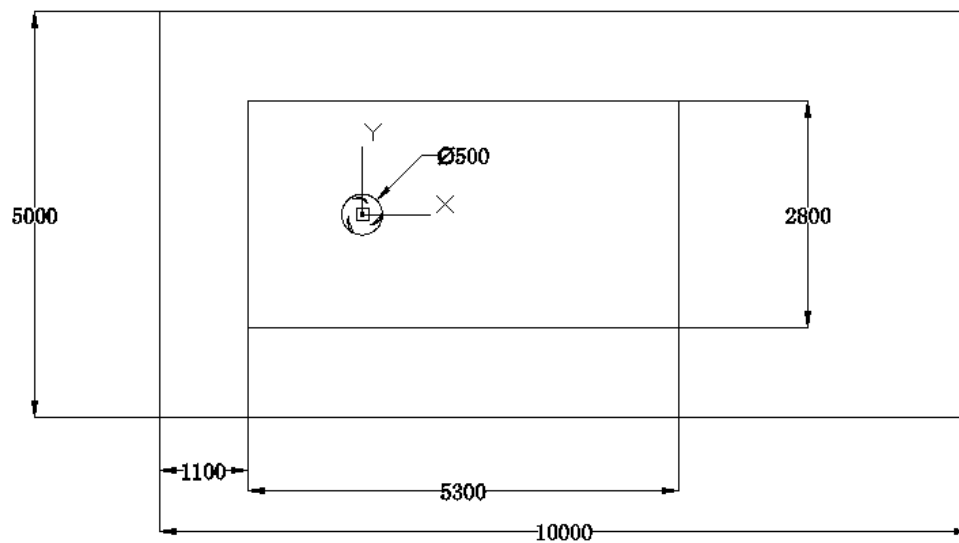


Figure 6. CAD drawing of wind wheel computational domain (unit: mm).

The fish-bionic wind wheel was constructed and computational domain was chosen according to equation (1) and equation (2), then transient and dynamic performance of wind wheel was analyzed by sliding mesh method of computational fluid dynamics.

Wind wheel diameter was 0.5 m, the distance between the wind turbine and left boundary was five times of the diameter of the wind wheel, the distance between the wind turbine and upper and lower bounds was five times of the diameter of the wind wheel, the distance between the wind turbine and right boundary was fifteen times of the diameter of the wind wheel. Mesh quality is the main factor affecting the results of the simulation experiment. In this paper, the triangular unstructured grids are used because the outer contour of wind wheel is very complex. After the mesh independent verification, the number of mesh was 5.86×10^5 .

Reynolds number was 2.50×10^5 , turbulence kinetic energy was 0.24, turbulent dissipation rate was 1.34, and RNG k- ϵ turbulence model was used in the simulation. And the inlet boundary condition was velocity inlet, wind speed set in the simulation, outlet boundary conditions was outflow, the upper and lower boundary conditions symmetry wall, the blade surface was moving wall, the central axis was stationary wall. The pressure-velocity coupling algorithm was SIMPLE, the transient formulation was discretized by the first order implicit scheme, and the turbulent kinetic energy and turbulent dissipation rate were discretized by the second order upwind scheme.

According to the simulation results, the last cycle of the wind wheel torque (final 360 torque values,) was selected, and the average as average torque of a wind wheel cycle was found, then we obtained the efficiency of wind turbines by following equation.

Wind power input

$$P_i = \frac{\rho H D v^3}{2 \times 10^3 \times 10^3} \quad (3)$$

Wind turbine power output

$$P_o = \frac{2\pi n T}{60} \quad (4)$$

Wind turbine efficiency

$$\eta = \frac{P_o}{P_i} \quad (5)$$

Where:

ν : Wind velocity (m/s).

ρ : Air density (1.225kg/m³).

H : Height of wind wheel (500mm).

D : Diameter of wind wheel (500mm).

n : Rotor speed (r/min).

T : Wind wheel output torque (N.m)

4. CFD simulation results

As it can be seen from Fig.7, there is large low-speed area at the rear end of wind wheel, which is caused by the rotation of the wind wheel. The low wind area is not only beneficial to the rapid flow of wind between the wind wheel blades, but also conducive to the wind wheel rotation. The rear end of wind wheel shows resistance-type characteristics when wind wheel movement, fishtail portion makes the air flow through the fish's belly impact on adjacent blades fish head, thereby increases the speed and output torque of the wind wheel.

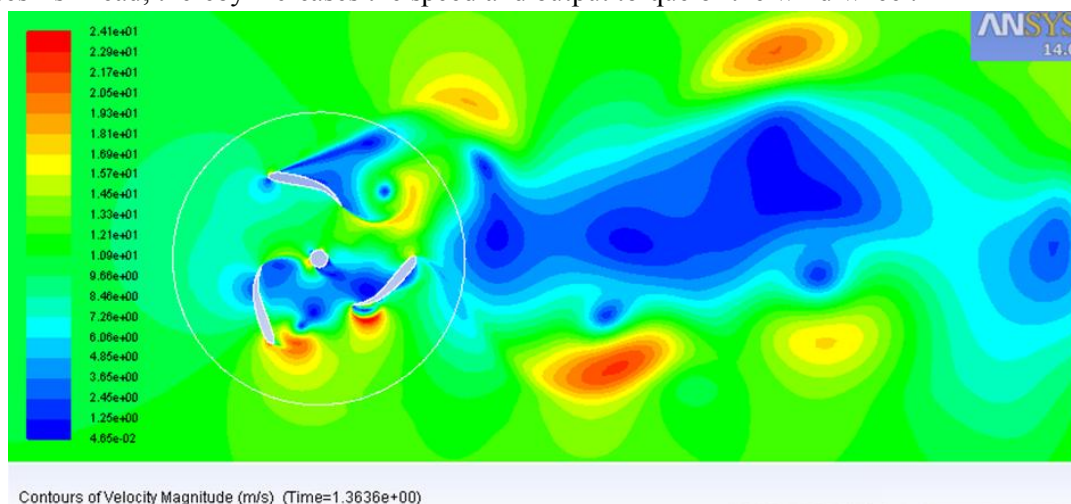


Figure 7. The velocity field (the setting angle is 38 degree)

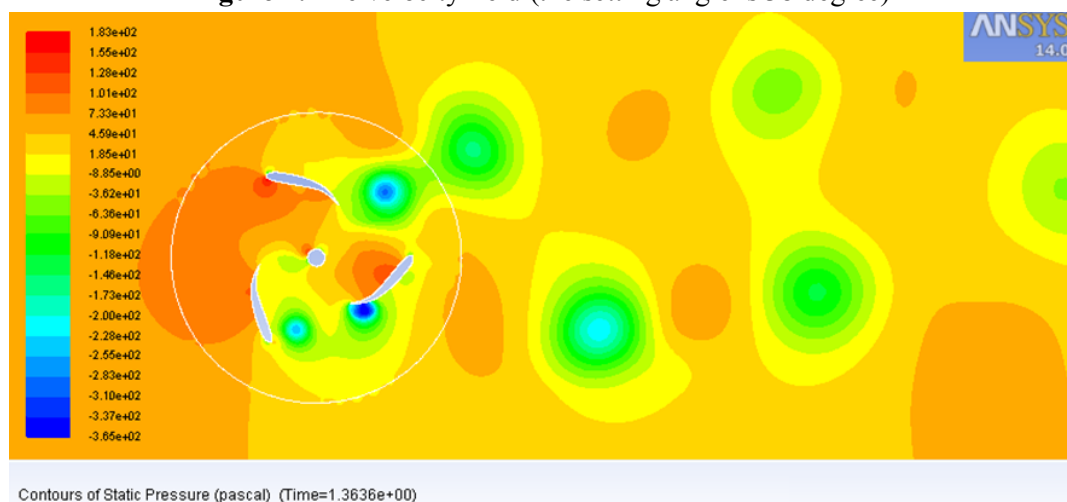


Figure 8. The pressure field (the setting angle is 38 degree)

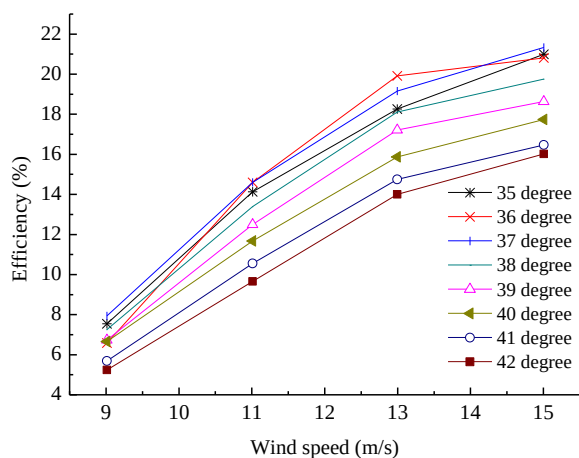


Figure 9. Relationship of wind speed and efficiency at different setting angles.

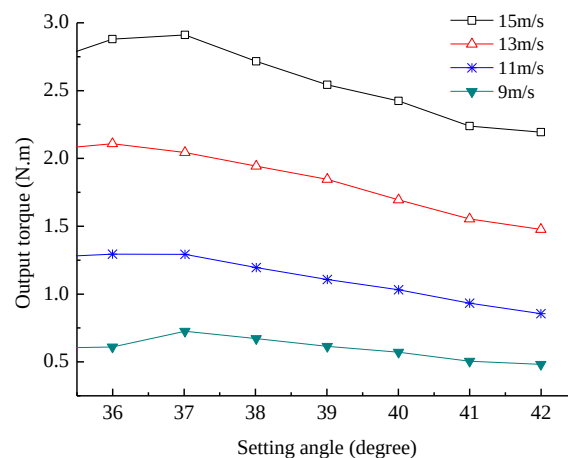


Figure 10. Relationship of setting angle and output torque.

We can see that the rotor surface pressure in the head is relatively larger in Fig.8, that is, the fish body portion and the surface inside and outside of head portion showing lift-typed wind turbine characteristics. The characteristics are related to the motion style of wind, and rotor rotation is relied on a pressure head inside and outside working surfaces; the pressure will push the rotating wind wheel, it improves the startup performance of lift-typed wind turbine because of the differential existence of pressure.

From the Figure 9, we can see that the setting angle has a greater impact on efficiency. and the setting angle is determined by the structure of the wind turbine, which affects secondary use of wind energy inside the wind wheel .

The efficiency increases obviously when wind speed goes from 9m/s to 13m/s, the efficiency increases gently when wind speed goes from 13m/s to 15m/s, and wind wheel achieves the maximum efficiency when setting angle is 37 degree.

As it can be seen from the Fig.10, the output torque of wind wheel increases at first and then decreases with the increase of setting angle.

5. Concluding remarks

The paper describes a kind of higher efficiency bionic structure wind wheel and gets wind turbine blade from bionic , then sliding mesh method of computational fluid dynamics was used to analyse the transient and dynamic performance of wind wheel. It was found that the setting angle has a direct impact on the efficiency of wind turbines and will achieve maximum efficiency in a particular installation angle.

Simulation results show that the proposed wind turbine structure has the advantage of doubled use of wind energy. The setting angle is an important factor which affects the efficiency of the wind turbine, and we can increase wind energy conversion rate by choosing the appropriate setting angle, and the angle is about 37 degrees.

Acknowledgements

We most gratefully acknowledge the financial support of the National Natural Science Foundation of China (NSFC) under grant No.71071078 & No.70671035, and the Doctoral Scientific Research Foundation of Henan University of Science and Technology.

References

- [1] Brekken T K A, Yokochi A, Jouanne A V, Yen Z Z, Hapke H M, and Halamay D A 2011 Optimal Energy Storage

- Sizing and Control for Wind Power Applications *IEEE Transactions on Sustainable Energy* **2** 69-77
- [2] Dai T, Song B, and Shu S W 2011 Study on the wind energy resources assessment in wind power generation *Management Science and Electronic Commerce (AIMSEC), 2011 2nd International Conference on Artificial Intelligence* 6804-07
- [3] Hu P, Karki R, and Billinton R 2009 Reliability evaluation of generating systems containing wind power and energy storage *IET Generation, Transmission & Distribution* **3** 783-91
- [4] Hoffman D L and Molinski T S 2009 How new technology developments will lower wind energy costs *Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium* 1-1
- [5] Hui J, Bakhshai A, and Jain P 2014 Power management supervisory control algorithm for standalone wind energy systems *2014 IEEE 36th International Telecommunications Energy Conference (INTELEC)* 1-6
- [6] Burke D J and Malley M J O 2011 Factors Influencing Wind Energy Curtailment *IEEE Transactions on Sustainable Energy* **2** 185-93
- [7] Lerch E 2007 Storage of fluctuating wind energy *2007 European Conference on Power Electronics and Applications* 1-8
- [8] Ni B and Sourkounis C 2009 Investigations on energy yield and power fluctuation from different control methods for wind energy converters at various wind conditions *2009. EPE '09. 13th European Conference on Power Electronics and Applications* 1-10
- [9] Xu X, Chen Y, Zheng Y, Bai X, Wei M, and Liu Y A 2010 Observation and Simulation of Wind Energy Resource in Jiangsu Coastal Area *2010 Asia-Pacific Power and Energy Engineering Conference (APPEEC)* 1-4
- [10] Karki R, Po H, and Billinton R 2006 A simplified wind power generation model for reliability evaluation *IEEE Transactions on Energy Conversion* **21** 533-40
- [11] Lu M S, Chang C L, Lee W J, and Wang L 2009 Combining the Wind Power Generation System With Energy Storage Equipment *IEEE Transactions on Industry Applications* **45** 2109-15
- [12] Guo Y, Hosseini S H, Tang C Y, Jiang J N, and Ramakumar R G 2013 An Approximate Wind Turbine Control System Model for Wind Farm Power Control *IEEE Transactions on Sustainable Energy* **4** 262-74
- [13] Kusiak A, Zhang Z, and Li M 2010 Optimization of Wind Turbine Performance With Data-Driven Models *IEEE Transactions on Sustainable Energy* **1** 66-76
- [14] Petersson A, Thiringer T, Harnefors L, and Petru T 2005 Modeling and experimental verification of grid interaction of a DFIG wind turbine *IEEE Transactions on Energy Conversion* **20** 878-86
- [15] Petru T and Thiringer T 2002 Modeling of wind turbines for power system studies *IEEE Transactions on Power Systems* **17** 1132-39
- [16] Dong L, Liao M, Li Y, Song X, and Xu K 2009 Study on Aerodynamic Design of Horizontal Axis Wind Turbine Generator System *2009. ICEET '09. International Conference on Energy and Environment Technology* 841-44
- [17] Schreck S J and Robinson M C 2007 Horizontal Axis Wind Turbine Blade Aerodynamics in Experiments and Modeling *IEEE Transactions on Energy Conversion* **22** 61-70
- [18] Khan S, Khan A, Irfan M, and Hussain S 2012 Aerodynamic analysis and dynamic modeling of small horizontal axis wind turbine *2012 International Conference on Robotics and Artificial Intelligence (ICRAI)* 117-24
- [19] Mesemanolis A and Mademlis C 2014 Combined maximum power point and yaw control strategy for a horizontal axis wind turbine *2014 International Conference on Electrical Machines (ICEM)* 1704-10
- [20] Murshed M, Arafat M Y, and Razzak M A 2016 Analysis of air foils and design of blades for a low-speed 250W horizontal axis wind turbine suitable for coastal areas of Bangladesh *2016 4th International Conference on the Development in the in Renewable Energy Technology (ICDRET)* 1-6

- [21] Qiu M, Zhou Z, and Zhang J 2009 Three-dimensional flow simulation for horizontal axis wind turbine 2009 *World Non-Grid-Connected Wind Power and Energy Conference* 1-5
- [22] Yu H, Zhang L, Wang J, Gao Z, and You Z 2011 The simulation and comparison of bound vortex of horizontal axis wind turbine 2011 *International Conference on Materials for Renewable Energy & Environment (ICMREE)* 575-79
- [23] Galani P A, Teixeira J C, and Guerra S M G 2015 Influence of failure rate and downtime in annual energy produced on a horizontal axis wind turbine *IEEE Latin America Transactions* **13** 2949-54
- [24] Shahariar G M H and Hasan M R 2014 Design and construction of a Vertical Axis Wind Turbine 2014 *9th International Forum on Strategic Technology (IFOST)* 326-29
- [25] Almohammadi K M, Ingham D B, Ma L, and Pourkashanian M 2015 2-D-CFD Analysis of the Effect of Trailing Edge Shape on the Performance of a Straight-Blade Vertical Axis Wind Turbine *IEEE Transactions on Sustainable Energy* **6** 228-35
- [26] Preen R J and Bull L 2015 Toward the Coevolution of Novel Vertical-Axis Wind Turbines *IEEE Transactions on Evolutionary Computation* **19** 284-94
- [27] Sharma M, Rieger B, Jou C, and Butka B 2012 Development of helical vertical axis wind turbine 2012 *Proceedings of IEEE Southeastcon* 1-5
- [28] Kumar A and Saini R P 2015 Investigation on performance of improved savonius rotor: An overview 2015 *International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE)* 151-56
- [29] Lei S, Hong-Zhao L, and Zong-Xiao Y 2015 Performance comparison for savonius type wind turbines by numerical analysis approaches 2015 *International Conference on Advanced Mechatronic Systems (ICAMechS)* 402-07
- [30] Sunyoto A, Wenehenubun F, and Sutanto H 2013 The effect of number of blades on the performance of H-Darrieus type wind turbine 2013 *International Conference on QiR (Quality in Research)* 192-96
- [31] Dai H K, Yang Z X, and Song L 2014 Mathematical modeling for H-type vertical axis wind turbine 2014 *IEEE 11th International Conference on Networking, Sensing and Control (ICNSC)* 695-700