THE PHILIPPINE-AMERICAN Academy of Science & Engineering

Characterization of the aerodynamic effects of surface modification on Magnus rotor blades using ANSYS CFX

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ABSTRACT

Past and present studies have proven that rotating cylinders can generate significantly higher lift forces in comparison to conventional aerofoil blade designs. Likewise, this generated force may be used to drive a wind turbine generator. The Magnus turbine can operate even at low wind speeds, making it perfect for urban applications. To further improve its performance, different surface modifications may be applied to the cylindrical rotor blade. In this study, a screening design of experiment was implemented to characterize the effects of different surface modifications to the lift and drag forces generated from a rotating cylinder. The experiments were run using the computational fluid dynamics simulation software ANSYS CFX. The results suggest which modification offers the highest potential for improvement. This information should provide leads for further research work on this area.

KEYWORDS: Magnus wind turbine; CFD; ANSYS CFX; aerodynamics

1 INTRODUCTION

Due to the growing demand of the world's energy source which are primarily met through fossil fuels; there is a need to expand and harness other forms of alternative energy. There are numerous advocates of increasing wind power generation over the years to ensure robust and environmental friendly response as an alternative energy source.

However, there are serious limitations for harnessing wind as means of power generation. One of the greatest limitations is the geographical barrier. Countries that do not have any coastal or hilly areas may not be able to exploit the full capacity of wind.

The Magnus wind turbine can be exploited by exhausting a wide range of velocities. The Magnus rotor would start at low-cut in wind speeds in the range of 1-2 m/s (Ito et al., 2007). Also, a Magnus turbine would naturally stall when the tip speed ratio is too high and structural damage could be avoided (Seifert, 2012; Web-1). A Magnus turbine would therefore serve as the intermediate answer which can engage in both low and high wind velocity conditions.

The Magnus wind turbine uses a new scheme wherein rotating cylinders are used instead of the conventional bladed type design (Onour et al., 2013). These cylinders would rotate on their own axis and create a rotational force by means of the Magnus force generated.

The current challenge is that there is no conclusive set of guidelines for designing the aerodynamic properties of the Magnus turbine. It is imperative for any wind turbine to maximize the lift component and reduce the drag to enhance the performance output of any given wind turbine. Magnus wind turbines possess and generate a high value of lift force compared to the streamlined aerofoils (Sedaghat, 2014). Finding the surface modification that would best enhance the lift-to-drag ratio (LDR) is the primary objective of this study. The aim of this paper is to characterize the effects of different surface modifications to obtain an enhancement in the lift and a reduction in the drag to increase the overall LDR.

2 PARAMETRIC CONSIDERATIONS

The study focuses on the lift and drag forces affecting the cylinder rotor blades of the Magnus wind turbine. Lift is the force propelling the generator and is defined in Eq. (1) as,

$$L = ½\rho V^2 A C_L \tag{1}$$

where L = lift force, V = velocity of wind flow, A = projected area of cylinder parallel to the flow, C_L = lift coefficient, and ρ = density of the fluid (Gonˇo et al., 2009).
Drag force, on the other hand, impedes the cylinder's rotation. The equation for drag force is,

$$D = ½\rho V^2 A C_D \tag{2}$$

where D = drag force, V = velocity of wind flow, A = cross-sectional area of cylinder, C_D = drag coefficient, and ρ = density of the fluid (Web-2). It should be noted that drag force acts parallel to the fluid flow (Web-3). Practical reasons for reducing drag include reducing wear and tear of turbine blades.
Illustrated in Figure 1 are the streamline flow of lift and drag forces acting on the rotating cylinder.
The concept on how the rotating cylinder and other objects like balls curve or experience lift is because of the Magnus effect theory (Briggs, 1959).

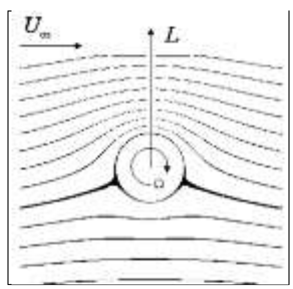

Figure 1: Magnus effect theory (Bychkov et al., 2007)

3 METHODOLOGY

3.1 Surface Modifications Considered

In this study, modifications are focused on the cylinder shape (regular cylinder vs conical frustum), surface roughness (smooth wall vs sand grain height of 2.5 mm), and structure of the surface (bump vs dimple vs none, and straight grooves vs helical grooves vs none). The summary of the levels and the factors considered in this study is shown in Table 1.
It is also important to take note that bumps have depth-to-width (k/c) ratio equal to 0.202818 and dimples have the k/c ratio equal to 0.338982 while both helical and straight grooves have the same height with reference to the surface of the blade which is 0.0375 meters. Moreover, the vertical distance between the

centers of two bumps is the same with that of the two dimples which is 0.1 meter while the pitch height between helical grooves is equal to that of straight grooves which is 0.1 meter.

Table 1 Factors and Levels Considered

Factor	*Cylinder Shape*	*Dimple or Bump*	*Surface Roughness*	*Grooves*
Levels	Regular	Circular Dimple	Smooth	Helical
	Frustum	Circular Bump	Rough	Straight
		None		None

3.2 Screening Design of Experiment (DOE)

Since this study intends to characterize the possible individual and interaction effects of the aforementioned factors, full factorial design of experiment was implemented. Each combination was simulated using the working model developed in ANSYS CFX. A total of 36 designs were generated using full factorial DOE of the four factors with their corresponding levels. Presented in Figure 2 are some of the surface modifications employed to the design of the rotor blade.

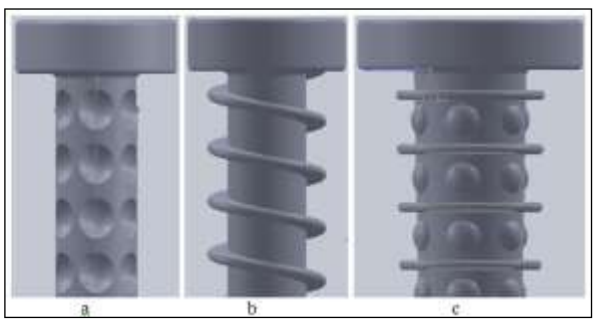

Figure 2: Some of the design geometries (a) regular-dimple, (b) regular-helical grooves, (c) frustum-bump-straight grooves. Note: Screenshots are made in different scaling.

3.3 Working Model

Each of the thirty-six geometries underwent rigorous CFD simulation using ANSYS CFX software for five different speed ratios. Since the wind velocity was held constant, the angular velocity of the rotor blade was the parameter being changed. Summarized in Table 2 are the corresponding angular velocity used for each speed ratio. The speed ratio is defined in Eq. 3 as,

$$\theta = \pi d n_c / 60V \tag{3}$$

where d = diameter in meters, n_c = angular velocity in revolutions per minute, and V = wind velocity in meters/second (Bychkov et al., 2007).
All design configurations were simulated using the working model developed and discussed in complete detail in Mara et al. (2014a, b).

Table 2 Angular Velocities Used (at wind speed of 4 m/s)

Speed Ratio	Angular Velocity, rad/s	Speed Ratio	Angular Velocity, rad/s
1.5	80	**4.5**	249
2.5	133.33	**5.5**	293.33
3.5	186.67		

3.4 Statistical Analysis

After the simulations for each cylinder design were finished and aerodynamic properties were obtained, the results were then analyzed using JMP Statistical software. A prediction model was fitted on the experiment data for analysis. A factorial degree model was used which analyzes the main effects of each model effect and also the two-way and three-way interactions between these model effects. It was ensured that all models used in the analysis had an $R^2 > 0.85$.

4 RESULTS AND DISCUSSIONS

Figures 3, 4 and 5 aim to describe the behavior of different surface modifications which significantly contribute to lift enhancement and drag reduction. An important finding was that the top effects vary in low and high speed ratios. For lift, converting the cylinder shape into a frustum was consistently the best lift enhancer for all speed ratios. Also, at low speed ratios, a dimple was more preferable than a bump. Beyond a speed ratio of 3.5, a bump becomes more effective than a dimple.

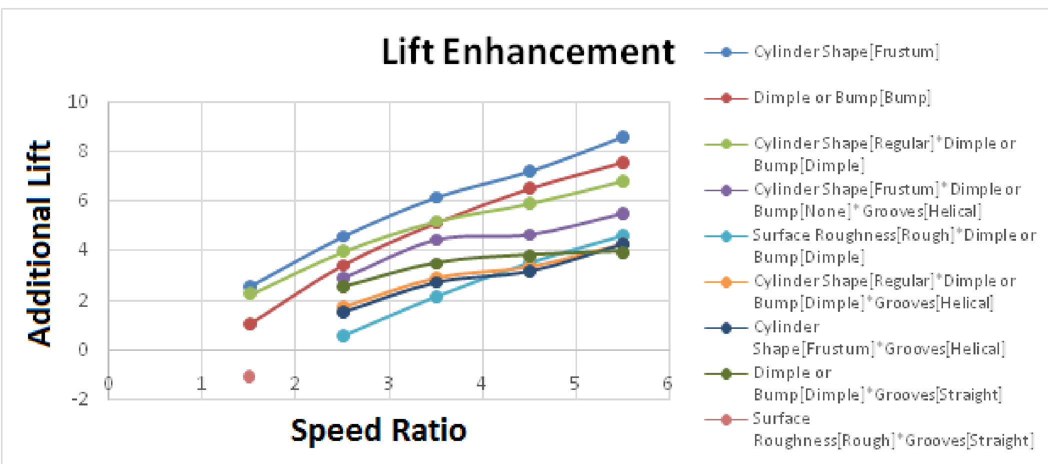

Figure 3: Estimate of additional lift provided by significant modifications

For drag, it was observed that majority of the significant effects exhibit an exponential increase in drag reduction as the speed ratio goes up. The slopes get uniform as the speed ratio goes up. Applying surface roughness is the most effective drag reducer at high speed ratios (3.5 to 5.5). At low speed ratios (< 2.5) introducing bumps has the largest drag reduction. However, it demonstrates a quadratic behaviour, as its drag reducing effect reduces significantly as it transitions to higher speed ratios (3.5 to 5.5).

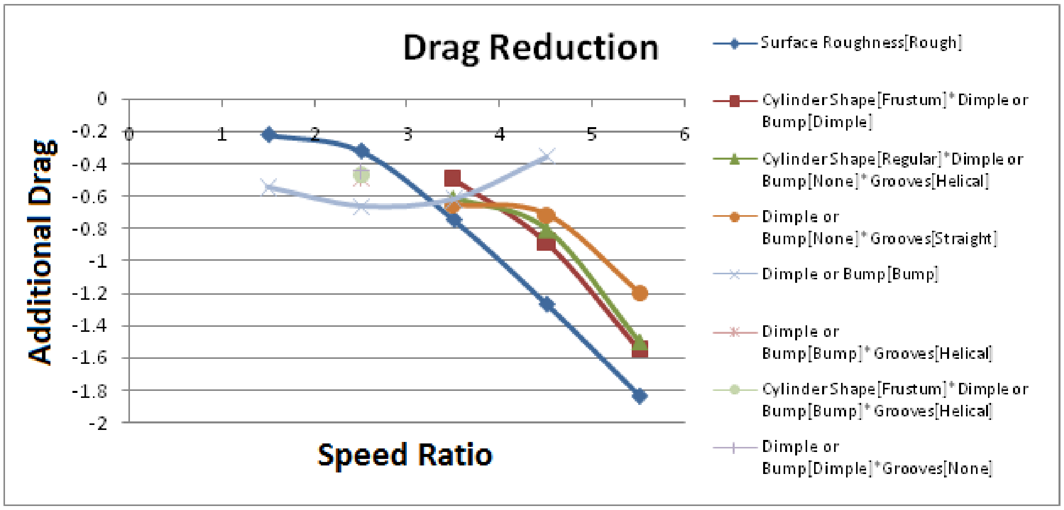

Figure 4: Estimate of additional drag provided by significant modifications

With regards to the lift-to-drag ratio (LDR), as expected, majority of model effects demonstrated a quadratic behaviour. Their contributions only peak at a certain speed ratio. Based on the LDR Enhancement plot, the bump is the most promising modification, followed by the combination of a rough, frustum cylinder with bumps.

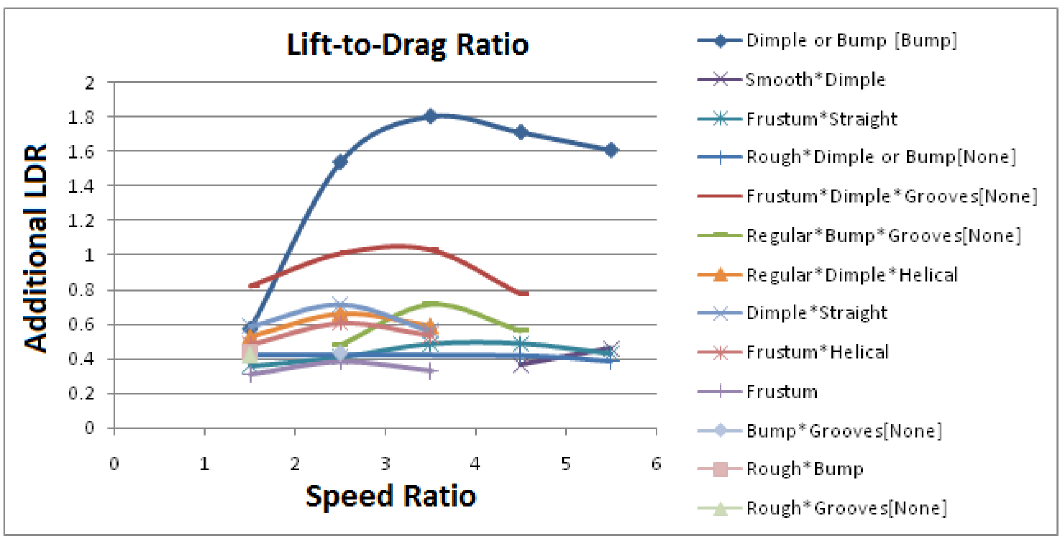

Figure 5: Estimate of additional LDR provided by significant modifications

5 CONCLUSIONAND RECOMMENDATION

With the use of full factorial design of experiment, the study was able to capture all the individual and interaction effects of different surface modifications on the aerodynamic properties of the Magnus wind rotor blade. Modifications which provided very good lift enhancement effects include frustum cylinder, bumps, and regular cylinder with dimples. Moreover, drag was reduced significantly with the use of surface roughness, bumps, frustum cylinder with dimples and regular cylinder with helical grooves. In terms of the overall effect which can be interpreted from the lift-to-drag ratio, the use of bumps was the most consistent modification, followed by using a frustum-shaped cylinder.

This study recommends pursuing higher level characterization that will vary the k/c ratio of bumps and dimples, pitch height of helical grooves, and diameter ratio of a frustum cylinder. Based on the raw data, applying surface roughness is consistently good for the aerodynamics of the Magnus wind rotor blade. Also, helical grooves will be part of the higher level characterization experiment based on previous merit from published literature. What remains to be a challenge now is that drag responds very minimally to the surface modifications we have introduced thus far.

6 ACKNOWLEDGEMENTS

The researchers would like to extend their heartfelt gratitude to the Mechanical Engineering Department of De La Salle University- Manila for providing valuable simulation and modeling resources needed in this study.

REFERENCES

Briggs, L.J. (1959). Effect of Spin and Speed on the Lateral Deflection (Curve) of a Baseball and the Magnus Effect for Smooth Spheres. National Bureau of Standards.

Bychkov, N.M., Dovgal, A.V., and Kozlov, V.V. (2007). Magnus Wind Turbines as an Alternative to the Blade Ones. Journal of Physics, 75, 012004. DOI: 10.1088/1742-6596/75/1/012004

Gonˇo, R., Rusek, S., and Hrabcˇı´k, M. (2009). Wind Turbine Cylinders with Spiral Fins. in "8th EEEIC International Conference on Environment and Electrical Engineering," Karpacz, Poland.

Ito, A., Kawashima, S., Nishizawa, Y., and Komatinovic, N. (2007). A Study on Savonius Magnus Wind Turbine. Ashikaga Institute of Technology.

Mara, B.K., Mercado, B.C., Mercado, L.A., Pascual, J.M., and Lopez, N.S. (2014a). Development and Validation of a CFD Model using ANSYS CFX for Aerodynamics Simulation of Magnus Wind Rotor Blades. in "7th International Conference Humanoid, Nanotechnology, Information Technology Communication and Control, Environment and Management (HNICEM)," Palawan, Philippines.

Mara, B.K., Mercado, B.C., Mercado, L.A., Pascual, J.M., and Lopez, N.S. (2014b). Preliminary Turbulence Model Validation for Flow Across Rotating Cylinders using ANSYS CFX for Aerodynamics Simulation of Magnus Wind Rotor Blades. in "7th International Conference Humanoid, Nanotechnology, Information Technology Communication and Control, Environment and Management (HNICEM)," Palawan, Philippines.

Onour, K.H., Sedaghat, A., and Samani, I. (2013). Innovative Design of Aerofoil Magnus Type Horizontal Axis Wind Turbines.

Sedaghat, A. (2014). Magnus Type Wind Turbines: Prospects and Challenges in Design. Renewable Energy, 62, 619-628.

Seifert, J. (2012). A Review of the Magnus Effect in Aeronautics. Progress in Aerospace Sciences, 55, 17-45.

Web sites:

Web-1: http://reuk.co.uk/Wind-Tip-Speed-Ratio.htm, consulted on September 2014

Web-2: http://www.grc.nasa.gov/WWW/k-12/airplane/drageq.html, consulted on September 2014

Web-3: http://science.howstuffworks.com/environmental/green-science/wind-power3.htm, consulted on November 2, 2014.