UNIVERSITI PUTRA MALAYSIA

AERODYNAMIC PERFORMANCE OF MAGNUS WIND TURBINE WITH TURBINE SUPPORTIVE STRUCTURE

AMER M. MAGAIDI

AERODYNAMIC PERFORMANCE OF MAGNUS WIND TURBINE WITH TURBINE SUPPORTIVE STRUCTURE

By

AMER M. MGAIDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2019

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

AERODYNAMIC PERFORMANCE OF MAGNUS WIND TURBINE WITH TURBINE SUPPORTIVE STRUCTURE

By

AMER M. MGAIDI

June 2019

Chairman : Associate Professor Azmin Shakrine Mohd Rafie, PhD
Faculty : Engineering

After going through a detailed literature review, it is perceived that the Magnus wind Turbine (MWT) can be a viable option for off grid energy conversion in certain cases of confined space and low wind speed region, where the counterpart of MWT cannot operate efficiently, However, the existing design is yet a matter of research to make it more useful in particular situation. In view of this, the main aim of present study is to improve the aerodynamic performance of MWT through adding a support structure for reduce the impact of free end status of the rotary cylinders on their aerodynamic characterises, where free end status of the cylinders depletes consumed power that uses to spin the cylinders through its impact in reduce the actual rate of cylinders rotation, and hence their tip speed ratio whose low value causes a poor performance of rotary cylinders. To overcome the above undesirable condition, this study suggests modifying magnus rotor through surrounding magnus wheel with an outer ring supported in an analogously order by supporting arms. Currently many research studies have concentrated on improving the aerodynamic performance of wind turbine through numerical, analytical and experimental studies. Computational Fluid Dynamics (CFD) offers inexpensive tool to aerodynamic blade analysis problem. Furthermore, Blade Element Moment (BEM) represents the most simplified common way to predict the overall performance of wind turbines. On the other hand, experimental studies represent the quickly assess of the computed predictive results. 2D Ansys Fluent 17.0 as a code of CFD was selected to analysis the fluid flow around the aerodynamic surfaces of the new rotor in order to predict the effectiveness of new design in improving the aerodynamic performance of MWT, where 2D simulation can provide a good result features of the fluid flow with lesser computational cost. Thereafter, BEM was directed to predict the overall performance of new designed in terms of cut-in speed and generated torque. On the other hand, experimental tests were chosen to perform on a real model of new MWT. Computed results have expected of an increase in lift force by up to 14 % which demonstrated the effectiveness of new design to improve the performance. Besides that, Analytic results of new MWT was

indicated firstly to that, the cut-in velocity decreases as the λ_2 increases in the specified range of $\lambda_2 \leq 2.8$. Also, the generated torque increases in effect of increasing both of wind speed and rotating rate of cylinders at delimited rang of 7.7 m/s and 2520RPM respectively. On other hand, experimental tests demonstrated the effect of tip speed ratio of cylinders (λ_2) on the effectiveness and variation of produced torque. Finally, the obtained results have also achieved the performance of $C_P = 0.47$ at λ_1 of 0.17, as well as disappearance of exhibiting the spinning motion of the cylinders in bell shape.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MENINGKATKAN PRESTASI AERODINAMIK TURBIN ANGIN MAGNUS MELALUI PENAMBAHAN SOKONGAN BULATAN LUAR

Oleh

AMER M. MGAIDI

Jun 2019

Pengerusi : Profesor Madya Azmin Shakrine Bin Mohd Rafie, PhD
Fakulti : Kejuruteraan

Setelah melalui kajian literatur yang terperinci, dapat dinyatakan bahawa Turbin Angin Magnus (MWT) boleh dijadikan satu pilihan yang baik untuk penukaran tenaga luar grid bagi kes-kes tertentu seperti ruangan terhad dan kawasan halaju angin yang rendah, di mana turbin angin yang sejenis dengan MWT tidak dapat beroperasi dengan cekap. Namun, reka bentuk yang sedia ada masih lagi merupakan satu perkara penyelidikan untuk menjadikannya lebih berguna dalam keadaan tertentu. Oleh itu, matlamat utama kajian ini adalah untuk menyiasat prestasi aerodinamik MWT dengan penambahan struktur sokongan untuk mengurangkan kesan pergerakan bebas pada hujung silinder berputar terhadap ciri aerodinamik mereka, di mana daya aerodinamik telah dipengaruhi oleh gegaran silinder berputar yang disebabkan oleh tekanan turun naik yang besar. Untuk mengatasi keadaan yang tidak diingini di atas, kajian ini mencadangkan untuk mengubahsuai rotor Magnus melalui mengelilingi bulatan rotor Magnus dengan struktur luar yang bertindak sebagai menyokong lengan, di mana beberapa tenaga yang digunakan untuk memutarkan silinder itu habis kerana kesan akhir percuma, yang membawa kepada penurunan kadar pusing silinder sebenar, dan kemudian nisbah kelajuannya .Ketika ini banyak kajian penyelidikan tertumpu pada peningkatan prestasi aerodinamik turbin angin menerusi kajian berangka, analitikal dan eksperimen. Komputasi dinamik bendalir (CFD) menawarkan perkakasan yang murah untuk permasalahan analisis aerodinamik bilah. Manakala, momen unsur bilah (BEM) memperkenalkan cara umum yang paling mudah untuk menjangkakan prestasi keseluruhan turbin angin. Sebaliknya, kajian eksperimen mewakili cara paling cepat menilai hasil jangkaan yang dihitung. 2D Ansys Fluent 17.0 telah dipilih sebagai kod CFD untuk menganalisa aliran bendalir di sekeliling permukaan aerodinamik rotor yang baru untuk mengkaji keberkesanan reka bentuk tersebut dalam meningkatkan prestasi aerodinamik MWT, di mana simulasi 2D dapat memberikan hasil yang baik terhadap ciri-ciri aliran bendalir dengan kos pengiraan yang lebih rendah. Selepas itu, BEM digunakan untuk mengenalpasti prestasi keseluruhan reka bentuk yang baru dari segi halaju permulaan dan kilasan yang dihasilkan. Sebaliknya, ujian eksperimen telah

dipilih untuk melaksanakan analisis prestasi model sebenar MWT yang baru. Hasil keputusan yang dikira telah menunjukkan peningkatan daya angkat sebanyak 14% yang mana menunjukkan keberkesanan reka bentuk baru bagi meningkatkan prestasi turbin angin MWT. Selain itu, keputusan analitik bagi MWT yang baru ditunjukkan terlebih dahulu, di mana halaju permulaan menurun apabila λ_2 meningkat dalam julat yang dinyatakan $\lambda_2 \leq 2.8$. Kilasan yang dijana meningkat berikutan peningkatan kedua-dua halaju angin dan kadar pusingan silinder pada julat batas masing-masing 7.7 m/s dan 2520 RPM. Sebalik itu, ujian eksperimen menunjukkan kesan nisbah halaju hujung silinder (λ_2) ke atas keberkesanan dan variasi kilasan yang dihasilkan. Akhir sekali hasil yang diperoleh juga telah mencapai prestasi $C_P = 0.47$ pada $\lambda_1 = 0.17$, serta menunjukkan kehilangan pergerakan silinder berputar dalam bentuk loceng.

ACKNOWLEDGEMENTS

Praise be to Allah for all the blessings and from what he has been guided me towards developing my abilities in the way of science, which he has ordered us in his holy book Al-Quran Al-Kareem.

I would like to thank my thesis supervisors and mentors, Associate Professor Dr. Azmin Shakrine Mohd Rafie, Associate Professor Ir. Dr. Kamarul Arifin Bin Ahmad, and Associate Professor Dr. Rizal Bin Zahari for their immeasurable support, guidance, and insight. The completion of this thesis would not have been possible without their moral and educational support. I greatly appreciate their availability and approachability as they were key in overcoming many obstacles faced during this thesis. They served as an inspiration and allowed me to produce the best work possible. One could not wish for a better supervisory Committee.

I wish to express my sincere gratitude to Dr Omar Faruqi Bin Marzuki, and Mr. Saffairus Salih for their help in my experiments, and to the Library staff at faculty of engineering. I truly appreciate their unconditional help.

I am grateful too for the support and advice from my dear family for their supportive relationship and positive outlook that has been meaning a lot to me.
It has been a wonderful experience working with all of you!

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ______________________ Date: ________________

Name and Matric No : Amer M. Magaidi, GS37821

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ______________________________

Name of Chairman of Supervisory Committee: Associate Professor Dr. Azmin Shakrine Mohd Rafie

Signature: ______________________________

Name of Member of Supervisory Committee: Associate Professor Dr. Kamarul Arifin Ahmad

Signature: ______________________________

Name of Member of Supervisory Committee: Associate Professor Dr. Rizal Zahari

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a_1	Axial Indictor Factor
a_2	Radial Indictor Factor
AR	Aspect ratio
B	Number of blades
C_D	Drag coefficient
C_L	Lift coefficient
C_Q	Torque coefficient
C_P	Power coefficient
d	Diameter of the cylinder
P_∞	Atmospheric pressure
P	Mechanical produced power
Q	Generated Torque
R	Diameter of the rotor
R_g	Universal gas constant
Re	Reynolds number
S	Rotor Swept Area
S_{ref}	Reference Area
T	Atmospheric temperature
U_∞	Wind speed
c	Chord of airfoil
h	Height of airfoil
t	Thickness of airfoil
α	Angle of attack
β	Angle of relative wind speed

δ	Boundary layer thickness
μ	Viscosity
ρ	Density
ν	Kinematic viscosity
Ω_2	Angular Velocity of Cylinder
Ω_1	Angular Velocity of Rotor
λ_2	Tip speed ratio of cylinder
λ_1	Tip speed ratio of Rotor

LIST OF ACRONYMS

2D	Two Dimensional
3D	Three Dimensional
BEM	Blade Element Momentum
CFD	Computational Fluid Dynamic
EFD	Experimental Fluid Dynamic
HAWT	Horizontal Axis Wind Turbine
GIT	Grid Independency Test
NACA	National Advisory Committee for Aeronautics
NREL	National Renewable Energy Laboratory
OBWT	Open Jet Wind Tunnel
VAWT	Vertical Axis Wind Turbine

CHAPTER 1

INTRODUCTION

1.1 Background

The extraction of energy from the wind defines one of the major sources of alternative energies. Wind energy as a source of the power is being favoured widely as an alternative to fossil fuels, as it is renewable, plentiful, clean, and so widely distributed. Wind turbine is a configuration, which transforms the kinetic energy from the wind into mechanical energy that can be used to generate electricity via a mechanical rotor, a drive train and a generator (Biadgo, 2017). Several types of wind turbines have been developed in some of categories such as the number of blades and rotating axis orientation, where horizontal axis wind turbines (HAWT) have been widely used due to the advantage of highly efficient in terms of extracted energy. Magnus rotor knows one of the main types that belong to HAWT kind. It distinct from other types by spinning cylinder that creates a whirlpool of fluid around itself and generates a lift force perpendicular to the flow direction as its boundary layer is influenced (Ramjatan and Fitz-coy, 2018), where the producing force defines the Magnus lift force, that has been much larger than streamlined airfoils (Gupta et al., 2017; Borg, 1986). This has motivated a large number of researchers and scientist to use the Magnus lift in aerospace, naval, and wind turbine industries.

From its very inception, the beginning of Magnus effect goes back to the early of nineteen- century when it was used to propel a ship using the Magnus force (De Marco et al., 2016; Nuttall and Kaitu, 2016). Given the success it had by generating high values of lift forces on spinning cylinders compared with airfoil. Flettner rotor was not commercialized due to low fuel prices at that time (De Marco et al., 2016). The potential of generating high lift forces then attracted many researchers in engineering applications, where many patents on using of Magnus forces were appeared. However, very few configurations were operated successfully. The renew interest in the Flettner device is becoming again a hot topic in naval engineering due to the increase in fuel costs and problems of environmental pollution.

Continually to research in related areas, researchers have been compelled to study more about the application of this physical phenomenon. As a result, the Magnus wind turbine which follows the Magnus effect theory had gained proportionate popularity in recent years as a new method of harnessing and exploiting wind for power generation (Bychkov and Dovgal, 2008). The technology actually solves the location-constraint encountered by traditional wind turbines due to the idea that the configuration can operate even at low wind speeds, which is the case in urban areas. Due to these benefits, Magnus wind turbine offers great potential in producing power as an evolving renewable energy, especially in low wind speed countries like Malaysia.

In the broader scope, use of Magnus effect in wind turbine is appeared in Russia and Japan in past decade. Japanese Akita Magnus Association proved that a wind turbine could rotate in effect of the mentioned phenomena Magnus impact, their cylindrical blades were necessary to spin by electric motors (Borg, 1986; Seifert, 2012).

1.2 Problem Statement

Compatible with development of modern life in all fields, the demand of energy has increased significantly. An estimation data by the International Energy Agency IEA (2014) mentioned to that over 80 percent of the world's total energy production results from the burning of fossil (Tietenberg and Lewis, 2016), and with the huge increasing consumption of energy in the world today, the focus of reliable may hurt to risk depletion of this source, Fossil fuels besides is limited , also it takes millions of years to form. In addition to the risk of depletion of fossil fuel, the increase in fuel price is another factor of the problem of energy sources, and more importantly, the factor of environmental pollution; where studies have shown that exceeds the amount of 35 billion metric tonnes of carbon monoxide has been escalating into the atmosphere yearly as a result of fuel combustion (Perera, 2017), that could pose other risks to environment and the balance of nature. Therefore, all of the above are mainly reasons that have promoted the human populations to search for alternative sources of energies and encouraged them to develop through engineering applications in accordance with the applied research and specialized studies and be at the same time are not harmful to nature.

Being one of the alternative energy sources, wind energy has therefore aroused a great deal of interest. Wind energy systems have been improved rapidly and advanced considerably to become an essential energy source. There are still researches and projects in process aiming to improve the wind energy systems and make a more efficient use of the wind rotors which could define the most important part of the wind power stations. Consequently, a number of different wind rotors and configurations have been designed, tried and used during this period. Large amounts of research and resources have been spending in order to improve the performance of wind turbines through determining of optimum specifications that should suite to certain operating conditions (Gupta et al., 2017 ; Pujol et al., 2018; Sedaghat, 2014; Sedaghat et al., 2014). According to some of guidelines and specific restrictions of the researches on the Magnus rotor specifications as a configuration, it could classify through the factors that has effect on the amount of power extracted, Power generated through applications of wind turbines mainly dependent on the size of the turbine, the wind speed and wind direction. This means that this source of renewable energy is not a stable supply of energy and requires creating some of modification to achieve the requests through special researches. According to the above causes and effects with some of a brief detail, there was a comprehensive incentive in searching to provide a new source of energy. At the same time, a relative underperformance of spindle cylinders within the region of a low- speeds in effect of lift force and the negative impact of flow-induced vibrations in terms the risks of vibrations arising particularly on rotary cylinders, have highlighted to special importance to the field of aerodynamics. Both reasons have embodied an incentive encouraging for researchers to contest the searching development for spindle cylinders and Magnus rotor through proceeding of some modifications to the geometrical configuration in order to achieve improved performance. As the free end rotating cylinders is the main tool for generating lift and then producing torque in MWT, the free end status of magnus rotary cylinder is the cause of depletion in consumed power that used to spin the cylinders, which lead to reduce the available rotational speed of cylinders and thus their speed ratio that considers one of the main factors determining the effectiveness of the rotating cylinders and their aerodynamic characteristics. Besides that, each cylinder exhibit alternating vortex shedding causing large fluctuating pressure force that could lead to structural failure.

Therefore, the present work is aimed to overcome the above deficiency through new design of surrounding magnus rotor with an outer ring supported in an analogously order by beams or supporting arms mounted on the hub of the rotor, in order to transfer the consumed power to spin the cylinders without depletion by preventing the emergence of each cylinder's spinning motion in bell shape that refers to the issue of power depletion. As the damping amplitude arising, the aerodynamic characteristics of the rotary cylinders predicated to be directly influenced, where the fluctuation of the generator lift force has been increased and hence the quality of the generated torque and produced power. Commonly there is no power generation without angular speed and a gyre torque, hence, there is no torque without aerodynamic forces.

1.3 Aims and Objectives

The main aim of this research work is to study the aerodynamic performance of the design of MWT through the implementation of numerical and analytic studies and then experimental, through which to investigate the effectiveness of new added support structure. Therefore, to achieve the above aim four objectives have to be achieved in the following sequence:

- To design new MWT by adding the support structure in order to improve the performance through reducing the depletion of consumed power.
- To investigate the aerodynamic characteristics of new MWT using computational method in terms of lift force generated on cylindrical blades and supporting arms.
- To analyse the performance of new MWT using BEM method due to the complexity of the computational method.
- To conduct the experimental work in order to validate the BEM method and obtain predictive results that can contribute for estimation of wind turbine performance. performance.

1.4 Scopes of Study

The limitation of the research could be mainly summarized in

- The specifications of both of chosen work section of Open Jet Wind tunnel at aerodynamic laboratory in University Putra Malaysia and used power supply to spin the rotating cylinder. Where the cross-section area of circular geometrical shape with diameter of 2.0 m and delimited range of wind speed of less than or equal 7.74m/s were identified the specifications of mentioned work section. Besides that, the wind flow was assumed to be uniform in order to simplify analysing computed results and obtained experimental results, where the velocity inlet represents one of major input parameters in both of CFD code, BEM and experimental tests; as well the influence of some other relevant factors that included the drag force and the effect of the hub dimensions on the performance of the rotor was ignored.
- As all modern electricity-generating wind turbines use the lift force derived from the blades to drive the rotor and generate the torque, of interest was directed to compute the lift force, where MWT mainly rotate due to exertion of lift force generated on the cylindrical blades when they rotate around a main horizontal shaft.
- On the other hand, the maximum an available power to spinning the cylinders of 0.84W was represent the other major limitation source in this research work. Moreover, there were dependent limitations in some of performance parameters such as rotor tip speed ratio, tip speed ratio of cylinders and Reynolds number, where the mentioned limitation was on the range of results limitation and not on their effectiveness and importance

1.5 Organization of the Thesis

This thesis has been organized in five chapters, the details of which could be summarized following:

Chapter 1: Introduction that includes background, problem statement, aims and Objectives, scopes of study and the organization of the thesis.

Chapter 2: Literature review which chosen to present a brief on wind turbines, then moves to historical evolution of magnus wind turbine, and then displays the aerodynamic components of magnus rotor.

Chapter 3: methodology, it includes calibration of wind flow speed at work section, 3.3.Technical specification of new Magnus rotor, three chosen approaches of numerical, analytical and experimental. Where numerical approach includes Information about turbulence models, geometrical design using of work bench Ansys, domain details, the boundary conditions, grid independence test and parametric study on Sn-airfoil, while analytical approach include Information about blade element theory and determine the aerodynamic performance of new magnus wind turbine. On the other hand, the experimental approach covers the fabrication of new magnus turbine equipment setup and the experiment methods.

Chapter 4: results and discussion: this chapter presents analysis and discussion of obtained results, and also the computed and experimental results were Compared. This chapter is important to validate the solver used and also to choose the most suitable turbulence model for further simulations.

Chapter 5: conclusion and future work, where concluding remarks are stated and recommendations for future work are addressed.

REFERENCES

Aftab, S. M. A. (2017). *Numerical Experimental Study of Leading Edge Turbercles with Vortex Generators on NACA 4415 Airfoil*. Electronic PhD Theses and Dissertation, University Putra Malaysia.

Ahmadi-baloutaki, M. (2015). *Analysis and Improvement of Aerodynamic Performance of Straight Bladed Vertical Axis Wind Turbines*. Electronic PhD Theses and Dissertation, University of Windsor. Retrieved from https://scholar.uwindsor.ca/etd Recommended

Elmiligui, A., Abdol-Hamid, K., Massey, S., & Pao, S. (2004, August). Numerical study of flow past a circular cylinder using RANS, Hybrid RANS/LES and PANS formulations. In *22nd Applied aerodynamics conference and exhibit* (p. 4959).

Alias, M. S., Rafie, A. S., Marzuki, O. F., Hamid, M. F., & Chia, C. C. (2017, December). Two dimensional numerical analysis of aerodynamic characteristics for rotating cylinder on concentrated air flow. In *Materials Science and Engineering Conference Series* (Vol. 270, No. 1, p. 012003).

Ali, M. H. (2013). Experimental Comparison Study for Savonius Wind Turbine of Two & Three Blades at Low Wind Speed. *International Journal of Modern Engineering Research*, *3*(5), 2978–2986.

Aneesh, D. S., Stanly, R., S, B. S., Suneesh, S. S., & D, Z. (2016). Numerical Analysis of Magnus Wind Turbine. In *7th International Conference on Mechanical and Aerospace Engineering* (pp. 191–195).

Badalamenti, C., & Prince, S. (2008, August). Effects of endplates on a rotating cylinder in crossflow. In *26th AIAA Applied Aerodynamics Conference* (p. 7063).

Bai, C., Wang, W., Chen, P., & Chong, W. (2014a). The Design of Turbine Blades with an Axial-Flux Permanent Magnet Generator. *Energies*, *7*, 773–793.

Balat, M. (2009). A review of modern wind turbine technology. *Energy Sources Part A Recovery Utilization and Environmental Effect*, *31*(17), 1561–1572.

Bai, T., Liu, J., Zhang, W., & Zou, Z. (2014b). Effect of surface roughness on the aerodynamic performance of turbine blade cascade. *Propulsion and Power Research*, *3*(2), 82–89. https://doi.org/10.1016/j.jppr.2014.05.001

BAPE. (2013). *Benchmarking of small and mediums size wind turbine technologies and legal framework. Baltic Energy Conservation Agency*. Retrieved from www.swipproject.eu

Beller, C. (2011). *Urban Wind Energy*. Electronic PhD Theses and Dissertation, Technical University of Denmark.

Bhutta, M. M. A., Hayat, N., Farooq, A. U., Ali, Z., Jamil, S. R., & Hussain, Z. (2012). Vertical axis wind turbine–A review of various configurations and design techniques. *Renewable and Sustainable Energy Reviews*, *16*(4), 1926-1939.

Biadgo, A. M. (2017). Aerodynamic Design of Horizontal Axis Wind Turbine Blades. *FME Transactions*, *45*, 647–660. https://doi.org/10.5937/fmet1704647M

Bourguet, R., & Jacono, D. Lo. (2014). Flow-induced vibrations of a rotating cylinder. *Journal of Fluid Mechanics*, *740*, 342–380. https://doi.org/10.1017/jfm.2013.665

Bulat, M. P. B. and P. V. (2013). Comparison of Turbulence Models in the Calculation of Supersonic Separated Flows. *World Applied Sciences Journal*, *27*(10), 1263–1266. https://doi.org/10.5829/idosi.wasj.2013.27.10.13715

Bychkov, N. M. ; Dovgal, A. V. and Kozlov, V. V. (2007). Magnus wind turbines as an alternative to the blade ones. *Journal of Physics*, (Conf. Ser. 75 012004), 1–8. https://doi.org/10.1088/1742-6596/75/1/012004

Bychkov, N. M., Dovgal, A. V., & Sorokin, A. M. (2008). Parametric optimization of the Magnus wind turbine. In *International Conference Methods Aerophysical Research (ICMAR), Akademgorodok, Novosibirsk, June* (p. 5).

Cao, H. (2011). *Aerodynamics analysis of small horizontal axis wind turbine blades by using 2D and 3D CFD modelling*(Doctoral dissertation, University of Central Lancashire).

Canonsburg, T. D. (2010). *ANSYS Meshing User's Guide*.

Cheng, M., Chew, Y. T., & L, S. C. (1994). Discrete vortex simulation of the separated flow around a rotating circular cylinder at high Reynolds number. *Finite Elements in Analysis and Design*, *18*, 225–236.

Chong, T. P., Joseph, P. F., & Davies, P. O. A. L. (2009). Design and performance of an open jet wind tunnel for aero-acoustic measurement. *Applied Acoustics*, *70*(4), 605–614. https://doi.org/10.1016/j.apacoust.2008.06.011

Chun, S. (2005). Air Speed Measurement Standards Using Wind Tunnels. In *Wind Tunnels and Experimental Fluid Dynamics Research*. Korea: www.intechopen.com.

Corrêa, L. C., Lenz, J. M., Ribeiro, C. G., Trapp, J. G., & Farret, F. A. (2013). Maximum power point tracking for Magnus wind turbines. In *IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society*.

Dimotakis, P. T. T. and P. E. (1993). The lift of a cylinder executing rotary motions in a uniform flow. *J. Fluid Mech.*, *255*, 1–10.

Divya, S., & Joseph, J. (2014). A Brief Review on Recent Trends in Alternative Sources of Energy. *International Journal of Electrical and Computer Engineering*, *8*(2), 389–395.

Douak, M., & Aouachria, Z. (2015). Starting Torque Study of Darrieus Wind Turbine. *International Journal of Physical and Mathematical Sciences*, *9*(8), 476–481.

Gowree, E. R., & Prince, S. A. (2012). A computational study of the aerodynamics of a spinning cylinder in a crossflow of high Reynolds number. *In Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS'12*) (pp. 1138-1147).

Driss, Z., Mlayeh, O., Driss, D., Maaloul, M., & Abid, M. S. (2014). Numerical simulation and experimental validation of the turbulent fl ow around a small incurved Savonius wind rotor. *Energy*, *74*, 506–517. https://doi.org/10.1016/j.energy.2014.07.016

Elfarra, M. A. (2011). *Horizontal Axis Wind Turbine Rotor Blade: Winglet and Twist Aerodynamic Design and Optimization Using CFD*. *PhD dissertation, Middle East Technical University*.

EL AKOURY, R., BRAZA, M., PERRIN, R., HARRAN, G., & HOARAU, Y. (2008). The three-dimensional transition in the flow around a rotating cylinder. *Journal of Fluid Mechanics*, *607*, 1-11.

Erich Hau, H. von R. (2013). *Wind turbines, fundamentals, technologies, application, economics*. *fundamentals, technologies, application*. London.

Giudice, F., & La Rosa, G. (2009). Design, prototyping and experimental testing of a chiral blade system for hydroelectric microgeneration. *Mechanism and Machine Theory*, *44*(8), 1463-1484.

Faruqi, O., Azmin, M., Mohd, S., Izzuddin, F., Kamarul, R., & Ahmad, A. (2017). Magnus wind turbine : the effect of sandpaper surface roughness on cylinder blades. *Acta Mech*, *229*, 71–85. Retrieved from https://doi.org/10.1007/s00707-017-1957-6

Ganapol, B. D. (2010). Highly Accurate Solutions of the Blasius and Falkner-Skan Boundary Layer Equations via Convergence Acceleration. *Mathematical Physics*, 27. https://doi.org/arXiv:1006_3888{math-ph}

Gasch R. and Twele J.(2012). Historical development of windmills. In *Wind Power Plants: Fundamentals, Design, Construction and Operation* (p. 28). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-22938-1

Gupta, Y., Dumon, J., & Hably, A. (2017). Modeling and control of a Magnus effect-based airborne wind energy system in crosswind maneuvers. In *International Federation of Automatic Control* (Vol. 50, pp. 13878–13885). Elsevier B.V. https://doi.org/10.1016/j.ifacol.2017.08.2205

Hara, Y., Hara, K., H. T. (2012). Moment of inertia dependence of vertical axis wind turbines in pulsating winds. *International Journal of Rotating Machinery*, *2012*, 1–12. https://doi.org/10.1155/2012/910940

Henderson, D. B. and R. D. (1996). Three-dimensional Floquet stability analysis of the wake of a circular cylinder. *Journal Fluid Mech.*, *322*, 215–241.

Heseltine, J. L. (2003). *Flow Around a Circular Cylinder with a Free End*. Electronic Msc Theses and Dissertation,University of Saskatchewan Saskatoon.

Hoffman J, J. C. (2007). *Computational turbulent incompressible flow*. Springer. Retrieved from http://www.csc.kth.se/~jhoffman/pub/v4

Holden, D., Socha, J. J., Cardwell, N. D., & Vlachos, P. P. (2014). Aerodynamics of the flying snake Chrysopelea paradisi: how a bluff body cross-sectional shape contributes to gliding performance. *Journal of Experimental Biology*, *217*(3), 382-394.

Houghton, E. L., & Carpenter, P. W. (2003). *Aerodynamics for engineering students*. Elsevier.

Howell, R., Qin, N., Edwards, J. and D. (2010). Wind tunnel and numerical study of a small vertical axis wind turbine. *Renewable Energy*, *35 No.2.*, 412–422.

Hsiao, F., Bai, C., & Chong, W. (2013). The Performance Test of Three Different Horizontal Axis Wind Turbine (HAWT) Blade Shapes Using Experimental and Numerical Methods. *Energies*, *6*, 2784–2803. https://doi.org/10.3390/en6062784

Ingram, G. (2011). *Wind Turbine Blade Analysis using the Blade Element Momentum Method*. Retrieved from http://www.dur.ac.uk/g.l.ingram

Jacobs, G. (1998). *Performance of two permanent magnet generators For use with small windchargers*. *Renewable Energy Development vof* (Vol. 5).

Jamieson, P. M. (2009). Beating Betz - Energy Extraction Limits in A Constrained Flow Field. *Journal of Solar Energy Engineering*, 1–19.

Jinbo, M., Junior, G. C., Farret, F. A., Hoss, D. L., & Dreher, J. R. (2015). MPPT for Magnus wind system with DC servo drive for the cylinders and boost converter. *Journal of Wind Energy.* 1-10

John Borg. (1986). *Magnus Effect - An Overview of Its Past and Future Practical Applications*.

Johnson, N. D. (2011). *High-Reynolds Number Flow Past a Rotating Cylinder With and Without Thom Discs* (Doctoral dissertation, The University of Manchester (United Kingdom)).

Karabelas, S. J., Koumroglou, B. C., Argyropoulos, C. D., & Markatos, N. C. (2012). High Reynolds number turbulent flow past a rotating cylinder. *Applied Mathematical Modelling*, *36*(1), 379–398. https://doi.org/10.1016/j.apm.2011.07.032

Khadir, L., & Mrad, H. (2015). Numerical investigation of aerodynamic performance of darrieus wind turbine based on the magnus effect. *Int. Jnl. of Multiphysics*, *9*(4), 383–396.

Kullmann, F. (2015). *Efficiency and Functionality of A Contra-Rotating Wind Turbine*. Satakunta University of Applied Sciences.

Launder, B. . and S. D. . (1974). The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering*, *Vol. 3*, 269–289.

Leble, V., & Barakos, G. (2016, September). Forced pitch motion of wind turbines. In *Journal of Physics: Conference Series* (Vol. 753, No. 2, p. 022042). IOP Publishing.

Leishman, J. G., Bhagwat, M. J., & Bagai, A. (2002). Free-vortex filament methods for the analysis of helicopter rotor wakes. *Journal of aircraft*, *39*(5), 759-775.

Li, Y., Li, M., & Jiang, F. (2017, September). Transient vibration of wind turbine blades. In *IOP Conference Series: Materials Science and Engineering* (Vol. 242, No. 1, p. 012063). IOP Publishing.

Luo, K., Fan, J., Li, W., & Cen, K. (2009). Transient , three-dimensional simulation of particle dispersion in flows around a circular cylinder (Re = 140 – 260). *Fuel*, *88*(7), 1294–1301. https://doi.org/10.1016/j.fuel.2008.12.026

Luo, D., Huang, D., & Wu, G. (2011). Analytical solution on Magnus wind turbine power performance based on the blade element momentum theory. *Journal of Renewable and Sustainable Energy*, *3*(3), 033104.

M. Bychkov, A.V. Dovgal, A. M. S. K. (2008). Parametric Optimization of the Magnus Wind Turbine. In *International Conference on Methods of Aerophysical Research,ICMAR 2008* (p. 1).

Mara, B. K., Mercado, B. C., Mercado, L. A., Pascual, J. M., & Lopez, N. S. (2014, November). Development and validation of a CFD model using ANSYS CFX for aerodynamics simulation of Magnus wind rotor blades. In *2014 International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)* (pp. 1-6). IEEE.

Marco, A. De, Mancini, S., Pensa, C., Calise, G., & Luca, F. De. (2016). Flettner Rotor Concept for Marine Applications : A Systematic Study. *International Journal of Rotating Machinery*, *2016*, 1. Retrieved from http://dx.doi.org/10.1155/2016/3458750

Marzuki, O. F., Rafie, A. S. M., Romli, F. I., & Ahmad, K. A. (2015a). An Experimental Investigation on the Effect of Surface Roughness on the Performance of Magnus Wind Turbine. *ARPN Journal of Engineering and Applied Sciences*, *10*(20), 9725–9729. Retrieved from www.arpnjournals.com

Marzuki, O. F., Rafie, A. S. M., Romli, F. I., & Ahmad, K. A. (2015b). Torque Performance Study of Magnus Wind Turbine. *Inertnational Review of Mechanical Engineering*, *9*, 38–42. https://doi.org/10.15866/ireme.v9i1.4726

Marzuki, O. F. bin. (2017). *Effect of Surface Roughness on Rotating Cylinder and Magnus Wind Turbine in Low Speed Conditions*. Electronic PhD Theses and Dissertation, University Putra Malaysia.

Massaguer, A., Massaguer, E., Pujol, T., Comamala, M., & Velayos, J. (2014). Blade shape influence on aerodynamic efficiency of a Magnus wind turbine using particle image velocimetry. *In International Conference on Renewable Energies and Power Quality (ICREPQ'14)* (pp. 8-10).

Menter, F. R., Kuntz, M., & Langtry, R. (2003). Ten Years of Industrial Experience with the SST Turbulence Model.

Mgaidi, A. M., Rafie, A. S. M., Ahmad, K. A., Zahari, R., Hamid, M. F. A., & Marzuki, O. F. (2018). Numerical and Experimental Analyses of the Flow Around a Rotating Circular Cylinder at Subcritical Regime of Reynolds Number Using K- ε And K - Ω -SST Turbulent Models. *ARPN Journal of Engineering and Applied Sciences*, *13*(3), 1–7. Retrieved from www.arpnjournals.com

Miklasz, K., Labarbera, M., & Tech, V. (2010). Effects of Body Cross-sectional Shape on Flying Snake Aerodynamics Effects of Body Cross-sectional Shape on Flying Snake Aerodynamics. *Experimental Mechanics*, *50*, 1335–1348. https://doi.org/10.1007/s11340-010-9351-5

Mohamed MH, Ali AM, H. A. (2015). CFD analysis for H-rotor Darrieus turbine as a low speed wind energy converter. *Engineering Science and Technology*, *18*. https://doi.org/10.1016/j.jestch.2014.08.002

Murakami, N. (2010). *U.S. Patent Application No. 12/522,538*.

MECARO Co. (2010). Revolutionary Magnus (Spiral Fin) Turbine Generates Power at a Low Cost. Retrieved from https://www.japanfs.org/sp/en/news/archives/news_id026726.html

Nair, M. T., & Chauhan, U. S. (1998). Flow Past Rotating Cylinders at High Reynolds Numbers Using Higher Order Upwind Scheme. *Computers & Fliuids*, *27*(1), 47–70.

Nuttall, P., & Kaitu'u, J. (2016). The Magnus Effect and the Flettner Rotor: potential application for future Oceanic Shipping. *The Journal of Pacific Studies*, *36*(2), 161-182.

Onour, K. H., Sedaghat, A., & Samani, I. (2013). Innovative Design of Aerofoil Magnus Type Horizontal Axis Wind Turbines, (May), 17.

Ozen, M. (2014). Meshing workshop.

Panda, S. K., & Chhabra, R. P. (2010). Laminar flow of power-law fluids past a rotating cylinder. *Journal of Non-Newtonian Fluid Mechanics*, *165*(21–22), 1442–1461. https://doi.org/10.1016/j.jnnfm.2010.07.006

Pang, A. L. J., Skote, M., Lim, S. Y., Avenue, N., & Avenue, N. (n.d.). k- ω (SST) turbulence model ., 1–29.

Paraschivoiu, I. (2002). Wind turbine design - with emphasis on Darrieus concept. *Polytechnic International Press, Montreal*.

Perera, F. (2017). Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: Solutions exist. *International journal of environmental research and public health*, *15*(1), 16.

Pujol, T., Massaguer, A., Massaguer, E., Montoro, L., & Comamala, M. (2018). Net Power Coefficient of Vertical and Horizontal Wind Turbines with Crossflow Runners. *Energies*, *11*(1), 110.

Ragheb, M. (2014). Wind energy converters concepts. *University of Illinois at Urbana-Champaign, Champaign, IL*.

Rahman, M., Karim, M., & AbdulAlim, A. (2007). Numerical Investigation of Unsteady Flow Past a Circular Cylinder Using 2-D Finite Volume Method. *Journal of Naval Architecture and Marine Engineering*, 27–42.

Ramjatan, S., & Fitz-coy, N. (2018). Magnus Effect on a Spinning Satellite in Low Earth Orbit. *American Institute of Aeronautics and Astronautics*, 1–20.

Rawat, M., Gupta, R., & Sarviya, R. M. (2013). High Reynolds number flow over cylinders. *International Journal of Application or Innovation in Engineering & Management*, *2*(6), 160–170.

Richmond-navarro, G., Calder, W. R., Leboeuf, R., & Castillo, P. (2017). A Magnus Wind Turbine Power Model Based on Direct Solutions Using the Blade Element Momentum Theory and Symbolic Regression. *IEEE Transactions on Sustainable Energy*, *8*(1), 425–430.

Ritz, R., Schomberg, T., Markus, R., & Kessler, R. (2015). Numerical Investigation of the Detaching Vortical Flow at Rotating Cylinders with Thom Discs. *22nd AIAA Computational Fluid Dynamics Conference*, (June), 1–13.

Salim, S. M., & Cheah, S. C. (2009). Wall y + Strategy for Dealing with Wall-bounded Turbulent Flows, *II*.

Sayres.A.T, and Lelimo, N. . (2007). Aerodynamic Coefficient of Stationary and Spinning Cricket Balls. *R&D*, *23No.2*.

Schubel, P. J., & Crossley, R. J. (2012). Wind Turbine Blade Design, 3425–3449. https://doi.org/10.3390/en5093425

Sedaghat, A. (2014). Magnus type wind turbines: Prospectus and challenges in design and modelling. *Renewable Energy*, *62*, 619-628.

Sedaghat, A., Ali Badri, M., Saghafian, M., & Samani, I. (2014). An Innovative Treadmill-Magnus Wind Propulsion System for Naval Ships. *Recent Patents on Engineering*, *8*(2), 95-99.

Sedaghat, A., Samani, I., Ahmadi-Baloutaki, M., Assad, M. E. H., & Gaith, M. (2015). Computational study on novel circulating aerofoils for use in Magnus wind turbine blades. *Energy*, *91*, 393-403.

Seifert, J. (2012). A review of the Magnus effect in aeronautics. *Progress in Aerospace Sciences*, *55*, 17–45

Kazemi, S. A., Nili-Ahmadabadi, M., Sedaghat, A., & Saghafian, M. (2016). Aerodynamic performance of a circulating airfoil section for Magnus systems via numerical simulation and flow visualization. *Energy*, *104*, 1-15.

Shen, C. (2012). Various Wind Turbine Technologies. *Global Energy Network Institute*, 1–30.

Slavica Ristić; Jovan Isaković; Biljana Ilić; and Goran Ocokoljić. (2004). Review of methods for flow velocity measurement in wind tunnels. *Scientific-Technical Review*, *LIV,No.3,2*(3), 60–71.

Sun, X., Zhuang, Y., Cao, Y., Huang, D., & Wu, G. (2012). A three-dimensional numerical study of the Magnus wind turbine with different blade shapes. *Journal of Renewable and Sustainable Energy*, *4*(6), 063139.

Tartibu, L.K.; Kilfoil, M.; and Van Der Merwe, A. J. (2012). Vibration Analysis of a Variable Length Blade Wind Turbine. *International Journal of Advances in Engineering & Technology*, *4*(1), 630–639.

Thouault, N., Breitsamter, C., Adams, N., Seifert, J., Badalamenti, C., & Prince, S. A. (2012). Numerical analysis of a rotating cylinder with spanwise disks. *AIAA journal*, *50*(2), 271-283.

Tietenberg, T. H., & Lewis, L. (2016). *Environmental and natural resource economics*. Routledge.

Van Bussel, G. J. W., Mertens, S., Polinder, H., & Sidler, H. F. A. (2004). TURBY®: concept and realisation of a small VAWT for the built environment. *In Proceedings of the EAWE/EWEA Special Topic Conference: The Science of making Torque from Wind, Delft, The Netherlands* (pp. 19-21).

Velázquez, M. T., Vega, M., Carmen, D., Francis, J. A., Pacheco, L. A. M., & Eslava, G. T. (2014). Design and Experimentation of a 1 MW Horizontal Axis Wind Turbine. *Journal of Power and Energy Engineering*, *2*, 9–16.

Wilcox, D. . (1988). Reassessment of the scale-determining equation for advanced turbulence models. *American Institute of Aeronautics and Astronautics Journal*, *Vol. 26, N*.

Willy Z. Sadeh; and Daniel B.Saharon. (1982). Turbulence Effect on Crossflow Around a Circular Cylinder at Subcritical Reynolds Numbers, (NASA Contractor Report 3622).

BIODATA OF STUDENT

Amer M. Magaidi was born in Tripoli-Libya on 6 February 1967. Is an aerospace engineering PhD student with the Aerospace Engineering Faculty of University Putra Malaysia. He received his Bachelor degree in aerodynamic design from Aeronautical Engineering Faculty of Tripoli University in 1991 and Master of Aerodynamic engineering from Kazan Governmental University in 2005. His current interest is in the application of Magnus wind turbine in low wind speed region.

LIST OF PUBLICATIONS

Numerical and Experimental Analyses of the Flow around a Rotating Circular Cylinder at Subcritical Regime of Reynolds number using k-ε and k-ω-sst Turbulent Models. A. M. Mgaidi, A. S. Mohd Rafie, K. A. Ahmad, R. Zahari, M. F. Abdul Hamid and O. F. Marzuki. Published, VOL. 13, NO. 3, FEBRUARY 2018, ISSN 1819-6608. www.arpnjournals.com.

A Review Study on Magnus Wind Turbine for Accessing the Aerodynamic Performance, A. M. Mgaidi, A. S. Mohd Rafie, K. A. Ahmad, O. F. Marzuki. Published, Vol. 5, Issue 3, 2019, ISSN 2454-695X. www.wjert.org

Improve the Aerodynamic Performance of Magnus Wind Turbine through Adding of a Supportive Outer Ring to the Rotor, A. M. Mgaidi, A. S. Mohd Rafie, K. A. Ahmad and O. F. Marzuki. Submitted to Q1 Journal "Applied Energy ".

Further Validate Characteristic and Parametric Study on Aerofoil of Flying Snake Cross Section Using of 2D Ansys Fluent. A. M. Mgaidi, A. S. Mohd Rafie, K. A. Ahmad, R. Zahari, O. F. Marzuki. Under Review"ARPN journals"

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : First Semester 2019/2020

TITLE OF THESIS / PROJECT REPORT :

AERODYNAMIC PERFORMANCE OF MAGNUS WIND TURBINE WITH TURBINE SUPPORTIVE STRUCTURE

NAME OF STUDENT: AMER M. MGAIDI

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as :

*Please tick (√)

☐	**CONFIDENTIAL**	(Contain confidential information under Official Secret Act 1972).
☐	**RESTRICTED**	(Contains restricted information as specified by the organization/institution where research was done).
☐	**OPEN ACCESS**	I agree that my thesis/project report to be published as hard copy or online open access.

This thesis is submitted for :

☐	**PATENT**	Embargo from __________ (date) until __________ (date)

Approved by:

(Signature of Student) New IC No/ Passport No.:	(Signature of Chairman of Supervisory Committee) Name:
Date :	Date :

[Note : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization/institution with period and reasons for confidentially or restricted.]