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CFD Simulation of Horizontal Axis Wind Turbine Rotor with fitted Guide Ring

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Abstract:
Horizontal Axis Wind Turbines (HAWT's) has losses due to the axial free stream wind velocity converting into radial and tangential velocity as it moves through the rotating rotor. By fitting a guide ring to the hub some of these losses could be recovered. Computational Fluid Dynamics (CFD) simulations were carried out on a conventional HAWT rotor, and a similar rotor fitted with a guide ring. The purpose of the guide ring is to direct the axial free stream velocity onto the rotor. Simulations were conducted at 0.5 m/s and 1 m/s free stream velocities. Water was used as the fluid for simulation as future experimental verification will be conducted in a water tunnel. Guide rings were placed at 15 % and 20 % of the rotor radius, to investigate the effect on rotor efficiency. Investigative CFD results showed that a guide ring placed at 15 % increased the rotor efficiency with 24 % at peak power coefficient rotor Tip Speed Ratio (TSR) for 1 m/s free stream velocity. A guide ring placed at 20 % increase the efficiency with 1 % at peak power coefficient rotor TSR for 1 m/s free stream velocity. This implies, that precise positioning of a guide ring to the hub can produce a significant increase in the efficiency. These investigative results justify further research for HAWT's fitted with guide rings and their placement.

Keywords:
Horizontal Axis Wind Turbine; Guide Ring; Computational Fluid Dynamics

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I. INTRODUCTION

Conventional Horizontal Axis Wind Turbines (HAWT's) consists of a hub with blades referred to as the rotor. The rotor rotates as wind moves in an axial direction through the rotor and in turn rotates a generator [1]. A comparison between a conventional rotor and one fitted with a guide ring was simulated. This guide ring aims to direct the axial wind stream onto the rotating rotor to increase its efficiency. Fig. 1a illustrates a conventional rotor and Fig. 1b a rotor fitted with a guide ring.

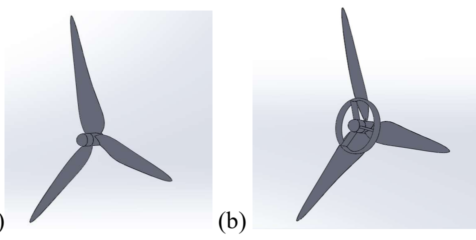

(a) (b)

Fig. 1 Conventional rotor (a) and rotor fitted with guide ring (b).

HAWT's have a maximum power efficiency of 59.3 % which is referred to as the Betz's Law. This law has been derived on the principles of mass and momentum conservation for an actuator disc extracting energy from the wind stream [2]. The Betz's law have many simplified assumptions and later studies in 2001 by Gorban et al. referred to as the Gorban, Gorlov and Silantyev (GGS) model which included non-uniform pressure, curvilinear flow and the degenerated flow of the wake which is the airflow downstream of the rotor predicted a peak efficiency of 30.1 % [3].

Since 2008 computational fluid dynamics (CFD) simulation with included viscous computation typically produce efficiencies between the GGS model and Betz's limit [4].

HAWT rotor efficiency improvement research covers several approaches. Blade profile optimization research for medium sized HAWT's increased the rotor efficiency with 7.42 % for a specific National Advisory Committee for Aeronautics (NACA) blade profile [5].

Enhancement of HAWT blade performance by means of using fences on the blade was studied by Muheisen et al. showing a rotor efficiency improvement of up to 16 % [6].

Automated pitch control for large HAWT's is another method to ensure that the rotor operate with an optimum efficiency for wind speed ranges greater than rated wind speed. Although this is not a rotor efficiency improvement, the pitch control illuminates poor rotor performance [7].

Findings by Nasrul and Rizianiza shows that shrouded rotors for small scale HAWT's for low wind speeds could increase rotor efficiency up to 62 % [8].

The rotor fitted with guide ring under this study aims not only to improve HAWT rotor efficiency from initial design but look at the possibility of retro fitting to already installed wind turbines.

II. Methodology

A. Rotor Efficiency

Wind turbine rotor efficiency referred to as power coefficient can be expressed in terms of axial induction factor, which is the fractional decrease of axial wind velocity as it approaches the rotor.

$$Cp = 4\alpha\,(1 - \alpha)^2 \quad (1)$$

where Cp is the power coefficient and α the axial induction factor. Axial induction factor, α is a function of Vi, the axial free stream velocity and Vt, the axial free stream velocity at rotor plane [9].

$$\alpha = \frac{Vi - Vt}{Vi} \quad (2)$$

In Fig. 2 is an illustration of Vi and Vt as axial velocity reach the rotor plane of rotation.

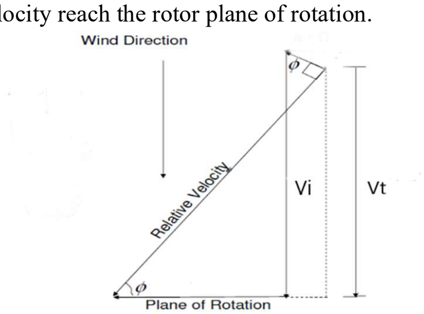


Fig. 2 Velocity vector diagram of Vi and Vt. [10]

B. Rotor Modelling and CFD Simulation

A rotor design from previous research was used to study the effect of adding a guide ring upstream of the rotor plane at specific intervals of 15 % and 20 % of the rotor radius [11]. Fig. 3a shows the guide ring at 15 %, Fig. 3b the guide ring at 20 % and Fig. 3c a close-up view of the 20 % guide ring.

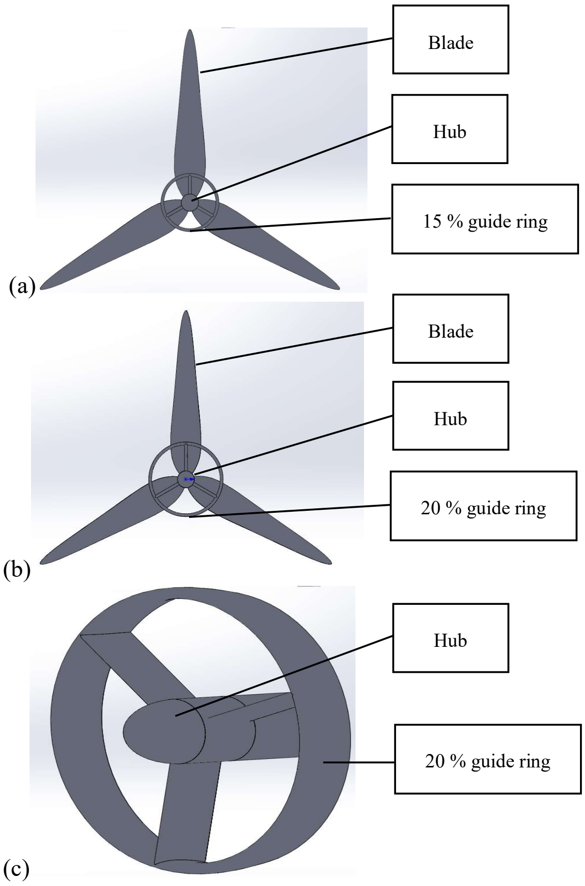


Fig. 3 Rotor with 15 % guide ring (a), 20 % guide ring (b) and close-up view of 20 % guide ring (c).

The guide rings had NACA 0025 air foil profiles in order to minimise drag and lift. The guide rings were attached to the rotor at the hub as shown in Fig. 3c and was stationary during CFD simulation.

Geometrical scaled rotor models were used for simulation and dimension are shown in Table 1.

Table 1 Rotor and guide ring dimension.

Specification	Unit
Rotor Diameter	376 mm
Hub Diameter	19 mm
15% Guide Ring Diameter	56.4 mm
20 % Guide Ring Diameter	75.2 mm
Gap Between Rotor and Guide Ring	4 mm

The CFD simulations were conducted with water as the working fluid at 20º Celsius at 0.5 m/s free stream velocity and at 1 m/s free stream velocity. Water as fluid medium was chosen as future experimental verification of CFD simulations will be done using a water tunnel. All simulations satisfied mesh independence using power as the output. Laminar flow regime was used for viscous computation due to the low Reynolds Number across the blade for chosen free stream velocities as shown in Fig. 4 [12].

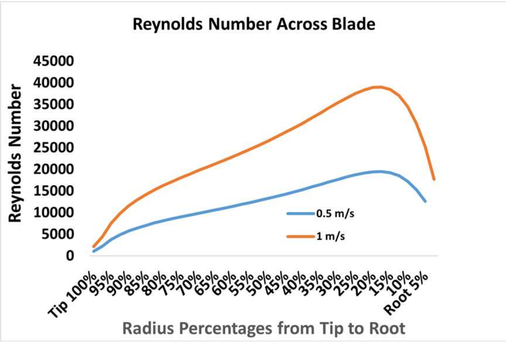


Fig. 4 Reynolds Number across blade for 0.5 m/s and 1 m/s free stream velocities.

Rotor simulations were done at various Tip Speed Ratios (TSR) in order to create power coefficient profiles for each rotor.

III. RESULTS AND DISCUSSION

Fig. 5 shows the power coefficient versus TSR for rotors simulated at free stream velocity of 0.5 m/s. At lower TSR the 15 % guide ring rotor underperformed compared to the conventional rotor. However, at higher TSR's it outperformed the conventional rotor. The 15 % guide ring rotor outperformed the conventional rotor with 1 % at respective peak power coefficient TSR's.

The 20 % guide ring rotor also underperformed at lower TSR's and outperformed at higher TSR, but the 20 % guide ring rotor underperformed with 2 % compared to conventional rotor at respective peak power coefficient TSR's.

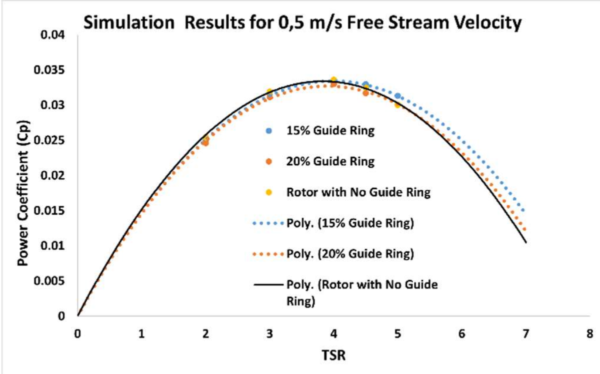


Fig. 5 Power coefficient (Cp) versus TSR for all rotors with 0.5 m/s free stream velocity.

In Fig. 6 results for free stream velocity at 1 m/s the 15 % guide ring rotor underperformed at low TSR but significantly outperformed the conventional rotor at higher TSR's with a 24 % power coefficient increase at respective peak power coefficient TSR's. The 20 % guide ring rotor only outperformed the conventional rotor with 1 % at respective peak power coefficient TSR's. The 20 % guide ring rotor under performed at low TSR and the increase power coefficient at higher TSR's is not as significant than the 15 % guide ring rotor.

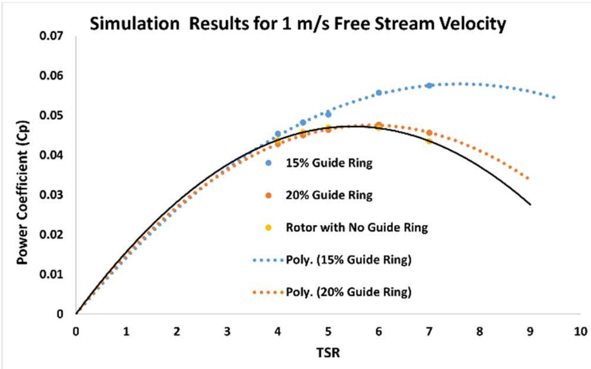
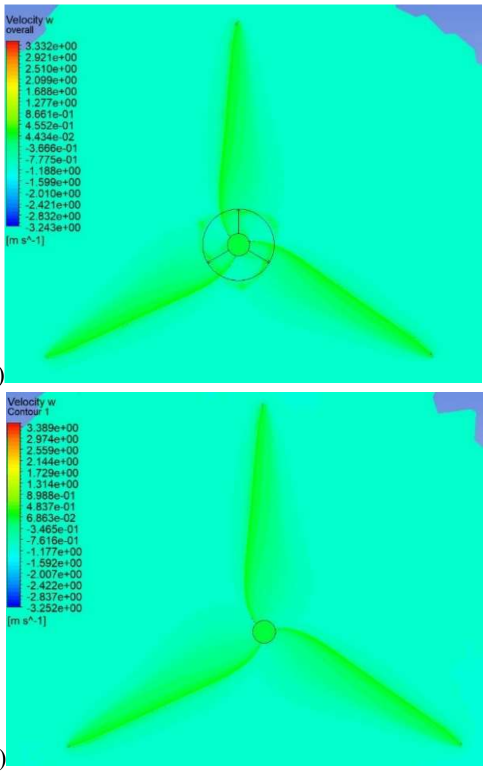


Fig. 6 Power coefficient (Cp) versus TSR for all rotors with 1 m/s free stream velocity.

A snapshot of the axial velocity contours at the rotor plane for the 15 % guide ring rotor and conventional rotor are shown in Fig. 7a and Fig. 7b respectively. The axial velocity within guide ring area is marginally higher than the conventional rotor without guide ring. This caused a lower axial induction factor for the 15 % guide ring rotor which improved the power coefficient with 24 % at peak power coefficient TSR.



(a) (b)

Fig. 7 Axial velocity contours at rotor plane for 15 % ring guide rotor (a) and conventional rotor (b)

IV. CONCLUSIONS

The investigative CFD results shows that performance increase is possible by adding a guide ring to the rotor. The position of the guide ring will impact the magnitude of performance increase. A guide ring placed at 15 % of the rotor radius improved the rotor efficiency with 1 % at 0.5 m/s free stream velocity and with 24 % at 1 m/s free stream velocity. The rotor with guide ring placed at 20 % of the radius had a decrease of efficiency of 2 % at 0.5 m/s free stream velocity and 1 % efficiency increase at 1 m/s free stream velocity. Results indicate that a guide ring at 20 % had poor efficiency increase compared to the 15 % placement. Further research is required to optimise the positioning of a guide ring which will maximise the efficiency increase in relation to free stream velocities.

ACKNOWLEDGEMENT

The idea of adding a guide ring to a horizontal axis wind turbine rotor to improve rotor efficiency originated from Howard Fawkes, senior lecturer at Cape Peninsula University of Technology.

REFERENCES

[1] M. O. L. Hansen, "AERODYNAMICS OF WIND TURBINES Hearth Scan," *London Sterl.*, 2008.

[2] M. A. McGowan J, Rogers J, *Wind Energy Explained - Theory, design and application, 2nd edition*. John Wiley & Sons Ltd., 2009.

[3] A. N. Gorban', A. M. Gorlov, and V. M. Silantyev, "Limits of the turbine efficiency for free fluid flow," *J. Energy Resour. Technol. Trans. ASME*, vol. 123, no. 4, pp. 311–317, 2001, doi: 10.1115/1.1414137.

[4] D. Hartwanger and A. Horvat, "3D MODELLING OF A WIND TURBINE USING CFD".

[5] C. Yiğit, "Improving the Horizontal Axis Wind Turbine Blade Profiles," *Sak. Univ. J. Sci.*, no. April 2018, pp. 1–1, 2018, doi: 10.16984/saufenbilder.417516.

[6] A. H. Muheisen, M. A. R. Yass, and I. K. Irthiea, "Enhancement of horizontal wind turbine blade performance using multiple airfoils sections and fences," *J. King Saud Univ. - Eng. Sci.*, no. xxxx, 2021, doi: 10.1016/j.jksues.2021.02.014.

[7] J. N. Hertel, T. A. Nygaard, and E. P. N. Duque, "Passive pitch control of small horizontal axis wind turbines," *Collect. ASME Wind Energy Symp. Tech. Pap. AIAA Aerosp. Sci. Meet. Exhib.*, no. January, pp. 211–223, 2004, doi: 10.2514/6.2004-1369.

[8] M. Nasrul and I. Rizianiza, "Shrouded wind turbine for low wind speed," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1034, no. 1, p. 012042, 2021, doi: 10.1088/1757-899x/1034/1/012042.

[9] T. M. Adams and B. E. Mertz, "Horizontal Axis Wind Turbine Power Coefficient as Relative Capture Area," *J. Fluid Flow, Heat Mass Transf.*, vol. 8, 2021, doi: 10.11159/jffhmt.2021.027.

[10] A. Sargsyan, "Simulation and Modeling of Flow Field Around a Horizontal," no. December, 2010.

[11] D. R. Barnard, "CFD modelling of the performance of various wind turbine rotors with experimental verification." Cape Peninsula University of Technology, 2021.

[12] J. Mbwiga, C. Z. Kimambo, and J. Kihedu, "Effect of Ambient Reynolds Number on Small Wind Turbine Subjected to Low Wind Speed Conditions," vol. 12, no. May 2019, pp. 223–231.

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Fareed Ismail obtained his Doctorate Degree in Mechanical Engineering in 2021 from the Cape Peninsula University of Technology (CPUT). He is an academic at CPUT with prior 16 years naval engineering design experience (submarines). He is a key figure in a community outreach programme; using his Doctoral research, he implemented a project that spans beyond the confines of academia, by expanding the field of multidisciplinary knowledge in the areas of engineering, design, renewable energy, marine life and agriculture, thus enriching the lives of children in a needy community in the Western Cape region of South Africa. Fareed has received the CPUT Outstanding Community Engagement Award in 2015 and his community project won the South African Provincial and National Early Childhood Development Programme Awards (2015). He is also the inventor and patent holder for the specific Solar Powered Modular Aquaponics Assembly. Some of his career high lights were his keynote address at the Lenses international conference (2016); participation in power talks by the United Nations Women's organization for the conference held on Women Resilience in Agriculture in Nairobi, Kenya (2016); and invitation by the Minister of Defence of the Netherlands to present and participate at their Future Force Conference held in The Hague, Netherlands (2017).