CFD Analysis of a Shrouded Vertical Axis Wind Turbine

Daniel Kalib Kang – W0093205@umail.usq.edu.au

* *School of Civil Engineering & Surveying, University of Southern Queensland*

INTRODUCTION

Wind power has been used for centuries for many purposes including pumping water, grinding grain, sawing timber and sailing ships. From the end of the 19th century wind power has been used to generate electricity. Since then interest in wind energy has waxed and waned based primarily on economic considerations. The oil crisis of the 1970's prompted many governments to look at their energy security with renewed interest in wind power. More recent environmental and sustainability concerns has seen Wind power become a rapidly growing component of the world's energy mix (Observ'ER 2012).

Wind turbines are divided into two classes Horizontal Axis Wind Turbines (HAWT) where the wind flows parallel to the axis of rotation and Vertical Axis Wind Turbines (VAWT) where the wind flow is perpendicular to the axis of rotation. HAWT's dominate the wind turbine market due to their lower cost and superior efficiency. HAWT's tend to be cheaper as their swept area is based on the square of the blade length so a small increase in blade length can dramatically increase the swept area. The swept area of VAWT's is based on the rotors radius times the rotor height. As the turbine being designed is a small turbine that may be mounted on or near dwellings VAWT's were chosen for this project due to their lower maintenance, lower noise, lower startup speed and omnidirectional characteristics.

This project intended to design a small wind turbine for rural Australia. Climatic conditions vary dramatically within Australia and its territories, ranging from the world record wind speed of 408 km/h to large areas of poor quality wind. To handle the range of wind conditions the use of shrouds was investigated. It was hoped that a shroud could be designed that would open to catch more wind in poor wind conditions and close to control over speed in high winds.

There are four shroud effects;

1. Concentrators; structures placed upstream to direct more flow onto the rotor.
2. Diffusers; structures surrounding the rotor designed to promote a pressure differential between the upstream and downstream flows.
3. Ducts; structures designed to prevent the flow from avoiding the rotor.
4. Shields; structures designed to protect the returning blade, only applicable to VAWTs.

Concentrators direct more wind through the rotor, this increases the velocity. As the power is a function of the cube of the velocity a small increase in velocity equates to a large increase in output. Lilley and Rainbird (1956) showed that ducted turbines would produce at least 65% more power than bare bladed designs, but believed the practical limit would be increasing output by 100%. Dr Yuji Ohya (2010) of Kyushu University has developed a Diffuser Augmented Wind Turbines (DAWT), labeled wind-lens technology, which claims to increase power by a factor of 2 to 5.

Benesh (1988) patented a shielded VAWT that had an efficiency of 33%, this design employed a vane to keep the shield facing into the wind. A paper by Mohamed, et al. (2010) used CFD software to analyze the optimal shielding of the returning blade Savonius turbines, which showed a 27% increase in performance with a two bladed Savonius rotor.

The proposed shroud would employ Concentration, Diffusion and Shielding. Ducting will not be employed as we want to retain the omnidirectional nature of the rotors being analyzed.

ANALYSIS

Rotor designs

A range of vertical axis wind turbine designs where selected for analysis they were

- Darreius a lift type rotor (figure 1).
- Savonius a drag type rotor (figure 2).
- Flat blades as the cheapest to produce (figure 3).

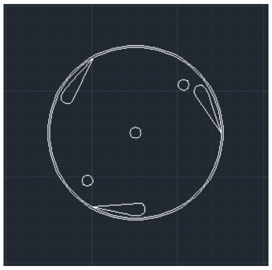


Figure 1 Darrieus Rotor

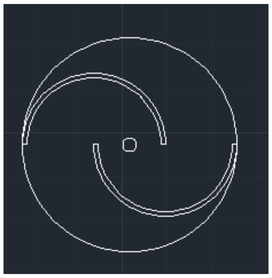


Figure 2 Savonius Rotor

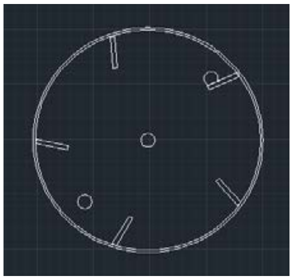


Figure 3 Flat bladed rotor

Shroud designs

The original design was to produce a shroud that could be opened and closed depending on wind speed which defined the size and shape of the shutters. It was assumed that the shutters would be flat panels as they would be the cheapest to produce and could easily be repaired. In the open position the shutters would be tangential to the rotor and in the closed position the shroud would describe a regular polygon. Three designs where chosen Hexagonal (figure 4), Octagonal (figure 5) and Hexadecagon (figure 6).

Figure 4 Top view open extended Hex Shroud

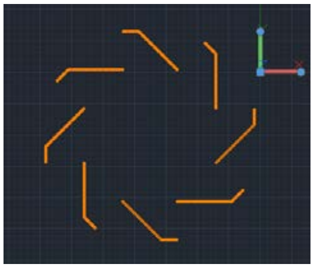


Figure 5 Top view open extended Octo Shroud

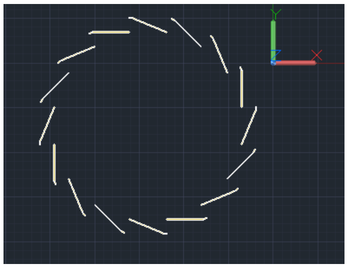


Figure 6 Top view open extended Hexadeca Shroud

The shrouds analyzed only covered the middle 80% of the total rotor height as it was planned that a potion of the rotor would be exposed when the shroud was closed to allow the system to monitor wind speeds during storm events.

In the optimum wind flow condition (figure 7) the Hex shroud concentrates double the wind through the first sector and the normal flow through the second sector which would produce nine times the output. In the worse case flow conditions the output would drop to 4.5 times the bare bladed baseline.

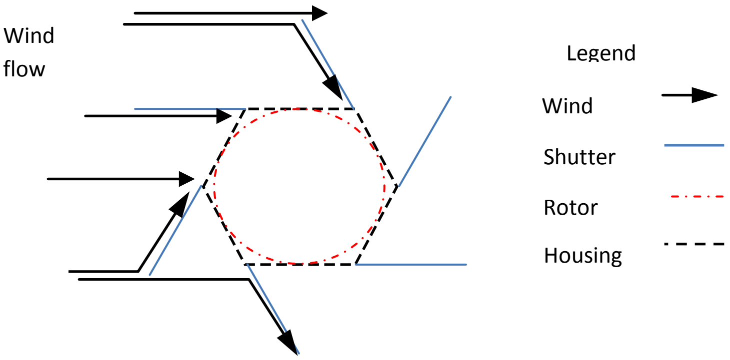
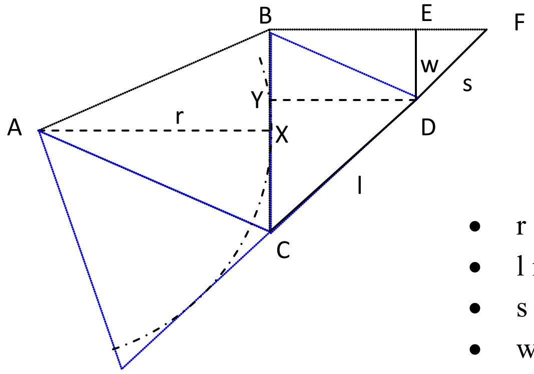


Figure 7 Original design in optimum wind flow condition

However in the worst flow orientation the returning blade is not fully shielded. Two extensions to the shutters were considered to fully shield the returning blade. The first was simply extending the existing shutter was rejected as the closed shroud would have protruding flaps. The second option bent the extensions so that when the shroud was closed it maintained the regular polygon shape.

The sizes of the extensions were calculated by considering the flat panel shroud as a series of similar isosceles triangles. The angle between the two equal sides α=360°/n where n is the number of sides. α would also be the angle the panel would need to open to direct the wind tangential to the turbine. Figure 8 shows the trigonometry used.



- r is the radius of the rotor (including clearance)
- l is the length of the panel required to close the shape
- s is the extended straight shield
- w is the extended bent wing

Figure 8 Shutter extension geometry

The inclusion of the bend wing shroud meant that there where 6 shroud designs plus the bare blade simulation for each of the rotor designs, a total of 21 combinations multiplied by the number of wind speeds tested.

CFD Software

Autodesk Inventor / simulation CFD software (figure 9) was chosen to perform the simulations primarily because it was available free as a student edition and previous experience with Autocad.

Inventor Pro 2013 was used to create individual rotor parts and shroud assemblies. Rotors were originally modeled as solid components but following online recommendations they were redefined as rotating regions with the solid components as voids, this allowed the rotors to be defined as single parts, gave tighter control over the rotating region size and reduced simulation time. The rotors and shrouds were combined to create turbine assemblies for analysis.

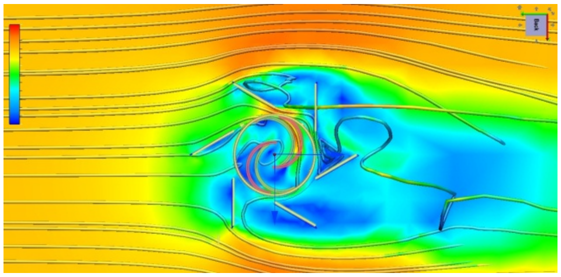


Figure 9 xy plane Velocity Magnitude using Simulation CFD

The turbine assemblies were exported to Simulation CFD via Inventor Fusion 2013. An external volume was defined within Simulation CFD to this permitted the volume to be redefined without exiting the program. This volume was set at 4 shroud diameters in each direction and 1 rotor height above and below. The boundary conditions were set with 4 sides as slip/symmetry, 1 side flow velocity and 1 side 0 gauge pressure.

As no real world experiments were conducted there was no data from which to tune the CFD model an arbitrary value of inertia was chosen and applied to all rotating regions.

The optimum and worse case wind flows were evaluated using 3 wind speeds on each rotor with the hexagonal shroud in both extended shutter and plain shutter configurations. After verification only the worst wind flow condition was used for subsequent analysis.

A series of simulations were conducted using the 3 rotors and 6 shrouds with a minimum 3 wind speeds for each configuration. These results were compared to the bare bladed performance for each rotor.

RESULTS AND DISCUSSIONS

Results by Rotor Type

The Darreius showed no improvement at the wind speeds tested and in all but the slowest wind speeds shrouds were detrimental.

The flat bladed rotor showed good improvement at low wind speeds but much less than the Savinous rotor with performance dropping off quicker. This could be due to the due to the relatively low solidity of the rotor tested and testing a higher solidity rotor is suggested.

The Savinous rotor showed exceptional improvement reaching a maximum 773% of the bare bladed output at 5 m/s wind speed however after that point there was a dramatic and unexpected drop off such that at 6 m/s the turbine was only producing 74% of the output.

Results by Shroud Type

Increasing the number of shutters decreased the improvement with the best results coming from the hexagonal shrouds, with the 16 sided shrouds having detrimental effects. There appears to be two main reasons for this. Firstly the decreased size due to smaller shutters and secondly the upstream effects of the shroud seems more pronounced with an increase in the number of shutters.

The plain shutters generally performed better that the extended shutters, though the drop in performance was less dramatic in the extended shutters.

Analysis of Best Combination

The power generated by the turbine was calculated by multiplying the rotational speed in radians per second by the torque in N.m giving the output in Watts, however as an arbitrary inertia was selected this value can only be compared to the results from a similar rotor with the same inertia. The Hexagonal shrouded Savinous rotor had the greatest output increase with the plain shutters generally producing the best results.

From figure 10 the behavior of the plain shroud shows;

- At 1m/s the increased output is near the theoretical 450% from the concentrator.
- At 2 m/s there is a drop possibly as upstream effects start to come into play.
- From 2 m/s to 5 m/s there is a steady increase in comparative output possibly as the diffuser effect draws more flow through the shroud.
- At 6 m/s there is a sudden and dramatic drop off in power. In real terms the rotational speed is still increasing but the torque has dropped, which would indicate that there is a lower volume / higher velocity flow than existed at 5 m/s.

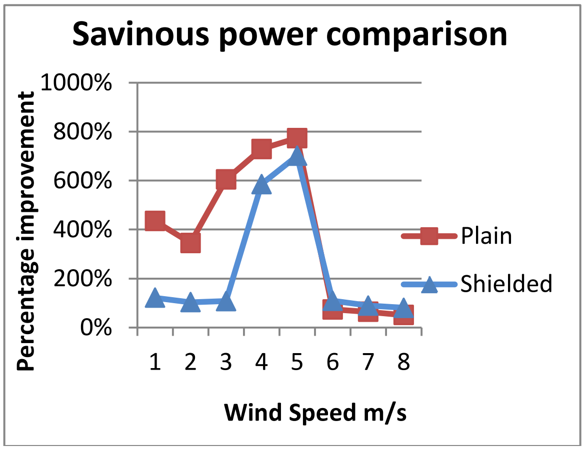


Figure 10 Power comparison chart for hex shrouded Savinous

The term "pressure locking" will be used for the phenomena that occurred between 5 m/s and 6 m/s for this model. Pressure locking appears to be caused by backpressure or upstream effects causing the wind to flow around the entire structure rather than through the shroud. The wind speed at which pressure locking occurs appears dependent on the size and geometry of the shroud.

Future work includes confirming that pressure locking exists and designing a shroud that exploits it to control over speed. The new shroud would be static which would save on the cost of the adjustable shutters and the control system. A static shroud would not be limited to the geometric constraints of the adjustable shroud and it has been suggested that more aerodynamic shapes could be employed. However the current research is currently using the flat panel hexagonal shroud as described earlier but with the shroud covering the full height of the rotor.

Cost analysis

Assuming that the cost per lineal meter for the shroud is the same as the rotor, then the shrouded turbine is more economical if the shroud can increase the output by more that 220%. From the simulations the plain hex shroud is more economical at all wind speeds up to 5 m/s. It is hoped that a larger turbine can produce economical power at wind speeds up to 12 m/s. If this can be achieved then the original design objectives can be met.

CONCLUSIONS

The original intent was to design an adjustable shrouded Vertical Axis Wind Turbine that would collect more wind at low wind speeds and shut to control over speed at high wind speeds. The CFD analysis seems to indicate that an economical shrouded VAWT is not only feasible but it is possible to use the fluid flow to prevent over speed with to geometry of the shroud alone. There appears to be a wind speed at which the flow starts avoiding the structure. After this wind speed the shroud dramatically reduces the output from the turbine which indicates that it is possible to build a static shrouded Savonius that will fulfill all the original design requirements but without the added cost of adjustable shutters and the associated control equipment. With no moving parts in the shroud and no wearing parts in the braking system this turbine would have low maintenance and cost, making the design ideal for development as a power source for remote locations.

Other advantages of a static shroud are;

- It could be built stronger to better handle cyclonic wind speeds.
- No moving parts to ice up in freezing conditions.
- No moving parts to jam in dusty or corrosive conditions.
- No moving parts to produce noise if mounted upon dwellings.

REFERENCES

Benesh, AH 1988, *Wind turbine system using a vertical axis savonius-type rotor*, US patent 4784568 A

Hills, RL 1996, *Power from Wind: A history of windmill technology*, Cambridge University Press, Cambridge, Great Britain

Mohamed, MH Janigaa, G Papa, E & Thévenin, D 2010, "Optimization of Savonius turbines using an obstacle shielding the returning blade", *Renewable Energy*, volume 35, issue 11

Lilley, GM & Rainbird, WJ 1956, *A Preliminary Report on the Design and Performance of Ducted Windmills*, Report No. 102, College of Aeronautics, Cranfield, UK

Observ'ER, 2012 , Worldwide electricity production from renewable energy sources, 14th edition, Paris, viewed 23/06/2013, <http://www.energies-renouvelables.org/observ-er/html/inventaire/Eng/conclusion.asp>

Ohya Y, Karasudani T, 2010, “A Shrouded Wind Turbine Generating High Output Power with Wind-lens Technology”, *Energies*, 3(4) pp634-649