Institute for Sustainable Energy, University of Malta

SUSTAINABLE ENERGY 2012:
THE ISE ANNUAL CONFERENCE PROCEEDINGS
Tuesday 21 February 2012, Dolmen Hotel, Qawra, Malta

PRELIMINARY STUDIES ON AN INNOVATIVE VERTICAL AXIS WIND TURBINE CONCEPT:

SATVAWT

D. Micallef(1), P. Mollicone(1), T. Sant(1), A. Urso(2), R. Xuereb(3) and A. Galea(1)
[1]Faculty of Engineering, University of Malta, Msida, MSD 2080, Malta,
Tel: (+356) 23402023, (+356) 21652249, Fax: (+356) 21650615
Corresponding Author E-mail: daniel.micallef@um.edu.mt
[2] CEO, Alurwind Ltd. Company Reg . C50769 86 Triq Il Belveder QLA 1314, Qala Gozo, Malta
Tel: +44(0)1275545872
[3]Managing director, Econetique Ltd. Xewkija Industrial Estate, Xewkija, XWK 3000, Gozo
Tel: +356 21569006

ABSTRACT: Vertical axis wind turbine concepts are particularly attractive for the urban environment for various reasons including adaptability to varying wind directions. On the other hand, these types of turbines suffer from various disadvantages including prohibitive costs. In this paper, we present an innovative concept of a Self Adjusting Lift Type Vertical Axis Wind Turbine (SATVAWT) being developed by the a consortium of local academia and industry. Although the project is still in its infancy some insight of the design is presented, particularly the aerodynamic and structural aspects of the blades which are being optimised for highest possible efficiency. Some results from numerical analysis tools are also presented. To provide easy start up, the turbine blades are at first retracted. Due to the accelerating motion, momentum is conserved by means of an increase in the polar moment of inertia about the axis of rotation. This causes the turbine blades to flex. In this position, advanced aerodynamic calculations using vortex methods have shown that the turbine should operate at a higher efficiency for the rated condition. Finite Element Analysis (FEA) tools have also been used to assess the structural feasibility of the turbine. The preliminary results presented here are encouraging and will form the basis for further computational and experimental analysis.

Keywords: Vertical Axis Wind Turbine, blade aerodynamics, finite element analysis

1 INTRODUCTION & RESEARCH HYPOTHESIS

The wind energy sector has been largely driven through the research and development of horizontal axis wind turbines (HAWTs). The prevailing market remained, throughout the past 10 years, on megawatt scale machines. Aerodynamic and aero elastic research has grown exponentially.

To a large extent, the application of vertical axis wind turbines (VAWTs) has been quite limited, with the main contribution coming from the research and development sector. VAWTs have important advantages over HAWTs including:

- Low sensitivity to varying wind directions
- Better performance in turbulent conditions
- Generator is usually located at the bottom of the turbine thus enabling easy maintenance. This also lowers the centre of gravity thus reducing the structural demands.
- The turbine blades are less susceptible to fatigue due to gravitational loads.
- Easier integration in the urban environment

The primary disadvantages which has caused the market to steer towards HAWTs include:

- Complicated aerodynamics and aero-elastic behaviour.
- Blade manufacturing cost
- Start up issues at low wind speeds

In this paper we propose an innovative lift type vertical axis wind turbine design called Self Adjusting Lift Type Vertical Axis Wind Turbine (SATVAWT). The objective of such a turbine is to alleviate the disadvantages of VAWTs and to introduce into the market a turbine which is both cost effective and aerodynamically efficient into the market.

The objective of this paper is to show that such a turbine is capable of overcoming the prevalent disadvantages of mainstream VAWT designs. In order to prove our hypothesis we use a numerical approach using advanced aerodynamic and structural tools. Further validation of the hypothesis will be performed through experimentation. The latter will however be the subject of future work.

3 SATVAWT DESIGN CONCEPT

The physical principle behind the SATVAWT is the conservation of angular momentum between the angular acceleration and the instant when the turbine reaches a steady state condition. When the wind speed is just above the cut-in speed (the speed at which the turbine just starts to rotate), the turbine starts to rotate. In doing so, centrifugal forces are generated and the blades are deflected to a larger radius from the axis of rotation. This causes the polar moment of inertia to increase. By conservation of angular momentum, the angular speed must also decrease such that the operating tip speed ratio (ratio between the equator velocity and the wind speed) attains a value equivalent to the maximum efficiency of the turbine.

. A drawing of the SATVAWT concept turbine is shown in Fig. 1 at start-up (extended condition) and Fig. 2 at steady state rotation (flexed condition).

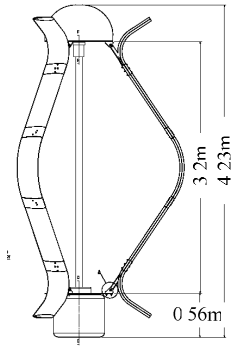

Figure 1 - SATVAWT at start-up (extended condition).

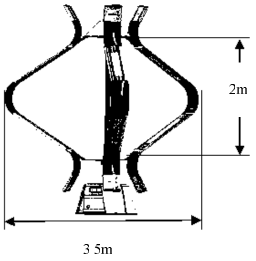

Figure 2 - SATVAWT during steady state rotation (flexed condition). Note: Dimensions are only indicative as the exact values will be determined later in the design process.

The SATVAWT is three bladed and uses an NACA0018 airfoil section. Although this type of airfoil is not usually used in lift driven turbines including modern HAWTs, its shape is symmetrical thus minimizing manufacturing costs. The blade is untwisted and has a constant chord of 0.3m.

3 METHODOLOGY

3.1 General approach

This research work is based on a purely numerical approach using a lifting line free-wake vortex methodology for the aerodynamic modelling. Such a model, through the inputs of suitable lift and drag polars for the airfoil used on the blade, outputs both the velocity field as well as the loading on the turbine rotor. The aerodynamic loading from this model is then used as an input to the Finite Element Analysis (FEA) software with ANSYS©. This approach is fast and relatively simple to implement. However, since the aerodynamic and structural equations are uncoupled, the methodology misses some of the detailed physics of the flow of air over the blades. For the purpose of this work however, such detailed physics should not be of detriment.

The aerodynamic simulations were carried out for both the extended and flexed conditions. On the other hand, the structural simulations were carried out on the extended condition only such as to quantify the deflection of the turbine blades.

3.2 Lifting line vortex method

Lifting line vortex methods represent a wing or blade by means of a vortex line which generates vorticity. Due to the finite nature of the wing, the bound vorticity will vary along the span. This results in trailing vorticity. Especially for a VAWT, the bound vorticity also varies in time thus result in the release of shed vorticity. The trailing and shed vorticity components form a vortex wake sheet which is modelled using the Biot-Savart law:

$$u(\vec{x}) = \frac{\Gamma}{4\pi} \int_{filament} \frac{d\vec{x} \times \vec{r}}{r^3} \qquad (1)$$

Where Γ is the circulation of a particular vortex straight line filament. The other symbols represent distances as shown in Fig. 3.

.

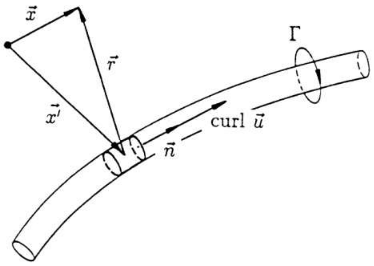

Figure 3 - Biot Savart law definitions. Reference: Spurk and Aksel [1].

Fig. 4 shows the representation of the vortex sheet modelling the trailing and shed vorticity in the wind turbine wake generated by one blade. Vertical lines represent shed vortices while horizontal lines represent trailing vortices. The wake is also allowed to deform in time by calculating the local velocity at each wake point.

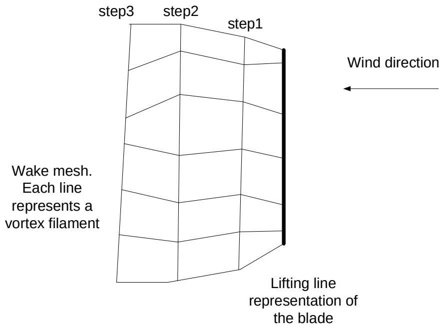

Figure 4 - Representation of the blade and vortex wake sheet.

At this stage of the research, no experimental validation of the model is possible. The model was however tested using various benchmarking exercises such as for the case of a finite wing having an elliptical chord distribution. The reader is suggested to refer to [2]. The blade was discretized into 38 elements and the azimuthal step of the simulation was set to 5º. Table 1 shows the salient inputs to the model. The rotor RPM was kept fixed and the wind speed was varied from 6m/s to 12m/s such that a range of tip speed ratios is produced.

Table 1: Simulation inputs.

	Extended	**Flexed**
Blade elements	38	38
Azimuthal step	5º	5
Rotor RPM	220	171
Tip speed ratio	variable	variable
Number of rotor revolutions	5	5
Dynamic stall model [3]	Gormont	Gormont

A verification study was performed to check convergence with increased number of blade elements and azimuthal step. The results with the discretization of Table 1 converge to within 2% which in wind turbine aerodynamics practice is considered to be sufficient. Further details can be found in the Alurwind Ltd. report [2].

3.3 FEA modelling

For the structural analysis, the aerodynamic loading for a design wind speed of 1.4*average wind speed of 8.5m/s is considered. This therefore corresponds to a turbine rotating at 220RPM and a wind speed of 12m/s.

The simplest, yet relatively accurate, form of finite element modelling was sought for this preliminary assessment of the blades' structural response. Beam elements were used for this assessment since the blades act as beams: relatively high length to section ratio, with primarily lateral loading as described above. This is a "line" class of elements, which is modelled with three-dimensional lines that follow the path corresponding to the blades' lengths, and to whom sectional properties are attached. Finite element software package ANSYS© was used to implement the analysis, with BEAM188 elements, which support many features, such as custom cross-section properties and large displacement analysis. One blade was modelled with 1010 elements along its length, following both the straight and curved parts. These elements use energy-based formulations derived from classic beam theory. The reason for using a finite element implementation, as opposed to a classical solution, is the overall convenient form of solution through the software package, with the possibility to include features such as the curved shape and large deformation effects. The latter is important since, due to the blade shape design, geometrical/deformation stiffening could be an important factor of the structural dynamic response.
Loads were taken directly from the aerodynamic model and which are represented by eqn. 2. A linear elastic analysis was carried out using an isotropic material model based on typical values for pultruded carbon fibre components. This proved sufficient for this preliminary study, since the main

aim was to get a feel for the overall structural response, rather than optimise the composite material construction.

$$\vec{F} = m\vec{R} \times \vec{\Omega}^2 + \vec{A} \tag{2}$$

where F is the total load, m is the mass of the blade, R is the distance from the axis of rotation and Ω is the rotor speed. A is the resultant aerodynamic loading. Gravitational loads were ignored.

The beam element is shown in Fig. 5.

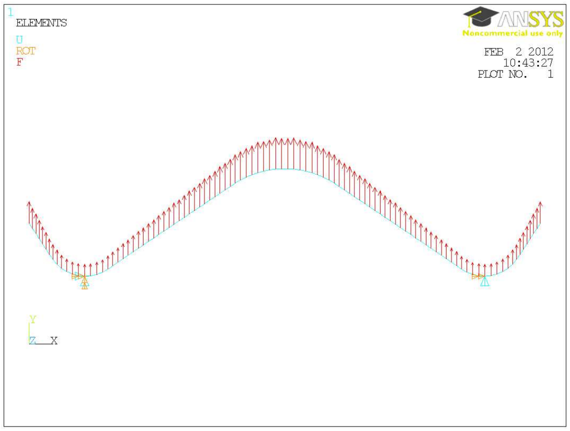

Figure 5 - Beam model representation of the blade.

4 RESULTS

4.1 Aerodynamic performance

The power coefficient of a wind turbine is defined as the ratio of the power produced to the power available in the wind (refer to Burton et al. [4]):

$$C_P = \frac{P}{\frac{1}{2}\rho U_\infty^3 A} \tag{3}$$

where P is the power produced (calculated from the simulations, ρ is the air density, U_∞ is the wind speed and A is the turbine projected area along a vertical plane. Fig. 6 shows the variation of the averaged power with wind speed at the rated RPM shown in tab. 1. For these curves the dynamic stall airfoil model of Gormont [3] was implemented to correct for the static airfoil data which was implemented in the model. As can be seen, the cut-in wind speed is around 5.5m/s for both flexed and extended conditions. At low wind speed the extended and flexed blades behave similarly. At higher wind speeds the flexed condition performs better. The power coefficient variation with tip speed ratio is shown in Fig. 7. The peak efficiency is obtained at a tip speed ratio of around 3.8.

To have a better insight into this phenomenon the power spectra is shown in Fig. 8.

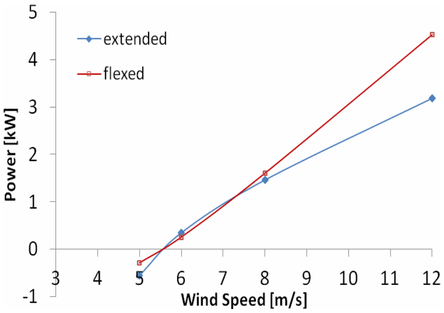

Figure 6 - Power against wind speed variation for the extended and flexed condition when dynamic stall model is included.

These results do show that the flexed condition should behave better than the extended condition. Nonetheless, the dynamic stall model implemented here could lead to questionable results. Further validation of the model is hence required using experimental data.

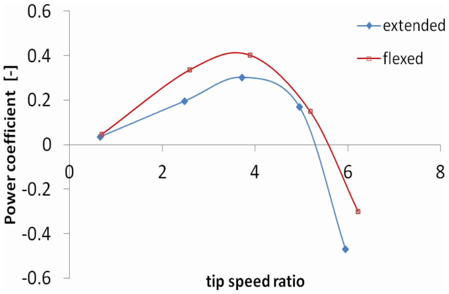

Figure 7 - Power coefficient against tip speed ratio.

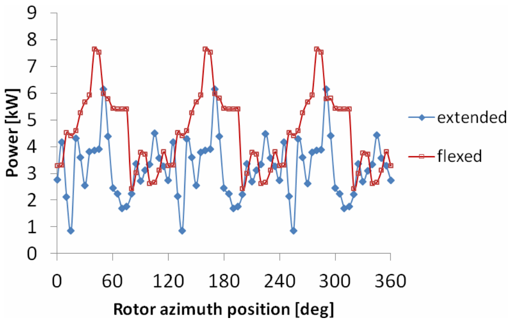

Figure 8 - Power variation with rotor azimuth when a dynamic stall model is incorporated.

4.2 Structural performance

Results gave an overall structural response which is assessed based on displacement and stresses. Fig. 9

shows a plot of local displacement of the blade while Fig. 10 and Fig. 11 show plots of the most important stress components, together with some typical limits for the material under consideration. The following can be noted:

- The largest stress components are the ones due to bending, indeed confirming that the blades are working primarily as beams. The axial stress (which are also included in the element formulation) are minimal
- Maximum values are well below the limits for both tension and compression
- Maximum values are located at the point of fixed support
- The winglets carry little to no stress
- Deformations are minimal, the vertical displacement (x component in the analysis) of the carriage was also minimal

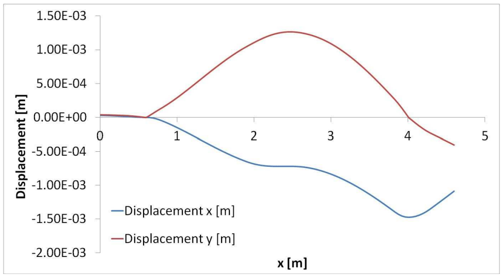

Figure 9 - Displacement against x-coordinate.

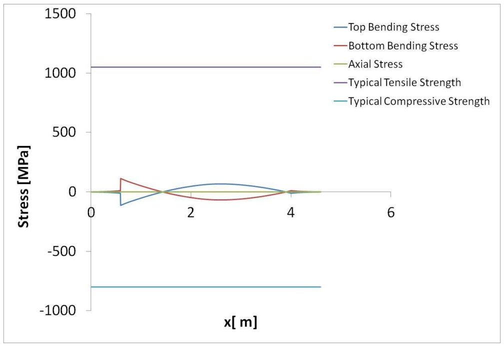

Figure 10 - Stress against x-coordinate.

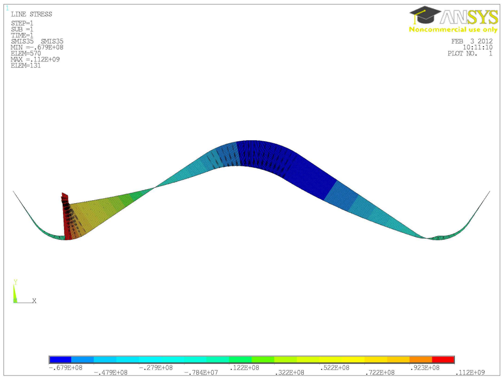

Figure 11 - Stress distribution visualisation using the beam model.

5.1 Aerodynamic performance

The aerodynamic calculations performed in this work indicate a tendency for the flexed condition to perform better. Nonetheless these results should be further assessed against more accurate modelling especially of the dynamic stall phenomenon. Experimental measurements should also help clarify some of these questions.

5.2 Structural performance & aero-elasticity

This preliminary finite element model proved useful in assessing the basic response of the blades. The chosen section and materials are adequate for the initial design. Other aspects, such as bucking, detailed stress analysis for fatigue assessment need to be developed in future models.

Although a full dynamic analysis of the turbine during the flexing motion will be discussion of more advanced work, the effects on the structural integrity should not depart from the static analysis by substantial amounts.

This cannot be said from a material fatigue perspective. An aero-elastic model will be carried out in future work were the complex effects of the coupled aerodynamic and elasticity equations are solved for. These types of models are highly computationally demanding. Although the description of this model is outside the scope of this work, it is still being mentioned as a further precaution to rigorously test this innovative VAWT concept.

6 MANUFACTURING CONSIDERATIONS

From the onset it became clear that the manufacturing processes used is critical to achieving the target of return on investment set for the project. Throughout the conceptual design phase of the turbine and its components, manufacturing was always a high priority. In the concept design most of the manufacturing costs are already being committed. Hence every decision and change in the concept is analysed under the perspective of the effect it has on the eventual manufacturing process.

The manufacturing process of the SATVAWT turbine adopts a number of basic ideas in its process which help keep price of manufacturing low whilst ensuring high quality in every component. A picture of a sample, pultruded blade section is shown in Fig. 12.

Reduction of cycle time by applying automated processes, wherever applicable: The necessity for a turbine to be light, having a low moment of inertia, usually means that exotic composites are needed. This in turn means hand laying and hence lengthy cycle times. By simplifying the shape of the turbine and using straight section blades, pultruded blades can be used. This reduces the cycle time of manufacturing the blades drastically reducing cost of the actual turbine.

Affordable quality control through minimization of manual manufacturing processes: As explained above the adaptation of pultrusion for the manufacturing of the main components also give repeatability. Through process control the blades are consistent in both dimension and weight. This has also reduces the need of balancing the blades before factory dispatch hence reducing another process at end of time and balancing the turbine when assembling on site.

Using Off-the-shelf items will keep tooling investment cost down reducing need of amortisation cost on each item sold:

- Blade pultrusion profile already available and can be bought by length needed. This gives a stable supply of consistent components without going through the initial problems with process control of the manufacturing process.
- Variable nature of turbine design ensures that radius of turbine can be varied in-order to match as close as possible a generator which can be bought off the shelf. This again will ensure a component which is already being manufactured in a stable process and hence is less prone to problems. Another benefit is that it will yield a lower component cost since no further design and tooling investment is needed
- Wherever custom features are needed concept uses repetitive features in the blades. Example the Curved parts of winglets use same mould as the curved part of the flexing component, hence higher volume per tool, investment reduces amortisation cost of tool.

Weight control through design and manufacturing processes chosen:

- Weight is kept to a minimum through design of the turbine and manufacturing process used. The fact that the process is automated a very fine control can be applied to the resin being injected hence ensuring thinner blade walls. This has an impact on the weight of the turbine and hence its performance.
- The shape of the blades are a close approximation to the natural shape a flexible element will take when rotated at speed. This means that the stresses on the blades will be lower than fixed geometry turbines on the market. Hence less material can be used to reinforce the blades themselves keeping weight and cost down.

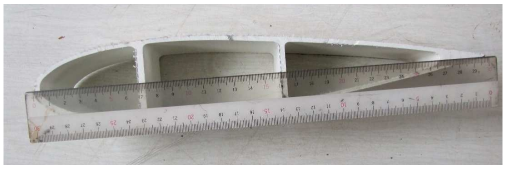

Figure 12 - Pultruded sample blade section.

7 CONCLUSIONS

A preliminary analysis of the design of a self adjusting vertical axis wind turbine has been presented.

The aerodynamic analysis has shown that such a turbine concept is indeed technically feasible. The cut-in wind speeds were found to be similar for both the extended and the flexed condition. The self adjusting concept helps in having a lower polar moment of inertia on start-up. The analysis has also shown that the flexed turbine should be more efficient but this result is inconclusive due to the flow complexity on the blades which the current model is not able to capture. An experimental campaign on the model turbine will help in clarifying this.

The turbine was also structurally modelled using an FEA model. The maximum stress levels reached on the wind turbine blade were well below the structural limits of the carbon fibre material which will be used for the blades. The deflections were however very small meaning that for the turbine to flex, a reliable method of flexure is required.

Some manufacturing aspects have been discussed. The scientific and engineering aspects of the design address the issue of having a marketable product which can compete and surpass the performance of other turbines in the market.

In this paper, the feasibility of the turbine was shown. Further work is however required especially from an experimental aerodynamics side. Future design modifications are expected as further understanding of the turbine behaviour is gained.

8 REFERENCES

[1] J. Spurk and N. Aksel, Fluid Mechanics, 2nd edition, Springer, Berlin, (2008). ISBN 978-3-540-73537-3.

[2] Alurwind Ltd., MCST Activity 1.2 report - Design parameters, (2011).

[3] R.E. Gormont , A Mathematical Model of Unsteady Aerodynamics and Radial Flow for Application to Helicopter Rotors, USAAVLABS TR 72-67, (1973).

[4] T. Burton and D. Sharpe and N. Jenkins and E. Bossanyi, Wind Energy Handbook, John Wiley and Sons Ltd (The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, England, (2001).