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The Performance of a Magnus Vertical Axis Wind Turbine in Typhoon Wind Speeds

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The study involved determining the performance of a Magnus-type Vertical Axis Wind Turbine (VAWT) subjected to typhoon wind speeds. The investigation is purely numerical, starting with the validation of the Magnus effect on lift and drag generation of a rotating cylinder in similar flow conditions as the wind turbine experiences. Validation data was culled from a related experimental study on Flettner rotors as used in ship propulsion augmentation applications. The validated aerodynamic performance of the cylinders is assumed to be sufficient to model the wind turbine performance. The scale of the 2-cylinder model rotor is equal to the actual Magnus VAWT of Challenergy Inc. The published rated capacity of the Magnus VAWT is 10 kW while the simulated rotor running at the same rated conditions produced 9.42 kW at a Tip Speed Ratio (TSR) of 1.17 resulting in a Power Coefficient (CP) equal to 0.5. Simulating the rotor at a wider range of TSRs reveals a peak performance point of CP = 0.58 at a tip speed ratio of 2. This does not take into account the input power consumed by rotating the cylinders and hence is expected to be significantly lower in the actual conditions. A 2-dimensional model of a 2-cylinder Magnus-type rotor was created with a cylindrical blade diameter of 1 m and a rotor radius of 3 m. Rated conditions are at 8 m/s wind speed with a rotor rotational speed of 30 rpm and cylinder rotational speed of 150 rpm. Experimental validation data was adopted from a wind tunnel test of a Flettner rotor under flow conditions of Reynolds number equal to 1×10^6. Lift and drag curves were compared between simulation and experiments, revealing an excellent agreement in lift while a significant disagreement in drag. Simulations underpredict the drag, which resulted in the unusually high predicted performance of the wind turbine. The VAWT performance agreed well with the published rated capacity of 10 kW with a predicted power output of 9.42 kW. A tip speed ratio sweep was conducted and revealed a peak performance point at TSR = 2 with CP equal to 0.58, subsequently dropping to CP = 0.35 at TSR = 5. When the rotor was simulated at typhoon wind speeds, the results showed increasing power outputs from 30.87 kW at 13.89 m/s, 99.67 kW at 20.83 m/s, 140.38 kW at 28.61 m/s, up to 176.79 kW at a cut-out wind speed of 40 m/s. The corresponding CPs are observed to decrease as wind speeds increase from 0.5, 0.31, 0.30, 0.16 down to 0.8.

1. Introduction

As the world population continues to rise, so does the demand for power. In the next decades, more power-generating devices are expected to be built to convert renewable energy into usable electrical energy. This will reduce the world's dependence on fossil fuels to heat homes, run vehicles, power industries, and provide communities with electricity. One of the said devices is the wind turbine which converts wind into electrical energy (Elliot, 2000). Elliot (2000) published a report containing the results of a wind resource analysis and mapping study for the Philippine archipelago. He discovered that the country's wind resource relies heavily on latitude, elevation, and proximity to the coastline — claiming that areas in Batanes, Ilocos Norte, and Samar have great potential for wind farms. Most of the wind farms already operating in the country have horizontal wind turbines installed for greater power generation.

The Philippines is frequently subjected to strong winds that result in heavy rains and monsoons, as well as storms that evolve into typhoons. In 2013, the Philippines was cited by Time Magazine to have been the country most exposed to typhoons, following being hit by Typhoon Haiyan, which had some of the highest recorded

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wind speeds of a tropical cyclone in the modern era. The Philippines has actually borne the brunt of some of the most powerful tropical cyclones to landfall in this century, with the most powerful being Goni from 2020 which hit Catanduanes. In 2021, the Philippines' first VAWT was installed on the island of Batanes; it is expected to withstand and take advantage of the strong winds in the area. It has been shown that VAWTS are more effective than HAWTs during harsher weather conditions where there is more turbulence. This is because direction fluctuations have minimal effect on VAWTs' power generation, and only velocity fluctuations will need to be accounted for (Kooiman, Tullis, 2010). It also produces lower sound at a lower tip speed ratio (Danao, 2013). For these reasons, VAWTs have increasingly grown popular as a power-generating device over recent years, especially in areas that regularly experience highly transient weather conditions.

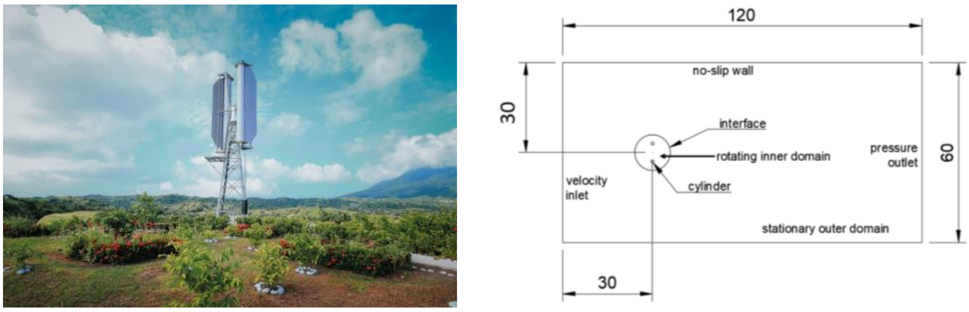
Only a few studies have been conducted to assess the power output of wind turbines during inclement or extreme weather. This is because the simulation of extreme weather is difficult given the unpredictable conditions of wind and other factors involved, thus requiring advanced technologies (Lin et al., 2012). With respect to VAWTs, its flow physics is also quite complex, making predictions difficult to achieve with mathematical or computational models alone (Edwards et al., 2012). There are especially lesser studies on Magnus VAWTs since the concept of Magnus VAWTs has only recently grown popular. The most recent was an unvalidated numerical study published last 2015 by Khadir and Mrad (2015). Magnus VAWT generates power by utilizing the lift force brought about by the rotation of its cylinders. This lift force acts vertically relative to the wind direction. Furthermore, the speed of the cylinders can be controlled so it can operate even in typhoon wind speeds. The objective of this study is to improve knowledge of Magnus Vertical Axis Wind Turbines. This study also aims to determine how extreme weather conditions, particularly increased wind speeds, affect the performance of a Magnus VAWT. This study specifically investigated the effect of typhoon wind speeds on the performance of the Batanes Magnus VAWT in terms of power generation. As such, the last objective of this study was to determine the potential of the Batanes Magnus VAWT for power generation during extreme weather conditions. The Batanes Magnus VAWT is the sole model of a Magnus VAWT that was studied. This limits the available information from what the manufacturer of the Batanes Magnus VAWT (Challenergy Inc.) can provide. The researchers were also limited to conducting the study through simulations, given the lack of access to wind tunnel testing. The researchers had no option but to utilize experiments on single cylinders as reference for validation of the parameters that will be used for the actual simulations.

2. Methodology

Due to limited studies on performance of Magnus VAWTs, the validation was based on experimental data found for rotating cylinders. The experiment chosen was conducted at a high Reynolds number since actual operating conditions of the Batanes Magnus VAWT (Figure 1a) occur in such. Specifically, the calculated Reynolds number for the rated operating conditions of the Batanes Magnus VAWT was at 6.57×10^5 given the rated wind speed of 8 m/s and the cylinder diameter of the blades at 1 m. A study conducted by Bordogna et al. (2019), which tested the effect of varied Reynolds number values on the performance of rotating cylinders through a series of wind-tunnel experiments, was used to validate the CFD model of the Batanes Magnus VAWT. Each series of wind-tunnel experiments conducted in the study was performed under different Reynolds numbers with the velocity ratio being varied among tests with the same Re. The experimental tests conducted at $Re = 10.01 \times 10^5$ were chosen as it was closest to the calculated Reynolds number of the Batanes Magnus VAWT under rated operating conditions. As such, four simulations were conducted corresponding to four different velocity ratios under the same Re. The lift coefficient Cl vs velocity ratio k and drag coefficient Cd vs velocity ratio k plots derived from the simulations were compared to the results obtained by the experiment to determine the accuracy of the CFD parameters used in the simulations. The turbulence model k-ω shear stress transport (SST) was adopted for this study as it is said to be the most accurate model for predicting the dynamic behavior of airfoil with a moving fluid (Danao et al., 2013). It is a combination of the k-ω model at the inner boundary layer and the k-ε model on the outside of the boundary layer. This model was employed in numerous studies involving wind turbines, including the investigation of the aerodynamic performance of H-type Darrieus VAWT by Belabes and Paraschivoiu (2021). Ozturk (2020) also adopted the same model to study the flow past a rotating cylinder with Reynolds Numbers of 7.33×10^5, 1.01×10^6 and 1.26×10^6, which are cylindrical diameter based. For k- ω SST models, the acceptable wall unit y+ for coarse mesh is around 30 to 300 and for finer mesh, less than 5. This was considered during the verification of the accuracy of the model such that results of simulations that yielded a y+ value greater than 5 were rejected. One round of simulation ran 20 full rotations of the cylinder, with the last 3 rotations considered in determining the accuracy of the results. This was to make sure the results had already converged. As such, the simulation was time-dependent, and the time step was specified for each round of simulation. In the simulations, each time step was made to correspond to a 5-degree angular displacement of the rotating cylinder. In terms of convergence, there were two convergence targets per round of simulation. The residual convergence criteria guaranteed minimal error in the results, while the periodic convergence criteria guaranteed that the values of torque were already consistent in magnitude despite fluctuations due to the changing position of the cylinder. Particularly, the convergence criteria were set to a tolerance of 10 $\times 10^{-6}$.

The computational domain of the simulation played a vital role in ensuring the accuracy of the results such that an incorrect replication of the experimental set-up implemented in real life would have led to inaccurate results in the simulation. The computational domain consisted of the rotating infinite cylinder represented by a circle, and the fluid domain, which is the region that confined the cylinder. An O-type mesh was used in a study by Padrino and Joseph (2006), as it has been proven to be advantageous for rotating surfaces. As such, an O-type mesh was employed in the meshing. The shape and size of the fluid domain must provide sufficient clearance between the geometry of interest and the walls of the fluid domain to avoid blockage effects that may compromise the quality of the results. In a wind tunnel experiment of Mcintosh (2009), the blockage effects of the tunnel walls being too close to the turbine led to higher flow velocity passing through the turbine. This resulted in a power coefficient higher than the actual, where air flow is unconstrained. As such, the experimental results had to be corrected to eliminate the discrepancy caused by blockage effects. To avoid this scenario, the dimensions of the fluid domain were initially set as the cylinder being concentric to the circular fluid domain with a radius twenty times the diameter of the cylinder. These values were increased and decreased depending on how fully the domain captured the wake and whether the boundary conditions altered the flow passing through the cylinder in the domain. The implemented node density in the simulation can also affect the quality of the results. Determination of the appropriate node density was thus performed by starting at 100 nodes and progressively increasing the density by a factor of 2 twice over. For the boundary conditions, the side from which fluid entered the domain was set as the velocity inlet and the opposite of it was the pressure outlet. A constant inlet velocity equal to the wind velocity experienced in the experimental conditions was assigned at the inlet, while the outlet was set at atmospheric pressure. This domain set-up has been widely used in previous CFD simulations on wind turbines for its convenient set-up and capability to sufficiently capture the behaviour of fluid around the studied object. The rotation of the cylinder was specified through the moving wall function in the wall boundary condition. After validation of the CFD set-up used to implement the experiments of Bordogna et al. (2019), the parameters used from the validation simulations were carried over to the simulation of the Batanes Magnus VAWT. The simulations for the Batanes Magnus VAWT were divided into two sets: the first set corresponded to rated operating conditions, while the second set corresponded to typhoon wind conditions. The accuracy of the model was limited by the available Batanes Magnus VAWT specifications that Challenergy was able to provide. Particularly, the rectifier plates attached to the cylinders of the VAWT were not reflected in the CFD model because of its proprietary design that Challenergy, Inc. could not disclose. The first set of simulations was conducted at the rated wind speed of 8 m/s in different tip speed ratios TSRs, specifically 1.17, 2, 3, 4, 5, 6, and 8. Since wind speed was fixed for all set-ups, the rotational speed of the rotor was made to vary to meet the specified TSRs. The second set of simulations was conducted at wind speeds observed in typhoon weather conditions. The Tropical Cyclone Wind Signal System of PAG-ASA updated as of March 2022, was used to determine the specific wind speeds. Since the cut-out wind speed of the Batanes Magnus VAWT is at 40 m/s, the wind signals considered in the simulations were only those below 40 m/s. The median of the range of wind speeds covered in each wind signal was identified and used in the simulations. Specifically, the second set of simulations subjected the Batanes Magnus VAWT to the following median wind speeds: 13.89 m/s (Wind Signal 1), 20.83 m/s (Wind Signal 2), 28.61 m/s (Wind Signal 3), and 40 m/s (cut-out wind speed). The TSRs for all these set-ups were varied as it was impossible to maintain TSR = 1.17 from the rated conditions without having the turbine rotational speed go beyond the maximum specified by Challenergy.

For the computational domain of the Batanes Magnus VAWT, an inner and outer domain was created. The inner domain contained the turbine, while the other domain represented the environment immediately outside the turbine. The inner domain was a circle concentric to the turbine's rotor shaft (not depicted in the CFD model) with a diameter of 12 m, twice the rotor diameter. The outer domain was a rectangle with dimensions of 60 m x 120 m. The 60 m sides corresponded to the inlet and outlet. The rotor was situated 30 m orthogonal from the inlet and 30 m orthogonal from the 120 m sides. Figure 1b shows the illustration of the model. For the set-up of the simulations in Fluent, most of the parameters implemented from the validation set-up were carried over, with alterations made mostly on boundary conditions. Firstly, mesh motion was implemented on the inner domain by adding a rotational velocity in the cell zone conditions. Inlet velocity was adjusted according to wind speeds. For the boundary conditions of the cylinder walls, aside from the rotational velocity of the cylinder at its own axis, the rotation axis origin of the cylinder was also specified through an expression to make sure the cylinders revolve around the rotor.



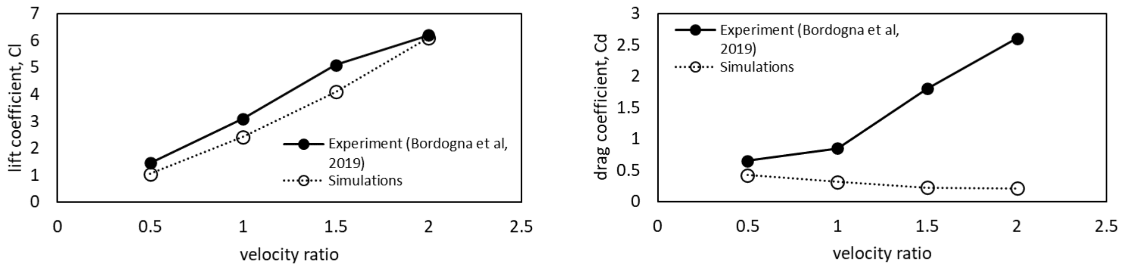
(a) Challenergy's Magnus VAWT in Basco, Batanes (Challenergy Inc., 2021)

(b) Illustration of 2D Domain

Figure 1: The VaWT illustration and the model diagram

3. Results and discussion

Among the different experimental set-ups from the reference study, the experiments carried out at a Reynolds number of 10 × 10^5 were used for validation as this was closest to the calculated Reynolds number of the Batanes Magnus VAWT at 6.57 × 10^5. Four simulations were conducted with varying velocity ratios specifically at k = 0.5, 1, 1.5, and 2.0. These were the only velocity ratios that Bordogna et al. (2019) carried out an experiment on at Re = 10 × 10^5. The simulation results are shown in Figure 2. Comparison was based on estimated values from the Bordogna's graph of sectional lift coefficient vs. velocity ratio since a table showing the exact values of the plotted points in the graph was not made available in the study. It can be observed that the trend of *Cl* over increasing velocity ratio satisfactorily resembled that of the reference. This indicates an accurate simulation of Bordogna's experiment. It must be noted that the peak value of *Cl* for rotating cylinders is yet to be conclusively defined by existing studies (Badalamenti, 2010). To date, existing studies have only proposed that *Cl* increases indefinitely with increasing velocity ratio. The Kutta-Joukowski theorem explains the continuous increasing trend of *Cl* over increasing velocity ratio as observed in both Bordogna's and the simulation results. It can therefore be said that the result of the simulation satisfactorily agrees with the prevailing knowledge that *Cl* increases with velocity ratio. However, no suggestions can be made regarding the behavior of *Cl* over higher values of *k* since the velocity ratios tested were only up to 2. Values for *Cd*, on the other hand, were smaller than the experimental values and did not follow the upward trend over increasing velocity ratio that was exhibited in Bordogna's experiments. Possible causes of this error could be the limitations of a 2D simulation, such as 3D factors that cannot be modelled in the simulations, particularly 2D assumptions that are not present in real-world observations. The setup of the experiment conducted by Bordogna et al. (2019) had the ceiling and floor of the wind tunnel significantly close to the top and bottom surfaces of the cylinder to minimize the vertical clearance.



(a)

(b)

Figure 2: Force Coefficient plots for experiments vs simulations, a) lift coefficient, b) drag coefficient

3.1 Batanes magnus VAWT simulations

The first set of simulations for Batanes Magnus VAWT was conducted at a constant rated wind speed with varied TSRs to produce a power curve. The angular velocity for the cylindrical blades, however, was maintained at the rated value of 150 RPM as the manufacturer did not disclose details regarding functions that vary the blades' angular velocity with respect to the wind velocity. The plot of the power coefficient *CP* shown in Figure 3 considerably resembles the typical performance of VAWTs as described by Edwards et al. (2012). However, the initial low performance common to that of VAWTs at low TSRs cannot be observed in Figure 4a as the simulations only started at TSR = 1.17. The broad peak of the power coefficient curve may be attributed to the high Reynolds number. Another notable observation from the results is that the highest *CP* is reached at TSR = 2. With the cylinder's rotational speed and the wind velocity maintained at constant values, TSR = 2 entails the rotor's rotational speed to be at 5.33 rad/s. This falls out of the provided maximum rotational speed of the turbine, which is at 35 rpm or 3.67 rad/s. This suggests that the current rated operating conditions of the Batanes Magnus VAWT may be below its optimal performing capacity. The calculated power extracted at rated wind speeds was found to be 941 W per unit length of the blade, and considering the rotor's 10 m long blade, it is close to the rated power output of 10 kW from Challenergy. It can also be observed that the power coefficients obtained are significantly high, with some being remarkably close to the 59.3 % Betz limit. It must be noted that due to a lack of information pertaining to the operation of the Batanes Magnus VAWT, the calculated power extracted does not consider the parasitic load of rotating the cylinders. During actual operation, the rotation of the cylinders would consume power and would thus reduce the *CP* of the Magnus VAWT.

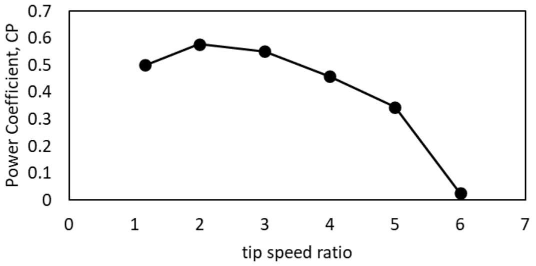
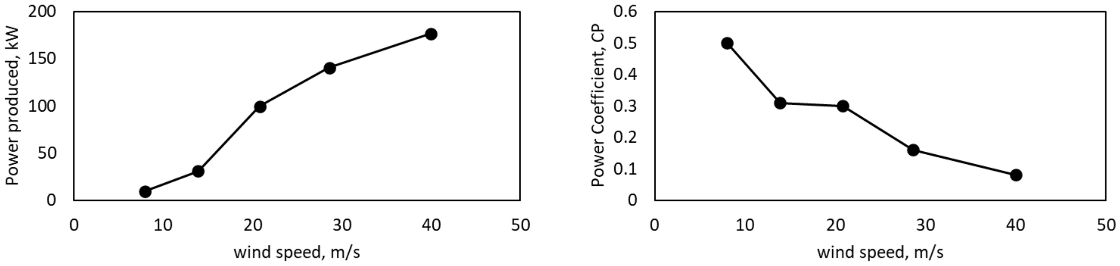


Figure 3: Power Coefficient curve of Batanes Magnus VAWT at rated wind speed of 8 m/s

3.2 Typhoon wind speeds

The extracted power and the power coefficient per typhoon wind speed are presented Figure 4a and Figure 4b. It must be noted that the parasitic load of rotating the cylinders were not taken into account in the calculation of the VAWT's extracted power. The *CP's* presented are higher than actual. It can be observed that the power coefficient is decreasing with increased speeds and decreased TSRs. This would be consistent with the trend shown in Figure 3 where *CP* decreases as the TSR decreases further from TSR = 2 where *CP* is at maximum. Although *CP* is decreasing as the wind speed increases, the extracted power, on the other hand, is increasing. The increase in extracted power is not very evident in the plot of *CP* because the available power is also increasing at a greater rate.



(a) Extracted Power of Batanes Magnus VAWT under typhoon wind speeds

(b) Power Coefficient of Batanes Magnus VAWT at typhoon wind speeds

Figure 4: Power performance of the turbine

It can be said that the increase in extracted power is significant at typhoon wind speeds. At wind signal 1, the extracted power is roughly three times greater than the extracted power of the turbine at rated wind speed; while at wind signal 2, the extracted power is ten times greater. These findings confirm the advantage of Magnus VAWTs in power generation amidst strong wind speeds during typhoons. Although the power coefficient is evidently decreasing over increased wind speeds, the extracted power is significantly increasing. It must be noted that the decreasing *CP* is accompanied by the rotor and the cylinders' rotational speeds being held at constant values.

4. Conclusions

The study deals with a series of CFD simulations investigating the aerodynamic performance of the Batanes Magnus VAWT when varying the TSR at the rated wind speed and varying the typhoon wind conditions. Based on the results discussed in the previous chapter, the following conclusions can be made:

- The optimum power extracted by the Magnus VAWT under the rated wind speed 8m/s is achieved at TSR = 2. For cylinders rotating at 150 rpm subjected to the said rated wind speed, the optimal rotation of the rotor is 5.33 rad/s. However, the current maximum rotational speed of the Batanes Magnus VAWT's rotor is at 3.665 rad/s. An additional 146 W can be generated if the optimal rotor rotation is implemented during operation.
- The Batanes Magnus VAWT power coefficient is decreased at typhoon wind speeds because of lowered TSRs at higher wind speeds but constant rotor angular velocity. However, despite lowered *CP* the power generated by the Batanes Magnus VAWT is improved. This means that the Batanes Magnus VAWT is indeed advantageous in generating power amidst typhoon conditions.
- It can be confirmed that the lift coefficient increases with increasing velocity ratio after exceeding a velocity ratio of 1. Additionally, this study has also found that increasing velocity ratio of a cylinder blade in a Magnus VAWT improves the performance of the VAWT such that the *Cl/Cd* ratio is improved at higher velocity ratios.

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