Comparison of simulations and wind tunnel measurements for the improvement of design tools for Vertical Axis Wind Turbines

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Abstract. As wind turbines are getting larger and cost reductions through up-scaling are reaching a limit, there is increasing pressure to reduce their installation and operating costs, making the business case for Vertical Axis Wind Turbines (VAWTs) more interesting again. However, in order to properly assess the economic potential of large-scale VAWTs, improved design tools are required. As the research budget for VAWT projects is generally too small to carry out expensive large-scale wind tunnel tests and field measurements, alternative methods are required. In this work, the application of small-scale, lower budget methods for improving VAWT design tools is assessed. It is shown that (a) currently available tools for VAWT design have not been sufficiently validated, (b) lower budget, small-scale wind tunnel tests can be effective for examining VAWT performance in terms of average power coefficient vs. tip speed ratio as well as the dynamics of the torque, and (c) Detached Eddy Simulations on small-scale VAWTs can be effective for examining their performance in terms of average power coefficient vs. tip speed ratio as well as the forces on the blades. Based on these results, a process for the transfer of the results of lower budget, small-scale measurements and simulations into recommendations for improved design tools is being developed.

1. Introduction
Vertical Axis Wind Turbine (VAWT) technology has not yet managed to establish itself as a reliable technology for wind energy projects. This is mainly because VAWTs have several disadvantages over Horizontal Axis Wind Turbines (HAWTs), including a lower efficiency, higher bearing loads and lower average height above the ground. However, advantages include the positioning of the drivetrain at the base, leading to reduced installation and service costs, and the independency of operation to wind direction, resulting in less fatigue. As wind turbines are getting larger and cost reductions through up-scaling are reaching a limit, there is increasing pressure to reduce their installation and operating costs. This is making the business case for Vertical Axis Wind Turbines (VAWTs) more interesting again.

This increased interest is reflected in the recent research activities aimed at better understanding the dynamics and aerodynamics of VAWTs - for example from the DeepWind project ([1], [2] and [3]) and from Sandia National Laboratories ([4], [5] and [6]) as well as the development of new offshore floating concepts such as [7], [8] and [9].

However, in order to properly assess the economic potential of large-scale VAWTs, improved design tools are required. Usually, design tools are improved by comparing them to costly wind
tunnel and full-scale field tests in which the shaft torque and blade loads are measured at a range of flow conditions, in order to better understand the physics. As the research budget for VAWT development projects is generally small and because very few large-scale VAWTs are actually in operation, it is currently not feasible to carry out such measurement campaigns.

In this work, the application of small-scale, lower budget methods for improving VAWT design tools is assessed. This is done by firstly reviewing the currently available design tools, then carrying out small-scale wind tunnel measurements and Detached Eddy Simulations (DES) and comparing the results to simulations using an open-source design tool, QBlade. Finally, the feasibility of these methods for improving design tools is assessed.

2. Review of currently available tools

Tools such as DNV GL’s Bladed [10], DTU’s HAWC2 [11] and NREL’s Aerodyn [12] are typically used in the wind energy industry for HAWT design. These tools consist of various different modules in which, for example, the aerodynamics, structural dynamics and control systems can be modelled. The aerodynamics are typically modelled with a simple Blade Element Momentum code [13] including corrections for blade tip and root vortex losses [13], for high tip speed ratios [14] and for dynamic stall [15] as well as additions for dynamic wake modelling [16]. The models have been shown to be accurate enough for design purposes and are well-established in the industry.

However, far less research and development work has been done on VAWT design. As the aerodynamic behaviour of VAWTs is significantly different to HAWTs, these codes cannot be directly used for VAWTs. Some of the first in-depth studies on the aerodynamics of VAWTs were focused on understanding the dynamic stall effects and vortex shedding in the wakes ([17], [18], [19], [20]). More recent studies have focused on the aerodynamics and structural dynamics of large-scale floating VAWTs by developing and applying design tools ([3], [6], [21] and [22]), CFD ([23], [24], [25], [26] and [27]) and wind tunnel tests ([28] and [1]).

The validation status in terms of power coefficient ($C_P$) or average shaft torque of some aerodynamic codes is summarised in Table 1 on the next page. It can be seen that most of the tools have not been properly validated in terms of their shaft torque production (or $C_P$). It is concluded that more VAWT validation measurements are required in the community order to improve the design tools.

3. Assessment of lower budget methods for design tool improvement

3.1. Small-scale wind tunnel tests

Small-scale wind tunnel tests were carried out in an open-section wind tunnel consisting of a fan connected to a 3 m long pipe of diameter 1.4 m with a honeycomb grid to smooth the flow. A three-bladed H-rotor VAWT model with a diameter of 0.7 m and a height of 0.5 m was built out of an aluminium frame and 3D-printed NACA 0024 blades with a chord length of 0.07 m as shown in Figure 1. An in-house Labview programme was developed in order to hold the rotational speed of the wind turbine constant at values ranging from 50 to 600 rpm using a Maxon RE 50 motor with a 4.3:1 gearbox and ESCON 50/5 servo controller.

In order to check the quality of the wind inflow conditions, the wind tunnel was first calibrated at the centre of the inflow plane with a PeakTech 5060 anemometer mounted on a positioning frame. Stable conditions were found for wind speeds up to 7 m/s, giving a maximum Reynolds number of 130,000 at the available rotational speeds and the measured air conditions of 14.4 oC and 96 kPa. The wind field of the inflow plane was then measured for a range of wind speeds with the anemometer positioned at 35 locations in a grid of $7 \times 5$ points as shown in Figure 2 for 2.85 m/s at the centre (the rotor area is shown by the black rectangle). This results in an average wind speed across the rotor plane of 25% more than the wind speed in the centre of the channel.
Table 1. Validation status of main VAWT aerodynamic tools.

| Tool name | Institute          | Model                                                                 | Validation status                                      |
|-----------|--------------------|----------------------------------------------------------------------|--------------------------------------------------------|
| -         | TU Delft           | Double multiple streamtube model [18]                                | Shown to be of poor quality                           |
| HAWC2     | DTU                | Modified linear actuator cylinder [3]                                | No published comparison to $C_P$ measurements          |
| CACTUS    | Sandia             | 3D vortex code with lifting line approximation [6]                   | Over-prediction of $C_P$ above max. $C_P$              |
| QBlade    | TU Berlin          | Lifting-line free-vortex wake code [29]                               | Mediocre performance of $C_P$ compared to RANS CFD      |
| U2DIVA    | TU Delft           | 2D unsteady multibody free-wake panel code [28]                      | No published comparison to $C_P$ measurements          |
| ARDEMA2D  | University of Uppsala / Areva | Free-vortex particle wake [30]                     | Poor performance of $C_P$ compared to wind tunnel tests |
| PHARWEN   | Nenuphar           | 3D vortex panel [8]                                                 | Average blade forces compare well to field measurements |
| -         | University of Glasgow | Vorticity transport model [21]                                      | Blade forces and wake profiles compare fairly well to wind tunnel experiments |

Figure 1. Wind tunnel set-up.

Figure 2. Measured inflow wind conditions at 2.85 m/s in the centre.
The key design parameter of a wind turbine is the shaft torque, allowing the rotor power coefficient \( C_P \) to be calculated as shown in Equation 1, where \( \tau \) = rotor torque (Nm), \( \omega \) = rotational speed (rad/s), \( \rho \) = air density (kg/m\(^3\)), \( V_0 \) = inflow wind speed (m/s) and \( A \) = rotor cross-sectional area (m\(^2\)).

\[
C_P = \frac{\tau \omega}{\frac{1}{2} \rho V_0^3 A}
\] (1)

A Lorenz Messtechnik in-line torque sensor type DR-2112R was mounted between the motor and the rotor and measurements were carried out at a frequency of 2 kHz for at least 30 seconds per measurement point. Blade loads are also key to assessing design tools; however, they were not measured due to the expense and complexity of installing strain gauges in the rotating system. The results in terms of power coefficient vs. tip speed ratio are shown in Figure 3 for wind speeds of 6.0 m/s, 6.5 m/s and 7.0 m/s, where the tip speed ratio \( \lambda \) is given by Equation 2 and \( R \) = rotor radius (m). They are compared to measurements on a similar-sized VAWT model from the University of New Hampshire [6], showing that the approximate magnitude is reasonable (the dimensions, aspect ratio, solidity and airfoil types are different). This shows that the chosen set-up could be used successfully to measure the full range of the power coefficient vs. tip speed ratio curve of the VAWT model.

\[
\lambda = \frac{R \omega}{V_0}
\] (2)

Examination of the 2 kHz torque signal allows the periodical behaviour of the rotor to be analysed. Figure 4 shows the frequency content of three typical measurements carried out for 60 seconds each at tip speed ratios of 0.82, 1.65 and 2.47 (200, 400 and 600 rpm), obtained by carrying out Fast Fourier Transforms on the measurement data. As expected, clear peaks can be seen at the rotational speed \( (IP) \), at the blade passing frequency (three times the rotational speed = \( 3P \)), at twice the blade passing frequency \( (6P) \) and at three times the blade passing frequency \( (9P) \). Large peaks at \( 2P \) can also be seen for every rotational speed, indicating a rotor...
imbalance from an error in manufacture or pitch setting of one of the blades. Additionally, large peaks at $4.3P$ can be seen. These are thought to be caused by the dynamics of the motor, which turns 4.3 times faster than the rotor. A small peak can be seen on each plot at a frequency of approximately 23 Hz, circled on the figure, indicating a dynamic that is independent of the rotor speed. This could be the first torsional natural frequency of the structure.

Figure 4. Frequency content of a three typical torque signals at tip speed ratios of 0.82, 1.65 and 2.47 (200, 400 and 600 rpm).

As the frequency content at $4.3P$ is due to the motor and not to the wind turbine rotor, it needs to be removed in order to examine the dynamic behaviour of the rotor. On the left-hand graph of Figure 5, a typical torque signal at a tip speed ratio = 2 is shown with a low-pass filter of 100 Hz applied. The periodic nature of the torque can be seen; however, the $4.3P$ content is dominating. Applying a 30 Hz low pass filter removes the $4.3P$ frequency, but also the interesting $6P$ and $9P$ frequencies (middle graph). Here only the blade passing frequency can be seen, as well as the asymmetry due to the misalignment of one blade as discussed above. The $4.3P$ peak was therefore removed manually from the Fourier transformed-data and then an Inverse Fast Fourier Transform was performed on the resulting dataset, giving the graph shown on the right-hand side of Figure 5.

This shows a distinctive periodical behaviour; the torque does not smoothly transition from the maximum to the minimum value, but it increases again slightly in the middle. This is thought to be caused by the interaction of the blades with the wake, and is examined further in the next section.

Figure 5. Typical torque signal at tip speed ratio = 2 (rotational speed = 435 rpm = 7.25 Hz).

In summary, it has been found that lower budget small-scale wind tunnel tests can be used to compare the performance in terms of power coefficient vs. tip speed ratio as well as to investigate
the natural frequencies and the dynamic behaviour of the total torque on the shaft within a rotor revolution. This has the potential for helping to understand the physics of VAWTs and thus improving design tools.

3.2. Detached Eddy Simulations on small-scale VAWTs

Computational Fluid Dynamics (CFD) can be used in order to gain detailed information of turbulent flows around objects. In this case, its application can potentially help to better understand the behaviour of VAWTs and therefore to improve design tools, either in combination with or instead of small-scale wind tunnel tests.

The basis of conventional CFD simulations are the Navier-Stokes equations, which define single-phase fluid flows and can only be solved for turbulent flows using turbulence modelling, as the resolution required to resolve all scales involved in turbulence is beyond what is computationally possible. The most common - and least computationally expensive - approach to turbulence modelling is to derive the Reynolds-Averaged Navier Stokes (RANS) equations from the instantaneous Navier-Stokes equations via a Reynolds decomposition. A more accurate - and more computationally expensive - approach is Large Eddy Simulations (LES), involving removal of the smallest scales of the through a filtering operation and modelling of their effect using subgrid scale models. This allows the largest and most important scales of the turbulence to be resolved, while greatly reducing the computational cost incurred by the smallest scales. A compromise between the two methods is Detached Eddy Simulations (DES), which uses RANS to resolve boundary layers and LES to resolve the larger eddies in the bulk flow. Therefore, the grid resolution for DES is not as demanding as pure LES, considerably reducing the cost of the computation.

As this work focuses on the application of small-scale, lower budget methods for improving VAWT design tools, it was decided to carry out Detached Eddy Simulations (DES) on the VAWT model in the small-scale wind tunnel. This was found to be the best compromise between computational expense and model accuracy, as the small scale of the simulations reduces the computational costs but retains the better accuracy of DES compared to RANS.

First of all, Detached Eddy Simulations were carried out using CFX ANSYS version 19.0 on one blade of the wind turbine for a Reynolds number of 88,000 as shown in Figure 6(a). The results in terms of lift coefficient ($c_L$) vs. angle of attack ($\alpha$) are compared to the results of other turbulence models (SST k-omega, SST k-omega coarse, k-epsilon and Scale-Adaptive Simulation [31]) as well as to XFOIL simulations [32] with different values of $N_{crit}$ in Figure 6(b). $N_{crit}$ is the log of the amplification factor of the most-amplified frequency which triggers transition, and should be set depending on the ambient disturbance level in which the airfoil operates (= 4-8 for a dirty wind tunnel, 10-12 for a clean wind tunnel). First of all, it can be seen that the XFOIL results are highly dependent on the value of $N_{crit}$. Also, it can be seen that DES is capable of reasonably predicting the flow over the blade.

Next, simulations were carried out on one half of the wind turbine and outlet pipe of the wind tunnel as shown in Figure 7. Two different meshes were used for the simulations, having 15 million and 44 million cells. The mesh around the structure and the blades was refined using inflation layers to reach a $y+$ of less than 30. Incompressible transient simulations were performed using the Detached Eddy Model for turbulence. The wall function is used to model the boundary layer very close to the blades. The time steps ranged from 0.5 to 1.0 ms, depending on the rotational speed of the turbine. The simulation results were checked for mesh and time-step independence. The simulations were run at the computing cluster at the University of Applied Sciences Rapperswil, using 80-120 cores per simulation. The input wind speed was set to a constant value of 6 m/s.
Figure 6. (a) Set-up of the Detached Eddy Simulations for one blade; (b) Results in terms of lift coefficient vs. angle of attack.

Figure 7. Set-up of the Detached Eddy Simulations.

The results in terms of power coefficient vs. tip speed ratio are shown in Figure 8 compared to the wind tunnel measurements. At and above the maximum $C_p$, the results match fairly well. At lower tip speed ratios, the simulations match less well, due to the increasing average angle of attack (leading to more flow separation, which is difficult to simulate) and the decreasing Reynolds Number (reducing the likelihood of a turbulent flow, which is easier to simulate). Further differences are thought to be caused by the non-uniform wind input field in the wind tunnel, which is not accounted for in the simulations.

In Figure 9, the variation of torque with time for a tip speed ratio = 2 is examined. In part (a), the torque exerted on the shaft by one blade is shown. One large peak is visible per revolution, when the blade passes the front of its swept area and is operating at its optimal angle of attack and producing lift. A second, smaller peak is seen as the blade passes the back of its swept area, producing a small amount of lift. The torque even becomes negative at two azimuth locations, because here the drag dominates. The torque produced by the other two blades shows a similar pattern, offset by one-third of a revolution. The total torque, shown in part (b), is
then given by the sum of these three torques at each azimuth position. Like the measurements shown in the previous section, this signal does not smoothly transition from the maximum to the minimum value, but it increases again slightly in the middle. This occurs due to the presence of the second small peak as each blade passes behind the tower. Additionally, it can be seen in part (b) that the magnitude of the torque fluctuations matches well with the measurements (both approximately 0.15 Nm), confirming the ability of the simulations to predict the physics correctly. Part (b) also shows a comparison between the positive torque produced by the blades and the resistance caused by the structure of the wind turbine, comprising approximately 10\% of the total torque.

![Figure 8](image8.png)

**Figure 8.** Comparison of measurements to DES.

![Figure 9](image9.png)

**Figure 9.** Variation of torque with time from DES: (a) For one blade; (b) For all blades (solid line) and for the structure (dashed line).

In summary, it has been found that lower budget Detached Eddy Simulations on small-scale VAWTs can be used to compare the performance in terms of power coefficient vs. tip speed.
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ratio as well as the dynamic behaviour of the wind turbine. This has the potential for helping to understand the physics of VAWTs and thus improving design tools. Further analysis of these results is on-going.

3.3. Open-source design tool
The design tool that is applied in this work is the open-source software QBlade [29] from TU Berlin, which is capable of Double Multiple Streamtube Model (DMSM) and Lifting Line Free Vortex Wake (LLFVW) simulations. The DMSM [33] applies the actuator disc and blade element theory to VAWTs by splitting up the stream tube flowing through the VAWT into a set of smaller stream tubes that are passed through by each blade twice per revolution. The LLFVW method [34] models the blades with a single line of vortices located on the quarter chord of the blade and updates the position of the wake end nodes based on the local velocity.

Simulations were carried out in the DMSM and LLFVW mode using the geometry and air conditions of the small-scale wind tunnel. The lift and drag coefficients were obtained from the results of the one-bladed DES from the previous section and extrapolated using the Montgomery method in QBlade [29]. A constant input wind speed was used. For the DMSM simulations, the blade was discretised into 40 elements and a maximum epsilon for convergence of 0.001 was used. Tip losses and variable induction factors were neglected. For the LLFVW simulations, 10 rotor revolutions were simulated with 720 time steps. Tower effects and drag of the structure were neglected.

The average power coefficient vs. tip speed ratio results from the QBlade simulations are shown in comparison to the small-scale measurements and DES in Figure 10(a). It can be seen that the DMSM and the LLFVW simulations overestimate the power coefficient compared to the measurements and the DES at tip speed ratios above the peak power coefficient. This is expected from previous work showing that DMSM generally overestimates at high tip speed ratios due to the fact that backflow effects are not taken into account [33] and that LLFVW generally overestimates the torque [29]. In Figure 10(b), the familiar variation of torque with time can be seen as discussed in the previous sections.

Figure 10. (a) Comparison of results from measurements, DES and QBlade in terms of power coefficient vs. tip speed ratio; (b) Power coefficient vs. time for the total torque from the QBlade LLFVW simulations for a tip speed ratio = 2.

3.4. Summary of lower budget methods
VAWT design codes were found to not match well with simulations and wind tunnel tests, both in the literature and in the present work. However, lower budget, small-scale wind tunnel tests
and Detached Eddy Simulations were successfully used to examine the average torque as well as its variation with time in order to examine the physics of VAWTs. This has the potential for improving VAWT design tools and ultimately improving VAWT design and reducing wind farm operating costs. Based on these results, a process for the transfer of the results of lower budget, small-scale measurements and simulations into recommendations for improved design tools is currently being developed.

4. Conclusions
This work has shown the following:

- Currently available aerodynamic tools for VAWT design have not been sufficiently validated in terms of the shaft torque and blade loads, the most important design parameters.
- Lower budget, small-scale wind tunnel tests can be effectively used for examining VAWT performance in terms of average power coefficient vs. tip speed ratio as well as the dynamics of the torque.
- Lower budget Detached Eddy Simulations on small-scale VAWTs can be effectively used for examining their performance in terms of average power coefficient vs. tip speed ratio as well as the forces on the blades.
- A process for the transfer of the results of lower budget, small-scale measurements and simulations into recommendations for improved design tools is currently being developed.

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