Scaled wind turbine setup in a turbulent wind tunnel

Frederik Berger, Lars Kröger, David Onnen, Vlaho Petrović, Martin Kühn
ForWind - University of Oldenburg, Institute of Physics, Küpkersweg 70, Oldenburg, Germany
E-mail: frederik.berger@uol.de

Abstract. Wind tunnel experiments with scaled model turbines are a viable complement to field tests and simulations. The scaling of a 5 MW reference turbine with the aim of maintaining the design tip speed ratio and lift distribution is introduced. The machine, named MoWiTO 1.8 (Model Wind Turbine Oldenburg 1.8 m), is described in this paper and the setup in the WindLab wind tunnel of the University of Oldenburg, featuring an active grid, is described. Based on aerodynamic simulations in a turbulent wind field flow, the calculated aerodynamic loads of the reference turbine and the scaled model are compared. Furthermore, the aerodynamic characterization of the machine is presented, with focus on power and thrust coefficients and sensitivity to changes in the Reynolds number. It is shown, that with the chosen approach many attributes of the reference turbine can be scaled into the controllable wind tunnel environment.

1. Introduction
Investigations with scaled model wind turbines in the controlled environment of a wind tunnel are a viable addition to simulations and field testing. The aforementioned have the disadvantage of mostly not being able to represent all relevant physical phenomena for simulation models, respectively the unknown and not reproducible boundary conditions of open field test measurements. For scaled wind turbine investigations in the wind tunnel these disadvantages are not present, however the main problem is that in the scaling process not all non-dimensional numbers can be maintained. In addition, space for sensors and actuators is limited.

Besides the large wind tunnel campaigns of NASA Ames [1] and of the Mexico project [2], which focused on aerodynamics, different model wind turbines in the size range of 1 m to 2 m have been designed and used for experiments by various researchers, e.g. [3, 4], with the main purpose being smart blades testing and control applications. Depending on the aim, the scaling process is different.

The objective of this contribution is to introduce a newly constructed model wind turbine with a diameter of 1.8 m, that represents the generic offshore reference wind turbine NREL 5 MW [5]. This includes the scaling process, comparison of aerodynamic loads and forces for reference and the scaled turbine under turbulent inflow, based on aerodynamic simulations, as well as the aerodynamic characterisation in the wind tunnel. The turbine model is aimed for investigations in the area of inflow and rotor aerodynamics, turbulence-turbine interaction and testing of control approaches.
2. Scaled wind turbine model and wind tunnel with active grid

2.1. Scaling

The scaling approach has the goal of maintaining the design tip speed ratio (TSR) of 7.5 of the reference turbine. Furthermore, the lift distribution over the blade length should be representative of the reference turbine, for all operational TSR. If these aims can be fulfilled, this results in a representative thrust as function of TSR curve and representative blade root bending moments in the flapwise direction, as these quantities are mostly an integration of the lift along the blade span. The turbine diameter should be as large as possible within the limitations of the wind tunnel size to benefit the Reynolds number, as well as to allow for the implementation of sensors and an individual pitch system in the blade root.

The model turbine diameter is chosen to be 1.8 m, on the basis of the target wind tunnel with an open test section and a square nozzle outlet of 3 m by 3 m and experiences with a smaller wind turbine in a smaller wind tunnel with a similar turbine to tunnel ratio [6]. The NREL 5 MW turbine with a rotor diameter of 126 m [5] is chosen as a reference, because of its prevalence in scientific studies and thus possibility to easily compare findings, as well as the availability of the design.

The rotor diameter is scaled with a length factor \( n_L \) according to eq. (1). Due to safety considerations the rated rotational speed is limited to 600 rpm, hence, the time scaling factor \( n_T \) is governed by eq. (2).

\[
\begin{align*}
n_L &= \frac{D_{\text{scaled}}}{D_{\text{reference}}} = \frac{1.8 \, \text{m}}{126 \, \text{m}} = \frac{1}{70} \\
n_T &= \frac{n_{\text{scaled}}}{n_{\text{reference}}} = \frac{600 \, \text{1/min}}{12.1 \, \text{1/min}} = 49.6
\end{align*}
\]

Based on the length and time scaling factors, the main parameters of the scaled wind turbine are obtained. These are listed in table 1 along with the reference values [5] and the specific scaling factor.

### Table 1. Scaling of main turbine parameters

| Rated values     | Factor | Reference | Scaled  |
|------------------|--------|-----------|---------|
| rotor diameter   | \( n_L \) | 126 m     | 1.8 m   |
| rotor speed      | \( n_T \) | 12.1 1/min | 600 1/min |
| tip speed        | \( n_L \cdot n_T \) | 80 m/s   | 57 m/s  |
| power            | \( n_L^5 \cdot n_T^3 \) | 5 MW     | 363 W   |
| torque           | \( n_L^5 \cdot n_T^3 \) | 3.95 MNm | 5.8 Nm  |
| wind speed       | \( n_L \cdot n_T \) | 11.4 m/s | 8.1 m/s |
| thrust           | \( n_L^4 \cdot n_T^2 \) | 700 kN   | 72 N    |
| max. chord Reynolds number | \( n_L^2 \cdot n_T \) | \( 1.1 \times 10^7 \) | \( 1.1 \times 10^5 \) |

2.2. Blade design

The approach to scale the lift distribution for the model turbine is to, in a first step, keep the twist distribution over the non-dimensional radius \( r/R \) of the reference turbine. Under the hypothetical assumption, that the profiles of the reference rotor blade have the same lift characteristics as when used in the scaled experiments, a simple geometrical scaling of the blade
would be sufficient. However chord based Reynolds numbers are decreased by a factor of 100 due to the scaling process (see table 1). The reference profiles would suffer severe separation at this reduced Reynolds number and the lift and drag polars would change significantly.

For the reference blade two representative airfoils are used to describe the aerodynamic properties. These are the DU35 for the root section and the NACA 64618 for the midspan and tip region. These profiles were exchanged with the two low Reynolds number airfoils SG6040 and SG6041 [7]. The root airfoil SG6041 has a relative thickness ratio of 16 % and is used from 0.2 R to 0.38 R and the midspan and tip airfoil SG6041 has a relative thickness ratio of 10 % and is employed from 0.5 R up to the tip. Between 0.38 R and 0.5 R the profiles are interpolated.

The airfoils were chosen on the basis, that both have their maximum glide ratio (GR) at the angle of attack, that the corresponding reference airfoils have theirs as well. Considering the low operational Reynolds number the maximum GR of these airfoils is comparably high. A further reason was the high relative thickness of the root airfoil, due to structural considerations. In addition, the SG6041 airfoil was chosen because it is a low lift airfoil, as is explained below.

In figures 1 and 2 the slope of the lift coefficient and glide ratio of the applied low Reynolds number airfoils is plotted together with the corresponding airfoils used on the base turbine [5]. The polars of the low Reynolds number airfoils are estimated with Xfoil, with a Reynolds number of $75 \cdot 10^3$ for the SG6040 airfoil and $115 \cdot 10^3$ for the SG6041 airfoil, which represent typical operation at 480 rpm, a $N_{crit}$ value of 7 [8] and without forced transition, within the QBlade environment [9]. The polars of the corresponding airfoils of the reference blade are taken from the FAST turbine model. The lift slope of the tip airfoil SG6041 has an offset to the reference NACA airfoil, because it is a low lift airfoil. To maintain the non dimensional lift, the chord length is extended, based on equation (3).

$$\frac{C_L(\alpha)}{c(r)} = const.$$  \[3\]
The chord is extended for the whole blade, based on the lift offset at the tip airfoil at a design angle of attack of 4°, corresponding to design operating conditions at 0.7 R - 0.9 R and results in a chord enlargement of 31%. This approach has the benefit of increasing the chord based Reynolds number along the scaled blade at a maintained design tip speed ratio of 7.5. For the manufacturing of the blade the airfoil shapes have been slightly modified with a constant finite trailing edge thickness (0.5 mm), as well as by increasing the minimum leading edge radius slightly for the tip airfoils ($r_{\text{min}} = 0.5 \text{ mm}$). The requirement for the first eigenfrequency of the blade was to be safely above the 3 P excitation of the rotor, which is at 30 Hz. This was achieved by a rotorblade design with a carbon fiber shell and a foam spar, weighing about 160 g per blade and providing a basically rigid blade. At the root the blade is glued on a metal adapter.

2.3. Turbine layout

Figure 3 shows the layout of the nacelle and figure 4 the assembled turbine. A brushless DC motor, designed for the use in RC airplanes, is used as a generator and converts mechanical rotor to electrical power. The generated electric power is then rectified and dissipated by an electronic load with a nominal power of 400 W. Connected to the generator is a planetary gearbox with a ratio of 1:5. Through a coupling a torque meter, with a nominal torque of 20 Nm, is connected, which also features a dual optical encoder with 360 steps per revolution. With a further coupling the torque meter is connected to the main shaft. This hollow shaft is mounted on two roller bearings with a slip ring with 24 channels in between. Through this slip ring, signals and power are transferred from the stationary nacelle to the rotating rotor hub and vice versa. The wires are layed through a hole in the hollow shaft and bypass so the rotor bearing. On the shaft,

![Figure 3. Nacelle of model turbine](image1)

![Figure 4. Turbine](image2)

a board with five measurement amplifiers is mounted. The amplifiers with an output range of ± 10 V are utilised to amplify the strain gauge signals used to measure flapwise blade bending moments on all blades and shaft bending moments. Full Wheatstone bridges are applied for the strain gauge measurements. Local bending is increased at the places of measurement by means of four symmetrical recesses on the hollow shafts of the blade roots and the main shaft. This way the signal output is increased and the recess openings are used as cable passages. In front of the rotor three motor boards are positioned, which drive the individual pitch motors. The motor boards are controlled with the CANopen protocol, which enables the control of the individual pitch motors with only five cables, including power supply, that have to be passed
through the slip ring. The cables are distributed to the single controllers with a distribution board.

DC motors with an encoder and a 1:159 planetary gearbox are used for pitching and are positioned within the root of each blade. The pitch system is preloaded with a torsional spring to prevent play in the pitch system. The metal adapter, glued to the composite blades, acts also as the housing for the pitch motor and shaft surface for the pitch bearings.

The turbine nacelle, which is aluminium milled and designed to allow for modular changes of different turbine components, is mounted on a hollow tower. All cables of the nacelle are layed inside the tower. At the tower base there are strain gauges to measure the bending moments in fore-aft and side-side directions. Again, the strain and thus strain gauge output are increased by four symmetrical recesses, which are also used to lead the cables out of the hollow tower. The tower is mounted on a height adjustable support structure. The first eigenfrequency modes in fore-aft and side-side directions are below the excitation of 1 P at 400 rpm.

The control and data acquisition runs on the Real Time System of a Compact RIO PAC system. Analog signals of the strain gauges on the blades, shaft and tower base are recorded synchroniosly, together with optional flow measurements, e.g. with hot wires. The current of the electronic load, which is proportional to the rotor torque, is controlled by 0-10 V output of the PAC system. Further modules for digital signals of the torque sensor encoder, which are processed on the integrated FPGA, and for the CANopen communication are used.

2.4. Setup in wind tunnel with active grid

The dimensions of the Göttingen type wind tunnel in the WindLab of ForWind - University of Oldenburg are 3 x 3 x 30 m$^3$, with maximum wind speeds in the open test section configuration of 32 m/s. In figure 5, the typical turbine setup in the tunnel is sketched. The turbine is mounted on a height adjustable support to bring the turbine hub to the center of the wind tunnel. The tunnel is operated in an open test section configuration, so that no blockage effects are to be expected [10]. The distance between nozzle and rotor plane is 4.8 m, corresponding to 2.7 D.

![Figure 5. Scaled turbine setup in tunnel w/o grid](image1)

![Figure 6. Turbine in tunnel w/ grid](image2)

To the nozzle, an active grid can be attached (see figure 6), with which specific turbulent flow patterns can be repeatedly impressed on the flow, as described by Heißelmann et al. for a smaller version of this grid [11]. These patterns, for example, can be wind characteristics as measured in the free field by Lidar systems, scaled in size and speeded up in time to match the scaling of the model turbine.
3. Investigations of aerodynamic scaling based on aeroelastic simulations

3.1. Simulation setup
A model of the scaled turbine has been set up in FAST v7 [12]. The model includes the aerodynamic shape of the turbine blade which consists of 14 segments. The polars are based on Xfoil simulations as described in section 2. The degree of freedom for aerodynamic forces is enabled for the considered simulations, whereas all other structural degrees of freedom are disabled. Furthermore an existing FAST model of the NREL 5 MW turbine is used, also only with the aerodynamic forces degree of freedom enabled and without the originally specified rotor tilt, in order to match the scaled model.

The Beddoes Leishman dynamic stall model and the implemented dynamic inflow model are turned on in the calculation of the aerodynamic forces. The NREL 5 MW turbine spins with a constant rotational velocity of 7 rpm, whereas the scaled model rotates at 490 rpm, that is 70 times the speed of the reference turbine. For the investigation a ten minute turbulent wind seed generated with TurbSim with the IEC Kaimal model is considered. The wind field (class 1A) is created for the NREL 5 MW wind turbine and has a mean wind speed of 6.17 m/s, turbulence intensity of 23.5 % and a shear layer with a power law exponent of 0.2. Using the same tip speed and upstream mean wind leads to the same mean tip speed ratio of 7.5, which is the design TSR. The ratio of rpm corresponds to the geometric scaling in this numerical investigation in contrast to the prior chapter for the hardware design. The length of the full size turbulence wind box corresponds to simulation time times the mean velocity, which leads to identical number of rotor revolutions. The wind field therefore is compressed in a next step in size by a factor of 1/70 and the time is speeded up by a factor of 70, thus leading to a time length of the wind field of 8.57 s for the scaled turbine.

3.2. Aerodynamic response in turbulent conditions
Both turbines, the reference and the scaled turbine, have been simulated with the described setup and the same number of simulation time steps. The pitch angle of the scaled turbine was set to 1° (in feather direction), as this was identified as the perfect operational point, as described in section 4. The output of the scaled turbine model simulation has been scaled back to the size of the 5 MW reference turbine. For a perfect scaling of the rotor blade all time series of aerodynamic forces and angle of attack distributions over the rotor radius, as well as integrated quantities like torque, thrust and flapwise blade bending moment should match.

In figure 7 scatter plots for the angle of attack variation, as well as the force component normal to the rotor plane, at three blade segments of 0.42 R, 0.67 R and 0.92 R, are presented. Firstly, a high correlation for both quantities can be seen at all three radii. However, the exchange of the airfoils and enlarging of the chord have an influence. The red lines, representing the best linear fit, depict, that the slope for the angle of attack is quite similar, whereas for the normal forces it is less steep, compared to the x=y function. That means there are slightly overestimated maximum normal forces and also underestimated minimal normal forces, for the scaled turbine. The main reason is, that the chord scaling was based on the design angle of attack at a radius of 0.7 R to 0.9 R. For operation off these conditions the chord scaling factor of 1.31 does not fit perfectly.

In figure 8 scatter plots for thrust, torque and blade bending moment in flapwise direction are presented. For these quantities, that represent an integration of the aerodynamic forces, again a good correlation is found, especially for thrust and torque. For the thrust and bending moment, the same trend as for the normal forces is visible, which is expected, since the forces normal to the rotor plane are the underlying forces for these quantities. For the torque, the values for the reference turbine are in general slightly higher. The main reason for this is that the glide ratios of the profiles used for the scaled blade are at least lower by a magnitude of two.
4. Wind tunnel experiments
The setup in the wind tunnel is sketched in figure 5. At the hot wire position, 1.5 D in front of the turbine where the flow is not yet disturbed by the rotor, an array of three hot wires is placed. One is on the center line and the two others are at 0.4 m in positive and negative x-direction. As a reference longitudinal velocity the mean value of these three hot wires is taken. Torque and revolutions are measured with the torque meter. The thrust is derived from the measured tower base bending moment in fore-aft direction. The characterisation curves are recorded at a constant rotational velocity and the wind velocity is adjusted to achieve different tip speed ratios. With this approach, the chord based Reynolds number does not change significantly along the radius, since the rotational velocity component is the main contributor.
4.1. Aerodynamic characterisation
For the aerodynamic characterisation, the rotational velocity is kept constant at 480 rpm with a PI controller. For every operational state average values of power coefficient ($C_P$) and thrust coefficient ($C_T$) are computed over five second periods. In figure 9 a contour plot of $C_P$ based on 56 measured operational states is presented. The tip speed ratio is varied from 5.5 to 9 with a step size of 0.5 and the pitch angle is changed from minus two (towards stall) to four (towards feather) in steps of one degree. The turbine performance at a pitch angle of one is the best. The optimal tip speed ratio is in the range between 7 and 8.

In figure 10 the thrust coefficient for the same experimental matrix is presented. For a pitch angle of one degree and tip speed ratios of 7 and 7.5, $C_T$ is close to a value of the optimal thrust coefficient of 8/9. The here given thrust coefficients are based on the tower bottom bending moment in fore-aft direction and are corrected for the tower and nacelle drag, which was measured on the structure without the blades attached.

Figure 9. Contour plot of power coefficient for different tip speed ratios and pitch angles

Figure 10. Contour plot of thrust coefficient for different tip speed ratios and pitch angles

The power coefficient as a function of the tip speed ratio for a pitch angle of one degree is plotted in figure 11 and compared to numerical results for the NREL 5 MW turbine obtained with the FAST model described in section 3. The error bars indicate the influence of an error of ±0.1 m/s in the measurement of the reference velocity, which is considered a conservative margin of uncertainty for the hot wire measurements. When increasing TSR, this uncertainty rises as well, since the wind velocity is decreased at constant rotational speed. The power coefficient shows a good match to the general slope over TSR, with the power coefficient peaking at a TSR of 7.5. For the offset between the curves, at least two reasons play a significant role. Firstly, the glide ratio of the profiles used for the scaled turbine are lower by a factor of at least two in comparison to the reference turbine. Secondly, in the experiment, the power is measured by the torque meter. Between this device and the rotor there are mechanical losses in the bearings of the main shaft and the slip ring contact, that have not been accounted for.

In figure 12, the thrust coefficient is plotted as a function of the tip speed ratio, again in comparison to the reference turbine. The experiment fits the reference in slope and also in absolute values.

4.2. Influence of Reynolds number
In some experiments, especially in turbulent flow with a controller, the rotational velocity is not constant. The main operational window of the turbine is in the range of 400 rpm to 600 rpm.
Chord based Reynolds numbers for the profiles range from $50 \cdot 10^3$ at the root to a maximum of $100 \cdot 10^3$ for operation at 400 rpm and from $70 \cdot 10^3$ to $140 \cdot 10^3$ for operation at 560 rpm.

For the three settings of 400, 480 and 560 rpm and the optimal pitch setting of 1 degree, the power coefficient and the thrust coefficient over tip speed ratio have been recorded and are plotted in figures 13 and 14, respectively. For the 560 rpm case not all tip speed ratio configurations are available, since these measurements would have exceeded the design loads of the machine. For the 400 and 480 rpm operating points the maximum $C_P$ is at a TSR of 7.5 and the slope for higher TSR matches, whereas the maximum for the 560 rpm operating points is slightly shifted to the lower TSR of 7. For tip speed ratios of 8 to 9 the operating measurements at the higher rpm values of 480 and 560 match with, whereas the measurements at 400 rpm show a faster decline in power coefficient. The thrust coefficient for all situations match, however at TSR higher than 8, again, the case with 400 rpm shows slightly lower values. This decline can be attributed to the change in Reynolds number and is due to a distinct flow over the blade. Laminar separation or a separation bubble on a blade section, due to the decreased Reynolds number, are a possible explanation, however not provable with the available data.
5. Conclusion

A scaled wind turbine model, based on a 5 MW reference turbine, has been introduced. This includes the scaling process, design of the blades, hardware introduction of the machine and setup in the wind tunnel. Aerodynamic forces and loads of the scaled turbine were compared to the reference turbine under turbulent inflow and in an aerodynamic simulation environment. These simulations were performed in preparation of experimental measurements in tailored turbulent inflow conditions. Furthermore the aerodynamic characterisation measurements obtained with the turbine in the wind tunnel were presented. The following conclusions can be drawn from the investigations in this paper:

- Based on the aerodynamic simulations it is presented, that the scaled turbine model maps the thrust, torque and flapwise blade bending characteristics, but also the normal forces and angle of attack variation at different blade segments of the reference turbine.
- In the experiments, the machine reaches the maximum power coefficient of 0.4 at the design tip speed ratio and shows a match of the general slope for power coefficient and a good fit for the thrust characteristic in comparison to the numerical results of the reference turbine.
- The power coefficient and thrust coefficient slope, for operation at different rotor speeds and thus chord Reynolds numbers, depict a good match, apart from slight deviations for the case with the lowest rotational speed at high tip speed ratios.
- The approach for enlarging the chord and thus the Reynolds number by 31% by applying low lift profiles without changing the design tip speed ratio proves useful, especially considering, that at 400 rpm first indication of the influence of the decreasing Reynolds number are visible.

Acknowledgment

This work is partly funded by the Federal Ministry for Economic Affairs and Energy according to a resolution by the German Federal Parliament (Smart Blades 2.0 0324032D) and by the Ministry for Science and Culture of Lower Saxony through the funding initiative Niedersächsisches Vorab (project ventus efficiens). We further thank the mechanical and electrical workshops of our institute for the help in realising MoWiTO 1.8 (Model Wind Turbine Oldenburg 1.8 m).

References

[1] Hand M M, Simms D A, Fingersh L J, Jager D W, Cotrell J R, Schreck S, Larwood S M 2001 NREL / TP-500-29955
[2] Snel H, Siccama NB, Programme F and Researcher S 2009 in AIAA 2009-1217
[3] Bottasso CL, Campagnolo F and Petrović V 2014 Wind tunnel testing of scaled wind turbine models: Beyond aerodynamics. *Journal of Wind Engineering and Industrial Aerodynamics* 127
[4] Hulskamp A W, Wingerden J W, Van Barlas T K, Champliaud H, Kuik G A M, Van Bersee H E N and Verhaegen M 2011 *Wind Energy* 14
[5] Jonkman JM, Butterfield S, Musial W and Scott G 2009 NREL / TP-500-38060
[6] Schottler J, Hölling A, Peinke J and Hölling M 2016 *J of Phys: Conf Ser* 753
[7] Giguere P and Selig M S 1998 *ASME Journal of Solar Energy Engineering* 120
[8] Drela M 1989 *XFoil: An Analysis and Design System for Low Reynolds Number Airfoils* Lecture Notes in Engineering (54). Low Reynolds Number Aerodynamics, Springer Berlin
[9] Marten D, Wendler J, Pechlivanoglou G, Nayeri CN, and Paschereit CO 2013 *International Journal of Emerging Technology and Advanced Engineering* 3(3) 264-269
[10] Ryi J, Rhee W, Chang HU and Chai JS 2015 *Renewable Energy* 79 227-235
[11] Heißelmann H, Peinke J and Hölling M 2016 *J of Phys: Conf Ser* 753
[12] Jonkman JM and Buhl ML J 2007 *FAST Users Guide* NREL / TP-500-38230