Design and implementation of a controllable model wind turbine for experimental studies

J Schottler, A Hölling, J Peinke and M Hölling

ForWind - Center for Wind Energy Research
University of Oldenburg, Institute of Physics, Oldenburg, Germany
E-mail: jannik.schottler@forwind.de

Abstract. This technical paper describes the design and characterization of a controllable model wind turbine for wind tunnel experiments. The setup of the turbine and the implementation of the control system are described in detail and tests of the control system are shown. Finally, results of one exemplary scientific application are presented, where the model turbine was exposed to turbulent, intermittent inflow and the controller influence on torque fluctuations is investigated.

1. Introduction

In order to meet the increasing need for scientific research in the field of wind energy, three different approaches can be distinguished. First, field measurements capture what actually happens in the real world, restricted to measurement limitations. However, costs are high, availability is limited and boundary conditions are subject to change and not controllable. Next, numeric simulations can give insight in further details. Since computational costs remain an issue, especially for high fidelity CFD simulations, not all scales can be resolved and a certain share of a problem needs to be modeled. This raises the question of validation of the results. As third approach, wind tunnel experiments allow an investigation of various effects in a controlled laboratory environment, complementing and validating field measurements and numeric simulations.

In recent years, model wind turbines of different sizes and designs were used to study various effects. The following outline lists some selected examples, without claims of completeness. For instance, in 2001 a two bladed turbine of 10 m rotor diameter, Phase VI, was tested in the NASA Ames wind tunnel [1]. The turbine was used in downwind and upwind configuration in order to investigate aerodynamic and structural effects. A 4.5 m diameter, three bladed turbine was used within the MEXICO project [2]. Amongst other aspects, up- and downstream induction, blade root bending moments and tip vortex trajectories were studied to establish a database for model improvement and validation. More recently, smaller models were tested in experiments focusing on several aspects. For instance, Medici and Alfredsson used a two bladed turbine of 0.18 m rotor diameter to investigate wake characteristics such as the wake’s rotation and its deflection by yaw misalignment [3]. Further, wake meandering was investigated with varying blade numbers [4]. At the Norwegian University of Science and Technology (NTNU) in Trondheim, two models of 0.9 m rotor diameter are being used to study various aspects. For instance, Krogstad and Adaramola [5] investigated the general performance and near wake characteristics of a single
turbine. Also, wake effects were studied in tandem configuration, quantifying power losses of a turbine operating in the wake of an upstream turbine [6], while Bartl et al. [7] examined wake properties of a two turbine array. In a boundary layer wind tunnel, Cal et al. [8] used a 3 × 3 array of models with a diameter of 0.12 m. Here, the vertical transport of momentum and kinetic energy was in focus. To isolate the effect of a fore-aft pitching motion, Rockel et al. investigated wake properties of fixed and oscillating model turbines of 0.2 m rotor diameter [9]. Similarly, this study was expanded to a tandem setup, where wake to wake interactions were examined [10]. Probably some of the most comprehensive model wind turbines are being used at the Politenico di Milano. With a rotor diameter of 2 m and active individual pitch and torque control, applications include aerodynamics, aeroelasticity and control [11].

In the present paper, we describe a model wind turbine featuring an automatic pitch and load control, whose applications to date include wake effects, active wake control and turbulent inflow. This paper is organized as follows: the design of the model turbine, two of which are used at the University of Oldenburg, is described in Sec. 2. Sec. 3 describes the principle of the load control, while Sec. 4 shows results of the turbine’s characterization. Giving one example of an application, Sec. 5 describes an experiment where the model turbine was exposed to turbulent, highly intermittent inflow. The effect of the load control on second order statistics of torque increments on different time scales is examined. The discussion and outlook is given in Sec. 6, while the conclusion in Sec. 7 finalizes this paper.

2. Turbine design

Fig. 1 shows a photograph of the three bladed, horizontal axis model wind turbine. At a rotor diameter of D = 0.58 m, the turbine features pitch and load controls, which are further described in Sec. 2.1 and 3. The nacelle, tower and foot of the turbine are made of aluminum. Acquiring thrust data is possible when placing the turbine on a force balance. Along with the pitching mechanism (cf. Sec. 2.1), the nacelle comprises a DC motor (Faulhaber 3863H048CR) used as generator, which is equipped with a two-channel magnetic encoder, resolving 4096 edges per revolution that allows rotational velocity measurements. The generator torque T is proportional to the electric current I according to the generator’s specifications [12], T = k · I with k = 79.9 mN A⁻¹. I is obtained by measuring the voltage drop across a shunt resistor of Rsh = 0.1 Ω, so that

\[ T = k \cdot I = k \cdot \frac{U_{sh}}{0.1 \Omega} \]  

and

\[ P = T \cdot \omega . \]  

The rotor blades are based on a SD7003 airfoil profile and were designed using the Blade Element Momentum (BEM) [13] method with Glauert optimization within the work of Odemark and Fransson [14], which lists further details on the blade design. The blades were manufactured by a vacuum casting method using a MG804 synthetic (isocyanate-polyol) compound. During the casting procedure, a T-shaped aluminum bold is inserted at the blade root for fixation at the blade mountings and for security reasons.
Data acquisition and turbine control are realized by a *National Instruments cRIO-9074* real time controller. Analog and counter based data (rotational velocity) are being recorded fully synchronous, whereby two different sampling frequencies can be set. While analog data is typically recorded at $f_s \leq 10 \text{kHz}$ (depending on the application), a trade-off between speed and accuracy is necessary when measuring the rotational speed. Limiting the sampling rate of $\omega$ to 200 Hz gave satisfying results.

### 2.1. Pitching mechanism

The pitching of the blades is initiated by a stepper motor (*Faulhaber AM2224-R3-4.8-36*) equipped with an optical encoder for monitoring and closed-loop control. The shaft of the stepper motor is connected to a thread, whose counterpart is placed in a slider on the main shaft. By rotating the motor shaft, a movement of the slider parallel to the main shaft is initiated, as sketched in Fig. 2. Via joint links, this motion is transferred to a rotation of the blade mountings. This principle allows a collective pitching of the blades of $\Delta \beta \leq 30^\circ$, $\beta$ being the blade pitch angle. A calibration of the pitching mechanism is achieved using a laser diode mounted to a blade mounting. At a distance $y$ to a screen normal to the rotor plane, a change in the stepper motor’s angle results in a variation of the length $z$, being the distance from the laser spot’s original position on the screen to its location after a certain change in pitch. Therewith, a variation of the motor’s shaft angle is related to a pitch angle alteration by

$$\Delta \beta = \arctan \left( \frac{z}{y} \right).$$ (3)

### 3. Load control

The closed-loop load control of the model wind turbine is achieved using a field effect transistor (FET) within the electric circuit. By applying an external voltage $U_{\text{FET}}$ to the transistor, the electric load is varied and the torque becomes adjustable. The closed-loop control is based on a reference velocity upstream of the rotor as the tip speed ratio (TSR) $\lambda$ is the process variable of a PI-controller, and therewith the constant set point. The manipulative variable is the voltage $U_{\text{FET}}$, altering the torque. With this approach, the model turbine automatically reacts to changing inflow conditions, keeping its TSR constant, which allows convenient, time efficient and reproducible experiments. Examples of application can be found in [15] and in Sec. 5.

Fig. 3 shows tests of the load control during step-like wind speed changes and constant pitch angle. The reference velocity $u$, based on hot wire measurements 2/3D upstream of the rotor at hub height, is shown in red, which is used to calculate $\lambda$, the controller process variable. The
turbine’s reaction in terms of power, TSR and power coefficient $c_P = 2P/A\rho u^3$ are shown for inactive (left column) and active (right column) control. $u$ is affected by the rotor’s blockage, consequently, $\lambda$ and $c_P$ are biased similarly. The setup during the tests is sketched in Fig. 4. Looking at the left column of Fig. 3 (inactive control), it becomes obvious that the model turbine cannot follow the sudden decrease in wind speed at $t \approx 15$ s, as the power, TSR and $c_P$ drop to zero. When the wind speed increases again at $t \approx 40$ s, it takes roughly 35 s until the turbine data recovers to initial values. The right column of Fig. 3 shows that, with active control, the model turbine follows the velocity changes with certain time lags and typical controller overshoots. As expected, the TSR is kept constant, while the power follows the velocity pathway. As the power coefficient is based on hot wire data upstream of the rotor and the power, unphysical overshoots are observed, because the power and wind speed face a controller and distance caused time lag. Summarizing, Fig. 3 shows that the described load control principle allows an automatic adaption of the turbine’s point of operation during changing inflow conditions.
4. Characterization

In this section, a characterization of the model turbine is described. The turbine was placed on a three component force balance (ME-Systems K3D120-50N) in order to record thrust data. Measurements were conducted in a wind tunnel of the University of Oldenburg with an outlet of 0.8 m × 1 m (height × width) in open jet configuration as sketched in Fig. 4. Throughout the following analysis, the inflow velocity $u_\infty$ is defined by the rotational speed of the wind tunnel fan, resulting in a certain wind speed in the test section without the model turbine being installed. Prior to the experiments, the relation between the fan’s rotation and the wind speed at the rotor’s position without the turbine was determined by means of pressure measurements and used to define $u_\infty$ during turbine operation. Accordingly, quantities depending on the wind speed are based on this velocity unless stated differently.

For characterizing the model wind turbine, $U_{FET}$ was systematically increased in steps of 5 mV until stall for wind speeds ranging from $u_\infty \approx 4.3$ m s$^{-1}$ to $u_\infty \approx 8.8$ m s$^{-1}$. For each configuration, data was recorded for 30 s at a sampling rate of $f_s = 2$ kHz. A waiting time of 15 s between a change of $U_{FET}$ ensured stationary operating conditions. Exemplary, Fig. 5 shows the influence of varying $U_{FET}$ on the torque for different wind speeds. Clearly, it can be seen that increasing the voltage applied to the FET is directly increasing the torque until stall of the turbine, which is the basis of the closed-loop control described in Sec. 3.

Next, Fig. 6 shows the power coefficient $c_P = 2P/A \rho u_\infty^3$ and the thrust coefficient $c_T = 2F_x/A \rho u_\infty^2$ [13] over $\lambda$ at constant pitch angle and $u_\infty \approx 8.3$ m s$^{-1}$, whereas $F_x$ is the thrust force in main flow direction, $\rho$ the air density and $A$ the swept area of the rotor. When increasing $U_{FET}$, the rotational speed and therewith $\lambda$ and the thrust decrease, while the power increases until the maximal power coefficient is reached at $\lambda_{opt} \approx 5$, where $c_P = c_{P,max} \approx 29\%$. It should be noted that the absolute values of power are facing uncertainties due to the definition of the torque, cf. Eq. (1).

Based on the same measurements, $T - \omega$ curves for the examined wind speeds are obtained and shown in Fig. 7. Values of maximal power coefficient are marked in red for each wind speed. The resulting curve, based on the $c_{P,max}$ values, is typically used for torque control strategies [13], which in principle is possible based on the present data. This approach, which does not require a reference wind speed as controller input, will be further pursued in future work in

![Figure 4: Experimental setup of the model turbine's characterization.](image-url)
Figure 5: Mean torque values for increasing voltages $U_{\text{FET}}$ for different inflow velocities, which are rounded to the next multiples of 0.5 m s$^{-1}$. Red crosses mark the maximal $c_P$ for each wind speed.

Figure 6: Power coefficient $c_P$ (black) and thrust coefficient $c_T$ (red) over TSR $\lambda$ for $u_\infty \approx 8.3$ m s$^{-1}$. The arrows indicate increasing values of $U_{\text{FET}}$ during characterization.

order to establish an alternative to the present concept described in Sec. 3. Especially when using multiple models of the turbine described in this paper to investigate wind farm effects, an automatic control without further measurements becomes beneficial.
5. Application example

In this section, we present one exemplary application of the model wind turbine described, further studies include [15] and [16]. The turbine is exposed to intermittent inflow conditions that were created using an active grid for flow modulation [17]. We analyze the probability density functions (PDF) of increments to study the controller influence on the system dynamics during intermittent, turbulent inflow.

5.1. Setup and methods

A similar setup as sketched in Fig. 4 was used, however, the outlet of the wind tunnel was equipped with an active grid as described in [17]. Here, the information about the experiment and the setup is limited as further details can be found in [16]. As previously stated, the TSR is the process variable of the load control, which is based on a hot wire probe 2/3D upstream of the rotor at hub height. During the experiment, the mean wind speed was \( u^* \approx 7 \text{ m s}^{-1} \). \( u^* \) is based on hot wire measurements at the rotor’s position without the turbine being installed, during the same excitation protocol of the active grid, see [16] for details. We consider the PDF of increments, \( p(x_\tau) \), with

\[
x_\tau = x(t + \tau) - x(t).
\]

Here, \( x \) is the velocity or the torque, respectively, details are listed in the legend of Fig. 8. Increments are normalized by the standard deviation of the time series of increments for better visual comparison of the PDF’s shape. Further, scales are shifted vertically for presentation purposes. We analyze three different scales as listed in Tab. 1, ranging down to sub-rotor scales in space. For each measurement series, data was recorded for 25 min at a sampling rate of \( f_s = 10 \text{ kHz} \). As noise should be excluded from the analysis, the signals were filtered using a 6th order Butterworth low pass filter set to 45 Hz, see [16] for a more detailed elaboration.

5.2. Results

Fig. 8 shows the increment PDF of the inflow based on hot wire data upstream of the rotor and the torque when exposed to the same inflow conditions during active and inactive load control.
| Physical Object | Length  | Time   |
|-----------------|---------|--------|
| Physical Object | 7 m     | 1 s    |
| Rotor Diameter  | 56 cm   | 80 ms  |
| Blade Length    | 28 cm   | 40 ms  |

Table 1: Overview of scales considered in relation to certain characteristic turbine lengths. Taylor’s hypothesis [18] is used to transfer from time to space with $\langle u^* \rangle \approx 7 \text{ m s}^{-1}$.

In the inactive case, the voltage applied to the FET was constant, $U_{\text{FET}} = \text{const.} = 2.352 \text{ V}$. First, the red graphs in Fig. 8 show $p(u_\tau)$, based on the hot wire data upstream of the turbine. Clearly, the distribution of increments strongly deviates from the indicated Gaussian fit (dashed, red line), showing intermittency on all three scales. Examining the torque data for the active control case ($\circ$), a similar deviation from the Gaussian distribution is observed. The intermittency of velocity increments results in intermittent distributions of torque increments on all three scales. The same experiment was repeated with the load control being inactive (+). For the largest scale in time of $\tau = 1 \text{ s}$, small deviations from the controlled case are observed, especially for positive increments, corresponding to an *acceleration* of inflow. In particular, increments of $T_\tau > 3 \sigma_\tau$, occur much more frequent in the controlled case as compared to the non-controlled. For the two smaller time scales, $\tau = \{80 \text{ ms}, 40 \text{ ms}\}$, differences between the two scenarios are much more pronounced. Without active control, the distribution of torque increments are nearly Gaussian distributed. The intermittency of the inflow is not observed in the torque data, in contrast to the controlled case. Here, the distribution of torque increments is far from Gaussian, being clearly heavy tailed with some deviations further discussed in Sec. 5.3.

5.3. Discussion of the results

Discussing the results shown in Fig. 8, the importance of a scale dependent analysis becomes obvious. Especially for the non-controlled case, results are significantly different depending on the time/length scale considered. The system dynamics essentially define how the dynamic input (wind) is transferred to the output dynamics (torque in this case) of the turbine. The system dynamics are subject to change, not only with the setting or presence of a controller, but also with the scales considered. Here, we show that the present setup allows an investigation of those effects in a controlled environment with purposely designed boundary conditions. Further, Fig. 8 suggests that the turbine follows wind speed changes more accurately with active load control, as keeping the TSR constant results in a close-to optimal point of operation of the turbine. On the one hand, approx. 5.6% more power is generated as compared to the non-controlled case. On the other hand, however, an intermittent distribution of torque increments has potentially negative effects on the drive train and other turbine parts, possibly increasing (long term) damages. Extreme torque increments are observed much more frequent during active control as compared to the non-controlled case. This raises the question whether sacrificing some power extracted by a suitable control strategy might be worth limiting extreme torque (and other turbine data) changes. Here, we do not claim full scalability of results. This exemplary application of the model turbine shows, that similar research questions might be of further interest and can be studied with the present setup.
6. Discussion & outlook

Generally, wind turbine models for experimental studies face limitations due to scaling. For example, one has to be aware of the Reynolds number mismatch, comparing an experiment to full scale situations. With the model turbine described in this paper, a chord based Reynolds number of $\text{Re}_c \approx 75\,000$ ($r/R = 50\%$) is achieved. Despite this shortcoming, previous experimental studies, some of which are listed in Sec. 1, proved the suitability to reproduce and investigate general effects such as wake effects and others. However, when discussing experimental results, caution has to be used when interpreting laboratory data and extrapolating findings to full scale cases. Nevertheless, as field data is limited and numerical simulations face uncertainties due to computational costs, experimental studies remain necessary in order to complement and validate simulations and field measurements.

Within the next years, $\sim10$ model turbines, similar to the one described in this paper, will be build in order to investigate wind farm effects at the University of Oldenburg. For this purpose, some improvements of the present turbine design are planned. The load control described in Sec. 3 is based on upstream wind speed measurements. Depending on the inflow conditions, single point measurements might be inappropriate to capture what the whole rotor is exposed to. Also, the blockage of the rotor is influencing measurements, making the distance from the sensor(s) to the turbine an important parameter. Despite those points of discussion, the present concept for controlling the turbine’s point of operation in partial load conditions has proven to work well for

Figure 8: PDF of velocity (red line) and torque (symbols) increments for $\tau = \{40\,\text{ms}, \, 80\,\text{ms}, \, 1\,\text{s}\}$ form top to button, normalized to the standard deviation of the respective time series of increments. Scales are shifted vertically for presentation purposes. Torque increments are shown for active (◦) and inactive (+, $U_{\text{FET}} = \text{const.} = 2.352\,\text{V}$) control.
certain applications [15], allowing time efficient, reproducible experiments. It should be noted, that control systems are not subject of the present research. The control strategy presented here is used as an experimental tool, one example of which is shown in Sec. 5. The approach is planned to be extended to a standalone control without additional sensors based on the data described in Sec. 4.

Along with a standalone control without velocity sensors, thrust measurements at each individual turbine are planned. Thus far, the turbine is placed on three component force balances to measure the rotor thrust, which is unpractical when upscaling the setup to multiple turbines. Therefore, individual thrust sensors using strain gauges are planned in future setups.

7. Conclusion

In this paper, the design, implementation and characterization of a model wind turbine for experimental studies are described. The three bladed turbine with a rotor diameter of 0.58 m features a collective pitching of the rotor blades and a closed-loop load control, whose principle and tests are shown. The load control is realized by a FET, which allows an alteration of the load and therewith the torque by an external voltage. This principle was successfully tested discretely for a spectrum of inflow velocities as well as dynamically during step-like wind speed changes. Characteristic $c_T$— and $c_p$— $\lambda$ curves where extracted from the discrete tests. Finally, an application example is shown, where the model turbine was exposed to turbulent inflow conditions created by an active grid. The influence of the controller of the distribution of torque increments is investigated. It is shown, that the present setup allows an investigation of the system dynamics for various conditions, including different control cases.

Acknowledgments

The authors thank Stefan Ivanell for providing the rotor blade design.

References

[1] Hand M M, Simms D a, Fingersh L J, Jager D W, Cotrell J R, Schreck S and Larwood S M Data Processing 292
[2] Schepers J G and Snel H 2008 ECN Report: ECN-E-07-042 54
[3] Medici D and Alfredsson P 2006 Wind Energy 9 219–236
[4] Medici D and Alfredsson P H 2008 Wind Energy 11 211–217 ISSN 10954244
[5] Krogstad P Å and Adaramola M S 2012 Wind Energy 15 743–756
[6] Adaramola M and Krogstad P Å 2011 Renewable Energy 36 2078–2086
[7] Bartl J, Pierella F and Sartran L 2012 Energy Procedia 24 305–312 ISSN 18766102
[8] Cal R B, Lebrón J, Castillo L, Kang H S and Meneveau C 2010 Journal of Renewable and Sustainable Energy 2 013106
[9] Rockel S, Camp E, Schmidt J, Peinke J, Cal R B and Hölling M 2014 Experimental study on influence of pitch motion on the wake of a floating wind turbine model vol 7 ISBN 494179839
[10] Rockel S, Peinke J, Hölling M and Cal R B 2016 Renewable Energy 85 666–676 ISSN 09601481
[11] Bottasso C L, Campagnolo F and Petrović V 2014 Journal of Wind Engineering and Industrial Aerodynamics 127 11–28
[12] Online data sheet accessed 17.05.2016 URL https://fmcc.faulhaber.com/resources/img/DE_3863_CR_DFF.PDF
[13] Burton T, Sharpe D, Jenkins N and Bossanyi E 2001 Wind Energy Handbook (John Wiley and Sons)
[14] Odenmark Y and Franzon J H M 2013 Experiments in Fluids 54 ISSN 07234864
[15] Schottler J, Hölling A, Peinke J and Hölling M 2016 34th Wind Energy Symposium p 1523
[16] Schottler J, Reinke N, Hölling A, Whale J, Peinke J and Hölling M 2016 Wind Energy Science Discussions 2016 1–21 URL http://www.wind-energ-sci-discuss.net/wes-2016-24/
[17] Reinke N, Homeyer T, Hölling M and Peinke J 2016 Experiments in Fluids Submitted
[18] Mathieu J and Scott J 2000 An introduction to turbulent flow (Cambridge University Press)