Design and testing of a model-scale yaw mechanism for an experimental wind turbine model

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Abstract. In this study a new yaw mechanism for a small existing wind turbine model is designed and tested. The special requirement for this yaw device is its compact design due to the small length scaling factor of the model turbine. Such a dense design is crucial in order for the wake of the model turbine not to be influenced by the yaw mechanism. Furthermore, it has to have a fast system response and high accuracy to take into account the time scaling. Different concepts are investigated and a design located at the tower base is realized. To limit its drag, the structure is being concealed in an aerodynamically shaped cover. Wind tunnel measurements confirmed that the wake of the turbine is not influenced by the structure. A system analysis, using a Simulink model of the turbine helps finding the right motor and shows that the device has a fast system response with high accuracy. Consequently, the designed yaw mechanism is suited for the small wind turbine model, which can be used for experimental wake and wind farm control studies in the future.

1. Introduction

Wind power is one of the fastest-growing renewable energy technologies. Usage is on the rise worldwide, which is not only due to the goal of becoming independent of fossil fuels but also because of the falling costs. They are mainly due to the technical development of wind turbines and their components. Another important field for further improvement is wind farm control. Several studies show its potential; a survey is given by Knutsen [1]. Amongst wind farm control techniques wake steering by intentional yaw misalignment is seen to have a large potential for wind farm optimization [2, 3]. More recent studies investigated the potential of employing dynamic pitch excitations to the turbine for faster wake recovery [4, 5]. These studies show a potential for power increases that is accompanied by a growth of loads. Another study [6] used large-eddy simulations to investigate the effect of dynamic yaw control for wind farm optimization and found that such dynamic yaw control has advantages to static yaw control if the flow environment is turbulent. All new control strategies are investigated by three different approaches: computer simulation, wind tunnel testing and field testing. Over the last decade, wind tunnel tests conducted with miniature wind turbine models have gained an increase attention from the research community [7]. To conduct realistic wind tunnel experiments on wind farm control small wind turbine models, equipped with similar control mechanisms as full-scale machines, are needed. As a result of the scaling laws, the control actuators of these turbines not only have to be very small, but they also need to have a faster system response as in full-scale applications to match the time scaling.

At TUM a small turbine model with a rotor diameter of $D = 0.6\ m$ named G06 was developed by Nanos et al. [8]. This model was mainly designed for performing wake and wind farm control studies in various wind farm configurations and complex terrain conditions. For such investigations it is crucial that the model is equipped with a fast response yaw mechanism, which allows the turbine to be controlled in real time. The goal of this study is to develop, implement and test a small-scale yaw mechanism for the G06 model turbine.

The first main objectives in the design process is that the device is constructed in such a way that it is not influencing the wake behaviour of the turbine. As the turbine was designed for wake studies, and has a rather small diameter of $D = 0.6\ m$, it is of crucial importance that the mechanism is very compact and not blocking or changing the flow field around the rotor. The second main objective is that the yaw device has the same, time-scaled response as a full scale machine. Consequently, the study should answer the question, if it is possible to design a very small yaw mechanism that is not influencing the wake behaviour of the turbine while having a suitably fast system response and high accuracy.

2. Methodology

2.1. Yaw mechanism design

The smaller the scaled wind turbine models are designed, the more difficult it is to develop control actuators that can adequately replicate the mechanisms driving full-scale turbines. Consequently, due the compact size of the G06 it was challenging to develop a yaw system fulfilling all the design requirements, which are mainly:

- Compact system design, that is not influencing the flow around and behind the turbine;
- Fast system response, for matching the turbine yaw rate considering a time scaling factor in the order of $n_t = \mathcal{O}(10^{-2})$, resulting in the time flowing about two orders of magnitude faster in the experiment [8]. This has to be achieved while maintaining a high positioning accuracy of 0.1°;
- Sufficient torque and force stability to counter the loading in both static and dynamic situations and prevent backlash.

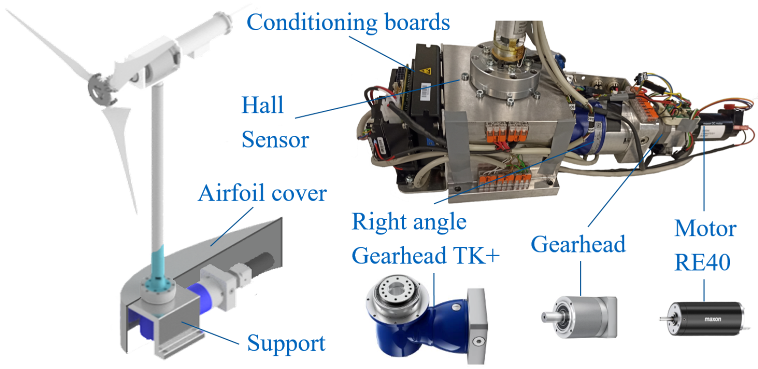

Figure 1. Final design of the yaw mechanism with all its components.

To find a suitable design for the yaw mechanism different concepts were engineered and evaluated. The first approach was to use a solution similar to the one of the existing, bigger G1 model turbines at the institute [9, 10], which features a mechanism similar to a real turbine located in the tower below the nacelle. However, due to the small tower size of the G06 it is impossible to integrate it in the tower structure. Consequently, the mechanism was moved to the tower base, what moreover, gives the advantage of housing a more power-full system there. Here also different concepts ranging from rotary stages to right angle gearboxes were investigated. After pondering advantages and disadvantages of the different concepts, the decision fell on a design, based on a right angle gearbox, as shown in detail in Figure 1.

The yaw mechanism is connected to the G06 turbine at the tower base. It consists of a support structure, which can be connected to the wind tunnel floor and, carries the other components: the right angle gearbox, the gearhead and the yaw motor. The right angle gearbox is a standardized industrial component transmitting torque at 90°. The selected gearbox *TK+* from the company *Wittenstein* has besides its robustness and high positioning accuracy, also the advantage of a high frictional torque, which prevents backlash and makes an additional brake unnecessary. However, to overcome this restraining torque an intermediate gearhead is needed to reduce the rotational speed of the motor before the *TK+*. The *Maxon RE40* motor, driving the system is located horizontally behind the gearhead. The selection of the motor is described in section 2.3. The exact angular position of the system is measured by a hall sensor located at the tower base and the support structure. Although, the right angle gearbox is a rather compact system, the yaw mechanism is still blocking the flow significantly at the tower base. Even though this structure is at the tower base and not directly in the rotor area, its relatively large size can influence the wake. To prevent this negative effect, the drag of the yaw mechanism is limited by an airfoil-shaped cover concealing the system. This cover is based on a *NACA0030* airfoil with a chord length of $c = 0.5\ m$. With its low drag coefficient of $C_D = 0.1$ the blocking effect of the covered device is drastically reduced to the same order of a cylinder with $d = 0.05\ m$, as shown in chapter 3. Furthermore, the airfoil cover has the advantage that all the control boards and connectors of the model turbine can be hidden inside.

2.2. Experimental setup wind tunnel tests

To test the airfoil cover and to be sure that the wake is not influenced by the yaw mechanism a wind tunnel study was conducted. The measurements were performed in the closed-loop (Göttingen-type) low-speed wind tunnel of the Chair of Aerodynamics and Fluid Mechanics of the Technical University of Munich.

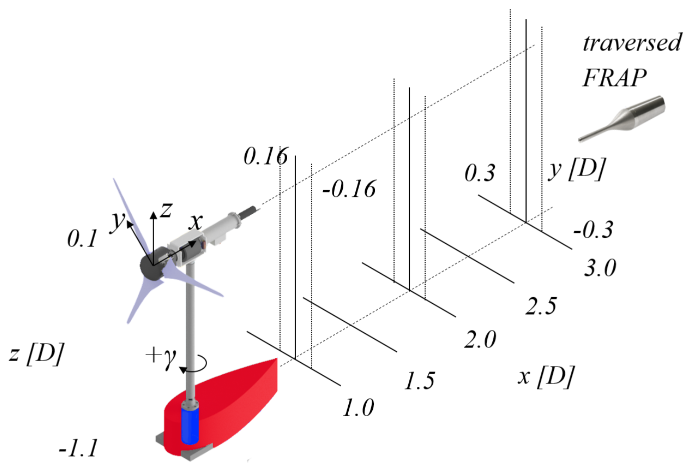

Figure 2. Sketch of the experimental setup for the wind tunnel tests, with the measurements grid.

The test section has a size of $1.8 \times 2.7 \times 21.0\ m^3$ (height x width x length). The tunnel was operated without turbulence generators. Consequently, the inflow turbulence intensity lies below 0.5%. The inflow velocity was adjusted to $U_\infty = 10.0\ m/s$ and the G06 turbine was operated at its optimum tip speed ratio (TSR) $\lambda = 7.1$. A sketch of the experimental setup is given in Figure 2. The velocities were measured using a fast-response five-hole probe (FRAP) mounted on a three-axes traversing system. A detailed description of the FRAP probe can be found in [11].

For the test campaign, the G06 was equipped with two configurations at the tower base. For the reference case with a cylinder of $d = 0.05\ m$ (indicated with blue in Figure 2) and for the comparison case with the airfoil cover (indicated with red in Figure 2). All measurements were conducted for this two configurations and several vertical and horizontal lines were measured as shown in Figure 2. The centre of the coordinate system is located at the turbine hub. The horizontal lines were measured in the centre of the airfoil cover atz/D = *-1.1* ranging from y/D = *-0.16* to y/D = *0.16* with an increment size of $\Delta y/D$ = *0.05* at the 5 downstream distances *x/D=1.0, 1.5, 2.0, 2.5* and *3.0.* The vertical lines were located at the turbine centre y/D = *0.0* ranging from z/D = *-1.1* to z/D = *0.1* with an increment size between $\Delta z/D$ = *0.05* and $\Delta z/D$ = *0.08* at the 3 downstream distances *x/D=1.0, 2.0* and *3.0.* Furthermore, it was investigated how the yaw mechanism is affecting the turbine wake in case the turbine is yawed. For these tests the turbine was yawed to $\gamma = +30°$ and three vertical lines were measured. In addition to the centre line also a line at y/D = *0.1* left and right of the centre line was measured. To take the wake deflection into account the centre line was shifted to the wake centre, which was calculated using the approach described in [12].

2.3. Dynamic yawing tests
For testing the system response and finding the right yaw motor, a *Simulink* model representing the whole yaw system of the model turbine was set up. This way, various scenarios could be simulated to check if the system response was fast enough and if the resulting torque was not exceeding the maximal ones of each component. This model was used to select the components. For the gearheads it was important to find the gear ratio of the whole system as well of the separate gearheads. Furthermore, the motor was selected based on its capability of following a demanded sinusoidal yaw signal with a yaw amplitude of $\gamma_{dyn} = 5°$at $f = 2\ Hz$, so that the mechanism will be able to perform dynamic yawing within a range of Strouhal numbers (St), which are exciting the wake [4, 5].

The simulation model pretends to recreate all the phenomena affecting the performance of the actual hardware. A sinusoidal wave is compared to the reference, and goes to the control loop. Two scopes are used to look at the setpoint tracking and the control signals. The control signals are mainly: the actual yaw angle (following the demanded signal), the motors current, and the torque at the output of the motor and the gearbox. These signals have to stay under the nominal value.

The simulations suggested a total gear ratio of $i_{tot} = 100$, which was divided in $i_{TK+} = 20$ for the *TK+* and $i_{GE} = 5$ for the gearhead, which resulted in the most balanced share between both components. The configuration of the motor resulted in a *Maxon* DC Motor *RE40* with a power of 150 W and a nominal torque of 177 Nmm.

To verify that the designed system can follow the demanded signals as expected with the *Simulink* model, the system was assembled, and dynamic yaw test were performed for different amplitudes and frequencies. The results of this experiment will be shown in the next chapter.

3. Results

3.1. Wake

The results for the horizontal velocity lines are shown in Figure 3. The absolute velocity u is normalised with $U_\infty = 10.0\ m/s$. A schematic draw of the airfoil (red) and tower (blue) from the top is shown for orientation. The velocity line plots in this and the following figure are in matching colour to the sketch: red for the airfoil and blue for the cylindrical tower.

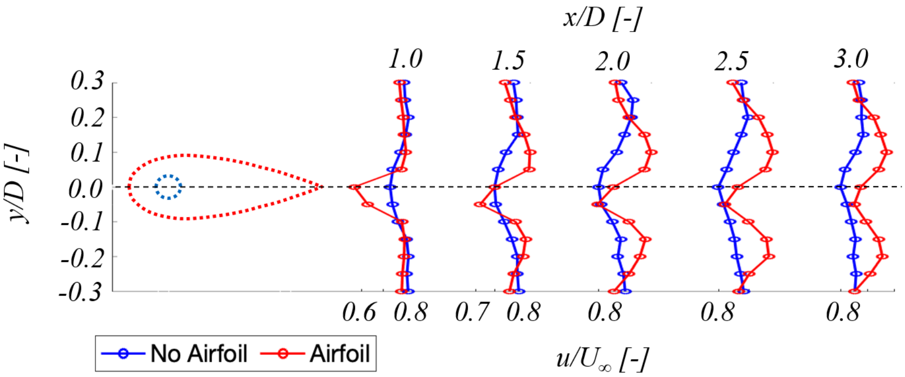

Figure 3. Horizontal profiles of normalized velocity close to the wind tunnel floor, at *x/D=1.0, 1.5, 2.0, 2.5* and *3.0*, red for the airfoil and blue for the cylindrical tower.

The horizontal line plots reveal no big differences in velocity close to the wind tunnel floor between the two tower base settings. Only directly behind the airoil at *x/D=1.0*, the airoil cover is causing a distinct reduction of u at the centre line, what is different from the wake behind the cylindrical tower base, which is more smoothly distributed. Nevertheless, the velocities are quite similar and with increasing downstream distance the wake of the airfoil cover recovers even faster. Overall, the velocity lines suggest that the turbine wakes should be similar and not be significantly distorted by the drag of the yaw mechanism at the tower base. This observations are confirmed by the vertical velocity lines for the non-yawed case presented in Figure 4.

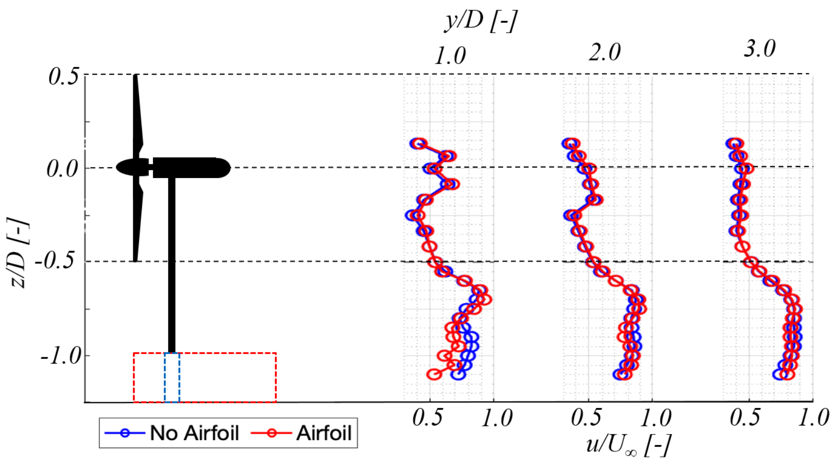

Figure 4. Vertical profiles of normalized velocity for the non-yawed case at the wind turbine centre, at *x/D=1.0, 2.0* and *3.0*, red for the airfoil and blue for the cylindrical tower, the dashed lines mark the rotor area and centre.

The figure shows, that the wakes are very alike in the rotor area, which is marked by the dashed lines, and differences can only be observed in the lower part of the wake Nevertheless, this differences are mainly at *x/D=1.0* and are only marginal at *x/D=2.0* and *3.0*. Furthermore, the plots show that the airfoil cover is not pulling down the wake and that the rotor wake behind the non-yawed turbine is not influenced by the covered yaw mechanism, thus fulfilling the design goal. This observations are also holding in case the turbine is yawed by $\gamma = +30°$. In Figure 5 contour plots for the difference in normalized velocity of the measured domain between the two tower base configurations at *x/D=1.0, 2.0 and 3.0* are presented.

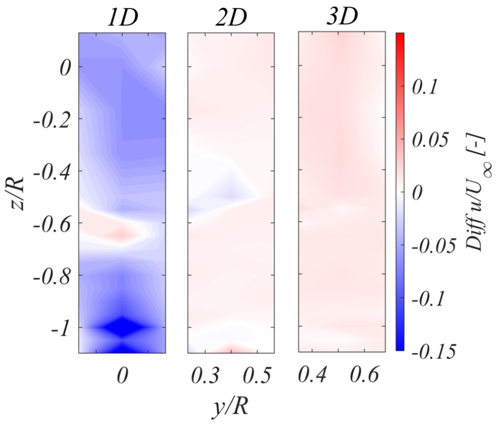

Figure 5. Differential plots of the normalized velocity for the yawed case $\gamma = +30°$, from *y/D=-0.1* to *y/D=+0.1* around the estimated wake centre at *x/D=1.0, 2.0* and *3.0*.

This plots confirm the observation of the non-yawed case. Significant differences are only present in the lower part of the investigated area at *x/D=1.0*. Further downstream the differences are only marginal.

3.2. System dynamics

Results from the *Simulink* simulations were used for selecting the components of the yaw mechanism. To check if the design of the finished device is working as predicted, the system was tested experimentally. In this experimental study a dynamic yaw test was performed for different amplitudes and frequencies, tracking how well the yaw mechanism could follow the demanded yaw amplitudes (A). The results of this tests are shown in Figure 6.

In the graph of Figure 6 a) the ratio between the demanded and reached amplitude is shown on the y-Axis. On the x-Axis the yawing frequency is presented in *Hz* at the lower scale; additionally, the Strouhal number for the G06 is shown on the upper scale. The experimental results confirm the *Simulink* simulation and show that the system can reach the desired dynamic yaw amplitude $\gamma_{dyn} = 5°$at $f = 2$ *Hz*. Furthermore, it can be seen that, as expected, the system can reliably reach higher amplitudes if the frequency is reduced. The findings of the graph are summarized in Figure 6 b) and classified in four different categories *Doable*, *Underperformance*, *Bad performance* and *Non-reachable*, indicating how well the yaw mechanism performs for each combination of dynamic yaw amplitude and frequency.

4. Conclusions

In the presented study a yaw mechanism for a small model wind turbine was designed and its integration and performance were investigated numerically and experimentally. The final design of the yaw mechanism consisting of a right angle gear box located at the bottom of the

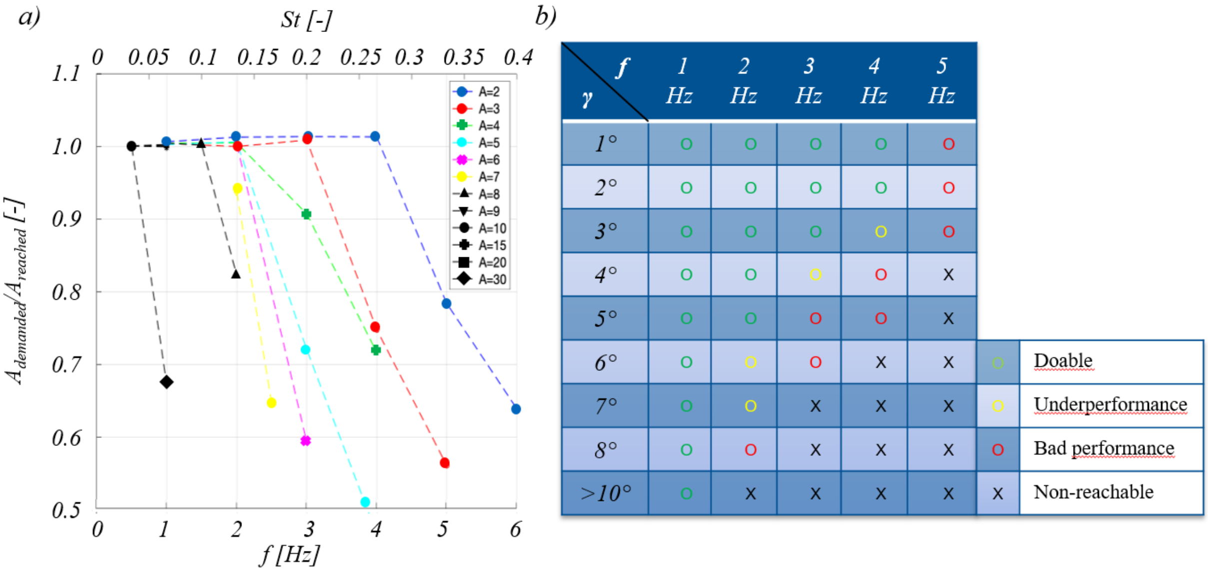

Figure 6. a) Capability to reach a certain demanded yaw rate for different yaw amplitudes (A) and excitation frequencies (f). b) Summary of performance for different yaw amplitudes and frequency combinations.

turbine tower. With its robustness, high positioning accuracy and high frictional torque, this design is the best compromise of durability, accuracy and reliability. To reduce the influence of the device on the turbine wake, the yaw mechanism is hidden in an aerodynamic airfoil cover. Measurements in the wind tunnel comparing the design with the cover to a reference with cylindrical tower base confirm that the turbine wake is not influenced or distorted by the yaw mechanism at the tower base. The system dynamics and its limitations were investigated by experimental dynamic yaw tests, where different combinations of dynamic yaw amplitude and excitation frequencies were applied to the turbine control. The yaw mechanism managed to perform at the design dynamic yaw amplitude $\gamma_{dyn} = 5°$at $f = 2\ Hz$ without problems. Finally, it can be concluded that the designed yaw mechanism is well suited for the small wind turbine model, fulfilling all the design requirements related to size, robustness and system response. With this yaw mechanism, the G06 model turbines can be used for experimental wake and wind farm control studies in the future.

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