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Wind tunnel setup for experimental validation of wind turbine control concepts under tailor-made reproducible wind conditions

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Abstract. To speed up validation and prototyping of novel control and design concepts in wind energy, wind tunnel experiments should be used in synergy with numerical simulations and field experiments. The paper presents a wind tunnel setup consisting of a scaled wind turbine model MoWiTO and an active grid for generation of tailor-made and reproducible inflow conditions. To demonstrate that the presented experimental setup is suitable for fast validation of advanced control concepts, several control algorithms have been implemented and validated in various inflow conditions, such as turbulent and sheared inflows, and wind gusts. The tested control algorithms include the baseline collective pitch and torque control, individual pitch control for load reduction, and a control algorithms for compensation of static aerodynamic imbalances. All control algorithms resulted in an expected behaviour of the model wind turbine, thus emphasizing that the presented experimental setup can be used for fast and inexpensive testing of control concepts.

1. Introduction

Ever increasing dimensions and rated power of modern wind turbines and wind farms have facilitated a significant reduction in the levelized cost of wind energy, but also lead to an increase of structural loads. This further emphasizes the need for advanced control methods for load reduction. Although the scientific literature reports various control and design concepts improving different aspects of wind turbine operation, their thorough validation in realistic turbulent conditions, as well as an optimization of their parameters, is needed before such controllers can find its industrial application. This is, however, not a straightforward task, especially for field experiments, which represent a costly and time consuming solution with nonnegligible chances of hazardous situations. Furthermore, non-reproducible wind conditions in the field make it more difficult to obtain conclusive results. Therefore, all concepts should be well tested before starting validation experiments in the field. To this aim, numerical simulations, such as aeroelastic simulations, are commonly used, but since they always come with certain simplifications, they might not represent the real world sufficiently well. To improve this process, we propose to use wind tunnel experiments with controllable scaled models, which can be employed both for improving numerical models and testing dynamic response of control systems in presence of repeatable and realistic turbulent conditions, thus complementing field experiments

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and numerical simulations. Exploiting the synergy among different validation methods can result in faster development and prototyping of new concepts and technologies in wind energy. Possible applications include testing of control algorithms for load reduction and power maximization, wake characterisation, improvement of induction dynamics models, etc.

Wind tunnel experiments have already been used for testing different wind turbine and wind farm control concepts, e.g. using a scaled blade segment [1], a scaled wind turbine model [2, 3], or using several scaled turbine models [4, 5]. We particularly emphasize the importance of active grids for generation of tailor-made and reproducible wind conditions, which is essential for a through validation and optimization of control concepts. Examples of such inflow generation can be found in [1], where inflow conditions for a blade segment were generated with the purpose of finding a control law for reducing variations in the lift coefficient, and in [3], where inflow conditions for a two-bladed wind turbine model were generated with the goal of optimizing and validating the control concept for reduction of periodic wind turbine loads. In this paper, we present a comprehensive wind tunnel testing platform for fast experimental validation of advanced control concepts and their interaction with aerodynamic effects under realistic, tailor-made and reproducible turbulent conditions. The setup is used to validate the baseline and individual pitch control algorithms in turbulent and sheared wind conditions.

The paper is organised as follows. The experimental setup is described in Section 2, and the implemented control algorithms are explained in Section 3. The obtained experimental results are summarized in Section 4, and the conclusions are given in Section 5.

2. Experimental setup

The threefold experimental setup consists of a Göttingen type wind tunnel at the University of Oldenburg, an active grid for generating the desired turbulent inflow conditions, and the aerodynamically scaled NREL 5 MW wind turbine MoWiTO (Model Wind Turbine Oldenburg).

2.1. Wind tunnel and the active grid

The dimensions of the wind tunnel are $3 \ge 3 \ge 30 \le 3$, with maximum wind speeds in the open test section configuration of $32 \le 3 \le 30 \le 3$. In Fig. 1, 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 centre of the wind tunnel. The distance between the nozzle and the rotor plane is $4.8 \le 3.7 \le 3.$

To the nozzle, an active grid can be attached (see Fig. 1(b)), with which specific turbulent and transient flow patterns can be repeatedly impressed on the flow [7]. 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. Additionally, it is possible to generate a sheared flow and wind gusts, thus enabling testing of the control concept in various conditions.

2.2. Model wind turbine MoWiTO

The model wind turbine, which can be seen in Fig. 2, is a fully controllable scaled NREL 5 MW wind turbine [8], with the rotor diameter of 1.8 m [9]. The scaling is performed so that the matching of the load distribution and angle of attack variation along the blades during dynamic changes of the inflow is achieved. When preparing the inflow and control algorithms, it is important to consider the scaling factors of MoWiTO – length is reduced 70 times, and time is speeded up 46 times.



(b) Turbine and active grid.

Figure 1. Experimental wind tunnel setup.

The turbine is highly sensorised, allowing for measurements of blade, shaft and tower loads, as well as pitch angles, electrical torque and rotor speed. Besides the regular blades, a set of blades equipped with rigid leading edge slats is also available [10].



Figure 2. Model turbine MoWiTO.

3. MoWiTO control algorithms

MoWiTO's actuators enable torque and individual pitch control, comparable to modern multimegawatt wind turbines. Three pitch motors are controlled using their control boards, to which the reference position is sent via CANopen protocol. Control of the electrical torque, along with the rest of the control algorithms and data acquisition, is implemented on a real time system cRIO from Natiaional Instruments. The measurements are taken with the sampling time of $0.2 \,\mathrm{ms}$, whereas the control algorithms run at 10 ms. Note that the controller sampling time corresponds to 460 ms at the full-scale machine, which is higher than the typically used values. This value is, however, suitable considering the wind turbine aerodynamic and structural time constants, especially since there are lower demands on the protection system compared to the full-scale machines and there is no need for fast control of frequency converters.

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The baseline controller has two distinct regions of operation – partial load and full load – and constraints imposed on the collective pitch and torque values ensure timely transitions between the regions. In the partial load region, the optimal torque strategy is followed, except close to the cut-in or the rated wind speed, when a torque PI controller is used to keep the rotor speed in the allowed region. In the full load region, pitch angle is set by a PI controller to keep the rotor speed at its rated value [11]. The rated parameters defined in the baseline controller are shown in table 1.

 Table 1. MoWiTO's rated parameters.

Parameter	Rated value
Power	$252 \mathrm{W}$
Rotor speed	$560\mathrm{rpm}$
Rotor torque	$4.3\mathrm{Nm}$

Besides the baseline controller, two additional control algorithms are implemented. Both exploit MoWiTO's capability to individually pitch each blade. Reduction of the once per revolution blade loads is described in Subsection 3.1, and the compensation of static rotor imbalances is explained in Subsection 3.2.

3.1. Individual pitch control

MoWiTO's capability to individually pitch each blade is exploited here to reduce the first harmonic (once per revolution, 1P) of the blade loads. To this aim, blade flapwise bending moments M_i are transformed with the d-q transformation, also known as Coleman transformation or multi-blade coordinate transformation:

$$\begin{bmatrix} M_{\rm d} \\ M_{\rm q} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\vartheta & \cos\left(\vartheta + \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{4\pi}{3}\right) \\ \sin\vartheta & \sin\left(\vartheta + \frac{2\pi}{3}\right) & \sin\left(\vartheta + \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}, \tag{1}$$

where $M_{\rm d}$ and $M_{\rm q}$ are the d-q transformations of the blade loads, and ϑ is the rotor azimuth, with $\vartheta = 0^{\circ}$ corresponding to the first blade pointing upwards. Eliminating the first harmonic of the blade flapwise loads is equivalent to ensuring that mean values of $M_{\rm d}$ and $M_{\rm q}$ are equal to zero, which can be achieved with a pair of PI controllers in the d-q coordinate system [12]. The control actions determined by the two PI controllers, $\beta_{\rm d}$ and $\beta_{\rm q}$, are then transformed into blade coordinate system:

$$\begin{bmatrix} \beta_1\\ \beta_2\\ \beta_3 \end{bmatrix} = \beta_{\rm c} + \begin{bmatrix} \cos\left(\vartheta + \varphi\right) & \sin\left(\vartheta + \varphi\right)\\ \cos\left(\vartheta + \frac{2\pi}{3} + \varphi\right) & \sin\left(\vartheta + \frac{2\pi}{3} + \varphi\right)\\ \cos\left(\vartheta + \frac{4\pi}{3} + \varphi\right) & \sin\left(\vartheta + \frac{4\pi}{3} + \varphi\right) \end{bmatrix} \begin{bmatrix} \beta_{\rm d}\\ \beta_{\rm q} \end{bmatrix},\tag{2}$$

where β_c is the collective blade pitch angle, defined by the baseline controller, and β_i is the pitch angle of the *i*th blade. The parameter φ is introduced to compensate the pitch actuator dynamics, i.e. time delays caused by the blade actuation, and thus to achieve static decoupling in the d-q coordinate system [13].

3.2. Compensation of pitch offsets

A pitch offset can be caused by a faulty actuation or a faulty measurement of the blade pitch angle. Regardless of the reason, a pitch offset leads to an unbalanced rotor, and thus to increased loads and fatigue damage. Such increased loads cannot be compensated by a standard individual

pitch control. Here, we used a method proposed in [13] for compensation of aerodynamic rotor imbalances, simplified to work only for static (i.e. low frequency) imbalances, such as pitch offsets. To this aim, the following load transformation is applied:

$$\begin{bmatrix} M_{\rm d0} \\ M_{\rm q0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \cos\frac{2\pi}{3} & \cos\frac{4\pi}{3} \\ 0 & \sin\frac{2\pi}{3} & \sin\frac{4\pi}{3} \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} .$$
(3)

The mean values of the transformed loads M_{d0} and M_{q0} correspond to the amplitude of the static rotor imbalance (c.f. [13] for more details), and it can, therefore, be compensated with two PI controllers reducing the transformed loads to zero, similar as with individual pitch control. The so determined control actions, β_{d0} and β_{q0} , are transformed back to the blade coordinate system:

$$\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} = \beta_{\rm c} + \begin{bmatrix} 1 & 0 \\ \cos\frac{2\pi}{3} & \sin\frac{2\pi}{3} \\ \cos\frac{4\pi}{3} & \sin\frac{4\pi}{3} \end{bmatrix} \begin{bmatrix} \beta_{\rm d0} \\ \beta_{\rm q0} \end{bmatrix}, \tag{4}$$

Since the compensation of the static rotor imbalances acts mainly around low frequencies (i.e. close to 0 Hz), there is no coupling between the two axes in the transformed coordinate system.

Note that the inverse transformation for static rotor imbalances (4) does not change the collective value of blade pitch angles, similar as the standard d-q transformation, i.e. $\frac{1}{3}\sum_{i}\beta_{i}=\beta_{c}$ for any β_{d0} and β_{q0} .

4. Results

The presented experimental setup is used for thorough validation of control algorithms in various inflow conditions, including Mexican hat profiles, sudden wind gusts, and turbulent inflows with different levels of turbulence intensity and wind shear. The main focus is put on the compensation of oscillatory blade loads and pitch offsets, reaction to wind gusts, and on the operation in turbulent inflow conditions. The obtained results are summarized in the remainder of the section.

4.1. Baseline controller

The baseline controller has been tested in various inflow conditions, including different turbulent inflow and wind gusts. Figure 3 shows the probability distribution of the applied turbulent inflow velocities, and the obtained measurements of the rotor speed, torque and collective blade pitch angle. Blue dots represent individual measurements as a function of the measured wind velocity, while the red lines represent averaged static characteristics. It can be observed that the static characteristics match with the parameters from table 1, indicating that the baseline controller is working as expected. One can also observe a high variation of the rotor speed in the partial load region, where rotor speed is supposed to be adjusting to the wind conditions in order to track the maximal power production point. In the full load region, there are considerably lower variations in the rotor speed and torque, since the controller is adjusting pitch angles in order to keep the rotor speed and the power production at the rated values, which is also an expected wind turbine behaviour.

Besides in turbulent inflow, MoWiTO was also tested in the presence of wind gusts. Figure 4 shows the turbine response to two consecutive Mexican hat-like gusts. The baseline controller uses only rotor speed measurements to determine needed control actions, and it was not tuned specifically for wind gusts. This leads to high variations in the collective pitch angle and the torque, as well as in the rotor speed. Analysing a series of 10 wind gusts, pitch excursions of 11° peak to peak are observed, with the higher peak reaching on average 8.2° above and the lower



Figure 3. Probability of the different wind velocities, and the obtained wind turbine response. Blue dots represent individual measurements, while the red curves represent the averaged static characteristics of the rotor speed, torque, and blade pitch angle.

peak 2.8° below the steady state value. The overspeed was on average reaching 35 rpm, which is considered acceptable.

Testing wind turbine response to wind gusts, as shown in Fig. 4, would be extremely difficult in field experiments, which additionally emphasizes the usefulness of the presented experimental setup. However, it should be noted that, considering the time scaling of MoWiTO, the duration of the applied wind gusts is longer than the duration of the extreme operating gust defined in the IEC norm [14], which is typically used in numerical simulations.

4.2. Individual pitch control

To validate individual pitch control (IPC), the experiments were performed with MoWiTO derated to the rotor speed of 480 rpm, and power of 135 W. With this rotor speed, once-perrevolution loads are occurring at the frequency of 8 Hz, and pitch actuation at exactly this frequency is needed to reduce them. To excite the once-per-revolution blade loads, a sheared inflow was generated with the active grid.

First, a series of open loop experiments was performed, in which β_d and β_q were set manually, and the load response was measured to determine the phase offset between the blade pitch and blade bending moment signals. At the frequency of the IPC actuation, this offset was identified as $\varphi = 110^{\circ}$. Using this value in the transformation (2) compensates static coupling between the axes in the d-q coordinate system [13].

Figure 5(a) shows time response of the (collective) pitch angle without IPC and the pitch angle of the first blade with IPC. As expected, the blade is actively pitching at frequency 8 Hz (corresponding to the once-per-revolution loads) when IPC is activated, leading to higher pitch actuation. However, such pitch actuation also leads to the significant load reduction, which can be seen in Fig. 5(b), showing the spectra of out-of-plane blade bending moments with and without individual pitch control. The peak at frequency of 8 Hz is clearly reduced, leading to the 15% reduction of the blade loads standard deviation. The results indicate that the individual



Figure 4. Wind velocity of two consecutive wind gusts, and the response of MoWiTO's rotor speed, collective pitch angle, and torque.



Figure 5. Time response of the blade pitch and the spectra of the blade out-of-plane bending moment with and without individual pitch control.

pitch control has been successfully implemented and tested on MoWiTO.

4.3. Compensation of static rotor imbalances

To validate the control algorithm for compensation of static rotor imbalances, pitch offsets were introduced. When the same pitch angles are measured for each blade, in fact, the second blade has a higher, and the third blade has a lower pitch angle compared to the first blade. Such an

imbalance causes additional loads and vibrations, thus also increasing the fatigue damage of the turbine.





(a) Time series of the filtered blade loads and of the pitch angles.

(b) Spectrum of thrust force with and without imbalance compensation.

Figure 6. Compensation of static rotor imbalances.

Figure 6(a) shows a time response of the blade pitch angles and filtered blade out-of-plane bending moments when the control algorithm for compensation of rotor imbalances is turned on. The blade bending moments are low pass filtered to eliminate harmonic components, thus making it easier to compare the mean values of loads. At first, a significant discrepancy among blade loads can be observed, although all pitch angles are measured to be equal. This is because of the introduced pitch offsets. After the control algorithm for compensation of rotor imbalances is turned on, blades are pitched in a way to eliminate discrepancies among the blade loads, thus compensating the introduced pitch offsets. In Fig. 6(b), spectra of the thurst force computed from the measured tower bending moment are shown. As expected, an imbalanced rotor results in significant vibrations, which are significantly reduced when the imbalance compensation is applied.

5. Conclusions

The paper presented our wind tunnel setup consisting of a scaled wind turbine model (MoWiTO) and an active grid for generation of reproducible and tailored turbulent or transient inflows. As such, the presented experimental setup provides a powerful tool for improvement of numerical models, optimization of control algorithms, validation of new concepts, etc., which could lead to faster development and prototyping of new concepts and technologies in wind energy when used in synergy with numerical simulations and field experiments.

Using the presented experimental setup, several control algorithms have been tuned and validated in different inflow conditions. This includes the baseline controller tested both in turbulent conditions and in presence of wind gusts, the individual pitch controller tested in turbulent and sheared inflow, and the control algorithm for compensation of static aerodynamic imbalances. The ability to generate repeatable and tailor-made inflow conditions made comparison of different control algorithms possible and significantly less time consuming compared to field experiments. Each testing scenario showed an expected behaviour compared to the results from numerical simulations available in the literature, further emphasizing that the experimental setup with MoWiTO and the active grid is a suitable tool for validation of new control concepts.

Our future work will include control algorithms utilizing wind preview measurements and optimal control theory, such as model predictive control, as well as smart blades. The analysis of the interaction between control algorithms and blade deformations will be given a special emphasis.

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