Experimental investigation of dynamic inflow effects with a scaled wind turbine in a controlled wind tunnel environment

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Abstract. Dynamic inflow is a phenomenon that leads to a load overshooting, for example by fast pitch angle changes. Established engineering models for this effect are known to still have deficits. Advanced control mechanisms for turbines like collective pitch control in order to alleviate tower loads or individual pitch control increase the need for accurate dynamic inflow models. We performed fast pitching step experiments with our MoWiTO 1.8 (Model Wind Turbine Oldenburg 1.8 m) in the WindLab wind tunnel of the University of Oldenburg and investigated the load overshooting of blade loads, torque and thrust as well as velocity transients in the near wake. Dynamic inflow phenomena were clearly visible and their non-dimensional time constants matched existing full scale and lab size experiments. The transient process of the different measured loads and flow in the near wake is discussed in the paper to gain a deeper understanding of the underlying physical phenomena.

1. Introduction
Dynamic inflow denotes the effect of sudden load changes due to variations of the inflow wind velocity, pitch angle or rotor speed of a wind turbine on the rotor aerodynamics, which lead to load overshooting. While the loads, such as blade flapwise moments and rotor torque, can suffer from very fast variations, the axial induced velocity in the rotor plane and the associated axial induction respond only with time delay due to the inertia of the global flow field, when transitioning from one operational state to another. Additional empirical engineering models have been developed to account for this effect in blade element momentum theory employed in industry standard aeroelastic codes [1, 2, 3].

Experiments are important means for validation and development of such models. The most well-known experiments here are the free field tests on the Tjæreborg turbine [4] and the wind tunnel tests in the NASA Ames facility [5]. Yu et al. [6] have recently indicated in a comparison of actuator disk wind tunnel tests, high fidelity simulations and current engineering models, that the latter still need to be improved, especially concerning their time constants, which describe the decay process after load overshoots.

The objective here is to present dynamic inflow experiments and investigations with a 1.8 m scaled wind turbine model in the controlled flow of the wind tunnel. The focus is on the time constants of blade loads, thrust and torque at fast pitching steps at two different operational tip speed ratios with additional hot wire flow measurements in the near wake of the turbine.
2. Setup and methods
Here at first the model wind turbine is introduced. Following this the setup in the wind tunnel and the experimental test matrix is presented. Furthermore the analysis methods of ensemble averaging and extracting the time constants from the experimental data are introduced.

2.1. MoWiTO 1.8 (Model Wind Turbine Oldenburg 1.8 m)
The turbine as shown in figures 1 and 2 features rotor blades, that are made of carbon fiber. The model has individual pitch capabilities with the pitch motors in the blade root. There are strain gauges at each blade root for measuring the flapwise blade bending and at the tower bottom for fore-aft and side-side moments. Signals are transferred by a slip ring from the rotating to the stationary nacelle system. The rotor torque is measured by a torque sensor. The control and data acquisition is handled with a CompactRIO PAC system and programmed in LabVIEW.

The aerodynamic design of the rotor blades was achieved by scaling the NREL 5MW turbine with the aim of mapping the lift distribution along the span, as is described in detail along in-depth information on the MoWiTO 1.8 turbine in [7]. The design tip speed ratio (TSR) was maintained in the scaling process, as can be seen by the similar curve of the power coefficient over TSR for the scaled experiment in comparison to numerical results in figure 3. Furthermore the thrust coefficient as function of TSR could be maintained as plotted in figure 4. The error bars indicate the influence of ±0.1 m/s in reference wind velocity.

2.2. Setup in wind tunnel
The Göttingen type wind tunnel in the WindLab Oldenburg has an outlet nozzle of 3 m by 3 m and a test section length of 30 m. The tunnel can be operated in an open jet configuration or with a closed test section, with maximum wind speeds of more than 32 m/s for the open jet configuration, respectively more than 40 m/s for the closed test section. A particular feature of this research infrastructure is an ‘active grid’, which is capable of reproducing turbulent patterns or transients in flow conditions in a controlled manner. This feature is not used in this study.

For the current study the model wind turbine is placed in the wind tunnel with the open jet configuration, as sketched in figure 5. The turbine’s rotor plane is located 4.8 m, i.e. 2.7 rotor diameter (D), behind the tunnel outlet. The nacelle is placed centered in the x-y plane (see coordinate system in figure 5) to the tunnel outlet as shown in figure 6. In a distance of 0.9 m, i.e. 0.5 D, in z direction a lateral hot wire array is placed behind the rotor plane. Three single...
Figure 3. \( C_P \) over TSR at 480 rpm and 1° pitch compared to the reference turbine

Figure 4. \( C_T \) over TSR at 480 rpm and 1° pitch compared to the reference turbine

direction hot wires are placed at lateral positions (x direction) of 40 %, 60 % and 80 % of the rotor radius (R). The hot wires are oriented, so that the longitudinal component (z) of the flow is measured in the near wake. The signals of hot wires, strain gauges at blade root and tower bottom as well as rotor torque are recorded synchronously at a sampling frequency of 5 kHz.

Figure 5. Scaled turbine setup in tunnel

Figure 6. Turbine in tunnel

2.3. Experimental test matrix
For the experiments the turbine rotor is kept at a constant rotational speed of 480 1/min by a simple PI control of the generator torque. Pitch steps are performed between 0° and 6° (towards feather) for two wind velocities. The wind velocities were chosen on the basis, that the tip speed ratio (TSR) of the lower velocity at 6.2 m/s relates to optimal operation in the partial load range and for the velocity of 6.9 m/s to the transition from partial to full load operation. Values for the steady state thrust coefficients and tip speed ratio for the two wind velocities at a turbulence intensity of 0.5 % are stated in table 1. The pitching step from the lower loaded case at a pitch angle of 6° to the higher loading at a pitch angle of 0° is refered to as downward pitching step and the reverse direction as upward pitching step. For both step directions the pitch time is 160 ms and the pitch trajectory is linear apart from a short acceleration phase at the start.
and stop of the maneuver. Data for at least ten pitching steps in both directions and for both configurations have been recorded in the wind tunnel.

Table 1. Steady turbine data

|            | 6.2 m/s | 6.9 m/s |
|------------|---------|---------|
| $C_T$ pitch 0° | 0.94    | 0.84    |
| $C_T$ pitch 6° | 0.52    | 0.53    |
| TSR        | 7.3     | 6.6     |

2.4. Analysis methods
The blade root bending moment in flapwise direction, the rotor torque, the thrust and the longitudinal velocity in the wake are considered for the analysis. The focus of the analysis is on the decaying time constants of load overshooting after a pitching step. For a good fitting of an exponential curve to extract this information a smooth signal is needed. The experimental measurements are influenced by a variety of external perturbations.

To minimise the influence of these perturbations on the signals ensemble averages based on ten measurements for each pitch step are computed. The signals are aligned based on the encoder reading of the pitch motors and for each timestep an average of ten time series is computed. In figure 7 three single cycle measurements for a downward pitching step and the ensemble average over ten cycles are plotted for the flapwise blade root bending moment of blade 1 (Myb 1), torque, thrust and longitudinal wind velocity in the near wake respectively. In (a) the aerodynamic interference of the tower passing is smoothed out by this approach. The torque ensemble in (b) is still noisy, so that this signal is further smoothed with a moving average. One reason for the large variation of the signal is the aggressively tuned torque controller. The thrust ensemble in (c) is a smooth signal, however the damped oscillation of the tower with the first tower eigenfrequency ($f_0 = 5.7$ Hz) after the load change dominates the signal. In the ensemble of the hot wire data in (d) the blade shed vorticity in the near wake of the turbine is smoothed.

The time constant $\tau$ of the decay for the moments (blade root bending and torque) is extracted by fitting an exponential function to the signal (1), as applied by Schepers [5].

$$M(t) = M_1 + \text{sig}(\Delta \Theta)\Delta M(1 - e^{\frac{t-t_0}{\tau}}) \quad t \in [t_0, 0.8 \text{ s}]$$ (1)

The function $\text{sig}(\Delta \Theta)$ denotes the sign according to the pitching actuation, thus negative for the downward and positive for the upward case. $M_1$ is the maximum value of the moment for the downward pitching step, respectively the minimum for the upward case. $t_0$ is the corresponding time of $M_1$ and in close proximity to the end of the pitch maneuver, which starts at $t = 0$ and is finished at $t = 0.16$ s. $\Delta M$ is the amount of the overshooting of the signal. $M_1$ was extracted by a simple max/min algorithm. The $\Delta M$ is the difference between $M_1$ and the mean value of the signal between $t = 0.8$ s and $t = 1.3$ s. The time constant $\tau$ is then chosen based on the best fit by means of a root mean square error for the time interval of $t_0$ to 0.8 s.

For the thrust data, the approach was altered to account for the structural oscillation of the tower. We found, that (1) written for the thrust $T$ multiplied with the formula for the damped oscillator provides a good match and lets us extract the time constant from the measured signal, despite the structural oscillation of the tower. In (2) the Amplitude $A$ of the oscillator, angular eigenfrequency $\omega_0$, phase shift $\varphi$ and damping coefficient $\beta$ were estimated from the experiment.

$$T(t) = [T_1 + \text{sig}(\Delta \Theta)\Delta T(1 - e^{\frac{t-t_0}{\tau}})] \cdot A \cos(\omega_0(t - t_0) - \varphi) \cdot e^{-\beta(t - t_0)} \quad t \in [t_0, 0.8 \text{ s}]$$ (2)
As expected the longitudinal wind velocity directly follows a delayed step response without oscillations or overshoots. The formula (1) is rewritten for the velocity in (3).

\[ v(t) = v_1 + \text{sig}(\Delta \Theta) \Delta v (1 - e^{\frac{-t-t_0}{\tau}}) \quad t \in [t_0, 0.8 \text{ s}] \]  

The time \( t_0 \) and corresponding value of \( v_1 \) were chosen in steps of 0.01 s in the close proximity to the end time of the pitch maneuver \( (t_0 = [0.14 \text{ s}, 0.22 \text{ s}]) \). The combination of \( t_0 \) and \( \tau \) with the best fit based on root mean square error was chosen.

3. Results

In figure 8 the ensemble averages of the flapwise blade root bending moment (Myb1), the torque and thrust for pitching steps at near design conditions at a TSR of 7.3 and a wind velocity of 6.2 m/s are plotted for the downward pitch step in the top row and for the upward pitch step in the bottom row. For all ensemble averages an exponential function as described in section 2.4 was fitted and the time constant and respective amount of overshooting are stated in the plot. The pitching step starts at \( t = 0 \text{ s} \) and is finished at \( t = 0.16 \text{ s} \). For the downward pitching step an overshooting of the loads and for the upward pitching step an undershooting of the loads can be observed after the pitch actuation. The decay of this over- respectively undershooting of the load is reasonable well captured with the exponential fit. Comparing the downward flapwise blade root bending moment in (a) and the corresponding upward moment in (d) it is visible, that the amount of over- respectively undershooting of the load, which is \( |\Delta M| \) in equation (1), is higher for the upward pitching step, where it is in the order of 2/5 of the difference between the two steady states. For the same comparison of the torque in subfigure (b) and (d) the difference in \( |\Delta M| \) is smaller and is in the order 4/5 of the change from one steady state to the other for both the downward and upward pitching case. For the thrust in subfigures (c) and (f) the
Figure 8. Ensemble averages of turbine data measurements at TSR 7.3 and wind velocity of 6.2 m/s for the flapwise blade root bending moment of blade 1 (Myb1) (a), the rotor torque (b) and the thrust (c) for the downward pitching step and Myb1 (d), torque (e) and thrust (f) for the upward pitching step with an amplitude of 6° and the exponential fit with the time constant \( \tau \) as well as the amount of delta values of torque and force.

Figure 9. Ensemble averages of hot wire data measurements at TSR 7.3 and wind velocity of 6.2 m/s 0.5 D behind the rotor plane at the radial positions of 0.4 R (a), 0.6 R (b) and 0.8 R (c) for the downward pitching step and 0.4 R (d), 0.6 R (e) and 0.8 R (f) for the upward pitching step with an amplitude of 6° and the exponential fit with the time constant \( \tau \).
difference $|\Delta T|$ is slightly higher for the upward pitching case and is like the blade root bending moment in the order of $1/2$ of the difference between the two steady states. So in the signals of blade root bending moment and to a lesser degree also the thrust the effect of dynamic inflow is more visible at the upward pitching step. The effect of the dynamic inflow is most apparent in the torque signal, for both the downward and upward pitching step.

Considering the time constants two observations are made. Firstly the time scale of the blade root bending moment and the thrust are similar within the downward and the upward pitching case, whereas the time constant of the torque is higher. Secondly the time constants for the downward pitching case are longer, than for the upward pitching case. Furthermore the maximum respectively minimum value for Myb1 and thrust are in close proximity to the end of the pitching step at $t = 0.18$ s, whereas the extreme value of the torque is reached approximately $0.1$ s later.

In figure 9, the ensembled velocity measurements with the hot wires 0.5 D behind the rotor plane are shown in the top row for the downward pitching case at 0.4 R (a), 0.6 R (b) and 0.8 R (c), as well as for the upward pitching case at 0.4 R (d), 0.6 R (e) and 0.8 R (f). The velocity transient after the pitch step was fit with the exponential function and the time constants are stated in the plots. For the downwards pitching step the velocity in the near wake is reduced, corresponding to an increase of loading of the rotor and vice versa for the upward pitching step. It can be seen that for both pitch directions the time constant decreases in spanwise direction. These measurements in the near wake indicate, that also the axial induction in the rotor plane changes with different time constants along the blade radius, with lower values towards the tip.

In figure 10, the corresponding plots as in figure 8 are presented for the operation at TSR 6.6 and wind velocity of 6.9 m/s. Similar observations as for operation at TSR 7.3 and 6.2 m/s can be made. For the time constants again the values for the upward pitch step are lower as for the downward case. For this tip speed ratio the time constants for the blade root bending moment and the thrust do not match any more but are still close.

Figure 11 shows the ensembled hot wire measurements analogously to figure 9 for the TSR of 6.6 and wind velocity of 6.9 m/s. For this configuration the difference between the steady state velocities in the wake is smaller as for the case at TSR 7.3, which can be expected from the also smaller difference in thrust coefficient between the two steady state pitch positions.

| Table 2. Dynamic inflow time constants |
|--------------------------------------|
| $\tau$ [s] | 6.2 m/s | $\lambda = 7.3$ | 6.9 m/s | $\lambda = 6.6$ |
| Myb1 | 0.177 | 0.152 | 0.178 | 0.146 |
| Myb2 | 0.171 | 0.150 | 0.175 | 0.154 |
| Myb3 | 0.190 | 0.150 | 0.178 | 0.150 |
| Torque | 0.214 | 0.192 | 0.195 | 0.188 |
| Thrust | 0.182 | 0.147 | 0.197 | 0.170 |
| $v_z$ 0.4 R | 0.231 | 0.286 | 0.231 | 0.271 |
| $v_z$ 0.6 R | 0.193 | 0.188 | 0.214 | 0.199 |
| $v_z$ 0.8 R | 0.170 | 0.177 | 0.179 | 0.169 |

The time constants $\tau$ of the presented cases are put together in table 2 and are complemented by the time constants of the flapwise blade root bending moment of the blades two and three. The time constants of the three blades for each case are similar, thus increasing the confidence in
Figure 10. Ensemble averages of turbine data measurements at TSR 6.6 and wind velocity of 6.9 m/s for the flapwise blade root bending moment of blade 1 (Myb1) (a), the rotor torque (b) and the thrust (c) for the downward pitching step and Myb1 (d), torque (e) and thrust (f) for the upward pitching step with an amplitude of 6° and the exponential fit with the time constant τ as well as the amount of delta values of torque and force.

Figure 11. Ensemble averages of hot wire data measurements at TSR 6.6 and wind velocity of 6.9 m/s 0.5 D behind the rotor plane at the radial positions of 0.4 R (a), 0.6 R (b) and 0.8 R (c) for the downward pitching step and 0.4 R (d), 0.6 R (e) and 0.8 R (f) for the upward pitching step with an amplitude of 6° and the exponential fit with the time constant τ.
4. Discussion

The observation, that the time constants for the upward pitching step are lower, thus the overshooting decays faster was also made by Schepers [5] for the NASA Ames measurements, which was explained by the difference in convection velocity of vorticity in the wake, which is initially slower for the higher loaded case and faster for the lighter loaded rotor.

The time constants for the investigated cases in table 2 of thrust are slightly higher than for the flapwise blade root bending moment for three of the considered cases (6.2 m/s down, 6.9 m/s both), which indicates, that there is a radial dependence of the time scale for the transient of normal forces along the blade radius, which underly the flapwise blade root bending moment. A weak radial dependence of these forces was found in [5]. The time constants of the hot wire measurements in the near wake emphasize this radial dependence with the highest values at 0.4 R and the lowest values at 0.8 R. As the wake width changes with rotor loading the time constants of the hot wire signals should only serve as an indicator for time scales on the rotor.

In the last three decades some dynamic inflow experiments were conducted, for example within the NASA Ames experiments [5], at the Tjæreborg turbine [4] and the Joule II project [3]. Snel [3] defined a dimensionless time constant $\tau^*$ as $\tau^* = \tau v_\infty/D$, which is applied to compare the present measurements with previous experiments.

For the 61 m diameter Tjæreborg turbine in [3, 4] a range for $\tau^*$ for the flatwise rotor blade moment in the range 0.3 - 0.5 was reported. In [3] the range for a two bladed 1.2 m diameter model turbine in the wind tunnel was in the range of 0.4 - 0.68. For the NASA Ames experiments only the non dimensional time constants of the normal forces at radii between 0.3 R and 0.95 R are reported in [5] and range from 0.39 - 0.77. For low pitch angles as in this study the flapwise blade root bending moment can be compared directly to the flatwise moment, which corresponds to the out of plane direction. For the experiments presented in this study the non-dimensional time constants for the flapwise bending are in the range of 0.52 - 0.68 and thus in agreement to existing experiments, however slightly higher than for the Tjæreborg turbine.

The time constants of the torque are slightly higher than for the blade root bending moments and the thrust. Furthermore for the downward pitching case at both wind velocities of 6.2 m/s (figure 8(b)) and 6.9 m/s (10(b)) the torque shows no clear peak after the pitching step from $t = 0.16$ s on, like for example the blade loads, but more like a shaved peak. For the downward pitching step the angle of attack along the blade is increased momentarily due to the pitching. Due to the inertia of the airflow, which causes the dynamic inflow effect, the angle of attack is higher as for the following steady state and might get in the region of dynamic stall, where the lift polars flatten and drag is increased, thus damping the torque overshoot. This might be an explanation for the longer plateau at the downward case at 6.9 m/s, where angle of attack are generally higher due to the lower tip speed ratio. For the upward pitching case the opposite is the case and low angles of attack occur. The lift curve is mostly linear here, as discussed also in [5]. Also a slight overshoot in rotor rpm in the size of $\Delta 7 \text{ rpm (1.5\%)}$ occurs after the pitch steps and consequently also has an influence on the measured torque, i.e. the aerodynamic torque plus the torque due to the change in angular momentum of the rotor. For figure 8 (e), it can be seen, that there is no clear peak but the minimum of the signal is located at $t = 0.28$ s, which is 0.1 s later than for the flapwise blade root moments, which have their peak at $t = 0.18$ s. This temporal delay of torque extreme behind the blade root moment peak can also be seen in the NASA Ames measurements [5], where it accounts to 0.23 s (measured from graph in publication).
Non-dimensionalised by equation (4) for the NASA Ames measurements the non-dimensional time is 0.14 in comparison to 0.34 in the current study.

As the measurements indicate the phenomenon of load overshooting for torque is firstly higher in relative terms than for the thrust and secondly has a time delay to the thrust and the flapwise blade root bending moment. With the measured integrated parameters of blade loads, thrust and torque, as well as the hot wire measurements in the near wake only indications on the transient behaviour of the flow around the turbine during a pitch step can be derived. Most engineering models like Øye [1], Pitt-Peters [2] and ECN [3], model the axial induction factor respectively aereal induced velocity. Detailed information on the axial induction along the span during a pitch maneuver obtained from experiments would enable the validation, respectively new develop of dynamic inflow models. The method proposed by Herráez in [8] could be used to measure the wake induced axial and tangential induction in a follow up experiment and thus provide deeper insights into the dynamic inflow phenomenon.

5. Conclusion and Outlook

The following conclusions are drawn from the presented study:

- The load over- respectively undershooting that is related to dynamic inflow is clearly visible in the measurements for the flapwise blade root bending moments, thrust and rotor torque.
- The non-dimensional time constants of the presented experiments are in accordance to those of measurements of the 61 m diameter Tjæreborg turbine [1], the 10 m diameter NASA Ames experiments [5] and a further study on a 1.2 m model turbine [3]. The measurements of the longitudinal velocity in the wake indicate a weak dependence of time constant on the radius, with lower values towards the tip, as was proven for the NASA Ames tests [5].
- A temporal delay of dynamic inflow related peak of the torque signal to that of the flapwise blade root bending moment in the time range of half of the dynamic inflow decay time constant was observed in the measurements.

In a next measurement campaign the dynamic inflow phenomenon will be investigated further with more detailed flow measurements with hot wires and a two dimensional Laser Doppler Anemometer. The focus will be on axial and tangential induction transients and near wake flow during pitching steps, to improve the understanding of dynamic inflow effects.

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