Comparison of a radially resolved dynamic inflow pitch step experiment to mid-fidelity simulations and BEM

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Abstract. In this paper a detailed comparison of the experimental and numerical results of a scaled wind turbine model in a wind tunnel subjected to fast pitching steps leading to the so-called dynamic inflow effect is presented. We compare results of an Actuator Line LES tool, a vortex code and four engineering models, to the experiment. We perform one and two time constant model analysis of axial wake induction and investigate the overshooting of integral loads. Our results show, that the effect is captured better by the two time constant models than by the one time constant models. Also the experiment and mid-fidelity simulations are best described by a two time constant fit. We identify the best dynamic inflow model to be the Øye model. Different possibilities for the improvement of dynamic inflow models are discussed.

1. Introduction
Dynamic inflow is an aerodynamic effect that describes the unsteady response of loads to fast changes in rotor loading. A main reason for dynamic inflow is fast pitching of the rotor blades. This leads to an overshooting of the loads, as the axial wake induction in the rotor plane is not changing instantaneously but only gradually. This effect is usually described in Blade Element Momentum (BEM) codes by engineering models.

For dynamic inflow only few experimental datasets, with limited information on the radial distribution of the induction transients, are available for validation. Within the Joule project \cite{1} engineering models were tested against pitch step measurements of integral turbine loads of the Tjæreborg turbine \cite{2}. For the NREL phase VI measurements also the force overshoot at five radial stations was investigated, based on measured pressure distributions \cite{3}. Yu et al. used an actuator disk (AD) which could change the porosity in the wind tunnel for a comparison of the wake flow dynamics to engineering and mid-fidelity models \cite{4}.

The objective of the present work is a comparison of the dynamic induction response after a fast pitch step of a scaled model turbine experiment to two mid-fidelity simulations and four engineering models, thus testing their accuracy and pointing out possible improvements.

2. Methods
2.1. Experimental data
The dataset of a pitch step experiment with the Model Wind Turbine Oldenburg with 1.8 m diameter (MoWiTO 1.8) \cite{5}, a scaled version of the NREL 5 MW reference turbine, in the
large wind tunnel of ForWind - University of Oldenburg (see Ref. [6]), is the basis for the comparison. The turbine operated at a wind velocity of 6.1 m/s and rotor speed of 480 rpm and was pitched in 70 ms, corresponding to about half a revolution, by 6° from high (thrust coefficient $C_{T,high} = 0.90$) to low loading (thrust coefficient $C_{T,low} = 0.48$) and vice versa. The wake inductions in the rotor plane have been obtained by the method proposed by Herráez et al. [7], based on a one point flow measurement with a 2-D Laser Doppler Anemometer (LDA) in the bisectrix between two rotorblades, where blade induction is cancelled out for axisymmetric homogeneous inflow conditions, as hinted in Figure 1. A tolerance of $\pm 3^\circ$ around the bisectrix is assumed for a compromise between data samples and accuracy. These raw wake induction results of 100 repetitions of the pitch step from a high to a low turbine loading are plotted in Figure 2 alongside the filtered signal and an exemplary fit of the signal. These filtered axial induction transients are the basis for the comparison and they are further used as an input to a Blade Element Theory (BET) code, which is based on the also used BEM code described in section 2.3. In this BET code the momentum part is deleted and the inductions are taken from the measurements. The geometrical inflow, consisting of axial and tangential velocity at different radii is fed into the BET code, which provides the integral loads used in our analysis. A detailed description and analysis of the experiment is available in Ref. [8].

2.2. Mid-fidelity simulations
Two different kinds of mid-fidelity simulations, both modelling dynamic inflow phenomena intrinsically, are used within this work.

2.2.1. Actuator Line Large Eddy Simulation (AL) The first simulation environment is the open-source CFD toolbox OpenFOAM and the actuator line method (AL) included in the Simulator fOr Wind Farm Application (SOWFA) by NREL [9]. In this approach, the forces on the wind turbine rotor are distributed along rotating lines representing the blade loadings. The acting forces are determined using a blade-element approach based on airfoil polars, which are fed into the flow field of a three dimensional Navier-Stokes solver. The flow simulations were conducted using a cubic grid consisting of five different refinement levels as shown in Figures 3, 4 and 5 alongside the dimensions, to obtain a higher resolution around the rotor plane and in the near wake in order to better resolve the vortices of the turbine. A total of approx. $19 \cdot 10^6$ cells are used. Three actuator lines replace the three rotor blades, neglecting the influence of the tower and nacelle. To account for the tip and root losses, the "New Tip Loss Correction Model" presented in Ref. [10] was applied to all CFD computations. The sides of the channel have been
defined with slip conditions to not influence the flow field. To avoid unphysical oscillations in the force projection, Sørensen and Shen [11] suggest to use a Gaussian approach for smoothing out the forces with increasing distance to the actuator line as:

\[ f_i(r) = \frac{F_i}{\epsilon^3 \pi^{3/2}} \exp \left( -\frac{(r/\epsilon)^2}{2} \right), \]

with \( f_i \) being the force field projected onto the CFD grid and \( F_i \) the load for each blade at the actuator line elements (in our case 40). The distance to the respective actuator line element is given by \( r \), while \( \epsilon \) controls the Gaussian width. The stability of the simulation is directly related to the ratio of the Gaussian width and the mesh resolution \( \Delta x \) in the area swept by the actuator lines. It was found, that \( \frac{\epsilon}{\Delta x} = 5 \) provides a good compromise between stability of the simulation and physicality of the force distribution along the blades (in agreement to Ref. [12]).

2.2.2. \textit{Free Vortex Wake Method Lifting Line Theory (FVWM LLT)} The second simulation environment is a FVWM LLT (LLT) code implemented in QBlade [13], based on the principles in reference [14]. The flowfield is assumed to be inviscid, incompressible and irrotational and is modelled as a potential flow. The blade is discretised in elements and modelled by a bound ring vortex per element, thus forming the lifting line. The circulation of the bound vortices is calculated iteratively based on the airfoil polars and relative velocity. The induced velocity is influenced by all present vortex elements. The vorticity is shed and trailed in each time step and convected, thus forming the wake. A first order method for forward integration of the wake convection is used. Twelve revolutions in the wake are considered, whereas the first six revolutions have a higher resolution than the last six, giving 6831 vortex elements at an azimuthal step of 10°. The initial core size is 4 mm, being 10% of the chord length of the tip.

2.3. \textit{Engineering dynamic inflow models in Blade Element Momentum theory (BEM)}

In addition to the mid-fidelity models also dynamic inflow engineering models are considered. These are the Øye [1], ECN [1] and recent DTU [15] dynamic inflow models, implemented in an in-house MatLab BEM code. The BEM code is based on the steady implementation described in detail in Ref. [16] with the ‘high thrust’ correction by Spera and the Prandtl tip loss correction model. The code is put in a time marching manner and three dynamic inflow models are implemented. Further the generalised dynamic wake model (GDWM), an extension of the Pitt-Peters dynamic inflow model, implemented in FAST v7 [17] is considered. All simulations are purely aerodynamic. In the following the different engineering models are described.
2.3.1. ECN model  The dynamic inflow model developed by ECN is based on an integral relation derived from a simplified cylindrical vortex wake sheet model [1]. For a constant inflow wind velocity $v_0$ the differential equation is shown in (2). $C_t$ is the thrust force coefficient on a blade annulus at radius $r$. The term $f_A$ is a function of the radial position and given by (3). The single time constant $\tau$ is adjusted to the turbine size by the rotor radius $R$.

$$\frac{R}{v_0} f_A(r) \frac{da(r)}{dt} + a(r)(1-a(r)) = \frac{C_t(r)}{4} \quad \text{where} \quad \tau(r) = \frac{R}{v_0} f_A(r)$$  (2)

$$f_A(r) = 2\pi \int_0^{2\pi} \frac{[1 - (r/R) \cos(\phi_r)]}{[1 + (r/R)^2 - 2(r/R) \cos(\phi_r)]^{3/2}} d\phi_r$$  (3)

2.3.2. Generalised Dynamic Wake Model (GDWM)  The GDWM is an extension of the Pitt and Peter’s model. The model is based on a potential flow solution to Laplace’s equation, leading to a smooth distribution of the axial induction, based on polynomials [18]. The GDWM models the effect of tip losses, skewed wake and dynamic inflow effects. Dynamic inflow is considered by an apparent mass that leads to the time lag in the induced velocities. The model and implementation to AeroDyn v14, used in FAST v7 [17], is explained in detail in Ref. [19]. The GDWM is no longer used in the current versions FAST v8 and openFAST.

2.3.3. Øye model  The Øye dynamic inflow model estimates the induced velocities in the rotor plane by filtering the steady values through two first order differential equations in (4) [1, 16].

$$W_{int} + \tau_1 \frac{dW_{int}}{dt} = W_{qs} + k \cdot \tau_1 \frac{dW_{qs}}{dt}, \quad W = \tau_2 \frac{dW}{dt} = W_{int}$$  (4)

$W_{qs}$ is the quasi-steady induced velocity, $W_{int}$ an intermediate and $W$ the final filtered induced velocity. The time constants and ratio $k$ were calibrated through an AD vortex ring model:

$$\tau_1 = \frac{1.1}{(1 - 1.3a) V}, \quad \tau_2 = \left[0.39 - 0.26 \left(\frac{r}{R}\right)^2\right] \tau_1, \quad k = 0.6$$  (5)

2.3.4. DTU model  The most recent DTU dynamic inflow model is described in [15]. Similar to the Øye model two first order time constants are used (6).

$$u_{av} = u - \Delta u \left[0.5847 \cdot \exp\left(-t \frac{f_1}{\tau_1}\right) + 0.4153 \cdot \exp\left(-t \frac{f_2}{\tau_2}\right)\right]$$  (6)

with  \begin{align*} f_1 &= 1 - 0.50802 \cdot a_{Req} \ , \quad f_2 = 1 - 1.9266 \cdot a_{Req} \end{align*}  (7)

$u$ is the axial velocity in the rotor plane at a specific radius. $u_{av}$ is the filtered flow speed and $f_1$ and $f_2$ are functions to adapt the time constants to the local flow speed. The axial induction factor $a_{Req}$ in (7) is the rotor equivalent induction in our implementation, following a discussion with an author of Ref. [15]. The time constants were tuned through an AD-CFD simulation:

$$\tau_1 = \left[-0.7048 \left(\frac{r}{R}\right)^2 + 0.1819 \frac{r}{R} + 0.7329\right] [s], \quad \tau_2 = \left[-0.1667 \left(\frac{r}{R}\right)^2 + 0.0881 \frac{r}{R} + 2.0214\right] [s]$$  (8)
2.4. Time constant analysis

The induction transients are investigated by a one time constant analysis as used by Schepers in Ref. [3]. The exponential function eq. (9) is fitted to the induction transient with the start point \( t_0 = 70 \text{ ms} \) directly after the pitch step is terminated. \( a_0 \) is the axial induction at time \( t_0 \) and \( \Delta a = a_0 - a_\infty \), with \( a_\infty \) being the new steady value of the axial induction. The time constant \( \tau \) is obtained by a least square error fit of the function to the signal (\([t_0, 0.8 \text{s}]\)).

\[
a(t) = a_0 - \Delta a \cdot \left( 1 - \exp \left( \frac{t_0 - t}{\tau} \right) \right)
\]  
(9)

Further the axial induction transients of the experiment, mid-fidelity simulations and the Øye and DTU engineering models are assessed by time constant investigations with a two time constant fit (eq. 10), with the ratio \( k \), to the axial induction \( a \), as proposed in [20].

\[
a(t) = a_0 - \Delta a \cdot \left( (1 - k) \cdot \left( 1 - \exp \left( \frac{t_0 - t}{\tau_{\text{fast}}} \right) \right) + k \cdot \left( 1 - \exp \left( \frac{t_0 - t}{\tau_{\text{slow}}} \right) \right) \right)
\]  
(10)

3. Results

3.1. Steady induction

In Figure 6 the annulus averaged axial induction is plotted over the radius for the stationary cases at high load (left) and low load (right) for the described models. Referring to the method of Herráez et al. [7] the measurement points at 0.25 \( R \) and 0.95 \( R \) should be treated with care because of their proximity to the blade root and tip, but we decided to still include them in the investigation. The BEM, AL and LLT simulations are very similar for radii 0.3 \( R \) to 0.9 \( R \) with some differences, especially of the LLT, in the tip and root region for both and the AL at the tip for the low load case. The experimental measurement is in good agreement with these from 0.6 \( R \) to 0.9 \( R \) and has a higher induction for both cases for 0.4 \( R \) - 0.5 \( R \). For the GDWM implemented in the outdated FAST v7 the axial inductions were converted to annulus averaged inductions in post processing for better comparability by multiplying the inductions by the respective Prandtl tip loss factor. The induction for the high load case shows significant differences to the experiment and the other simulation cases. The values at low radii up to 0.6 \( R \) are lower, whilst the values from 0.6 \( R \) to the tip are higher. For the low load case, the match is good, apart from the root region up to 0.3 \( R \), where the inductions are estimated to be lower.

![Figure 6. Axial induction over radius for the experiment and numerical models.](image-url)

3.2. One time constant analysis of induction transients

The axial induction transients for the pitch step to low load are plotted in Figure 7 for the three radii at 0.3 \( R \), 0.6 \( R \) and 0.9 \( R \) in a non-dimensional form, where equalling to 1 before the transient (induction \( a_1 \)) and equalling to 0 after the transient (induction \( a_2 \)). For the case of
the GDWM this form is slightly altered to $a_1$ being the maximum axial induction, as this model models a clear overshooting of induction in contrast to the other models. For the experiment

![Graph showing induction transients](image)

**Figure 7.** Induction for step to low load: experiment, LLT, AL and Øye at different radii.

and the mid-fidelity models a clear difference is obvious between the non-dimensioned induction transients at 0.3 $R$ and those at 0.6 $R$ and 0.9 $R$, where the 0.3 $R$ case has an initially slower decay indicating a radial dependance. Also differences between the decay time are already obvious by visual inspection, when comparing the GDWM to the LLT.

In Figure 8, the fitted time constant $\tau$ for the one time constant approach is plotted over the radius for the different cases for the pitch step to high (left) and low (right) loads.

For both pitch directions the AL and Øye model give results very close to the experiment. The LLT and DTU model have higher values than the experiment for both step directions, with similar results for the step to low load and the LLT also having higher values than the DTU model for the step to high load. The LLT, AL and experiment have no linear radial trend along the radius for the step to high load and a slight trend to lower time constants towards the tip for the step to low load. The LLT and AL show an increase of the time constant at the very tip for both pitch directions. The ECN model has for both pitch directions a similar time constant course with strongly decreasing values towards the tip. For the step to high loads the time constant is lower than the experiment over the whole blade with increasing difference towards the tip. For the step to low load the ECN model fits the experiment well for radii up to 0.7 $R$ and then the difference is increasing due to the strong decrease of the ECN time constant towards the tip. The GDWM shows the lowest time constants with an increase towards higher radii for the step to high loads and the opposite behaviour for the step to low load.

### 3.3. Two time constant analysis of induction transients

In Figure 9 the fitting results for the two time constant analysis are presented for the experiment, the two mid-fidelity codes (AL and LLT) and the two engineering models based on two time constants (Øye and DTU) for the step to high load (top) and to low load (bottom). Additionally the analytical values used for the Øye model in the BEM code are presented as a measure of accuracy for the fitting approach. Comparing the $k$-value present a wide spread of the values between models for both pitch directions. The experiment gives a generally higher $k$-ratio than the simulations, with higher values towards the root. The AL and DTU model show values
around \( k \approx 0.5 \) for both pitch directions, thus having a similar contribution of fast to slow time constant for the decay process. The LLT model seems to be closest to the experiment but generally at lower \( k \) values followed by the Øye model. For \( \tau_{\text{fast}} \) the experiment has higher values near the root and then between 0.4 \( R \) while for the tip lower values than all simulations for both pitch directions are observed. The AL and LLT models also show an increase of \( \tau_{\text{fast}} \) towards the root for the step to low loads, similar in trend to the experiment. The engineering models of Øye and DTU both have a decreasing trend towards the tip, apart from the very tip for the Øye at the step to high load, at generally higher \( \tau_{\text{fast}} \) than the experiment. There is no clear general difference of \( \tau_{\text{fast}} \) obvious in Figure 9 between the pitch directions for the experiment and the mid-fidelity models, whereas the engineering models are by design slightly faster for the step to low load. The slow time constant \( \tau_{\text{slow}} \) has no clear radial dependance for the experiment with a slightly lower value for the step to low load. The LLT and DTU model show also a flat trend at about three times the value for the step to high load and two times for the step to low load compared to the experiment. The AL also has a flat trend and its values are between the LLT and experiment, also showing a lower value for the step to low load. The Øye model is similar to the experiment apart from the step to high load towards the tip, where \( \tau_{\text{slow}} \) increases due to the local high axial induction (before applying the tip correction). The analytical values of the Øye model indicate a good quality of the fit for the time constants and slightly higher deviations for the \( k \)-ratio.

In Figure 10, the same fitting results are plotted, however here the \( k \)-ratio is set to 0.79, which is the mean value of the experiment considering both pitch directions, for all cases. This approach increases the comparability between the cases on the cost of the fitting accuracy. The general behaviour of the experiment matches that of the fitting with a fitted \( k \)-ratio as in Figure 9. For \( \tau_{\text{fast}} \) the LLT matches the experiment with slightly higher values for the step to high load, but also capturing the increase towards the root, especially for the step to low load. The AL also has an increase towards the root but general lower values than the experiment, especially near the root for the step to low load. The Øye and DTU models do not have the increase towards the root and decrease in a linear fashion towards the tip, with the exception of the very tip of the Øye model for the step to high load. For the step to low loads, the two engineering models are nearly coincident for the step to low load, whereas the Øye model has higher values than the DTU model for the step to high load. For \( \tau_{\text{slow}} \) for all cases, the step to low load gives lower values than the one to high loads. Further all cases for both pitch directions show no clear radial dependency, but especially for the LLT for the step to high load and also for the AL for both step directions \( \tau_{\text{slow}} \) increases towards the tip and root. The Øye model is in good agreement with the experiment for both pitch directions and so is the AL, apart from the very root region. The DTU model gives higher time constants and the LLT even higher ones, especially for the step to high load.
Figure 9. Comparison of two time constant fit $\tau_{\text{fast}}$ and $\tau_{\text{slow}}$ of the axial induction between experiment, LLT, AL, Øye and DTU. The k-value is also a free variable in the fitting.

Figure 10. Comparison of two time constant fit $\tau_{\text{fast}}$ and $\tau_{\text{slow}}$ between experiment, LLT, AL, Øye and DTU model for a prescribed k-value.
In Figure 11 the root mean square error (RMSE) for the fitting of the section at 0.6 \(R\), describing how good the fit represents the data it is fitted to, is plotted for the single (\(\tau_{\text{single}}\)) and the two variants of the two time constant analysis (\(\tau_{2c,k=\text{var}}\) and \(\tau_{2c,k=0.79}\)) for the experiment, mid-fidelity models (AL and LLT) and two time constant engineering models (Øye and DTU). The error for the experiment is highest for the \(\tau_{\text{single}}\) fit and lowest for the \(\tau_{2c,k=\text{var}}\) fit, with the \(\tau_{2c,k=0.79}\) case being slightly higher than the former. It should be noted that the RMSE of the experiment is also influenced by noise, which is not the case for the simulations and engineering models. The same holds true for the AL and LLT, however with a bigger difference between the two variable fits. For the Øye and DTU model, the error for \(\tau_{2c,k=\text{var}}\) approaches zero as should be by design on these models. The error for the described k-value for the Øye model still is very low whereas it is higher for the DTU model.

![Figure 11. Comparison of root mean square error of the one and two component fits to the respective axial wake inductions at 0.6 \(R\) for experiment, simulations and models from \(t_0\) to 0.8 s.](image)

3.4. Load overshoot analysis
The aerodynamic rotor torque, flapwise blade root bending moment and thrust are plotted for the experiment and the simulations for the step to low load in Figure 12. The overshoot is defined as the difference between the maximum peak for pitch to high load, respectively minimum peak for pitch to low load, at \(t_0 = 70\) ms and the new steady value long after the pitch step at \(t_\infty\). The steady values of these loads of the simulations generally are close to the experiment with

![Figure 12. Loads for experiment (BET based), LLT, AL and engineering models Øye, DTU and ECN implemented in an own BEM code and the GDWM in FAST v7.](image)
relative deviations to it by 3% to 11% for the LLT, 1% to 7% for the AL, -4% to 4% for the in-house BEM (Øye, DTU and ECN) but considerably higher deviations for the FAST v7 model with -13% to 16%. Similar to the pure axial induction plot (Figure 6), a clear difference can be seen between the GDWM model and e.g. the LLT. The GDWM adapts much faster to the new steady value, but also shows a lower overshoot.

The overshoot is plotted in Figure 13 normalised with the value of the experiment for the simulations for both pitch directions. Considering all three load sensors, AL and DTU predict the overshoot for the step to high load best, whereas the first slightly underpredicts and the second slightly overpredicts. The Øye model is similar to the DTU model and only marginally worse. The LLT and GDWM overpredict the overshoot for single loads by more than 20%, whereas the ECN model underpredicts single loads by nearly 20%. For the step to low load the LLT performs best, closely followed by the Øye model. DTU and ECN model perform similar and overpredict slightly by 9% to 15%. The AL underpredicts the overshoot by up to 20% and the GDWM even by up to 23%. Overall the Øye model estimates the overshoot closest to the experiment, closely followed by the DTU model.

4. Discussion

The good agreement of the steady axial inductions for the high and low load cases between the experiment, obtained with the Herráez method [7], the mid fidelity simulations and the in house BEM code allows for the further detailed comparison of the dynamic behaviour between those two load states due to pitch steps. The GDWM implemented in the FAST v7 version does not match well for the stationary high load case, being a general issue with this model as discussed in Ref. [18].

The faster decay for the step to low load as observed by Ref. [3] for the NASA Ames experiment is also seen in the one time constant investigation of the experiment, LLT and AL and caught by the Øye and DTU models but not the GDWM and ECN model.

The two time constant comparison with a free $k$-ratio of time constants indicates the difficulty of comparing the different models with three parameters. The choice of fixing the ratio $k$ of the time constants enabled us to compare these at a justifiable cost in fitting error. The high $\tau_{fast}$ values for experiment, LLT and AL towards the root for the step to low load are not mapped by the Øye and DTU models but not the GDWM and ECN model.

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A tuning of the Gaussian width in the swept area of the AL could be an improvement here. Further we also see considerable room for improvement in the modelling of tip losses. The error comparison for the experiment, LLT and AL fits showed, that the dynamic inflow effect should be described by two time constants, as discussed in Ref. [20]. The radial dependance obvious
by visual inspection for the inductions in Figure 7 of experiment and mid-fidelity models was not captured in the one time constant analysis but in the two time constant analysis in $\tau_{fast}$.

In the load study the LLT, Øye and DTU model overpredict the overshoot whereas the AL underpredicts it. The one time constant models however both overpredict one direction and underpredict the other, thus seeming less reliable. The differences also are connected to the two time constants, e.g. the underestimated $\tau_{fast}$ of the AL leading to the underprediction of the step to low load and the strongly overestimated $\tau_{slow}$ value of the LLT leading to the overprediction of the overshoot for the step to high loads, as the overshoot at $t_0$ depends on the axial velocity in the rotor plane and by how much it has already adapted to the new equilibrium.

5. Conclusions
The investigation showed, that of all the engineering models, the Øye model performed overall closest to the experimental pitch case, followed by the DTU model. The Øye model is currently implemented in OpenFAST 2.0 and GH Bladed and the DTU model in HAWC2 12.8. The tested models based on a single time constant cannot be recommended. The comparison of the mid-fidelity models with the experiment indicated general good performance but also specific weaknesses, which should be considered for simulations with such tools where dynamic inflow phenomena or the wake dynamics due to load changes are of importance.

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