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Assessment of the effects of BEM correction models on aerodynamic loads and power under yawed inflow

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Abstract. The classic blade element momentum theory (BEM) assumes an inflow normal to the rotor surface, whereas in practice the inflow effectively hits the rotor skewed. To take this fact into account, the BEM is expanded with appropriate algorithms that correct the BEM results that represent the effects of the skewed inflow. This work compares four yaw correction models, Glauert, Øye, IFPEN, and Branlard, using MoWiT simulations. The effects of each correction model on one-revolution averaged sectional aerodynamic loads and power output are assessed for different yaw angles and wind speeds. For selected skew inflow angles, predictions are compared with CFD is also carried out. The results show that no model outperforms the others for all load quantities, and power prediction becomes less accurate with increasing yaw misalignment. IFPEN provides the closest agreement with power at the available yawed CFD comparison point. This study demonstrates the need to assess load and power prediction separately and stresses the need for variable yaw-loss exponent models across operating conditions.

1 Introduction and Motivation

Wind turbines encounter complex wind flows. They are affected by turbulent fluctuations in wind speed and a permanently changing main wind direction. The flow towards the wind turbine rotor differs from the assumptions underlying the aerodynamic approaches used for the design of wind turbines. The conventional blade element momentum theory (BEM) algorithm theory used in calculation tools for wind turbines was derived for non-yawed conditions (Branlard, 2017), i.e., the inflow is perpendicular to the rotor surface; however, actual inflow impacts the rotor at an angle. This skew is due to variations in wind direction, the tilt angle of the main shaft, the cone angle of each rotor blade, and the elastic deformation of the blades. As a result, wind turbines consistently operate under skewed inflow conditions. BEM codes need to apply engineering correction models to account for the yawed inflow for assessment of turbine performance and load calculation.

The application of the axial 1D momentum theory for a turbine rotor with a skewed inflow with steady yaw angle γ is introduced in Burton et al. (2011). The resulting equations for the axial velocity at the rotor, thrust coefficient, rotor thrust, power and power coefficient can be used to derive a satisfactory general rule for the decrease in power as function of the yaw angle γ, by means of determining the rotor average axial induced velocity. However, this approach is not capable of determining the induced velocity at each blade element position to a satisfactory accuracy (Burton et al., 2011).

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Several BEM compatible models have been developed to correct the difference in axial induced velocities by the application of an axial induction correction factor. As an example, the Glauert's yaw-model is extensively quoted in the literature and used in a variety of investigations in association with turbines in yaw. As quoted in (Rahimi et al., 2016), many attempts were made in the past to improve the Glauert model by more accurate modelling of the wake expansion and deflection. Branlard et al., (2024) applied Glauert's skew momentum correction and added a continuous skew dependent extension, which showed improved predictions at large skew. Using the IFPEN correction model for BEM simulations, Höning et al., (2024) captured the main azimuthal pattern in blade-root bending moment, but its mean was underestimated relative to other measurements. Recent research has found that corrected BEM errors can still exceed 20% in highly yawed conditions, where CFD had unsteady vortex interactions and spanwise structures not represented by steady state BEM (Hu et al., 2025)

In this work, selected aerodynamic extensions to take skewed inflow into account are presented and their results are compared. The quality of the results of these extensions plays a crucial role in the simulations for the design of wind turbines. Typical load calculation tools are still based on BEM (Popko et al., 2021). This means that the load calculation depends on the correction models in the same way as the determination of the power curve. Beyond the design phase, the correction models for the skewed inflow also play a special role in the operational phase. Modern methods for controlling wind farms rely, among other things, on controlling the direction of the wakes, whereby the wind turbine is intentionally exposed to an increased skewed inflow. Flow angles outside the operating range covered by the design certification ("IEC 61400-1," 2019), e.g. larger than 8~10 deg, are also realistic. In addition to the design phase, the quality of the correction models plays a crucial role in the operating phase to predict the resulting loads and effect on power output. In this paper, both load and power quantities are compared for larger skewed inflow angles. Comparison with CFD is also carried out for selected skew inflow angles.
Following the introduction and motivation in Section 1, the correction models considered in this work are presented in Section 2. Section 3 presents simulation scenarios, the results of which are compared in Section 4. In the last Section 5, conclusions are drawn from the results and a summary is given.

2 Yaw correction models

In this work, four BEM compatible models are considered, which include two recently developed yaw correction formulations. These are introduced below and summarized in Table 1.
The modification of the momentum balance based on Glauert's theory, which is explained in detail by Burton et al., 2011, proposes a correction model of axial inductions for yawed rotors which takes both the radial and azimuthal variations of the axial induction into account. As described by Branlard, (2017), the model assumes that the induced velocity normal to the rotor is decomposed into a constant component and a component that varies linearly with the radius and sinusoidally with the azimuth angle. Eq. (1) shows the axial induction correction.

$$a_{yaw} = a\,(1 + 2\,F_t\,K \sin\psi), \tag{1}$$

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The corrected axial induction which takes the oblique flow into account is expressed here as a_{yaw}, where a is the axial induction determined without yaw model, $F_t = \tilde{r}/2$ is the flow expansion function ($\tilde{r}$ is the dimensionless radial position r/R or radius ratio), and K is a function dependent on the wake skew angle, denoted χ. The wake skew angle χ is the angle formed between the line of the deflected wake and the rotor axis of rotation. The sinusoidal component varies with the azimuth angle and takes the azimuthal position of the blade into account. A limitation of this model described in the literature is that only the tip vortices are considered, while the neglection of the root vortex has been shown to affect the loading effects near the root, which don't show sinusoidal behavior in the root region (Rahimi et al., 2016).

The formulation attributed to Øye in the literature (Hur et al., 2019) differs from the Glauert's model by the application of a nonlinear function F_t. The resulting model is given by Eq. (2).

$$a_{yaw} = a\left(1 + (\tilde{r} + 0.4\,\tilde{r}^3 + 0.4\,\tilde{r}^5)\,tan\left(\frac{\chi}{2}\right)\cos(\psi_m)\right). \quad (2)$$

The angle ψ_m is defined such that $\psi_m = \psi - \psi_0 = 0$ (Branlard, 2017), where ψ_0 is referred to as "deepest wake angle" and is the reference azimuthal position for which the blade tip is in the most downwind position of the rotor with oblique inflow. This means that the component of the correction model which varies sinusoidally has its maximum value at this position. This condition should result in a higher induction on the downwind side of the rotor with BEM.

Another model for the BEM method considered in this work was developed based on the analysis of vortex solver results at IFP Énergies Nouvelles (IFPEN) which is presented in by Blondel et al., (2017) and considers both root and tip vortex influence using increasing and decreasing functions. The influence of the tip vortex is linearly increased along the blade span, while the influence of the root vortex is linearly decreased towards the blade tip. Besides, it includes the radius of the hub when taking the root vortex into account for the yaw correction. The resulting model is given by Eq. (3)

$$a_{yaw} = a_{local}\big(1 + k_1\,\tilde{r}\,K\,sin(\psi - \phi_1) + k_2(1 - \tilde{r})\,K\,sin(\psi + \phi_2)\big), \quad (3)$$

with $\tilde{r}$ the radius ratio, the function $K = tan(\chi/2)$, and the phase angles $\phi_1 = -\pi/9$ and $\phi_2 = \pi$. The parameters k_1 and k_2 are given by Eq. (4) and Eq. (5)

$$k_1 = (1 - A_0) + A_0\left(\frac{r - r_{hub}}{R - r_{hub}}\right), \quad (4)$$

$$k_2 = 1 - A_0\left(\frac{r - r_{hub}}{R - r_{hub}}\right), \quad (5)$$

with $A_0 = 0.35$ and r_{hub} the hub radius.

In the work presented by Branlard, (2017) and Branlard and Gaunaa, (2016), a cylindrical vortex model of a rotor of finite or infinite tip-speed ratios is used to study rotors in yaw. In accordance with the literature, the use of vortex models may give much more detail about the flow field and structure than the momentum theory. An extension of the Glauert's model based on the cylindrical vortex wake model is introduced as a new yaw-model applicable within BEM codes by Branlard and includes more components of vorticity. This model also includes a correction of the tangential induction. The four components of the skewed cylinder vortex model can be visualized in Figure 1. It combines the tangential vorticity γ_t, the longitudinal tip-

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vorticity γ_l, the root-vortex Γ_r and the bound vorticity γ_b (Branlard, 2017). The cylinder is skewed with the wake skew angle χ.

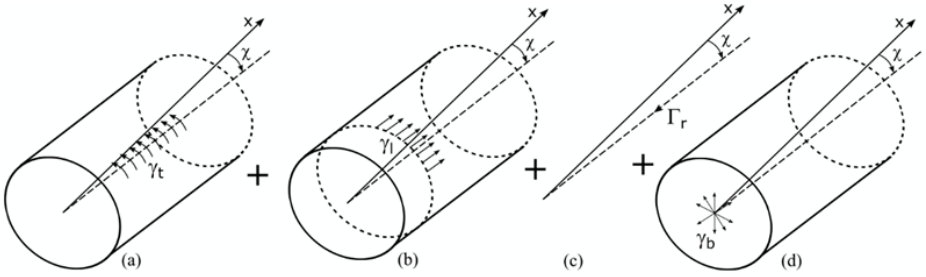


Figure 1: Components of cylindrical vortex wake model, figure adapted from (Branlard, 2017)**.**

The total velocity in axial direction to be used in the velocity triangle is

$$U_n = (1 - a_{yaw})U_0 - u_{n,r} \tag{6}$$

with U_0 the longitudinal wind velocity far upstream and U_0 the velocity normal to the rotor. The additional component $u_{n,r}$ is the axial component of the velocity induced by the root vortex Γ_r, which was absent in the Glauert's yaw-model.

The velocity tangent to the rotor to be used in the velocity triangle can be obtained by

$$U_t = (1 + b_{yaw})U_t + u_{t,t} + u_{t,l} \tag{7}$$

while b_{yaw} is the corrected tangential induction, U_t the tangential velocity computed without yaw and $u_{t,t}$ and $u_{t,l}$ the velocity components in tangential direction, which are induced by the tangential and by the longitudinal tip-vorticities γ_t and γ_l. The complete equations for computing all model components are given by (Branlard, 2017).

Table 1 summarizes the four presented BEM yaw corrections expressed in terms of an axial induction correction for the skewed inflow condition, as well as showing the dependency of parameters (exception is the model of Branlard, which is expressed in terms of correction of axial and tangential velocities).

Model	Yaw correction		Dependencies
Glauert	$a_{yaw} = a\,(1 + 2\,F_t\,K \sin\psi\,)$		$F_t = f(r)$ $K = f(\chi)$
Øye	$a_{yaw} = a\,(1 + 2\,F_t\,K \cos(\psi - \psi_0)\,)$		$F_t = f(r)$ $K = f(\chi)$
IFPEN	$a_{yaw} = a\,(1 + k_1\,F_t\,K\,sin(\psi - \phi_1) + k_2(1 - F_t)\,K\,sin(\psi + \phi_2)$		$F_t = f(r), K = f(\chi)$ $(k_1, k_2) = f(r, r_{hub})$
Branlard	$U_n = (1 - a_{yaw})U_0 - u_{n,r}$	$U_t = (1 + b_{yaw})U_t + u_{t,t} + u_{t,l}$	$u_{n,r} = f(\Gamma_r, \psi, r, \chi)$ $u_{t,t}, u_{t,l} = f(r, \chi, \psi, \Gamma)$

Table 1: Overview of BEM yaw correction models

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3 Simulation methodology and scenarios

The reference turbine used in the BEM simulations was the INNWIND 10 MW developed within the INNWIND.EU project. As described in ("MoWiT"), this offshore wind turbine with traditional design was established as initial reference for the INNWIND project. A description of the aerodynamic and aeroelastic model, rotor design parameters, performance and characteristics based on BEM and CFD models can be found in (Bak et al., 2013) and (Chaviaropoulos et al., 2013).

The simulations obtained with the simulation tool using the different BEM yaw models were compared with CFD simulation results performed by Fraunhofer IWES for the INNWIND reference turbine, using the open-source CFD software OpenFOAM with the Spalart-Allmaras-DDES model (Rahimi et al., 2016). The simulations and outputs are for 1 blade, which points upwards and has an azimuthal angle of $\psi = 0°$ in the beginning of the simulation. The blades are rigid and are not pitched, and no tower is present. Table 2 summarizes the main parameters of the CFD simulations.

Turbine parameter	Value
Wind speed far from the turbine	11 m/s
Constant yaw angle in simulation tool hub coordinates	30°
Wind speed components far from turbine in hub coordinates	$U_x = 11\cos(\pi/6) = 9.526\ m/s$ $U_y = 11\sin(\pi/6) = -5.5\ m/s$ $U_z = 0$
Tip speed ratio	0.9254 rad/sec (8.836919 rpm)
Blade pitch / shaft tilt / rotor precone angle	0° / 0° / 0°

Table 2 Main parameters of available CFD results

The axial and tangential inductions and angles of attack determined from the CFD results were based on estimates of the velocities induced at the blade section at the airfoil center performed with the 3-Point method. As described by Vimalakanthan et al., (2018), for this method, the induced velocity at the airfoil center is estimated by averaging the velocities from three points on each side of the airfoil section, located at 25, 50 and 75% of the chord length. The estimation of the induced axial and tangential velocities allows the calculation of the axial and tangential inductions. Once the induction factors are known, the inflow angle and the angle of attack can be computed.

Three cases of simulations with BEM were performed with a stiff structure, in accordance with the CFD simulation results, with an inflow wind velocity of $11m\ /s$ and a yaw angle of 30°. For turbine performance assessment, a wind velocity of 7 m/s was further considered as well as yaw angles from -50° to 50°. The simulations conditions are summarized in Table 3.

Turbine parameter / simulation tool configuration	Case 1	Case 2	Case 3
Wind speed far from the turbine	11 m/s	11 m/s	7 m/s

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Turbine parameter / simulation tool configuration	Case 1	Case 2	Case 3
Constant yaw angle in global coordinate	30°	-50° to 50° in 10° steps	-50° to 50° in 10° steps
Wind model	steady	steady	steady
Rotor speed	0.9254 rad/s (8.836 rpm)	0.9254 rad/s (8.836 rpm)	0.628 rad/s (6 rpm)

Table 3 Main parameters of BEM simulations

The real-time aero-elastic BEM simulation model MoWiT ("MoWiT"), is used for the work presented here (Neshati et al., 2022). It couples physical models for aerodynamics, structural dynamics, hydrodynamics and control and computes them in the time domain. This computational model is developed by Fraunhofer IWES and primarily used for load analysis of (offshore floating) wind turbines as well as for automated simulation and optimization. Further, MoWiT has been in productive operation as a virtual rotor for Hardware-in-Loop (HiL) application in the Dynamic Nacelle Testing Laboratory (DyNaLab) and the HilGridCop test bench for several years now. In essence, for MoWiT a multi-body approach to model the interaction between the individual structural components is used. The major structural components like the rotor blades and the tower are modeled as flexible bodies using modal reduced, anisotropic beam elements where the superposed eigenmodes represent the elastic degrees of freedom. This allows the frequencies remaining in the model, and thus the model dynamics, to be set in a targeted manner. The three-dimensional, turbulent wind inflow, including horizontal and vertical inclination, shear, and tower shadow, complies with the requirements of IEC 61400-1 and is converted into a realistic driving torque by the implementation of the unsteady BEM aerodynamics. MoWiT uses an iterative aerodynamics model to solve for the local wind velocities along the rotor blades. Since the BEM solves for steady flow conditions only, several corrections, such as Øye's dynamic inflow and dynamic stall, are applied to reproduce the unsteady flow conditions along the rotor blade.

4 Comparison of simulation results

Reference simulations were performed for the non-yawed case and with a yaw angle of 30°, the yaw-models described in Section 2 were tested. Hereby different parameters and models (e.g. for expansion function F_t, function K, wake skew angle χ) and aspects of the BEM implementation of the correction models were tested, taking the CFD results as reference.

In Figures 2 and 3, the average thrust and tangential forces for one rotor revolution over the radial positions are shown. The average axial forces are slightly underestimated by BEM in the midspan and overestimated in the tip region, except for the model of Øye, for which the axial forces are lower than CFD near the blade tip. The average tangential forces are systematically underestimated by BEM for $\tilde{r}$ from around 0.2 to 0.8. It is visible from Figure 3 that improvement for these blade sections can be obtained using the model of Branlard. In the blade tip region, BEM average tangential forces are larger than CFD. Nevertheless, Figure 3 shows that the average normal and tangential forces for one rotor revolution over the radial positions obtained with the different BEM models are generally in very good agreement with the CFD results.

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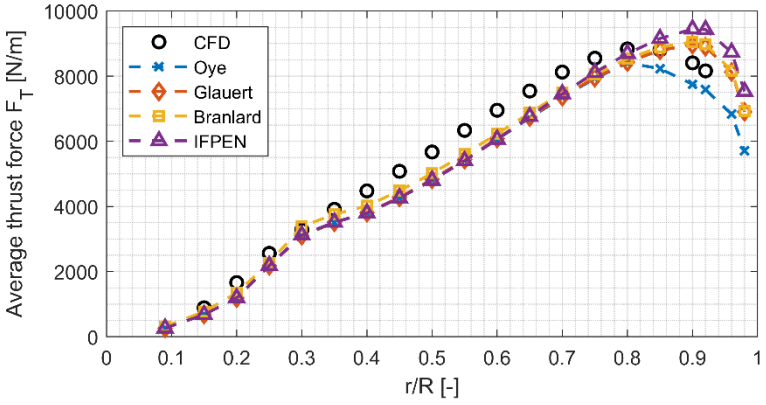


Figure 2 Average thrust forces along the blade span, average values for rotor revolution, blade 1, $U_\infty = 11$ m/s, $\gamma = 30°$.

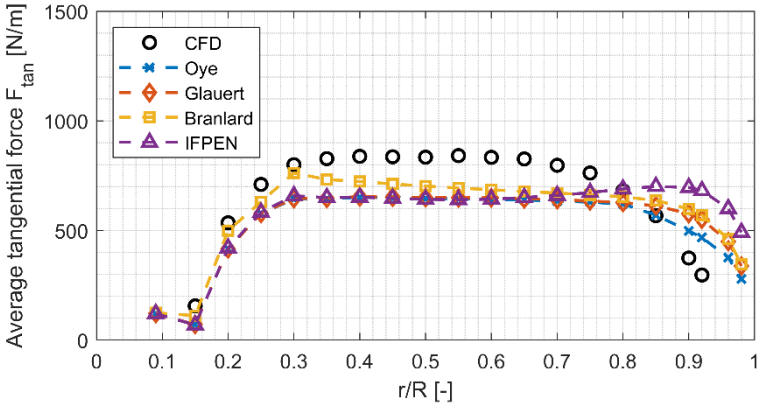


Figure 3 Average tangential forces along the blade span, average values for rotor revolution, blade 1, $U_\infty = 11$ m/s, $\gamma = 30°$.

To assess the turbine performance in yaw for the different yaw models, simulations were performed for wind velocities of 11 m/s (Figure 4) and 7 m/s (Figure 5) and for yaw angles from -50° to 50° (see Table 3). As shown in Figure 4, using BEM a general lower turbine performance is obtained at 30° compared with CFD. The differences in power output among the different yaw models are generally more pronounced for higher yaw angles. It can be observed in Figure 4 that the models Branlard and IFPEN deliver the best results for the yaw angle to 30°, whereas IFPEN even matches the power output from CFD for this yaw angle. In Figure 5, it is evident that for the lower wind speed, at higher yaw angles IFPEN differs from the other models, predicting higher power relative to the other models.

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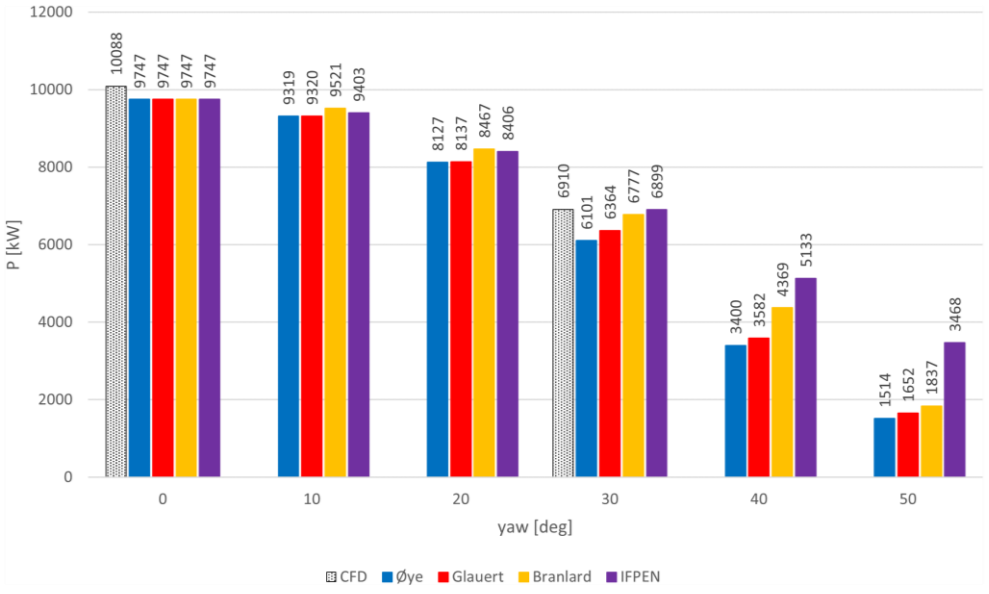
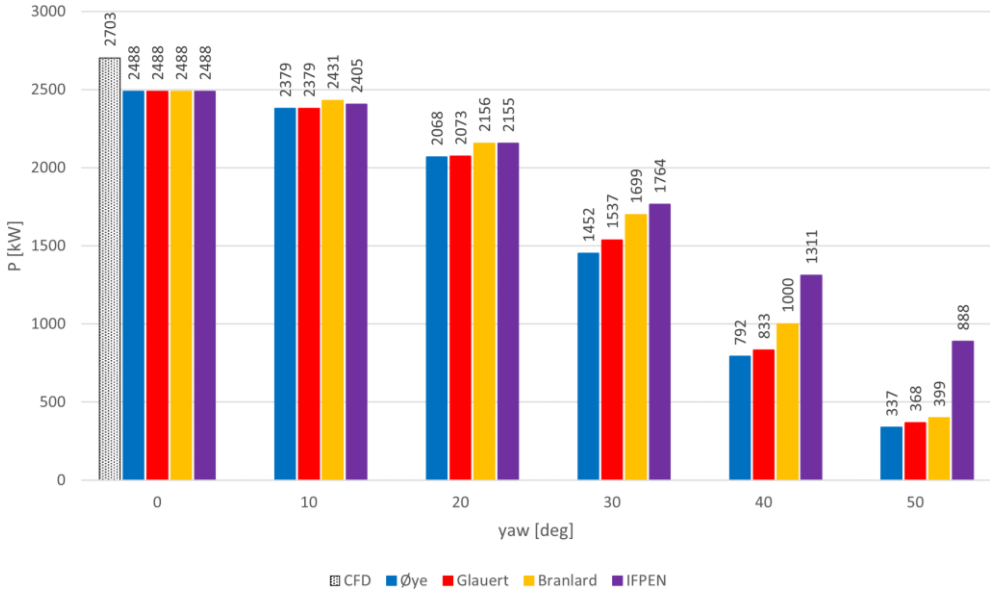


Figure 4 Comparison of power output obtained with CFD and BEM for different yaw angles and wind velocity of 11 m/s.



175 **Figure 5 Comparison of power output obtained with CFD and BEM for different yaw angles and wind velocity 7 m/s.**

Power loss exponents α_P and $cos^{\alpha_P}\gamma$ curves, for which the power output in yaw $P_\gamma = P_0\, cos^{\alpha_P}\gamma$ are typically normalized against the nominal power P_0 for the aligned case and are used for the characterization of the power loss due to the oblique inflow, were obtained from simulation results using BEM and compared with values from the literature. The reference values

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from the literature include studies using wind turbines measurements and experimental data as well as CFD and other aerodynamic simulation tools results for performance considerations.

Individual exponents α_P calculated for the $cos^{\alpha_P}\gamma$ rule for each simulation and each yaw angle are shown in Figure 6. The determined exponents from BEM simulations are in the range between 1.5 and 4.5. For IFPEN, the exponents are almost constant and similar for both wind velocities, with a mean value of 2.38, and from the BEM models, overall closer to the reference value of 2.65 (which was assumed as a reference for the INNWIND turbine for a yaw angle of 30° based on CFD results). The models of Øye and Glauert have similar behavior, with almost constant values for γ up to 20°, with increasing α_P from 20° reaching the value of 4. The exponents for the model of Branlard show the largest variability, starting at 1.5 for $\gamma = 10°$ and increasing almost linearly to 4.1 for $\gamma = 50°$. For $\gamma = 30°$, the model of Branlard is close to the reference value for both wind velocities.

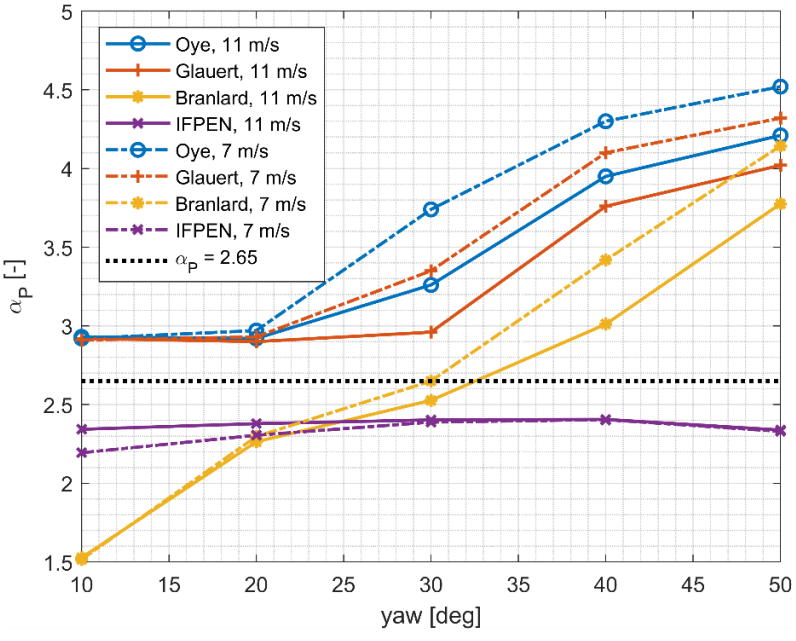


Figure 6 Exponents α_P for 7 m/s and 11 m/s from BEM simulation results.

In Figure 7 below, the values of P/P_0 obtained from BEM simulations for the wind speed 11 m/s are compared with reference curves following the $cos^{\alpha_P}\gamma$ rule with the exponents obtained from the literature. The considered literature values in Figure 7 range from 1.57 (determined with BEM for a 2.3 MW turbine, (Urbán et al., 2019)) to 2.6 (1.5 MW full size turbine, (Doekemeijer et al., 2021)). The theoretical exponent based on the momentum theory applied to an actuator disc under skewed inflow takes the value $\alpha_P = 3$ (Burton et al., 2011). With exception of IFPEN, MoWiT's results show generally larger losses compared with the power curves obtained with all other determination methods. IFPEN shows the best results in comparison with the literature values.

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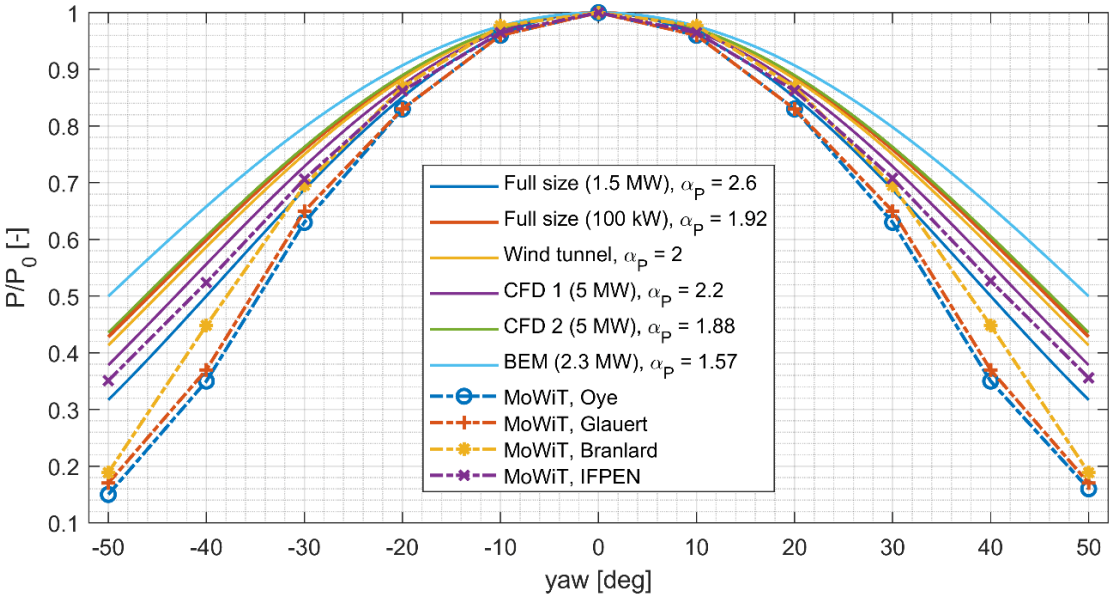


Figure 7 Comparison of power loss dependence of yaw angle, values from literature and BEM simulations for wind speed 11 m/s.

5 Summary and Conclusions

The paper compares different models for considering the effect of oblique flow in BEM simulations. The models from Øye, Glauert, IFPEN and Branlard are presented, and differences are described. The results of the different models from BEM simulations are compared with each other and with high-fidelity CFD results. The simulated thrust force and the tangential force of the different models only differ significantly around the blade tip from 80% span. In comparison to CFD, the forces are initially underestimated and overestimated from 80% span, with Øye, followed by Branlard and Glauert, coming closest to CFD.

The electrical output power was compared at wind speeds of 7 m/s and 11 m/s. For small yaw angles up to 20 deg the results are close; here it makes no difference which yaw correction model is used. From 20 deg the differences become clearer. Since CFD results are only available for 30 degrees yaw at 11 m/s, conclusions about the model quality can only be drawn there. Here the IFPEN model performs best, followed by the Branlard model.

The respective power loss coefficient α_P was also determined for the yaw models mentioned. This shows that the coefficient is not constant but depends on the wind speed and the yaw angle. The model from IFPEN shows the lowest dependence on the yaw angle and wind speed. The variability in the power loss coefficient is also reflected in the resulting power loss. As expected, the values here in the paper lead to different power loss curves than those available in the literature, which were generated for constant power loss coefficients.

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Overall, there is only a low quantity of high-fidelity simulation or even validation data, especially for large skew inflow angles. Unfortunately, the CFD results are only available for 2 angles; it is recommended for future work to simulate significantly more angles and make the results available to the community. Beyond the steady state conditions considered, interaction between yaw corrections and dynamic flow warrant more investigation. Further study needs to evaluate both mean quantities and azimuth resolved loads since the averages alone do not necessarily imply accurate prediction of cyclic loading.

In this study, IFPEN's yaw model was found to be the most promising to enhance aero-elastic BEM simulations. Both on the load side and especially when it comes to power losses, the model is convincing in comparison to the other models and in comparison, to CFD and seems to be a good choice for assessing the influence on loads and power in wind farm control with wake steering.

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