Comparison of Free Vortex Wake and BEM Structural Results Against Large Eddy Simulations Results for Highly Flexible Turbines Under Challenging Inflow Conditions

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Abstract. Throughout wind energy development, there has been a push to increase wind turbine size due to the substantial economic benefits. However, increasing turbine size presents several challenges, both physically and computationally. Modeling large, highly flexible wind turbines requires highly accurate models to capture the complicated aerodynamic response due to large deflections and nonstraight blade geometries. Additionally, development of floating offshore wind turbines requires

5   modeling techniques that can predict large rotor and tower motion. Free vortex wake (FVW) methods model such complex physics while remaining computationally tractable to perform the many simulations necessary for the turbine design process. Recently, a FVW model—cOnvecting LAgrangian Filaments (OLAF)—was added to the National Renewable Energy Laboratory engineering tool OpenFAST to allow for the aerodynamic modeling of highly flexible turbines along with the aero-hydro-servo-elastic response capabilities of OpenFAST. In this work, FVW and low-fidelity blade-element momentum (BEM)

10   structural results are compared to high-fidelity simulation results for a highly-flexibly downwind turbine for varying TI, shear exponent, and yaw misalignment conditions. Through these comparisons, it was found that for all considered quantities of interest, SOWFA, OLAF, and BEM results compare well for steady inflow conditions with no yaw misalignment. For OLAF results, this strong agreement was consistent for all yaw misalignment values. The BEM results, however, deviated significantly more from SOWFA results with increasing absolute yaw misalignment. Differences between OLAF and BEM results

15   were dominated by yaw misalignment angle, with varying shear exponent and TI leading to more subtle differences. Overall, OLAF results were more consistent than BEM results when compared to SOWFA results under challenging inflow conditions.

1   Introduction

Over the years, wind energy researchers have focused on increasing wind turbine rotor size, yielding substantial reductions in wind energy costs. As rotor size increases, substantially more energy is captured through greater swept area, thus reducing

specific power while increasing turbine capacity factor. Low specific power rotors, with correspondingly higher capacity factors, have been shown to lead to higher economic value (Bolinger et al. (2021)). One important consideration for such large

25 turbines, however, is increased blade flexibility and the use of multi-element airfoils, such as the use of flaps. In particular, large blade deflection likely results from large, highly flexible wind turbine blades. The dynamic and complex nature of large blade deflections leads to the violation of many assumptions used by common aerodynamic models, such as the blade element momentum (BEM) method. Such aerodynamic models are only valid for axisymmetric rotor loads contained in a plane and for which there is little to no interaction between the turbine blades and the near wake of the turbine. When operating under

30 normal conditions, large blade deflections may cause a swept rotor area that deviates significantly from the rotor plane and the turbine near wake to diverge from a uniform helical shape. Such deviations violate the planar swept area assumption, causing three-dimensionality of the aerodynamic effects and increasing the importance of accurate and robust dynamic stall models. Further, a non-uniform near wake increases interactions between turbine blades and the local near wake may, thus violating assumptions of models that do not account for the position and dynamics of the near wake. In addition to the complications

35 from large blade deflection, there are many other complex wind turbine situations that violate simple engineering assumptions. Such situations include accurately capturing aerodynamic loads for nonstraight blade geometries (e.g., built-in curvature or sweep); skewed flow caused by yawed inflow, turbine tilt, or strong shear; and large rotor motion due to placing a turbine atop a compliant floating offshore platform.

Large, flexible rotors and complex operating conditions necessitate higher-fidelity aerodynamic models. By definition, com-
40 putational fluid dynamic (CFD) methods are able to capture the necessary physics of such problems. However, the high computational cost limits the number of simulations that can be practically performed for a given problem, which is an important consideration in load analysis for turbine design. Free vortex wake (FVW) methods model the complex physics required for such problems, while remaining less computationally expensive than CFD methods. Many FVW methods have been developed throughout the years, ranging from the early treatments by Rosenhead (1931), the formulation of vortex particle methods

45 by Winckelmans and Leonard (1993), to the recent mixed Eulerian-Lagrangian compressible formulations of Papadakis (2014). Established FVW codes in wind energy include the vortex particle approach of GENUVP (Voutsinas (2006)) and the vortex filament approach of AWSM (van Garrel (2003)), both of which are coupled to structural solvers. The method was extended by Branlard et al. (2015) to use vortex methods in the aeroelastic modeling of wind turbines in sheared and turbulent inflow.

This work focuses on the FVW model that was recently implemented into the modeling tool OpenFAST (Shaler (2020)).
50 cOnvecting LAgrangian Filaments (OLAF) is an FVW model used to compute the aerodynamic forces on moving two- and three-bladed horizontal-axis wind turbines. This module is incorporated into the National Renewable Energy Laboratory (NREL) physics-based engineering tool OpenFAST, which solves the aero-hydro-servo-elastic dynamics of individual wind turbines. OLAF is incorporated into the OpenFAST module *AeroDyn15* as an alternative to the traditional BEM option. Incorporating the OLAF module into OpenFAST allows for the modeling of highly flexible turbines along with the aero-hydro-

55 servo-elastic response capabilities of OpenFAST. The purpose of this work is to determine the accuracy of an aeroelastically coupled FVW method under conditions known to be challenging to lower-fidelity aerodynamic methods. This is done by comparing OLAF results to large-eddy simulation results and low-fidelity BEM results for a large range of turbulence intensity

(TI), shear exponent, and yaw misalignment conditions. These comparisons provide better understanding of OLAF, BEM, and
SOWFA relative performance when subjected a range of inflow conditions, both simple and challenging. This will aid in the
60 selection of the most appropriate modeling tool based on the application and available resources.

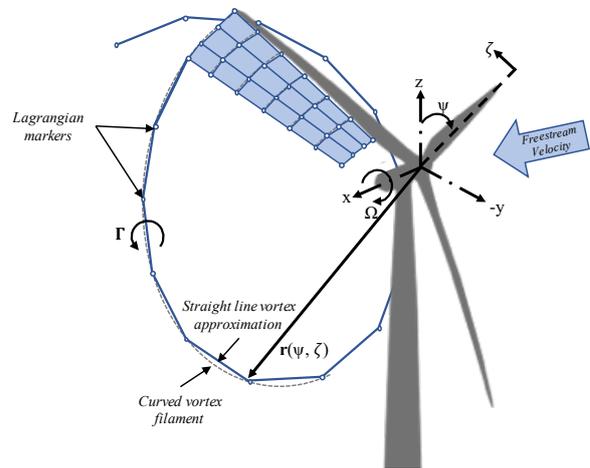
2 Approach and Methods

2.1 Overview of OLAF

The OLAF module uses a lifting-line representation of the
blades, which is characterized by a distribution of bound
65 circulation. The spatial and time variation of the bound cir-
culation results in free vorticity being emitted in the wake.
OLAF solves for the turbine wake in a time-accurate man-
ner, which allows the vortices to convect, stretch, and dif-
fuse. The OLAF model is based on a Lagrangian approach,
70 in which the turbine wake is discretized into Lagrangian
markers. There are many methods of representing the wake
with Lagrangian markers (Branlard (2017)). In this work,
a hybrid lattice/filament method is used, as depicted in Fig-
ure 1. Here, the position of the Lagrangian markers is shown
75 in terms of wake age, ζ, and azimuthal position, ψ, though

Figure 1. Evolution of near-wake lattice, blade tip vortex, and La-
grangian markers.

in the code they are defined in terms of Cartesian coordinates. A lattice method is used in the near wake of the blade. The
near wake spans over a user-specified angle. Though past research has indicated that a near-wake region of $30°$ is sufficient
(Leishman et al. (2002); Ananthan et al. (2002)), it has been shown that a larger near wake is required for high thrust and
other challenging conditions. This is further investigated in this work. After the near wake region, the wake is assumed to
80 instantaneously roll up into a tip and root vortex, which are assumed to be the most dominant features for the remainder of the
wake (Leishman et al. (2002)). Each Lagrangian marker is connected to adjacent markers by straight-line vortex filaments. The
wake is discretized based on the spanwise location of the blade sections and a specified time step (dt), which may be different
from the time step of *AeroDyn15*. The wake is allowed to move and distort with time, thus changing the wake structure as
the markers are convected downstream. To limit computational expense, the root and tip vortices are truncated after a specific
85 distance downstream from the turbine. The wake truncation violates Helholtz's first law and hence introduces an erroneous
boundary condition. To alleviate this, the wake is "frozen" in a buffer zone between a specified buffer distance and the wake
length. In this buffer zone, the markers convect at the average ambient velocity. In this way, truncation error is minimized
(Leishman et al. (2002)). The buffer zone is typically chosen as the convected distance over one rotor revolution.

As part of OpenFAST, induced velocities at the lifting line/blade are transferred from OLAF to *AeroDyn15* and used to
90 compute the effective blade angle of attack at each blade station, which is then used to compute the aerodynamic forces on

the blades. The OLAF method returns the same information as the BEM method, but allows for more accurate calculations in areas where BEM assumptions are violated, such as those discussed above.

The governing equation of motion for a vortex filament is given by

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{V}(\boldsymbol{r}, t) \tag{1}$$

95   where $\boldsymbol{r}$ is the position vector of a Lagrangian marker and $\boldsymbol{V}$ is the velocity. Vortex filament velocity is a nonlinear function of the vortex position, representing a combination of the freestream and induced velocities (Hansen (2008)). The induced velocities at each marker, caused by each straight-line filament, are computed using the Biot-Savart law, which considers the locations of the Lagrangian markers and the intensity of the vortex elements (Leishman et al. (2002)):

$$d\boldsymbol{v}(\boldsymbol{x}) = F_\nu \frac{\Gamma}{4\pi} \frac{d\boldsymbol{l} \times \boldsymbol{r}}{|\boldsymbol{r}|^3} \tag{2}$$

100   Here, Γ is the circulation strength of the filament, $d\boldsymbol{l}$ is an elementary length along the filament, and $\boldsymbol{r}$ is the vector between a point on the filament and the control point $\boldsymbol{x}$. The regularization factor F_ν is introduced because of the singularity that occurs in the Biot-Savart law at the filament location (Vatistas et al. (1991)). Viscous effects prevent this singularity from occurring and diffuse the vortex strength with time. OLAF uses a different regularization value for the blades and the wake, and the wake regularization factor increases with time according to a parameter referred to as the core spreading eddy viscosity.

105   The circulation along the blade span is computed using a lift coefficient-based method. This method determines the circulation within a nonlinear iterative solver that utilizes the polar data at each control point on the lifting line. The algorithm ensures that the lift obtained using the angle of attack and the polar data matches the lift obtained with the Kutta-Joukowski theorem. This method is based on the work of van Garrel (2003) and is further detailed in the OLAF User's Guide and Theory Manual (Shaler et al. (2020)).

2.2   Discretization and Regularization Study Results

110   Discretization and regularization studies were performed using the Big Adaptive Rotor (BAR) Downwind Rail Carbon (DRC) turbine (Bortolotti et al. (2021)), described in Table 1, to determine recommended values for various OLAF input parameters. The studies were performed with uniform wind speeds ranging from 4 to 12 m/s, with the ranges for each study shown in Table 2. The studies were done sequentially as presented here. Meaning, the wake discretization study was the first to be completed, from which an optimal value was determined. This value was used as the wake discretization value for all remaining studies. The near wake extent study was performed next, and this optimal value was used for the remaining studies, and so on. Output quantities of interest (QoIs) are summarized in Table 3. These quantities are used to evaluate the convergence and accuracy for a set of parameters. An overview of the results is included here; for detailed results, see the online OLAF documentation (Shaler et al. (2020)).

Table 1. Main parameters of the BAR-DRC baseline wind turbine.

Parameter	BAR-DRC
Rotor Position (-)	downwind
Number of Blades (-)	3
Rated Generator Power (kW)	
Rotor Diameter (m)	212.0
Rated Blade Pitch (°)	~ 24
Rated Rotor Speed (rpm)	7.88
Rotor Tilt (deg)	5
Hub Height (m)	140.09
Max. Chord (m)	4.74

Table 2. Discretization and convergence study ranges.

Wake Disc.	Near Wake Extent	Far Wake Extent	Wake Reg. Factor	Wing Reg. Factor	Core Spread Eddy Visc.
$2.5°$-$15°$	$30°$-$2520°$	3D-12D	0.1-5	0.1-5	100-5000

Table 3. Quantities of interest for discretization and regularization studies.

Quantity of Interest	Component	
Blade-root moments	OoP bending	Pitching moment
Tower-base moment	FA bending	SS bending
Axial induction	25% blade span	75% blade span
Tangential induction	25% blade span	75% blade span
Circulation	25% blade span	75% blade span
Shaft torque		

2.2.1 Discretization

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The wake discretization and convergence studies observed how wind turbine QoIs varied with changing wake discretization, near wake extent, and far wake extent. These are all user-defined parameters for OLAF and are known to have a large effect on both wind turbine response and simulation time. The wake discretization is specified by the *AeroDyn15* time step, using the equation $d\psi = dt \times \Omega$. Because rotor speed is a turbine characteristic, $d\psi$ is defined using dt, which remains constant

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throughout the simulation. A smaller time step results in a finer wake discretization. The near wake extent is specified by the number of revolution degrees to be used in the lattice near-wake computations. Similarly, the far wake extent is determined by specifying the remaining length of the turbine wake length used in the straight-line filaments for wake calculations. By reducing the time step or increasing the wake length, the simulation accuracy is expected to improved, along with the computational

Table 4. Recommended values selected from the results of the discretization study

Parameter	Value
Wake Discretization	$5°$
Near Wake Extent	2D
Far Wake Extent	5D

expense. Accuracy is assessed by computing the percent difference in the mean QoI value at each test point relative to the finest
130 or largest value for the discretization and wake extent studies, respectively. To balance model accuracy with computational cost,
a convergence criteria of ~2% was selected.

An optimal value was found across all wind speeds for each study, as reported in Table 4. Generator power convergence
for each parameter is shown in Figure 2. The convergence is hard to observe for the wake discretization study. Results for
fine wake discretization are likely to be a function of the wake regularization factor, which is a topic that we believe needs
135 further research (see Section 2.2.2). The power converges for increasing near wake extend, since it is expected that a longer
wake captures more induction at the rotor (see the discussion related to Figure 4). Variability in relative error is observed for
increased far wake extends, but the error generally decreases for longer far wakes. Computational time for variations in each
parameter is shown in Figure 3. Computational time increased linearly with far wake extent (not shown). All simulations are
run using a tree-code algorithm with a time complexity $\mathcal{O}(n\log n)$. Note that the values reported in Table 4 were deemed
140 optimal for the specific wind turbine used in this paper under uniform inflow wind, and are not necessarily optimal for other
configurations. However, they can serve as a starting point for other systems and inflows.

The wake length required for a given accuracy can be assessed by comparing the induced velocity at the rotor plane as
obtained from a vortex cylinder of finite length (u_L) and from a vortex cylinder of infinite length (u_∞), the ratio of which is
shown in Figure 4. Both velocities can be obtained using closed form formulae (Branlard and Gaunaa (2014)). It is seen that
145 99% of the axial induction is provided by the first 4 diameters of the wake of a vortex cylinder. This observation supports the
recommended value of $5D$ selected in Table 4.

2.2.2 Regularization

Wake regularization factor, blade regularization factor, and core spreading eddy viscosity were examined for the regularization
150 study. The method was the same as the wake discretization and extent studies, except that results were compared against
those obtained using the actuator-line formulation of SOWFA (Churchfield et al. (2012)) to determine the optimal parameter
values. This was done because it is not possible to know *a priori* which regularization parameter can be used as a reference
for the convergence study. The questions remains as to whether the actuator-line simulations can be used as a reference. The
different parameter values found to minimize the difference with SOWFA for different wind speeds are reported in Table 5.
155 Computational time was generally insensitive to parameter values, so is not reported. An example plot is shown in Figure 5

(a) Wake discretization	(b) Near wake extent	(c) Far wake extent
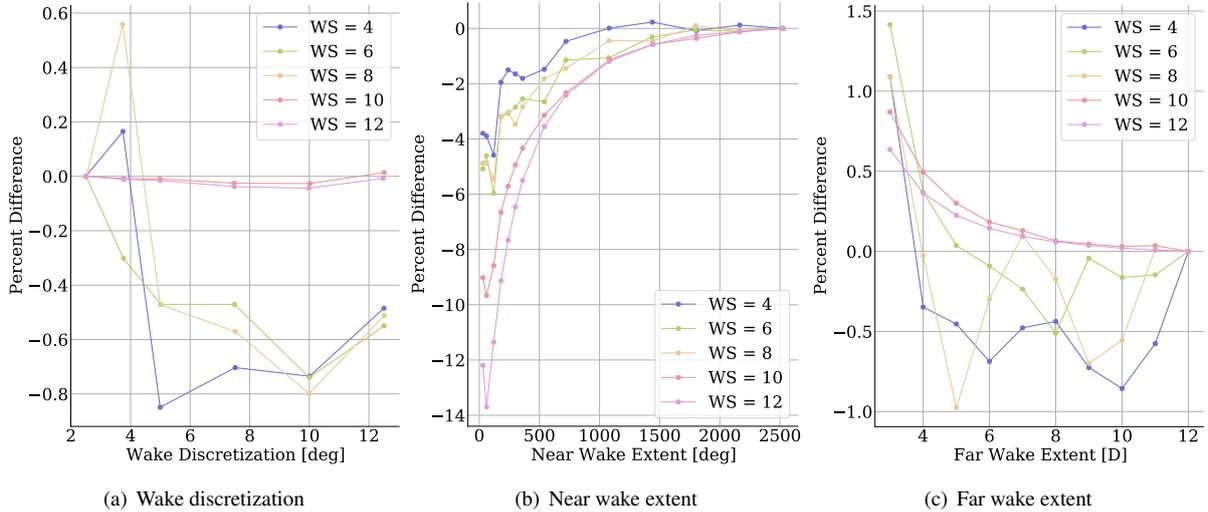
Figure 2. Percent differences of time-averaged rotor power with varying for (a) wake discretization, (b) near wake extent, and (c) far wake extent. Wake discretization results are relative to $2.5°$. Near wake extent results are relative to $2520°$ (7D). Far wake extent results are relative to 12D.

(a) Wake discretization	(b) Near wake extent
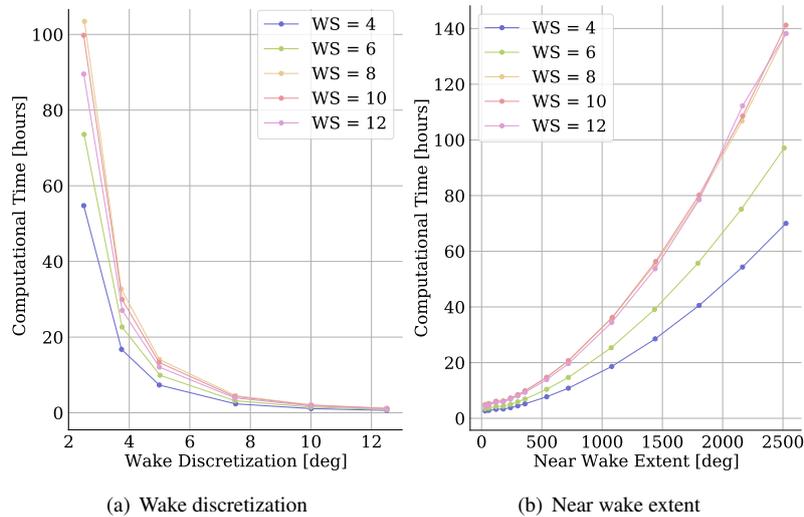
Figure 3. OLAF computational time for varying (a) wake discretization and (b) near wake extent.

for the study of the wake regularization factor. Based on the results given in Table Table 5, no clear trend is found between the regularization factors and the wind speed. It appears that a reasonable approximation would consist of setting the regularization parameters to $0.5\ dr$, where dr is the blade spanwise discretization. More research is nevertheless needed, both for actuator line CFD and lifting-line based codes, to find the optimal values of these parameters.
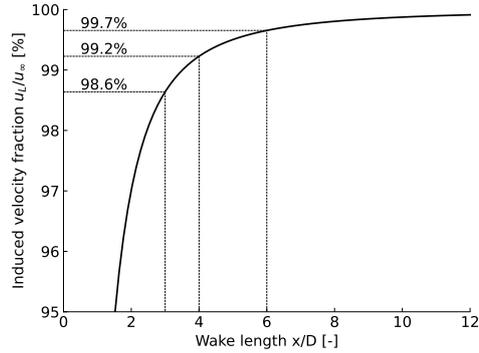
Figure 4. Fraction of induced velocity for various wake length as obtained using vortex cylinders of finite and infinite lengths.

Table 5. Recommended values selected from the results of the regularization convergence study

Parameter	4 m/s	6 m/s	8 m/s	10 m/s	12 m/s
Wake Regularization [1/dr]	0.44	0.44	0.29	0.87	0.87
Blade Regularization [1/dr]	0.15	0.87	0.87	0.58	0.15
Core Spread [-]	700	-	-	-	10000
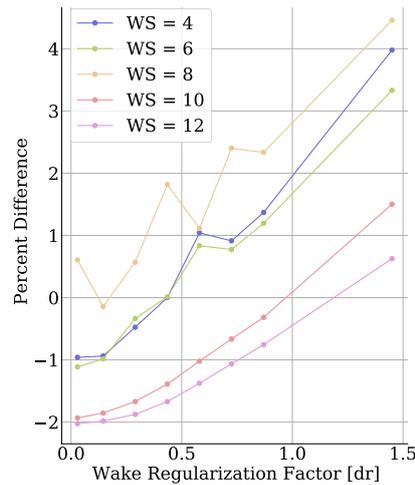
Figure 5. Power percent difference between OLAF and SOWFA simulation results for various wake regularization factors.

3 Modeling Cases

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In this work, the OpenFAST-FVW code was compared to traditional OpenFAST-BEM and large-eddy simulation results. Comparison of the FVW method to the traditional BEM method in OpenFAST is performed using the BAR-DRC turbine

(Bortolotti et al. (2021)). Some characteristics of the turbines are given in Table 1. Large-eddy simulations were performed
using the Simulator fOr Wind Farm Applications (SOWFA) (Churchfield et al. (2012)). SOWFA solves the filtered Navier-
165 Stokes equations in primitive variables using a second-order control volume formulation. The wind turbines blades are modeled
as actuator lines (Sørensen and Shen (2002); Martínez-Tossas et al. (2015)). For all simulations, structural modeling was done
using the structural module *ElastoDyn* from OpenFAST. For BAR-DRC comparisons, the turbine controller was not used and
all simulations were performed at a set rotor speed and blade pitch.

Simulations were performed at a range of freestream velocities, turbulence intensities (TI), and yaw misalignment angles, as
summarized in Table 6. For steady OpenFAST simulations, *InflowWind* was used to specify the hub-height inflow velocity and

Table 6. Variation of inflow conditions for code comparisons.

Freestream Velocity	TI	Yaw Misalignment	Shear
8 m/s	$0 - 20\%$	$-30°$ to $+30°$	$0 - 0.2$

170

shear exponent. For the turbulent OpenFAST simulations, ambient wind inflow is generated synthetically by TurbSim (Jonkman
(2014)), which creates two-dimensional (2D) turbulent flow fields. Turbulence is simulated using the Kaimal spectrum with
exponential coherence model and the standard IEC turbulence model was used. The time-dependent 2D wind field is propagated
along the wind direction at the mean wind speed of the midpoint of the field. Each case from the measurements is simulated
175 in TurbSim and OpenFAST six times, using six different random turbulence seeds to generate the wind data at the spatially
coherent points. This was done to capture variability in the numerical simulation results associated with the uncertainty imposed
by the unmeasured wind inflow.

4 Results

For the BAR-DRC turbine, the results focus on verification of statistical results between OLAF, BEM, and SOWFA. The QoIs
180 were turbine performance, blade-root bending moments, and tower-base bending moments. Blade-span and azimuthal results
were also considered.

4.1 Code-to-Code Comparisons

For this code-to-code comparison, many QoIs were considered, as summarized in Table 7. The blade forces and induction
quantities are only considered as blade-span quantities, whereas the others are also considered as time- and azimuthally-
185 averaged quantities. Though all these QoIs were considered, only a select few are presented for much of the analysis. All QoIs
are included in box-and-whisker plots. All inflow conditions are for steady inflow unless stated otherwise. Yaw misalignment
cases were simulated in constant inflow (shear exponent $= 0$) and sheared and TI comparison cases were simulated with no
yaw misalignment.

Table 7. Quantities of interest for SOWFA-OpenFAST comparison study.

Quantity of Interest	Component		
Blade tip displacements	OoP	IP	
Blade-root moments	OoP bending	IP bending	Pitching moment
Tower-top deflections	FA	SS	
Tower-top moments	FA bending	SS bending	Yaw moment
Tower-base moments	FA bending	SS bending	Yaw moment
Shaft torque			
Rotor power			
Rotor thrust			
Blade forces	Normal	Tangential	
Blade induction	Axial	Tangential	

4.1.1 Yaw Misalignment

190 Shown in Figure 6 are time-averaged quantities for several QoIs from OLAF, BEM, and SOWFA simulations for a range of yaw misalignment angles, along with percent differences, computed using Equation 3, of OLAF and BEM results relative to SOWFA results.

$$\%_{\text{Diff,Mean}} = \frac{|\overline{x} - \overline{x}_{\text{SOWFA}}|}{(\overline{x} + \overline{x}_{\text{SOWFA}})/2} * 100 \tag{3}$$

For all QoIs, the results from each computational method follow the same trend with changing yaw misalignment. The trend
195 depends on the QoI, with most showing reduced values with increasing absolute yaw misalignment. Tower-base side/side and yaw moments showed decreasing values with non-absolute increasing yaw misalignment, and blade-root pitching moment showed the opposite trend. Though the same trends were captured by each computational method, the actual results differ. In particular, OLAF and SOWFA results show comparable values with an average percent difference of <5% for all yaw misalignment angles, including the most extreme. However, BEM results deviated significantly more from SOWFA results
200 with increasing absolute yaw misalignment, with percent differences at yaw misalignment of $\pm30°$ reaching up to 48.6%. Alternatively, the percent difference between OLAF and SOWFA results does not appear to be dependent on yaw misalignment. Shown in Figure 7 are box and whisker plots of percent difference values between time-averaged mean and standard deviations, computed using Equation 4, of SOWFA results and OLAF or BEM results for all QoIs listed in Table 7 except the blade distributed quantities and those with means near zero.

205 $$\%_{\text{Diff,Std}} = \frac{|\sigma(x) - \sigma(x)_{\text{SOWFA}}|}{(\sigma(x) + \sigma(x)_{\text{SOWFA}})/2} * 100 \tag{4}$$

Percent differences of time-averaged means of BEM results increase with increasing absolute yaw angle, averaging 5.46% for no yaw misalignment and increasing to 15.9% for $\pm30°$ yaw misalignment. OLAF results show no dependence on yaw

(a) Rotor power

(b) Rotor torque

(c) Out-of-plane blade-root bending moment

(d) In-plane blade-root bending moment

(e) Blade-root pitching moment

(f) Side/side tower-base bending moment

(g) Fore/aft tower-base bending moment

(h) Tower-base yaw moment
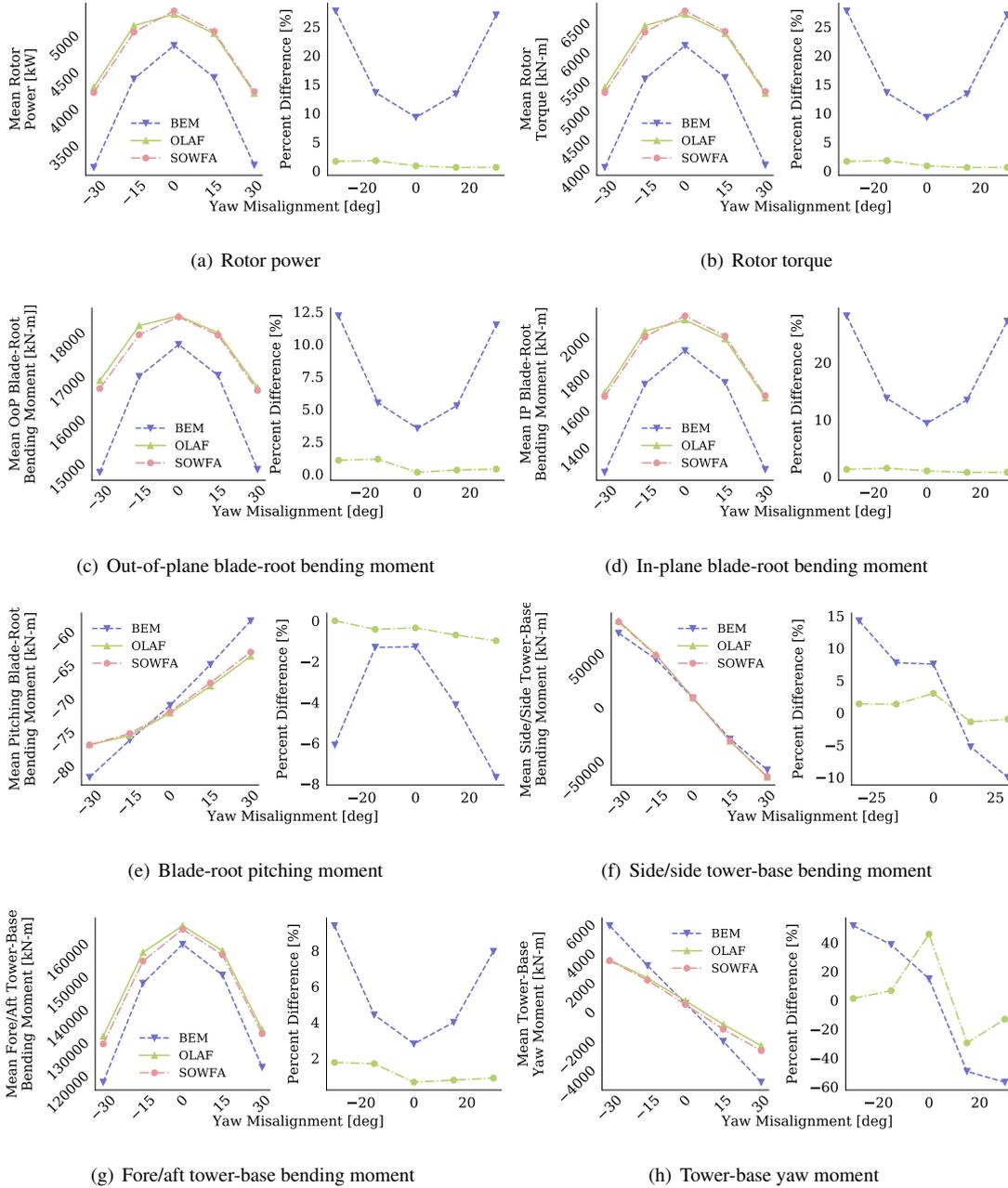
Figure 6. Time-averaged quantities for OLAF, BEM, and SOWFA results with varying yaw misalignment angles. Plots on the right show mean quantities and plots on the left show percent difference of the means from SOWFA results.

misalignment, with percent differences for all yaw misalignment angles reaching no higher than 1.2%. Percent differences of standard deviation values tend to be larger for both BEM and OLAF results, averaging 20.6% and 15.1%, respectively across
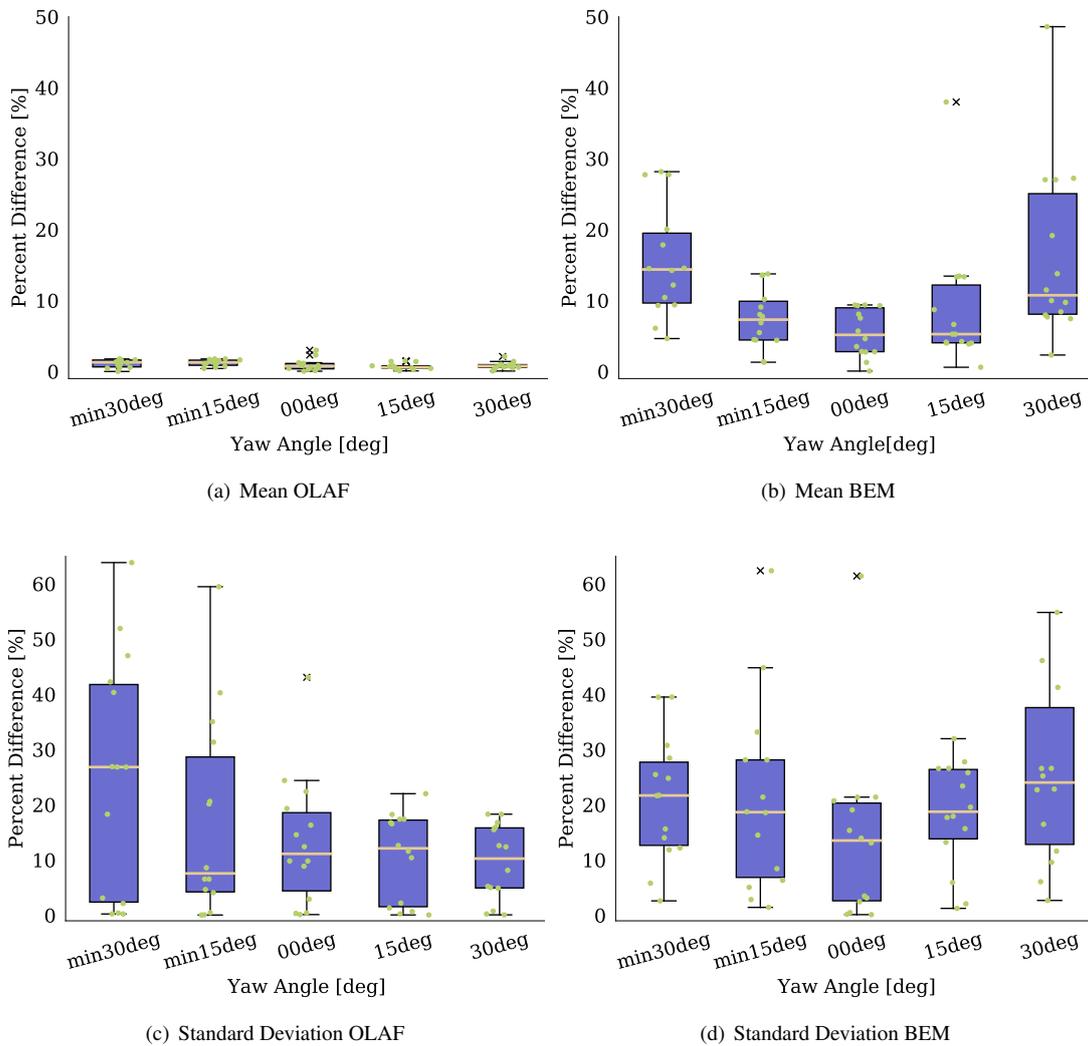
Figure 7. Average percent difference between OLAF and BEM versus SOWFA results across all QoIs for varying yaw misalignment angles.

all yaw misalignment angles. Though OLAF standard deviation values do differ with yaw misalignment, the average standard deviations across all QoIs does not seem to depend on yaw misalignment. BEM standard deviation results show dependence to yaw misalignment with increasing percent difference for large absolute yaw misalignment values, but to a lesser extent than what was seen for mean values. Thus, the accuracy of BEM mean and standard deviation results compared to SOWFA results seems to decrease with increased absolute yaw misalignment, whereas OLAF accuracy stays mostly consistent regardless of yaw misalignment.

To further investigate the reasons for the differences between BEM, OLAF, and SOWFA results, blade-span results are shown in Figure 8 for both time-averaged and percent difference from SOWFA results. Percent difference results are computed

(a) Normal force

(b) Tangential force

(c) Axial induction

(d) Tangential induction
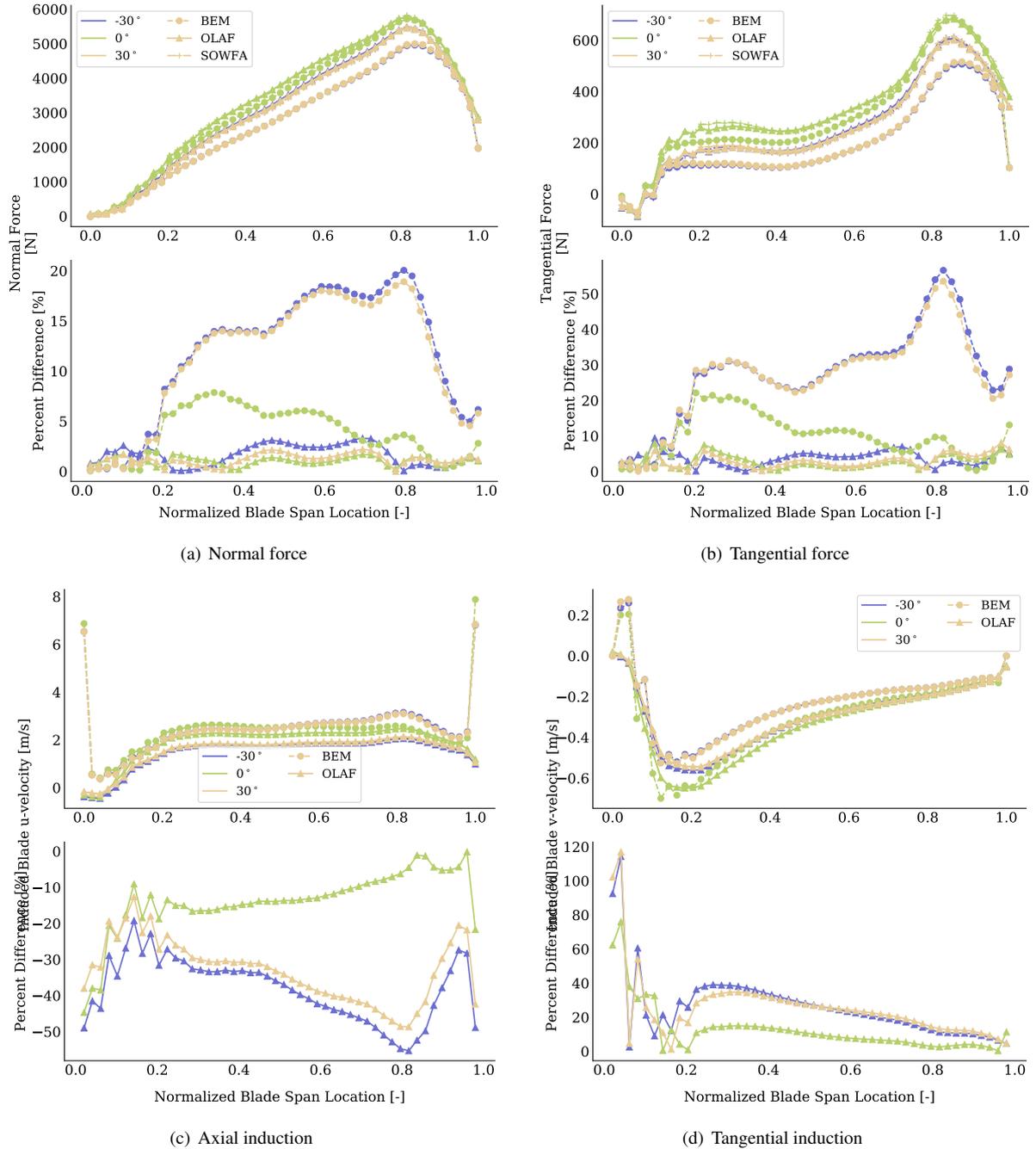
Figure 8. Blade-span loads for varying yaw misalignment angles for BEM, OLAF, and SOWFA (normal and tangential forces only) results. Line color distinguishes yaw misalignment angle and line style and symbol distinguishes computational method. For each subfigure, the top plot shows the time-averaged results and the bottom plot shows the percent difference.

using Equation 4.1.1.

$$\%_{\text{Diff,Blade}} = \frac{|\overline{x}_i - \overline{x}_{i,\text{SOWFA}}|}{\left(\sum_i \overline{x} + \sum_i \overline{x}_{\text{SOWFA}}\right)/2} * 100 \tag{5}$$

220   For the normal and tangential force components, all codes show comparable results near the blade root. OLAF results are comparable to the SOWFA results across the whole blade span and for all yaw misalignment angles, with results averaging 0.95% and reaching up to 7.9% for both loads. BEM results compare well for no yaw misalignment results, averaging 3.29% but reaching up to 22.1%. The results are especially comparable at the blade root and tip, with BEM predicting lower loads along the blade interior. With increasing yaw misalignment BEM predicts markedly lower blade forces than the other codes.

225 At these conditions, BEM results further deviate from SOWFA and OLAF results starting near the 20% chord and continuing down the blade length, but reducing near the blade tip. At yaw misalignment angles of $\pm 30°$, percent differences reach up to 56.6%.

(a) Rotor torque

(b) Out-of-plane blade-root bending moment

(c) Fore/aft tower-base bending moment

(d) Tower-base yaw moment
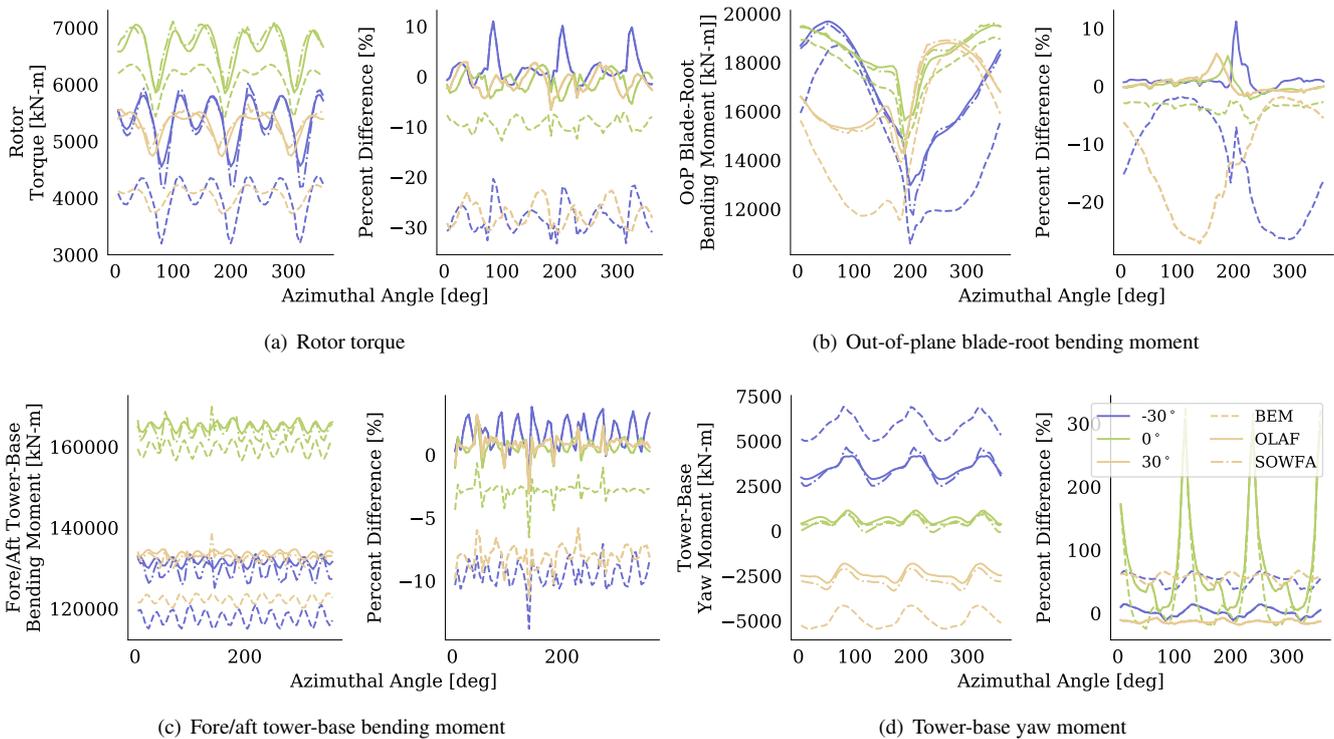
Figure 9. Azimuthal-averaged quantities for OLAF, BEM, and SOWFA results with varying yaw misalignment angles. Plots on the right show mean quantities and plots on the left show percent difference of the means from SOWFA results. Line color indicates yaw misalignment angle and line style indicates computational method. SOWFA results are shown as a dashdot line, OLAF result are shown as solid lines, and BEM results are shown as dashed lines.

Shown in Figure 9 are azimuthal-averaged results for all computational methods as well as percent differences of OLAF and BEM results relative to those of SOWFA. For all QoIs, all codes follow comparable trends. Rotor torque and tower-base yaw

230   moments show three large dips corresponding to the blade passing behind the turbine. Similarly, OoP blade-root bending results show a dip where the blade passes behind the tower. For OoP blade-root bending moment results, OLAF and SOWFA results are in close agreement for all azimuthal blade locations, though increased differences are seen behind the tower, at which point OLAF predicts a sharper drop in bending moment. BEM results show comparable results, but predict a lower bending moment at all azimuthal locations. When yaw misalignment is introduced, OLAF and SOWFA results remain comparable, again with

235   OLAF predicting lower bending moments when passing behind the tower. As before, BEM predicts lower bending moments at all azimuthal locations, and during the portion of the blade motion where the blade is downstream of the tower the results are actually closer to SOWFA and OLAF results. During the blade motion where the blade is upstream of the tower, however, BEM predicts nearly 30% lower bending moment results compared to SOWFA, with $-30°$ performing the worst.

     While accuracy is crucial to the success of a computational method, it is important to consider the differences in computation

240   cost of each method used in this work. Shown in Figure 10 is a comparison between the computation time in CPU hours for each method, as well as the average percent difference values of the same quantities considered in Figure 7. The average
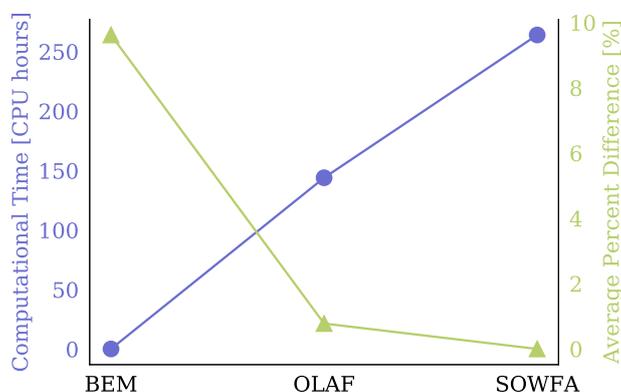
Figure 10. Computational time and average percent difference for each simulations method. computational time is shown by the blue line corresponding to the left axis and average percent difference is shown by the green line corresponding to the right axis. Average percent difference was computed for all results presented in this section.

percent difference for SOWFA is shown as zero because this is the highest fidelity code. This chart clearly shows the near $12\times$ error reduction when using OLAF instead of BEM. OLAF does, however, require significantly more computational power than BEM, with OLAF simulations taking $\mathcal{O}(40$ CPU hours to complete for the simulation specifications used here, whereas

245   BEM requires minutes. When compared to SOWFA, however, OLAF is significantly faster, with SOWFA simulations for this work requiring approximately 260 CPU hours to complete. As always, the choice of which computational method to use is a balancing act between computational cost and accuracy. These results indicate that, given the problem being considered, OLAF could be a reasonable middle ground between engineering models and CFD.

4.1.2 Shear Exponent

250 Shown in Figure 11 are the time-averaged quantities for several QoIs from OLAF and BEM simulations for a range of shear exponents, along with percent differences of BEM results relative to OLAF results. Note that SOWFA results are only included

(a) Rotor torque

(b) Out-of-plane blade-root bending moment

(c) Fore/aft tower-base bending moment

(d) Tower-base yaw moment
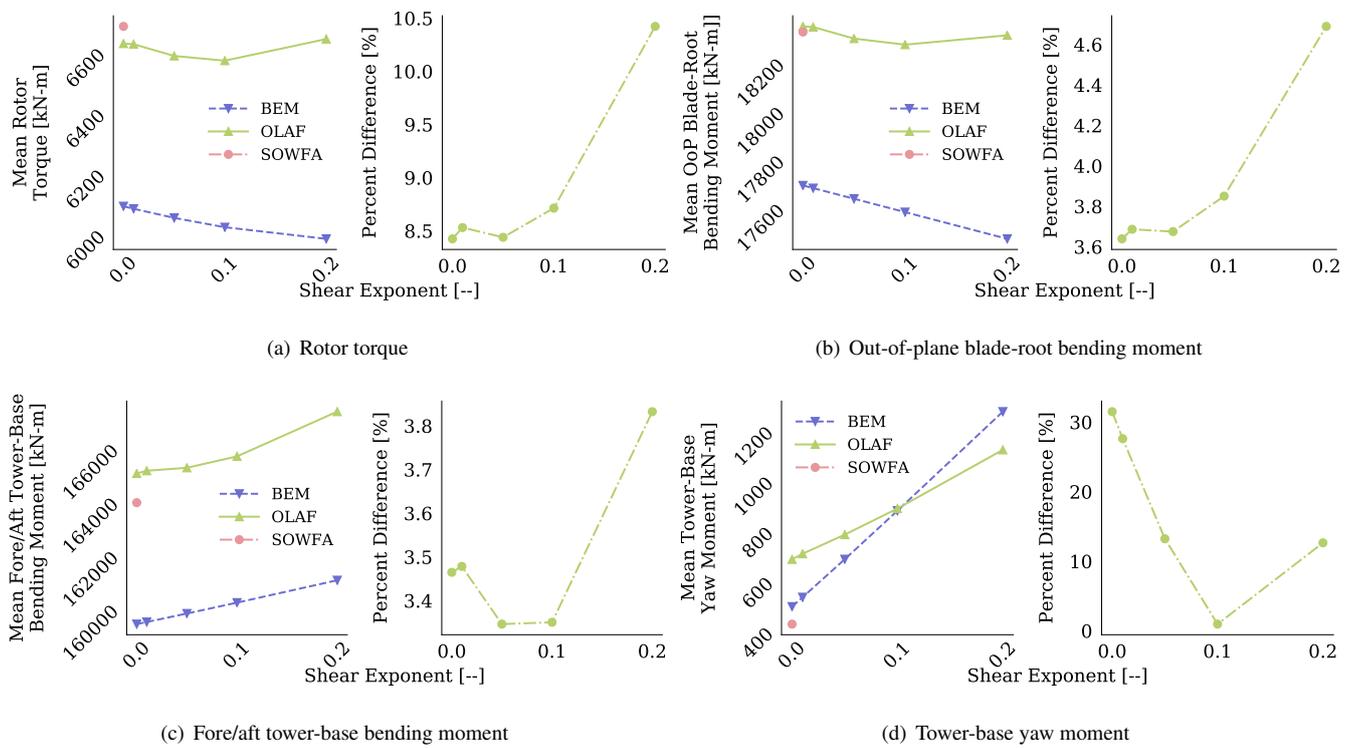
Figure 11. Time-averaged quantities for OLAF, BEM, and SOWFA results with varying shear exponent. Plots on the right show mean quantities and plots on the left show percent difference of the mean results.

here at the zero-shear point. This is because of the complexities within SOWFA of running steady inflow with a specified shear exponent as well as the additional computational expense. For all results but tower-base yaw moment, the relative trends of OLAF and BEM are the same with changing shear exponent, though the percent difference between the results does increase

255 slightly with increasing shear exponent. For all shear exponents, OLAF predicts higher loads for the considered components. Tower-base yaw moment, however, increases at a sharper rate for BEM result compared to OLAF results. In fact, at low shear exponents OLAF predicts a higher tower-base yaw moment, while BEM predicts a higher yaw moment at a shear exponent of 0.2. This results in a reduced percent difference between the methods. These results are summarized in Figure 12, which shows box-and-whisker plots for each shear exponent, made up of the percent difference values of each QoI for mean (left)

260 and standard deviations (right) of the results. These results show consistent percent differences for all shear exponents across all QoIs. For mean results, percent differences deviate at the highest shear exponent only, with the median percent difference increasing. For standard deviation results, the median percent difference remains consistent across all shear exponents, but the

(a) Mean   (b) Standard Deviation
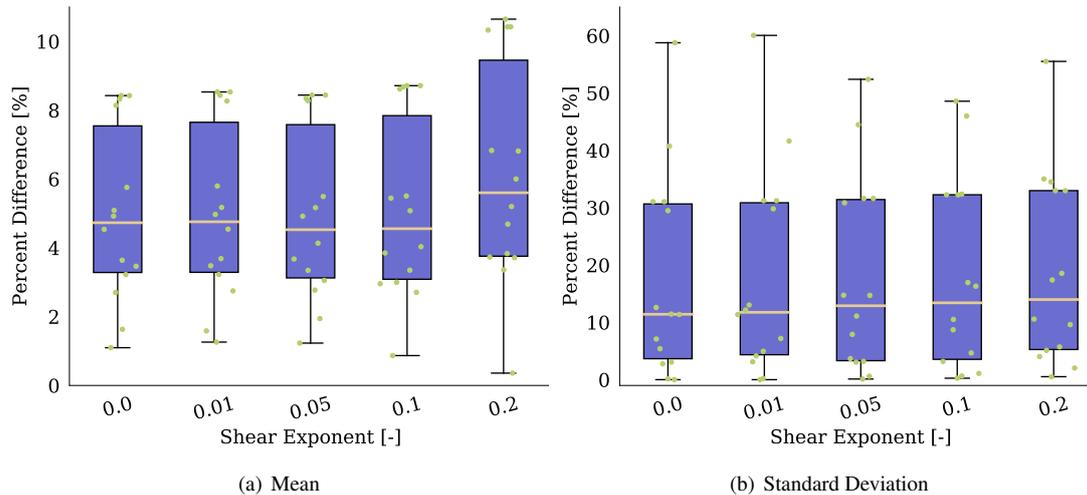
Figure 12. Average percent difference between BEM and OLAF results across all QoIs for varying inflow shear exponents.

upper range of these values does fluctuate slightly. These results indicate that though shear exponent does have a slightly higher impact on time-averaged BEM results compared to OLAF results, it is to a much lesser extent than yaw misalignment.

265   Shown in Figure 13 are azimuthal-averaged results for all computational methods as well as percent differences between BEM and OLAF results. The overall shapes of these results are comparable to those shown for the varying yaw misalignment cases in Figure 9. For rotor torque and and tower-base fore/aft bending moment, there is a clear separation between OLAF and BEM results. For rotor torque, the results compare best at the dips corresponding to the blades passing behind the tower. For each method, there is minimal change to the results at this point in the blade path with changing shear exponent. This is

270 expected, since the flow behind the tower is dominated by the tower wake and likely unaffected by the inflow shear exponent. When the blades are not behind the tower, shear exponent has more of an effect on the results, though to a greater extent for BEM results, with a higher shear exponent resulting in reduced rotor torque. Minimal differences in tower-base fore/aft bending moment are seen for each method. Overall the moment increases with increasing shear exponent, though OLAF shows appreciably higher moment at all azimuthal angles at a shear exponent of 0.2. This results in higher percent difference

275 at this inflow condition. When comparing results for out-of-plane blade-root bending moment, the largest difference are seen when the blade passes behind the tower. At this location, OLAF predicts a higher bending moment compared to BEM. For both methods, this bending moment decreases with increasing shear exponent. The bending moment increases until the blade is above the turbine, with this maximum value increasing with increasing shear exponent. For all shear exponents, OLAF predicts a higher bending moment than BEM. Though these overall trends are comparable between OLAF and BEM, the

280 average percent difference between these results does increase with increasing shear exponent, though to a greater extent when the blade is in the tower wake.
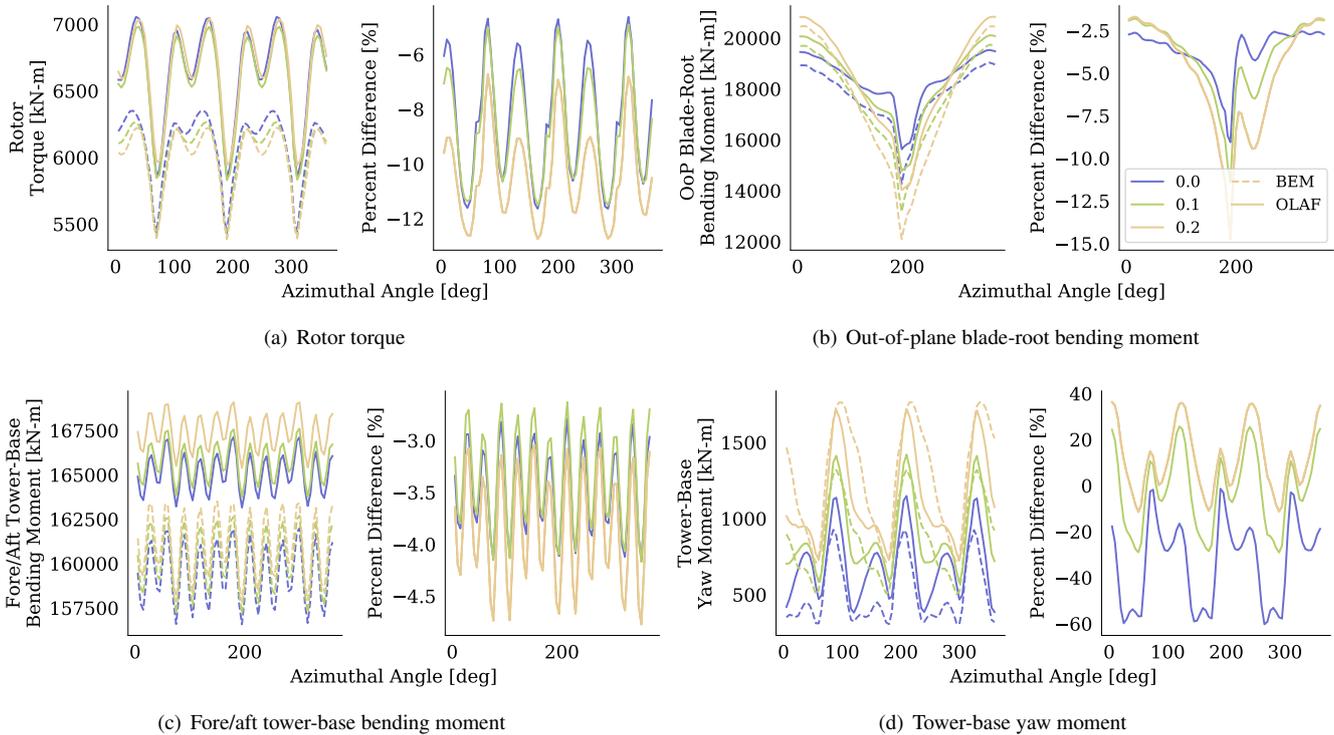
Figure 13. Azimuthal-averaged quantities for OLAF and BEM results with varying shear exponent. Plots on the right show mean quantities and plots on the left show percent difference of the means from OLAF results. Line color indicates shear exponent and line style indicates computational method. OLAF result are shown as solid lines and BEM results are shown as dashed lines.

Differences in tower-base yaw moment are considerable between OLAF and BEM, with different azimuthal trends seen at all shear exponents. For all OLAF results, the yaw moment spikes when a blade is behind the tower, followed by a sharp decrease and then another smaller spike before another blade passes behind the turbine. This trend is seem for all shear exponents, though the sharp drop becomes shallower with increasing shear exponent. BEM results are also characterized by a spike when a blade is behind the tower. However, at low shear exponents, the value of this spike is considerably less than that predicted by OLAF, and is preceded by a sharp drop to a value that remains constant until another blade passes behind the tower. This drop value is comparable to that predicted by OLAF, but the secondary bump that OLAF predicts is not present for the BEM results. As shear exponent increases, the large spike predicted by BEM surpasses that predicted by OLAF, and the sharp drop is instead a gradual reduction until the minimum value is reached. Thus, while percent difference between the methods remains large for all shear exponents, the primary takeaway is that changing shear exponent drastically changes the azimuthal trend predicted by BEM, whereas OLAF trend changes are more subtle. While these differences are not seen for most other QoIs, it is important to note that changing shear exponent can have a significantly different effect on OLAF compared to BEM results for certain important QoIs.

4.1.3 Turbulence Intensity

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Shown in Figure 14 are the time-averaged quantities for several QoIs from OLAF and BEM simulations for a range of TI values, along with percent differences of BEM results relative to OLAF results. In terms of mean results, varying turbulence
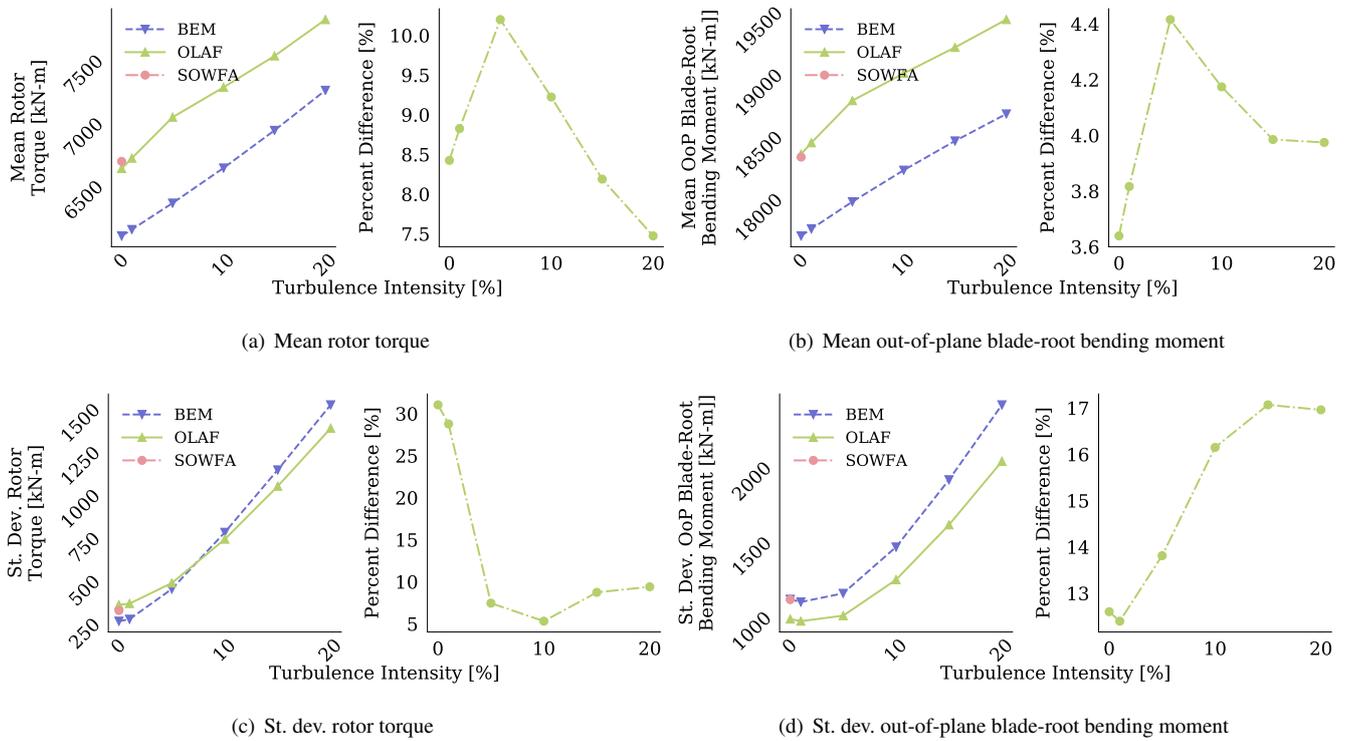
Figure 14. Time-averaged (a and b) and standard deviation (c and d) quantities for OLAF, BEM, and SOWFA results with varying inflow turbulence intensity. Plots on the right show mean quantities and plots on the left show percent difference of the means from BEM results.

intensity effects OLAF and BEM comparably. There is some change in percent difference for varying turbulence intensity, but it remains within a few percentage points. This is further supported in Figure 12, which shows box-and-whisker plots for each

300 shear exponent, made up of the percent difference values of each QoI for mean (left) and standard deviations (right) of the results. Here, minimal differences for all QoIs are shown for mean results. However, standard deviations of results show larger changes with varying TI. Though the median percent difference value remains comparable across the TI values, the upper limit spans from 60% for $TI = 0\%$ down to 20% for $TI \geq 5\%$.

Shown in Figure 16 are azimuthal-averaged results for BEM and OLAF computational methods as well as percent differences

305 of BEM results relative to those of OLAF. As is expected, both methods show increased variability with increasing TI. For all unsteady flow, percent difference results are comparable and there seems to be negligible comparable change due to increasing TI. However, there is a significant change between steady and unsteady inflow. In particular, for steady flow, i.e. when $TI = 0\%$, BEM predicts significantly larger rotor torque and OoP blade-root bending moments at all azimuthal locations. However, as

(a) Mean (b) Standard Deviation
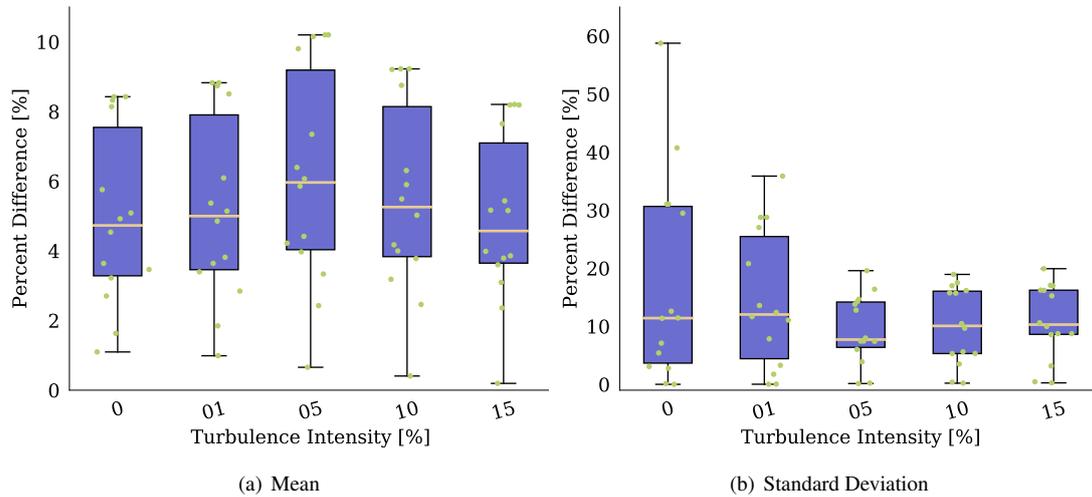
Figure 15. Average percent difference between BEM and OLAF results across all QoIs for varying inflow turbulence intensity levels.

(a) Rotor torque (b) Out-of-plane blade-root bending moment
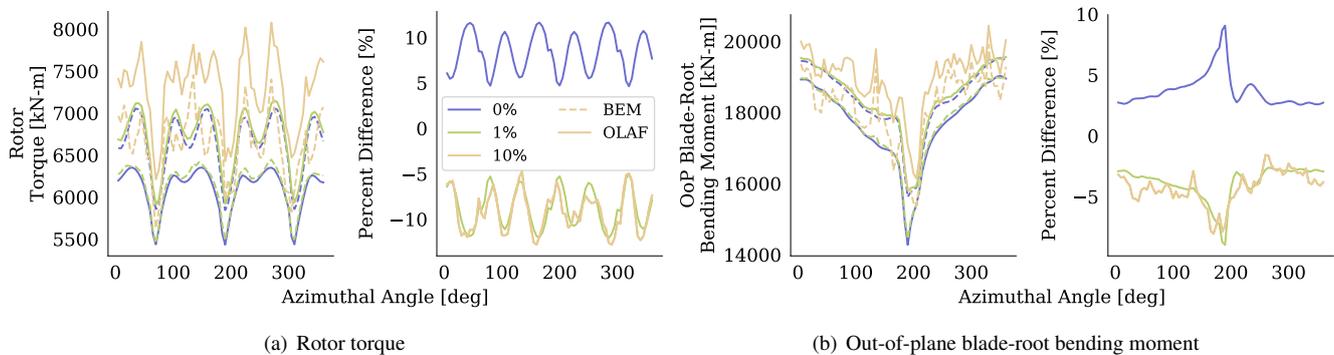
Figure 16. Azimuthal-averaged quantities for OLAF and BEM results with varying inflow turbulence intensity levels. Plots on the right show mean quantities and plots on the left show percent difference of the means from OLAF results. Line color indicates turbulence intensity level and line style indicates computational method. OLAF result are shown as solid lines and BEM results are shown as dashed lines.

soon as turbulence is introduced into the inflow, this relationship flips and BEM predicts significantly lower rotor torque and
310   OoP blade-root bending moment for all azimuthal locations.

5   Conclusions

The purpose of this work was to determine the accuracy of an aeroelastically coupled FVW method under conditions known to be challenging to lower-fidelity aerodynamic methods. This was done by comparing OLAF results to high-fidelity SOWFA results and low-fidelity BEM results for a large range of TI, shear, and yaw misalignment conditions. Through these comparisons,

315 it was found that for all considered QoIs, SOWFA, OLAF, and BEM results compare well for steady inflow conditions with no yaw misalignment. For OLAF results, this strong agreement was consistent for all yaw misalignment values, with percent difference values of time-averaged results remaining within 1.2% across all QoIs and varying little with yaw misalignment. The BEM results, however, deviated significantly more from SOWFA results with increasing absolute yaw misalignment, with percent differences at yaw misalignment of $\pm 30°$ reaching up to 48.6%. These trends were true for standard deviations of the
320 results as well, though the BEM results showed less of a change with increasing absolute yaw misalignment. Similar trends were seen when comparing blade-span loads, with OLAF results remaining within 7.9% of SOWFA results across the blade span and for all yaw misalignment angles. Maximum BEM percent difference results increased from 22.1% for no yaw misalignment up to 56.6% for $\pm 30°$ yaw misalignment, with the differences beginning at 20% blade span and continuing outboard of the blade.

325 Consideration must also be given to modeling computational cost. When looking at percent differences of time-averaged results for all QoIs, OLAF showed a near $12\times$ error reduction when using OLAF instead of BEM. As with all methods, increased accuracy comes with increased computational cost, with BEM, OLAF, and SOWFA simulations taking on the order of minutes, 10 CPU hours, and 100 CPU hours to complete for the simulations performed in this work, respectively.

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330 tion and convergence studies. LM ran all SOWFA simulations. EB and NJ provided support for this project. KS prepared the article, with support from BA, EB, NJ, and LM.

Competing interests. The authors declare that they have no conflict of interest.

Disclaimer. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government

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