Aerodynamic code-to-code comparison via IEA 22 MW reference turbine

Title	Aerodynamic code-to-code comparison via IEA 22 MW reference turbine
Author(s)	Britton, Barry;Connolly, Aengus;Conway, Oisín;Leen, Sean B.
Publication Date	2025-12-29
Publisher	American Society of Mechanical Engineers (ASME)
Repository DOI	https://doi.org/10.1115/IOWTC2025-164262

Proceedings of the ASME 2025
6th International Offshore Wind Technical Conference
IOWTC2025
October 27–29, 2025, Université de Toulon, Toulon, France

IOWTC2025-164262

AERODYNAMIC CODE-TO-CODE COMPARISON VIA IEA 22 MW REFERENCE TURBINE

Barry Britton
University of Galway
Galway, Ireland

Aengus Connolly
Wood
Galway, Ireland

Oisín Conway
Wood
Galway, Ireland

Seán Leen
University of Galway
Galway, Ireland

ABSTRACT

Large turbines are already operational in fixed offshore wind, and it is anticipated that similar sizes will logically follow in the floating sector. Reference wind turbines play an important role in the global wind energy community, providing open access to realistic contemporary and futuristic designs. Reference models allow researchers to identify potential technological challenges associated with future turbine sizes, including an assessment of the supporting sub-structures, and mooring in the case of floating systems. Such models also facilitate an assessment of the suitability of currently available numerical modelling tools to accommodate future turbine sizes.

This paper considers the IEA 22 MW reference wind turbine and performs a code-to-code comparison of simulation models built using the mid-fidelity aero-elastic tools OpenFAST, OrcaFlex and Flexcom. As the study is focused on the aeroelastic response, the turbine is fixed at its base, and no hydrodynamic effects are considered. Time invariant wind cases are firstly used to characterise turbine steady state response, before control is examined by an incrementally increasing stepped wind speed scenario. Finally, a realistic power production case is considered via fully time dependent turbulent wind. The codes show good agreement overall, notwithstanding some minor discrepancies in certain areas, and the results serve as a credible code-to-code validation of the tools considered. Findings from the study supplement prior research into the IEA 22 MW turbine and provide verification and validation information for research and industry applications. The simulation models are open access and freely available from the authors.

Keywords: IEA 22 MW, 22 MW, Reference Wind Turbine, Aerodynamic, Aeroelastic

NOMENCLATURE

(D)BEMT	(Dynamic) Blade Element Momentum Theory
DOF	Degree of Freedom
DTU	Technical University of Denmark
FEM	Finite Element Method
(F)OWT	(Floating) Offshore Wind Turbine
FVW	Free Vortex Wake
IEA	International Energy Agency
MW	Megawatt
NREL	National Renewable Energy Laboratory
RWT	Reference Wind Turbine
WindIO	Wind Input/Output Data Framework

1. INTRODUCTION

Wind turbine sizes are steadily increasing, particularly in the offshore sector (Figure 1). For example, Mingyang released its MySE 18.X-20 MW turbine in 2023, with a flexible power rating of between 18 and 20 MW. The manufacturer has already announced plans to produce a larger turbine, with a capacity rating of 22 MW and a rotor diameter of over 310 metres [1]. Numerical modelling tools must stay abreast of developments, as larger turbines will require more advanced designs for the supporting structures, both fixed and floating.

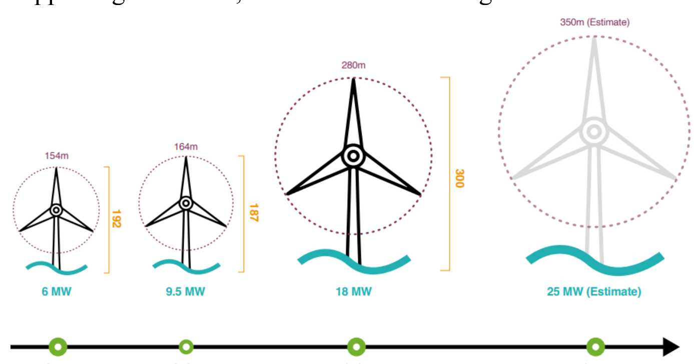

FIGURE 1: TREND OF OFFSHORE TURBINE SIZE, 2015-2030, adapted from [1]

The purpose of IEA (International Energy Agency) Task 55 is to coordinate international efforts to facilitate the definition of reference wind turbines (RWTs) and plants. The first major outcome has been the detailed design of the IEA 22 MW RWT, jointly developed by the Technical University of Denmark (DTU) and the National Renewable Energy Laboratory (NREL). It is an upwind, three-bladed, direct-drive class 1B wind turbine, with a rated power of 22 MW and a rotor diameter of 284 m. Each blade is 137.8 m in length and weighs over 82 tonnes. Cut-in, rated and cut-out wind speeds are 3, 11 and 25 m/s respectively. The rotor has a pre-cone angle of 4° degrees and a shaft tilt angle of 6°. The control system is based on a variable rotor speed regulated by collective blade pitch. The rotor is designed for a maximum rotor speed of just over 7 rpm resulting in a maximum blade tip speed of 105 m/s. The supporting monopile and tower give the turbine a hub height of 170 m above sea level. A detailed description of the turbine is provided in the publicly available IEA report [2]. Readymade input datasets are available from the IEA GitHub site [3] for the OpenFAST, HAWC2, QBlade and WISDEM tools, as well as a generic 'WindIO' definition. WindIO is a common framework defining the inputs and outputs of wind turbines and plants. This study is based on Version 1.0.0 of the turbine definition.

2. SIMULATION TOOLS

A recent review of modelling techniques for FOWTs [4] noted the most popular mid-fidelity numerical modelling tools as OpenFAST (NREL), HAWC2 (DTU), SIMA (SINTEF), Bladed (DNV), SIMPACK (Dassault Systems), OrcaFlex (Orcina) and Flexcom (Wood). Previous research [5] has already examined the IEA 22 MW RWT using OpenFAST, HAWC2, Bladed and QBlade, so this study examines an alternative set of tools, namely OpenFAST, OrcaFlex and Flexcom. Consideration of the latter two is interesting in the sense that both are traditionally associated with the oil and gas industry, while OpenFAST has been designed for wind turbine modelling from its very inception.

2.1 OpenFAST

OpenFAST [6] is an open-source engineering tool for simulating the coupled dynamic response of wind turbines. It incorporates several component modules – AeroDyn (aerodynamics), ElastoDyn and BeamDyn (structural dynamics), and ServoDyn (control) models, to enable coupled nonlinear aero-servo-elastic simulation in the time domain. AeroDyn is traditionally based on BEMT, with standard corrections for skewed wake (Pitt and Peters), and hub and tip losses (Prandtl). Dynamic BEMT is supported by Oye's dynamic inflow model. Tower influence is modelled using a potential-flow model with an option to include Bak correction, while tower shadow effects are handled by either Powles or Eames shadow models. Unsteady aerodynamic models account for flow hysteresis, including unsteady attached flow, trailing-edge flow separation, dynamic stall, and flow reattachment. OpenFAST offers three semi-empirical models based on (i) the original Beddoes-Leishman theory, (ii) extensions developed by González, and (iii) extensions developed by Minnema/Pierce. Recent versions of OpenFAST offer a free vortex wake (FVW) model known as OLAF (cOnvecting LAgrangian Filaments), a higher fidelity aerodynamic model which addresses many of the limitations associated with BEMT. OpenFAST also offers two structural modelling solvers, ElastoDyn and BeamDyn. BeamDyn is based on geometrically exact beam theory (GEBT) and is implemented using Legendre spectral finite elements. The model includes full geometric nonlinearity supporting large deflection with bending, torsion, shear and extensional DOFs. ElastoDyn offers a more simplified blade structural model which is strictly only valid for straight isotropic blades dominated by bending [6]. OpenFAST has been extensively validated via its extensive use in various IEA research projects and numerous independent publications.

2.2 OrcaFlex

OrcaFlex [8] is a general-purpose dynamic analysis software program suitable for a wide range of applications, including oil and gas, and offshore wind. Its aerodynamic model is based on BEMT with standard corrections for skewed wake (Pitt and Peters), and hub and tip losses (Prandtl). Unsteady aerodynamics are modelled using the Beddoes Leishman dynamic stall models, namely González and Minnema Pierce. Dynamic inflow is available via Øye's model. Structural dynamics are modelled using the FEM (finite element method), via a lumped mass approach, and the solver accommodates fully coupled tension, bending and torsion. OrcaFlex's aerodynamic model has been validated by code-to-code comparisons with OpenFAST, HAWC2 and Bladed for a 5 MW turbine [10], and comparisons with OpenFAST for both 15 MW [11] and 22 MW [12] RWTs. Its structural model has been extensively validated over many years via comparisons with other software, analytical solutions and other published work [9].

2.3 Flexcom

Flexcom [13] is an engineering design tool for time-domain dynamic analysis of slender structures, traditionally used in offshore oil and gas. Recent versions include a software coupling with OpenFAST component modules enabling wind turbine simulation. Given that Flexcom uses AeroDyn as its aerodynamic solver, in theory it offers the same aerodynamic capabilities as OpenFAST, although some of the advanced models (e.g. OLAF FVW) have yet to be investigated and validated within Flexcom. For structural dynamics, Flexcom uses its own FEM solver, a 3D hybrid beam-column finite element formulation with fully coupled axial, bending and torsional DOFs. Although Flexcom has been validated for small turbines, including code-to-code comparisons for a 5 MW fixed [14] and a 3.6 MW floating platform [14][16], this is the first study which benchmarks Flexcom for a large turbine size. The Flexcom structural model has been extensively validated over many years via comparisons with other software, analytical solutions and other published work.

3. NUMERICAL MODELS

OrcaFlex 11.5b is used throughout this study. The OrcaFlex model is sourced from Orcina's website [12], created by Orcina personnel, and largely based on the WindIO ontology. Any data required by OrcaFlex which is absent from the WindIO ontology, is sourced from the OpenFAST and HAWC2 datasets [3], including the generator inertia, Rayleigh damping coefficients for the blade and tower elements, and tower drag coefficients. Unsteady aerodynamics is modelled using the González variant of Beddoes-Leishman theory, and the baseline potential flow formulation is used to model tower influence. Other minor changes were made to keep the OrcaFlex model as consistent as possible with the OpenFAST model [3] used in this study. These include suppression of the tower torsional DOFs, switching off dynamic inflow, removing nacelle drag, and minor changes to air density and speed of sound.

OpenFAST 3.5.2 is used throughout this study. The OpenFAST model is taken directly from the IEA GitHub site [3], with some minor alterations. Unsteady aerodynamics is modelled using the González variant of Beddoes-Leishman theory, and the selected wake model is BEMT. The original model used the ElastoDyn structural solver, while this present study investigates both ElastoDyn and BeamDyn.

Flexcom 2025.1.2 is used throughout this study. As the IEA GitHub site does not include Flexcom, the model is created manually using the (modified) OpenFAST model as a reference guide, with all inputs replicated as closely as possible.

All simulation models use ROSCO 2.9.0 (Reference Open-Source Controller) which is distributed as part of the monopile edition of the IEA 22 MW RWT [17].

4. TEST CASES

This study considers three separate loading scenarios, steady wind (time invariant), stepped wind (wind speed increasing incrementally in steps over time), and turbulent wind (full field wind turbulence).

The steady wind test cases comprise a series of individual simulations, each of which has a constant wind speed between cut-in (3 m/s) and cut-out (25 m/s). The rotor is aligned with the incoming wind flow so there is no skew angle in the horizontal plane. Each simulation is analysed for a significant period, which ensures full dissipation of initial transients. Results are presented in the form of mean values at each wind speed, which are computed over the final 100 seconds of simulation time.

In the stepped wind test case, a time varying wind load is applied in a single continuous simulation. The time history of wind speed starts off with a magnitude of 4 m/s. This is simulated for a period which is sufficiently long to dissipate the effects of initial transients associated with turbine start-up (only the final 120 seconds of this stage is shown in the results section). Beyond this point, the wind speed magnitude is increased in steps of 1 m/s every 40 seconds, up to the cut-out speed of 25 m/s, providing a good test of the controller. The rotor is misaligned with the incoming wind flow, creating a horizontal skew angle of 30°. Results are presented in the form of time histories.

The turbulent wind test cases comprise a series of individual simulations, each of which has a mean wind speed between cut-in (3 m/s) and cut-out (25 m/s). Full-field wind turbulence is simulated, according to IEC 61400-1 standard (class 1B). The wind field files are generated by TurbSim, a component module of OpenFAST, using the Kaimal spectrum (IECKAI) and extreme turbulence (1ETM) options. These test cases are representative of real-world power production conditions. Each wind condition is analysed for 10 minutes simulation time. OpenFAST and OrcaFlex support the specification of non-zero initial rotor speeds in dynamic simulations, thereby reducing initial transience and increasing overall solver efficiency. This also tends to assist the numerical stability of the control system. Hence anticipated mean values of rotor speed and blade pitch angle are specified as user inputs. Flexcom does not yet offer this option, so rotors always start with zero angular velocity. To align the turbulent simulations as closely as possible, preliminary steady-wind simulations are run with Flexcom, followed by the actual turbulent simulations. Results are presented in the form of statistical values (mean and standard deviation) at each wind speed. Sample time histories for the largest wind speed (25 m/s) are also included for additional insight.

In addition to benchmarking solution accuracy, the stepped wind test case was used to compare the run-time performance of each tool. Run-time comparisons are facilitated by command prompt batch files, which ensure consistency and a valid comparison. Each dynamic simulation is performed on its own, with no other simulations competing for CPU resources, affording the solvers a good chance of achieving the quickest possible run time.

5. RESULTS

5.1 Overview

Figure 2 presents results from the steady wind test cases, summarising the mean values of key turbine characteristics as a function of wind speed. The first three rows present turbine performance metrics, the next two rows focus on the blade structural responses, while the final row considers tower parameters.

Figure 3 presents results from the stepped wind test case, displaying the turbine behaviour as a function of time. The upper two rows of figures present turbine performance, while the lower rows focus on blade structural response.

Figure 4 presents results from the turbulent wind test cases. The upper three rows present statistics (mean and standard deviation, the latter as shaded) of turbine performance and blade structural responses as a function of wind speed, while the lower three rows present some sample time histories for the largest wind speed considered (25 m/s).

5.2 Benchmarking

The steady wind test cases show very close agreement (Figure 2) between OrcaFlex, OpenFAST and Flexcom models for the main turbine performance characteristics, including rotor speed, tip speed ratio, generator torque, blade pitch and generator power. These variables are effectively governed by the control system which operates consistently in all cases and ensures agreement between the numerical models. For rotor thrust, Flexcom gives a slightly higher aerodynamic force for wind speeds close to rated. Similar deviations are observed in other parameters, including rotor thrust coefficient C_t, blade tip

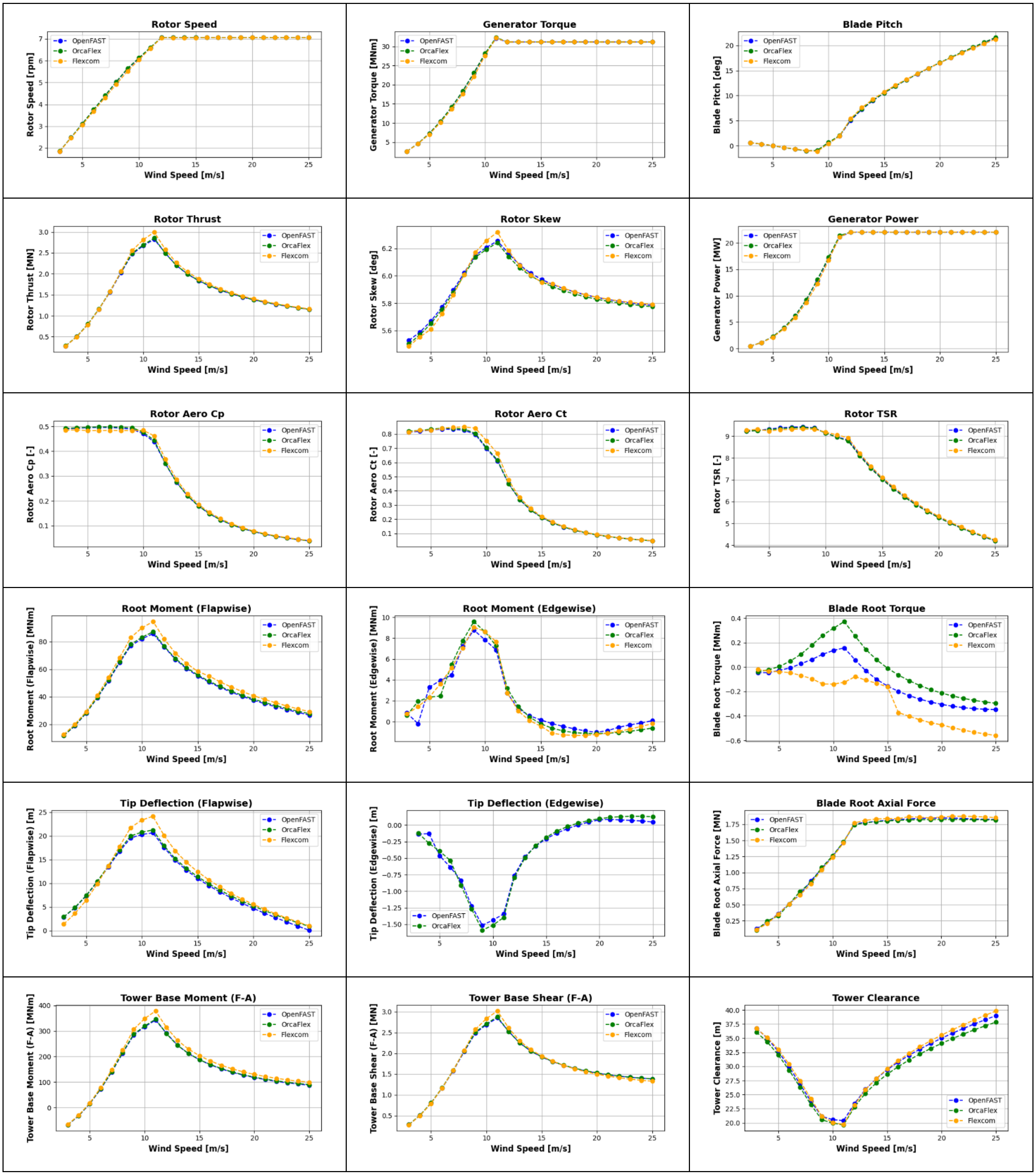

FIGURE 2: COMPARISON OF STEADY WIND SPEED RESULTS FOR FLEXCOM, ORCAFLEX AND OPENFAST FOR RANGE OF KEY WIND TURBINE PERFORMANCE PARAMETERS, INCLUDING ROTOR SPEED, GENERATOR TORQUE, BLADE PITCH, THRUST, SKEW, POWER, CP, CT, TSR, BLADE ROOT MOMENTS & TIP DEFLECTIONS, AND TOWER MOMENT, SHEAR & CLEARANCE

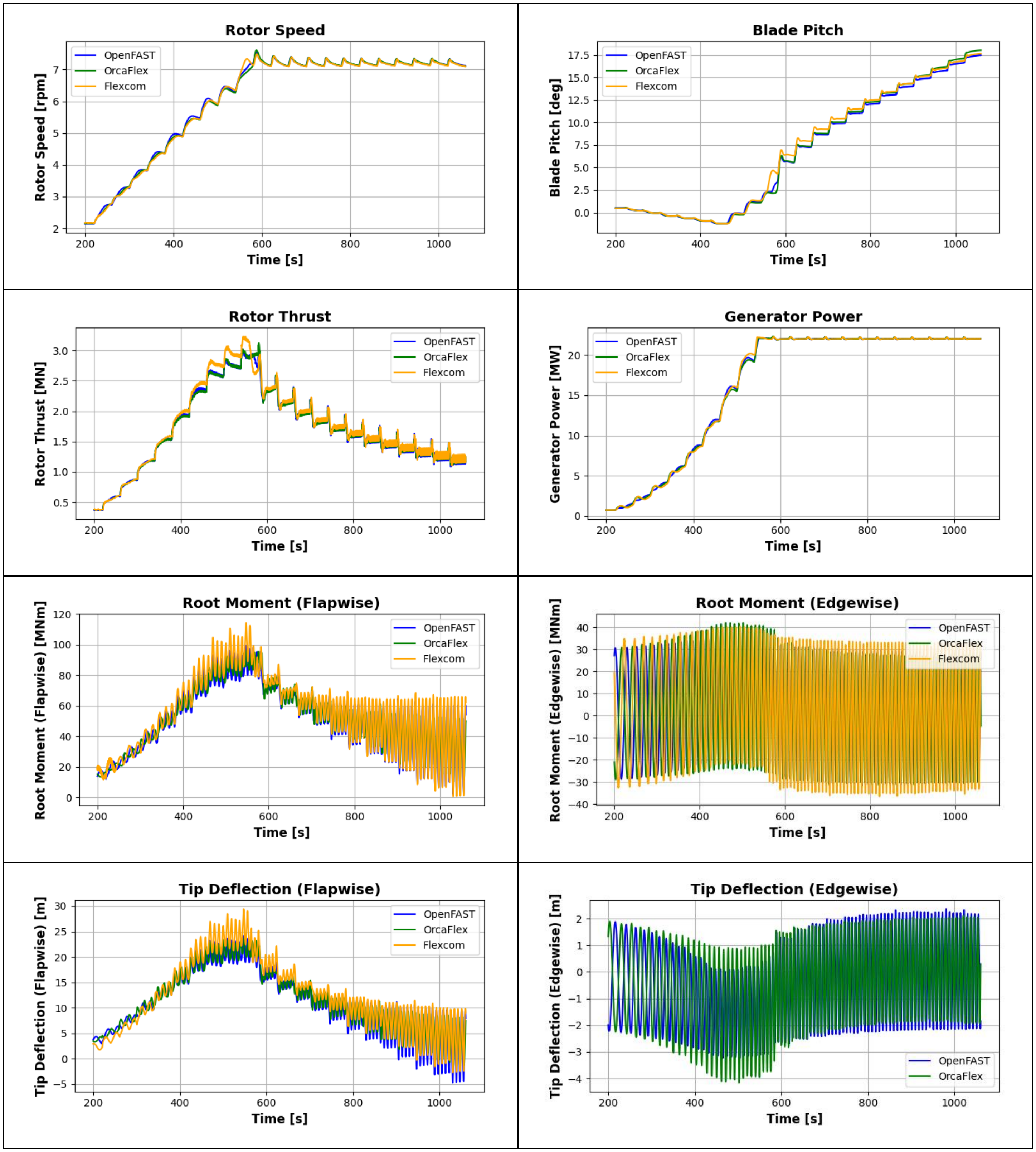

FIGURE 3: COMPARISON OF STEPPED WIND SPEED RESULTS FOR FLEXCOM, ORCAFLEX AND OPENFAST FOR RANGE OF KEY WIND TURBINE PERFORMANCE PARAMETERS, INCLUDING ROTOR SPEED, BLADE PITCH, ROTOR THRUST, GENERATOR POWER, BLADE ROOT MOMENTS & TIP DEFLECTIONS

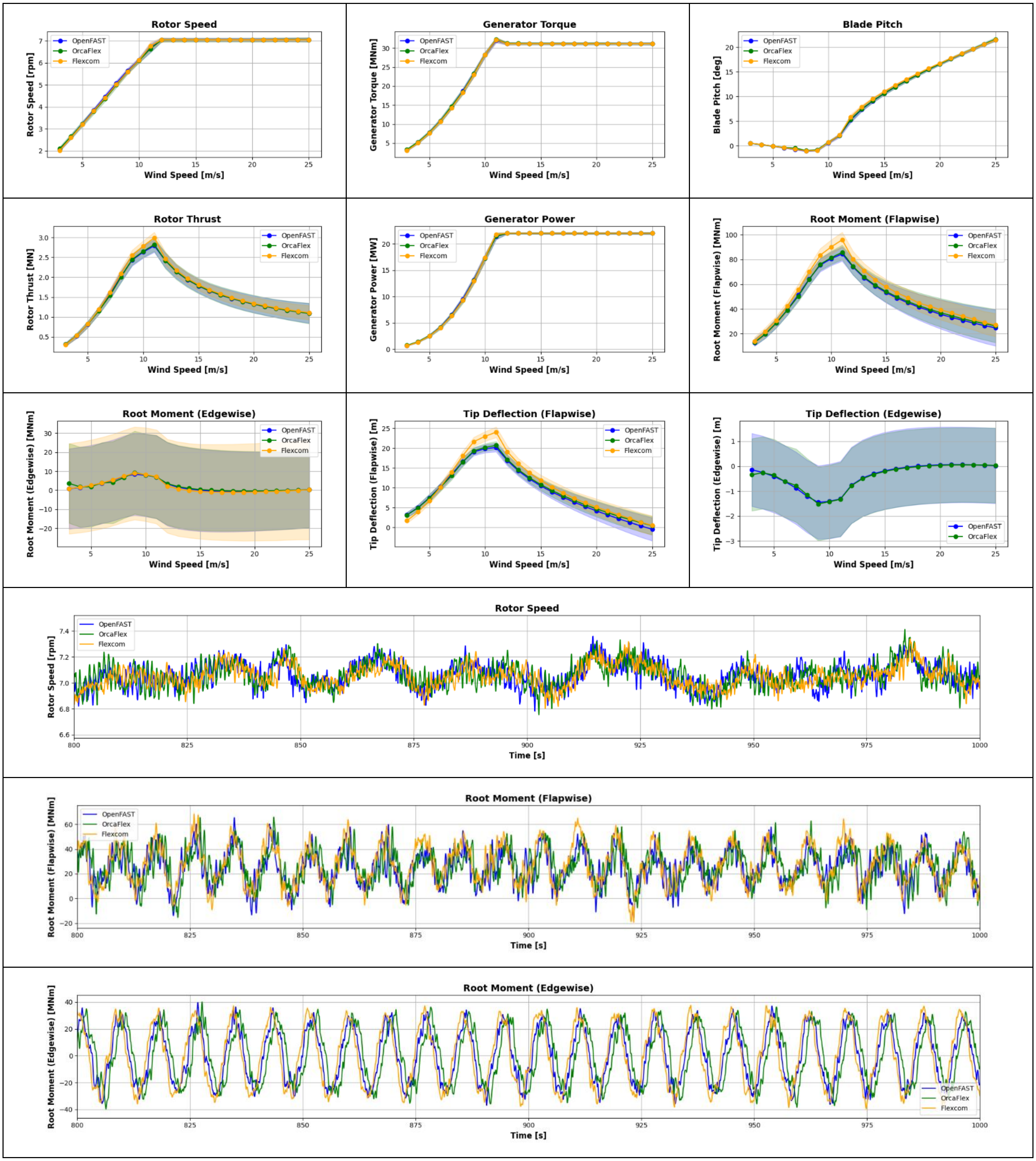

FIGURE 4: COMPARISON OF TURBULENT WIND SPEED RESULTS FOR FLEXCOM, ORCAFLEX AND OPENFAST FOR RANGE OF KEY WIND TURBINE PERFORMANCE PARAMETERS, INCLUDING ROTOR SPEED, GENERATOR TORQUE, BLADE PITCH, ROTOR THRUST, GENERATOR POWER, BLADE ROOT MOMENTS & TIP DEFLECTIONS, SHOWING MEAN AND STANDARD DEVIATION (SHADED) IN UPPER THREE ROWS, PLUS TIME HISTORIES IN LOWER THREE ROWS

deflection and root moment in the flapwise direction, and tower base shear force and bending moment. These are all interrelated secondary parameters, and the discrepancies stem from the rotor thrust which is the driving cause. Minor deviations in blade structural responses are evident in the edgewise direction also, but these are smaller in magnitude and less significant than in the flapwise direction. Note that results for edgewise deflections are presented for OrcaFlex and OpenFAST only, as Flexcom does not yet offer this parameter as an output variable. Blade root axial forces are consistent as these are closely related to blade mass and rotational speed. Blade torque shows significant deviations between all three codes, but these are much lower in magnitude than the root moments. Also, the discrepancies tend to appear magnified due to the sign change of root torque with increasing wind speed (below rated wind speed, torque increases with wind speed as the blade pitch angle remains relatively constant, while torque reduces above rated wind speed as the blades are feathered). Tower clearance shows good general agreement, with OrcaFlex estimating slightly lower clearances at higher wind speeds.

The stepped wind test case also shows close agreement (Figure 3) between the numerical models, which represents a significant variation on the steady cases given the inclusion of a wind inflow skew angle of 30°. Rotor speed and generator power show very close agreement between the three numerical codes as before, as well as tip speed ratio and generator torque (not plotted here). The Flexcom model appears to slightly overpredict the aerodynamic force in the rated wind speed region, resulting in elevated levels of blade root moment and flapwise tip deflection. For these parameters, the Flexcom model shows more fluctuation at higher wind speeds, though the mean values show good agreement.

Statistical results from the turbulent wind simulations show good agreement generally (Figure 4). The main performance characteristics, as governed by the control system, including rotor speed, generator torque, blade pitch and generator power, show close agreement between the numerical models. As for the simpler test cases, Flexcom predicts a higher mean rotor thrust force in the rated wind speed region. OrcaFlex and OpenFAST show significantly larger variations in thrust force than Flexcom at wind speeds above rated, particularly above 20 m/s. Flapwise blade deflections appear consistent with rotor thrust, with Flexcom predicting higher deflections for medium wind speeds. At high wind speeds, OrcaFlex and Flexcom show close agreement for both mean and standard deviation of deflection, whereas OpenFAST shows a slightly lower mean and larger deviation. Flexcom predicts higher flapwise root moment at mid-range wind speeds. OrcaFlex and OpenFAST both show larger fluctuations than Flexcom for root moment, particularly at the higher wind speeds where the blade pitch angles are greatest. Edgewise deflections show close agreement between OpenFAST and OrcaFlex. Root moments show reasonable agreement between all three codes, with Flexcom showing larger fluctuations at higher wind speeds than the others. This seems consistent with the (reverse) trend exhibited for flapwise moment. For the largest wind speed considered (25 m/s), time histories of rotor speed and root moment show very good agreement between all numerical models. Very slight phase offsets are evident, which are likely due to differences in blade azimuth over time, as the predicted blade rotations may deviate between the solvers during the initial transient phase.

6. DISCUSSION

6.1 Blade Structural Damping

Table 2 summarises the damping coefficients used in the numerical models. Structural damping in OpenFAST/BeamDyn is achieved via the specification of the diagonal components of a 6x6 stiffness-proportional damping matrix, denoted μ_1 to μ_6, where μ_1 to μ_3 relate to blade displacements in the flapwise, edgewise and axial directions, while μ_4 to μ_6 relate to blade rotations. OrcaFlex and Flexcom accept entries for stiffness-proportional damping coefficients corresponding to the axial, bending and torsional deformation modes. In the OrcaFlex and Flexcom models, λ_{axial} is set equal to μ_3. In the OrcaFlex model, $\lambda_{bending}$ is taken as the mean of μ_4 and μ_5. Flexcom supports separate coefficients in the flapwise and edgewise directions, hence $\lambda_{flapwise}$ and $\lambda_{edgewise}$ are set equal to μ_4 and μ_5 respectively. In the OrcaFlex model, $\lambda_{torsion}$ is set equal to μ_6. Some of the Flexcom simulations exhibited numerical instability, manifested in high frequency fluctuations in blade pitch, so it was decided to use a larger damping coefficient for the torsional DOF. The instability is considered to be related to blade torsional deformation (see next section), and a slight incompatibility between the control system and the structural model in Flexcom. In other words, while the additional damping is helpful, it is symptomatic of an underlying root cause. Additionally, the extra damping may affect the rate of elastic torsional deformation and may contribute to the discrepancies in aerodynamic forces between Flexcom and the other tools.

TABLE 1: BLADE STRUCTURAL DAMPING COEFFICIENTS

Mode	BeamDyn	OrcaFlex	Flexcom
Flapwise	0.0041	0.0036	0.0041
Edgewise	0.0031	0.0036	0.0031
Axial	0.00014	0.00014	0.00014
Torsional	0.00014	0.00014	0.055

6.2 Blade Torsional Deformation

To better understand the discrepancies in aerodynamic forces, localised blade twist is examined in more detail. Given that the OpenFAST and OrcaFlex aerodynamic models have already been validated by code-to-code comparisons [12], The Flexcom blade twist is only compared with OpenFAST here. Figure 5 compares the average local twist angle as a function of blade span for the 10 m/s steady wind test case. This is close to the rated speed, where the aerodynamic torque experienced by the turbine is greatest.

Extraction of torsional deformation (like edgewise deflection) involves a separation of rigid body motion and elastic structural deformation. At present, this variable is not directly output from Flexcom. Instead, a representation of torsional deformation can be derived from the aerodynamic twist angle (θ) obtained from AeroDyn, which is governed by the instantaneous orientation of the Flexcom structural elements. The aerodynamic twist angle θ includes the (manufactured) structural twist, the pitch imposed by the control system, and the torsion-induced deformational twist. Torsional deformation-induced twist is thus computed by subtracting both structural twist and steady-state blade pitch angle, from the aerodynamic twist angle θ. This torsional deformation is presented relative to the blade root node in Figure 5. This method is validated using OpenFAST-only data with BeamDyn, where torsional deformation is readily available as an output parameter. Close agreement between the computed AeroDyn θ-based method and the standard BeamDyn output confirms the validity of this approach. In contrast, significant deviations are observed with Flexcom, particularly towards the blade tip, where cumulative twist angle is largest.

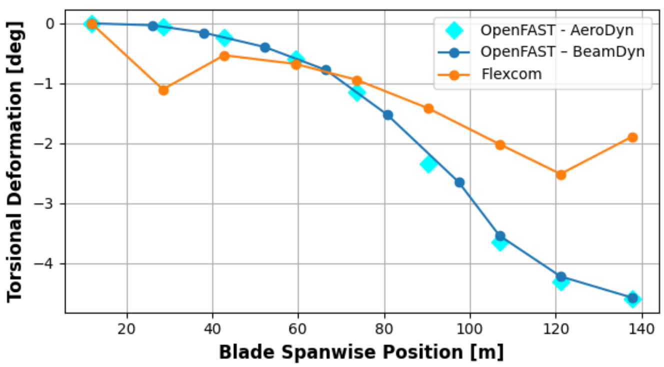

FIGURE 5: FLEXCOM AND OPENFAST PREDICTIONS OF TORSIONAL DEFORMATION (LOCAL TWIST ANGLE) FOR STEADY 10 M/S WIND SPEED

Following consultation with the Flexcom developers, it has become apparent that the application of aerodynamic forces and moments in the Flexcom model does not account for spatial offset between the structural centre and the aerodynamic centre on the blade cross section. A similar comment applies to the application of mass terms at the centre of gravity, although this is likely to be less significant. So, although the blade structural properties are correctly represented by the relevant stiffness terms, the twisting moment induced by the spatial offset is neglected. This leads to inaccuracy in deformational blade twist induced by wind loads, particularly near rated wind speed where these forces are largest. This is apparently the root cause of discrepancy in aerodynamic force between Flexcom and OrcaFlex/OpenFAST. It is not possible to prove this conclusively as the modelling fault exists at the time of writing, although it is scheduled for correction in the next maintenance release of Flexcom. Notwithstanding this limitation, the structural twist due to the physical shape of the blade, and the rigid body twist imparted by the control system, are both correct. As these terms account for the majority of the overall twist angle, the local angle of attack and the corresponding aerodynamic forces are close to the theoretical values.

The ability to model flexible blades is a relatively recent addition to Flexcom, introduced in 2025. The feature was validated via code-to-code comparisons with OpenFAST, using the IEA 15 MW RWT, where no appreciable variation in aerodynamic force was observed between the two codes [19]. This further serves to highlight the increased flexibility associated with larger turbines such as the IEA 22 MW RWT, with increased blade length (+18%), blade mass (+27%), rotor swept area (+40%), and blade prebend (+75%) relative to the 15 MW turbine. Once the issue is corrected, updated results will be made available on the publicly available tool validation site [19].

6.3 Blade Modelling Theory

Although perhaps not significant, it should be noted that the turbulent wind simulations performed by OrcaFlex from 3 m/s to 11 m/s were performed using DBEMT rather than BEMT, as this aided numerical convergence. BEMT was used throughout for the other solvers.

6.4 Run Time Performance

Figure 6 presents simulation computational effort in terms of wall-clock time for the stepped wind test case. Despite some differences in the total number of elements used in the models (Table 2) – largely due to the independent nature of blade property interpolation from the original WindIO dataset – there are significant differences in times. For the stepped wind case, with a total simulation time of 1060 s, OpenFAST (with ElastoDyn) returns the quickest run time of just 2:09 (mm:ss), resulting in a computation to simulation time ratio of just 12%. Notwithstanding the fact that the model does not include a support structure such as a monopile or floating platform, this is exceptionally quick. It should be noted however that the ElastoDyn solver is strictly only valid for straight isotropic blades dominated by bending [6], so its modelling accuracy is limited. Next quickest is Flexcom, which completes in 5:13 (mm:ss), giving a computation to simulation time ratio of 30%. Although Flexcom adopts the OpenFAST aerodynamic solver, it uses its own structural solver, a non-linear FEM formulation with fully coupled axial, bending and torsional DOFs, with greater computational effort. Next comes OrcaFlex, which completes in 8:03 (mm:ss), offering a computation to simulation time ratio of 46%. This is somewhat unexpected given that the OrcaFlex model has fewer blade structural elements than the Flexcom model (37 rather than 58). Given that both aerodynamic solvers use BEMT, this suggests that the Flexcom solution technique is more efficient than that of OrcaFlex, an observation which coincidentally aligns with a previous study on mooring line modelling [18]. OpenFAST with BeamDyn returns the slowest (significantly) run time of 4:23:43 (hh:mm:ss), equating to a computation to simulation time ratio of almost 1500%. The comparatively poor performance of OpenFAST-BeamDyn is due to the small time-step of 0.001s used in the BeamDyn model (necessary to avoid numerical convergence issues); the other models use a time-step of 0.05 s. According to NREL [20], a new tight coupling algorithm is under development and will enable much larger time-steps and significantly improved computational performance for BeamDyn (a new release is expected later in 2025).

TABLE 2: ELEMENTS AND TIMESTEPS

Model	No. of Blade Elements		Time-Step
	Aero.	Structural	
OpenFAST-BeamDyn	58	30	0.001s
OpenFAST-ElastoDyn	58	58	0.05s
OrcaFlex	37	37	0.05s
Flexcom	58	58	0.05s

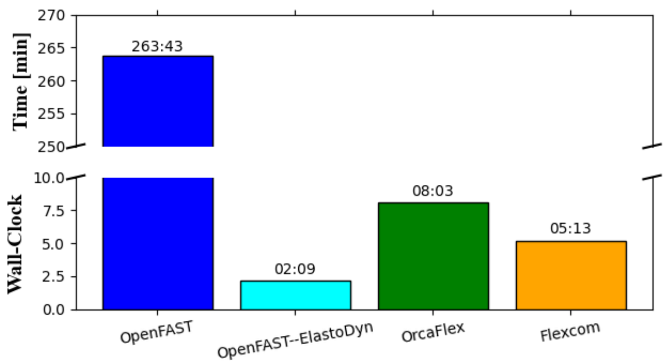

FIGURE 6: COMPARISON OF WALL CLOCK RUN TIMES BETWEEN OPENFAST (ELASTODYN AND BEAMDYN OPTIONS), ORCAFLEX AND FLEXCOM

6.5 Additional Observations

All numerical models in this study use the BEMT modelling option. BEMT is most accurate when the aerodynamic loads are axisymmetric about the rotor hub, and the rotor plane is perpendicular to the wind inflow. It has been shown [21] that the highly flexible wind turbine blades associated with larger wind turbines create a swept rotor area which deviates significantly from the rotor plane and causes the near wake to diverge from a uniform helical shape. Moreover, this tends to increase 3D interactions between the blade elements and challenges the assumption of blade annulus independence. Apart from the aerodynamic complexities, basic aspects such as skewed wind inflow, shaft turbine tilt, and wind shear all challenge the fundamental assumptions underlying BEMT. Notwithstanding the above, BEMT results have proven quite accurate for steady inflow conditions with no yaw misalignment [21], such as the steady wind test cases in this study. However, the stepped wind (due to yaw misalignment) and the turbulent wind (due to wind shear, speed fluctuations due to turbulence intensity, and lateral wind flow) test cases are more complex. Further research is required to investigate and quantify the increased accuracy provided by higher fidelity aerodynamic models, such as FVW, particularly for skewed wind inflow and turbine yaw misalignment.

CONCLUSION

This paper investigates the IEA 22 MW reference wind turbine and provides a code-to-code comparison of simulation models built using the mid-fidelity aero-elastic tools OpenFAST, OrcaFlex and Flexcom. Overall, the codes show general agreement, with some minor discrepancies in certain aspects, and the results serve as a credible code-to-code validation of the tools considered.

Close agreement is observed for the main turbine performance characteristics, including rotor speed, tip speed ratio, generator torque, blade pitch and generator power. The main deviations relate to rotor thrust, with the Flexcom model giving higher aerodynamic force at speeds close to rated. Similar deviations are observed in related parameters such as blade deflection and root moment in the flapwise direction. This difference is attributed to a limitation in the current Flexcom implementation whereby spatial offset between the structural centre and the aerodynamic centre on the blade cross section is neglected. The issue is scheduled for correction in the next maintenance release.

Regarding run-time performance, there is quite a large variation between the tools. For a model containing a turbine and tower only, sample results suggest a computation time to simulation time ratio as follows: OpenFAST (ElastoDyn) 12%, Flexcom 30%, OrcaFlex 46% and OpenFAST (BeamDyn) 1500%. Essentially, Flexcom is shown to have good computational efficiency when compared to OrcaFlex and OpenFAST (BeamDyn), all of which offer similar levels of modelling fidelity. A new version of BeamDyn, with a tighter coupling algorithm, currently under development, will likely significantly improve computational performance.

Further research is required to investigate and quantify the increased accuracy provided by higher fidelity aerodynamic models particularly for skewed wind inflow and turbine yaw misalignment.

ACKNOWLEDGEMENTS

The authors are grateful to:

- NREL and DTU for publicly sharing the IEA 22 MW RWT.
- Orcina and Wood for supplying academic licenses of OrcaFlex and Flexcom respectively.
- NREL, Orcina and Wood, for providing technical support and guidance.
- The Sustainable Energy Authority of Ireland (SEAI) for part-funding travel costs.
- Grant aid from Research Ireland under Grant number 22/FFP-A/10299. For Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

REFERENCES

[1] Global Wind Energy Council (GWEC), 2024. GWEC global wind report 2024. Global wind energy council: Brussels, Belgium.

[2] Zahle, F., Barlas, T., Lonbaek, K., Bortolotti, P., Zalkind, D., Wang, L., Labuschagne, C., Sethuraman, L. and Barter, G., 2024. Definition of the IEA Wind 22-Megawatt Offshore Reference Wind Turbine (No.

NREL/TP-5000-88593). National Renewable Energy Laboratory (NREL), Golden, CO (United States).
[3] IEAWindSystems, 2025, IEA-22-280-RWT GitHub. Online: https://github.com/IEAWindTask37/IEA-22-280-RWT, accessed March 2025.
[4] Otter, A., Murphy, J., Pakrashi, V., Robertson, A. and Desmond, C., 2022. A review of modelling techniques for floating offshore wind turbines. Wind Energy, 25(5), pp.831-857.
[5] Collier, W., Ors, D., Barlas, T., Zahle, F., Bortolotti, P., Marten, D., Jensen, C.S.L., Branlard, E., Zalkind, D. and Lønbæk, K., 2024, June. Aeroelastic code comparison using the IEA 22MW reference turbine. In Journal of Physics: Conference Series (Vol. 2767, No. 5, p. 052042). IOP Publishing.
[6] NREL, 2025. OpenFAST Documentation. Online: https://openfast.readthedocs.io/, accessed March 2025.
[7] Guntur, S., Jonkman, J., Schreck, S., Jonkman, B., Wang, Q., Sprague, M., Hind, M. and Sievers, R., 2016. Fast v8 verification and validation for a megawatt-scale wind turbine with aeroelastically tailored blades (No. NREL/CP-5000-65389). National Renewable Energy Lab.(NREL), Golden, CO (United States).
[8] Orcina, 2025. OrcaFlex Theory Manual. Online: https://www.orcina.com/webhelp/OrcaFlex/Default.htm, accessed March 2025.
[9] Orcina, 2025. OrcaFlex validation. Online: https://www.orcina.com/resources/validation/, accessed March 2025.
[10] Orcina, 2018. Orcina Project 1405, Wind Turbine Validation Report. Online: https://www.orcina.com/wp-content/uploads/resources/validation/R14050101-Wind-Turbine-Validation-Report.pdf, accessed March 2025.
[11] Orcina, 2023. Orcina Project 1512, Comparison of loads from OrcaFlex and OpenFAST for the IEA 15 MW RWT. Online: https://www.orcina.com/wp-content/uploads/resources/validation/R15120101-OrcaFlex-15MW-RWT-Validation-Report.pdf, accessed March 2025.
[12] Orcina, 2024. Orcina Project 1554, Comparison of loads from OrcaFlex and OpenFAST for the IEA 22 MW RWT. Online: https://www.orcina.com/wp-content/uploads/resources/validation/R15540101-OrcaFlex-22MW-RWT-Validation-Report.zip, accessed March 2025.
[13] Wood, 2025. Flexcom Theory Manual. Online: https://flexcom.fea.solutions/index.html, accessed March 2025.
[14] Connolly, A.J. and O'Mahony, G., 2021, June. Validation of a Novel Wind Turbine Simulation Tool via Benchmarking: Case Study of Jacket Structure. In ISOPE International Ocean and Polar Engineering Conference (pp. ISOPE-I). ISOPE.
[15] R. Bergua et al., "OC6 Project Phase IV: Validation of Numerical Models for Novel Floating Offshore Wind Support Structures," Wind Energy Sci. Discuss., pp. 1–36, Aug. 2023, doi: 10.5194/wes-2023-103.
[16] Conway, O., Connolly, A. and Leen, S., 2024, June. Numerical Modelling of Novel Floating Offshore Wind Turbine Concept. In International Conference on Offshore Mechanics and Arctic Engineering (Vol. 87851, p. V007T09A038). American Society of Mechanical Engineers.
[17] NREL. 2025. Reference Open-Source Controller (ROSCO) for wind turbine applications. Online: https://github.com/NREL/ROSCO/releases/tag/v2.9.0, accessed March 2025.
[18] Connolly, A., Lang, D. and Conway, O., 2024, June. Validation of a Truss Finite Element for Mooring Applications via Code-To-Code Comparisons. In International Conference on Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers.
[19] Wood, 2025. (Wind Turbine) Validation. Online: https://flexcom.fea.solutions/validation.html, accessed March 2025.
[20] Jonkman, J. 2025. Run times with ElastoDyn and BeamDyn. Online: https://forums.nrel.gov/t/run-times-with-elastodyn-and-beamdyn/8524, accessed March 2025.
[21] Shaler, K., Anderson, B., Martínez-Tossas, L.A., Branlard, E. and Johnson, N., 2022. Comparison of Free Vortex Wake and BEM Structural Results Against Large Eddy Simulations Results for Highly Flexible Turbines Under Challenging Inflow Conditions. Wind Energy Science Discussions, 2022, pp.1-22.