Best practice for verification of wind turbine numerical models

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Abstract. The analysis of wind turbines relies on aero-hydro-servo-elastic simulation tools. OC3, 4, 5, 6 projects showed that much effort is required to obtain consistency in numerical models set up and the agreement in the simulation results. To mitigate the uncertainty in the model setup and to reduce the time spent on its verification, a robust verification procedure is necessary. The presented verification procedure provides a structured and efficient way of checking and comparing aeroelastic wind turbine models. In case a discrepancy between the two models or the model and documentation is found, a procedure for finding the source of this discrepancy is suggested. During several successful applications of the presented verification procedure, it proved to reduce the effort, the number of iteration loops and thus the consumed time that is required to achieve a verified model.

1. Introduction

The analysis of wind turbines relies on aero-hydro-servo-elastic simulation tools. These coupled time-domain based tools account for the interaction of various environmental conditions and the entire structural assembly of the WT, including its control system. These tools are mainly based on engineering-level models.

It is often the case that a WT model has to be:

- Set up from scratch based on the design basis documents, which are often provided by an external party;
- Set up in another simulation tool for the sake of verification of previously simulated load effects.

OC3, 4, 5, and 6 projects [2, 3, 4, 5, 6, 7] showed that much effort is required to obtain consistency in numerical models set up and the agreement in the simulation results. This happens due to the following reasons:

1. These are mid-fidelity empirical, semi-empirical, phenomenological, and analytical models. More detailed information about these models can be found in [1, pp. 9–21].
2. The WT model is a numerical representation of the entire WT dynamics, consisting of a foundation, a support structure, and a rotor-nacelle assembly (RNA). A set of geometrical, structural, and aerodynamic properties is necessary for the definition of the model.
3. Offshore Code Comparison, Collaboration (OC3), Continuation (OC4), with Correlation (OC5), and unCertainty (OC6) projects operated under the International Energy Agency Wind Tasks 23 and 30.
Different aeroelastic simulation tools may have different simulation capabilities and limitations, which may lead to discrepancies in the simulated results. This should be kept in mind during verification: Either—if possible—by clearly assigning a difference in the simulation results to a specific modeling aspect (e.g., different dynamic stall models), or by reducing the level of detail in both models (e.g., deactivating dynamic stall model in both tools);

• Some modeling errors caused by human factors are also common e.g., misinterpretation of coordinate systems, incorrect simulation settings.

A robust procedure for model verification is necessary to mitigate the uncertainty in the model setup and to reduce the time spent on its verification. The suggested verification procedure is based on the authors’ experience in the verification of many models of WTs for multiple international research and industrial projects. In [8], a model is compared between different tools, but more focused on verifying a tool rather than the correct implementation of a model. The authors are not aware of other publications focused on the best practice for verification of WT numerical models.

The verification procedure, which is presented in this paper, is addressed to engineers and researchers working with numerical models at engineering level for both onshore and offshore WTs. The objective is to provide a general guideline for the verification of numerical models of WTs before their use for the load analysis. In this paper, the term verification is used as assuring that the computer programming and implementation of a conceptual model are correct, as defined in [9, p. 185] as computerized model verification. The suggested procedure helps to mitigate errors and discrepancies coming from the model set up in individual simulation tools, which are often based on similar, but not the same, principles. In the case a discrepancy between the two models or the model and documentation is found, a procedure for finding the source of this discrepancy is suggested. Furthermore, the most common sources of the discrepancies are presented.

2. Procedure
The model verification procedure presented in this paper consists of steps of increasing complexity. At each step, an additional physical aspect is taken into account. This enables the user to trace back possible errors coming from the implementation of different models. The main outline of the procedure is shown in Figure 1. A detailed description of the steps involved is presented in the next section. The aim is to reach a sufficient agreement between two numerical models or a numerical model and its reference documentation. The authors deliberately do not provide either tolerances or accepted value ranges, as they should be defined by an engineer based on his/her experience and the analysis aim.

4 These principles include the ways how the numerical models are set up and simulation capabilities of the tools.
5 This means that “...the global dynamics of an OWT [offshore wind turbine - author’s note] and external loading conditions are reproduced to such extent that the simulated load effects (including safety factors) are adequate for a reliable design of an OWT according to certification standards...” [1, p. 11].

![Figure 1. Outline of the model verification procedure.](image-url)
3. Results
The results presented in this paper are the descriptions of each step of the model verification procedure. For the investigation in the time domain, it should be assured that the simulation results at the beginning of a simulation are cut out in order to eliminate the effect of transient effects. The simulation time at the beginning of the simulation, referred to as Pre-Sim-Time, depends on the model and the intended use of the model. In most cases, 50s is sufficient. However, 200s to 300s might be required in some cases, especially if the controller has a long initialization time. Furthermore, the user should take care of corresponding wind and aerodynamic settings in both tools.

3.1. Structural properties of sub-components
It is recommended to check the basic structural properties of the system sub-components between the documentation and the numerical model or between diverse numerical models. It should be noted that different tools may use different coordinate systems. Therefore, a translation from one coordinate system to another might be necessary, which is not always a straightforward task. For example, in Bladed [10], the majority of structural and geometrical blade properties are defined with respect to the leading edge of the blade, whereas in HAWC2\(^6\) [11], the majority of these properties are defined with respect to the half chord length\(^7\). In addition, certain components might be specified differently. For example, in HAWC2 main shaft bearing can be defined, whereas in Bladed there is no such possibility. For this step, it is reasonable to compare all main parameters in a side-by-side table, which includes parameter groups such as mass, geometry, location of the center of gravity (CoG), inertia, imbalance, and drivetrain parameters. An example of the groups mass and geometry is shown in Table 1.

| Table 1. Check of structural properties of sub-components. |
|----------------------------------------------------------|
| **Tool Name 1** | **Tool Name 2** |
| Mass | | |
| Nacelle | t | |
| Rotor | Hub | t |
| 1 Blade | t | |
| Generator | Rotor | t |
| Stator | t | |
| Entire rotor-nacelle assembly | t | |
| Support structure (monopile, transition piece, tower) | t | |
| Entire wind turbine | t | |
| Geometry | | |
| Tilt angle of shaft (upwards from horizontal plane) | deg | |
| Cone angle of rotor (coned against wind) | deg | |
| Blade length (distance along blade) | m | |
| Blade root length | m | |
| Nacelle | length | m |
| width | m | |
| height | m | |

\(^6\) Horizontal Axis Wind turbine simulation Code 2nd generation (HAWC2)

\(^7\) A detailed description of Bladed, HAWC2, and MoWiT [12, 13] blade coordinate systems and conversion of blade structural and geometrical properties between these systems can be found in the files accompanying the documentation of the IWT-7.5-164 WT [14].
3.2. Mass and static forces of the entire structure

After checking all relevant input parameters, the resulting masses and forces should be checked in the simulation results of static load cases (LCs), which just include gravity, but no air — so-called dead LCs. At first, a LC with a rigid WT and a rigid foundation is considered (LC 1.1 — for LC definitions see Table 2). The resulting masses, as well as forces and bending moments, have to be compared numerically between two models. The authors recommend following the sequence provided in Table 3. An example of the application of the model verification procedure is given in Section 3.6 and Table 4. If the values show no sufficient agreement, the parameters of mass, CoG, coordinate systems (including a proper assembly of components), as well as further geometrical properties and correct definition of the output sensors, have to be rechecked and after the correction, the simulation is repeated. In case of agreement, proceed with a LC with a flexible turbine and foundation (LC 1.2). Having assured an equal loading condition in both models, LC 1.2 enables to verify the stiffness properties by comparing the displacements and rotations of the flexible bodies under gravitational loading. The detailed procedure to verify the structural parameters of the entire WT is shown in Figure 2. After achieving an agreement in LC 1.2, the modal analysis is the next step.

| Load case | Enabled DOFs | Wind conditions | Aerodynamic Setting | Simulation conditions | Objective |
|-----------|--------------|-----------------|---------------------|----------------------|-----------|
| 1.1       | - Only rotor rotational DOF - Rigid foundation | - No air - Air density = 0.0 | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Parked - Pitch angle = feather position - Blade 1 pointing upwards | - Mass and CoG |
| 1.2       | - Flexible OWT - Flexible foundation | - No air - Air density = 0.0 | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Parked - Pitch angle = feather position - Blade 1 pointing upwards | - Mass and CoG |
| 2.1       | - Only rotor rotational DOF - Rigid foundation | - Stepped wind from \( V_{cut-in} \) to \( V_{cut-out} \) - Flow inclination = 0 deg - Direction angle = 0 deg | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Power production | - Control system and aerodynamics |
| 2.2       | - Flexible OWT - Flexible foundation | - Stepped wind from \( V_{cut-in} \) to \( V_{cut-out} \) - Flow inclination = 0 deg - Direction angle = 0 deg | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Power production | - Control system and interaction of aerodynamics and elasticity |
| 3.1       | - Flexible OWT - Flexible foundation | - Turbulent wind with \( V_{ave} \) average wind speed of \( V_{ave} \) - Flow inclination = 8 deg | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Power production | - OWT dynamics and control system in turbulent conditions |
| 3.2       | - Flexible OWT - Flexible foundation | - Turbulent wind with \( V_{ave} \) average wind speed of \( V_{ave} \) - Flow inclination = 8 deg | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Power production | - OWT dynamics and control system in turbulent conditions |
| 3.3       | - Flexible OWT - Flexible foundation | - Turbulent wind with \( V_{ave} \) average wind speed of \( V_{ave} \) - Flow inclination = 8 deg | - Tip losses = true - Hub losses = true - Dynamic wake = true | - Power production | - OWT dynamics and control system in turbulent conditions |

3.3. Modal analysis

The modal analysis is used for the determination of the WT natural frequencies and the eigenmode shapes. If the structural dynamics of the WT is modeled (in a given tool) with
### Table 3. Examination sequence for LC 1.1.

| Sequence | Component/ Assembly | Sensor to examine                     |
|----------|---------------------|---------------------------------------|
| 1        | Blade               | Blade1 axial force at root             |
| 2        | Rotor               | Vertical force at flange hub - shaft axis |
| 3        | RNA                 | Tower top vertical force               |
| 4        | Entire Wind Turbine | Tower bottom vertical force            |

| Sequence | Component/ Assembly | Sensor to examine                     |
|----------|---------------------|---------------------------------------|
| 1        | Blade               | Blade2 flapwise bending moment at root |
| 2        | Rotor               | Fore-aft bending moment & yaw moment at flange hub - shaft axis |
| 3        | RNA                 | Tower top fore-aft & side-side bending moment |
| 4        | Entire Wind Turbine | Tower bottom fore-aft & side-side bending moment |

### Figure 2. Detailed procedure for checking structural properties.
the flexible modal reduced bodies, then an adequate number of modes should be selected. A larger number of eigenmodes results in a longer simulation time, whereas too few eigenmodes may lead to unrealistic results. The choice of the number of eigenmodes for the entire WT depends on the analysis aim:

- **Global system dynamics**—In this case, it is sufficient when the fraction of the effective modal mass (effective modal mass divided by total rigid body active mass) is larger than around 0.90–0.95 in horizontal directions of response [15]. The global system dynamics is usually well captured when eigenmodes up to the cut-off frequency of 5 Hz are included in the case of WTs with monopile support structures. This frequency is usually an upper bound for the global dynamics analysis of the MW-class WTs. The energy of the higher eigenmodes is faster dissipated.

- **Dynamics of sub-components** (e.g., vibration of jacket support structure braces)—The number of eigenmodes should be increased until the desired mode shape appears. It is also important to make sure that twin eigenmodes are either included or excluded from the analysis. The twin eigenmodes are those, which eigenfrequencies are very close to each other (double root eigenvalue). Therefore, both or none of them should be included as uncoupled structural modes that contribute to structural dynamics.

### 3.4. Steady-state performance

Many of the WT simulation tools offer a possibility to calculate steady-state performance characteristics, which are time-independent and contain several simplifications, such as wind perpendicular to the rotor plane, no wind shear, no gravity loads, no tower shadow. The steady-state analysis is performed as a function of wind speed and often accounts for the following:

- Aerodynamic properties;
- Power, torque, and thrust curves;
- Steady operational loads.

If there is no possibility for calculating the steady-state performance in the given tool, the check of aerodynamics and loads can be incorporated into the time-domain simulation (Section 3.5). The aerodynamic properties are calculated for the given wind speed for each blade section along the rigid blade. These are usually axial and tangential induction factors, lift and drag coefficients, inflow angle, angle of attack, etc. The examination of these aerodynamic properties helps to confirm that the blade aerodynamics has been correctly defined in the tool.

Power, torque, and thrust curves can be calculated for a rigid WT as a function of the rotor speed and the pitch angle—either defined by the controller or manually prescribed by the user for the given wind speed. These curves are useful for the evaluation of the basic performance of WT.

Steady operational loads should be calculated for the flexible WT at different operating points defined by the wind speed and the corresponding rotor speed and the pitch angle. They are useful for the basic evaluation of a steady load magnitude. Furthermore, the partial derivatives of aerodynamic torque, which are calculated during the analysis, can be used to estimate gain scheduling, which is used for the adjustment of the controller gains.

The obtained steady-state performance characteristics can be compared between different tools in terms of the percentage difference at individual operating points. The expected difference should be negligible.

### 3.5. System dynamics and controller behavior time-domain simulation

The time-domain simulation is the final check if all aspects of the WT model work properly and if the coupling of all effects is correct and can be split into two groups:
• Deterministic (stepped) wind;
• Turbulent wind.

This way, the controller step response is checked as well as the steady-state behavior of the WT model. Investigating the former enables to check if the controller (in most cases a DLL) is embedded correctly in the WT model. The steady-state behavior of the WT model allows checking if the aerodynamics and loss models are implemented correctly. Here it is a useful way to execute the stepped wind simulation with a rigid WT model first in order to check the aerodynamic parameters and equations. Following this, the stepped wind simulation should be executed with a flexible WT model to check the aeroelastic interaction. Finally, the WT models should be checked with turbulent simulations, at several wind speeds below rated, around rated and above rated. In doing so, the complete WT dynamics will be checked, including controller dynamics and transient effects. For the turbulent wind, it is essential to use the same turbulent wind file for both models.

LCs with deterministic wind can be visually compared in terms of their time series. The accuracy of these results can be checked by the nondimensional root mean square error (RMSE), which is the measure of the difference between time series data points computed by one tool and the time series data points, obtained from another tool. These individual differences, at each time point, are aggregated by the RMSE into a single value.

LCs with turbulent wind should be examined in terms of probability density functions (PDFs) and power spectral densities (PSDs). Therefore, the measures of each tool should be plotted in one figure for PSD and one for PDF. Using these measures, the dynamics of the models like eigenfrequency and damping can be examined.

3.6. Application
The model verification procedure has been successfully applied at Fraunhofer IWES to assure that the aeroelastic model of a specific WT in tool 2 shows the same results as its model in tool 1. In order to achieve this agreement, two requirements have to be fulfilled. On the one hand, the parameters defining the model (e.g., geometry, airfoils, material, etc.) have to be set correctly, and on the other hand, the submodels representing the physics have to be implemented correctly (e.g., BEM, beam model, etc.). Having several discrepancies at the first run of LC 1.1, within each iteration of runs, the agreement between both tools could be increased in a specific physical aspect, as shown in Table 4.

At run01, the axial force of Blade1 (pointing upwards) and the flapwise bending moment at root of Blade2 show a good agreement and thus the total mass of the blade as well as the total CoG are considered as accurately defined. The modifications of the model in tool 2 are documented in the second row. Red-colored cells mean that the difference between the simulation results of the models is very high, yellow that the difference is not very high, but could be improved whereas green indicates a good agreement.

The classification ranges used here are valid for this model and the case of intended use and do not claim to be appropriate in general. At run01, there was an unphysical discrepancy in the rotor drive torque, which has been fixed in run02. In run03, the rotor overhang has been modified, which lead to a good agreement in the Tower Top Fore-aft bending moment. The increasing difference in the rotor fore-aft bending moment is due to a different position of the hub-sensor in the tools.
| RunName       | LC11_run01 | LC11_run02 | LC11_run03 | LC11_run04 | LC11_run05 | LC11_run06 |
|--------------|------------|------------|------------|------------|------------|------------|
| Modification compared to previous run | - | several modifications | rotor overhang | sign of lateral nacelle CoG | position of Hub-sensor | linear density of tower |
| Sensor Description | Difference of value [%] | Difference of value [%] | Difference of value [%] | Difference of value [%] | Difference of value [%] | Difference of value [%] |
| Fore-aft shear force | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Side-to-side shear force | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Vertical force | 0.20% | 0.20% | 0.20% | 0.20% | 0.20% | 0.20% |
| Side-to-side bending moment | -207.58% | -200.00% | -200.00% | 0.00% | 0.00% | 0.00% |
| Fore-aft bending moment | -1.07% | -0.97% | 0.00% | 0.00% | 0.00% | 0.00% |
| Fore-aft shear force | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Side-to-side shear force | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Vertical force | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Side-to-side bending moment | -207.58% | -200.00% | -200.00% | 0.00% | 0.00% | 0.00% |
| Fore-aft bending moment | -1.07% | -0.97% | 0.00% | 0.00% | 0.00% | 0.00% |
| Fore-aft displacement | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Side-to-side displacement | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Rotation around fore-aft axis | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Rotation around side-to-side axis | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Rotor thrust | not provided | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Rotor lateral force | not provided | -100.00% | both = 0 | both = 0 | both = 0 | both = 0 |
| Rotor vertical force | not provided | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Rotor drive torque | very large | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Rotor fore-aft bending moment | not provided | -10.02% | -21.73% | -21.73% | -0.02% | -0.02% |
| Rotor yaw moment | not provided | both = 0 | both = 0 | both = 0 | both = 0 | both = 0 |
| Shear force at root, flapwise direction | -0.75% | 0.01% | 0.01% | 0.01% | 0.01% | 0.01% |
| Shear force at root, edgewise direction | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Axial Force at Root | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Edgewise Bending Moment at Root | 0.28% | 0.28% | 0.28% | 0.28% | 0.28% | 0.28% |
| Flapwise Bending Moment at Root | -5.91% | -6.09% | -6.09% | -6.09% | -6.09% | -6.09% |
| Torsion at root | -4.44% | -4.37% | -4.37% | -4.37% | -4.37% | -4.37% |
| Shear force at root, flapwise direction | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Shear force at root, edgewise direction | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Axial Force at Root | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Edgewise Bending Moment at Root | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% |
| Flapwise Bending Moment at Root | 0.10% | 0.10% | 0.10% | 0.10% | 0.10% | 0.10% |
| Torsion at root | 0.31% | 0.31% | 0.31% | 0.31% | 0.31% | 0.31% |
As the reason for this difference was known, the cell was colored blue. Having a rotor drive torque around zero, the existing discrepancy in the tower top side-to-side bending moment could be identified as a consequence of a different sign in the lateral nacelle CoG position. This has been fixed in run04. With run05, the position of the hub-sensor was adjusted and the difference of the rotor fore-aft bending moment could be diminished. Following the examination sequence presented in Section 3.2 and Table 3, the difference of 0.0% in the tower top vertical force but 0.2% in the tower bottom vertical force could be traced back to an error in the linear density definition of the tower of the model in tool 2. This error has been fixed for run06, leading to good agreement of both models in all relevant static loads. Having achieved a good agreement for LC 1.1 it can be proceeded with LC 1.2.

4. Conclusions

The presented verification procedure provides a structured and efficient way of checking and comparing WT models. The increasing complexity of the procedure enables the user to trace back possible errors coming from the implementation of different models. The model verification procedure has already been successfully used in multiple industrial projects run at Fraunhofer IWES and it proved to mitigate discrepancies between the numerical WT models. Furthermore, it proved to reduce the effort, the number of iteration loops, and thus the time required to achieve a verified model.

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