Real-time simulation of aeroelastic rotor loads for horizontal axis wind turbines

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Abstract. Wind turbine drivetrain research and test facilities with hardware-in-the-loop capabilities require a robust and accurate aeroelastic real-time rotor simulation environment. Recent simulation environments do not guarantee a computational response at real-time. Which is why a novel simulation tool has been developed. It resolves the physical time domain of the turbulent wind spectra and the operational response of the turbine at real-time conditions. Therefore, there is a trade-off between accuracy of the physical models and the computational costs. However, the study shows the possibility to preserve the necessary computational accuracy while simultaneously granting dynamic interaction with the aeroelastic rotor simulation environment. The achieved computational costs allow a complete aeroelastic rotor simulation at a resolution frequency of 100 Hz on standard computer platforms. Results obtained for the 5-MW reference wind turbine by the National Renewable Energy Laboratory (NREL) are discussed and compared to NREL’s fatigue, aerodynamics, structures, and turbulence (FAST)-Code. The rotor loads show a convincing match. The novel simulation tool is applied to the wind turbine drivetrain test facility at the Center for Wind Power Drives (CWD), RWTH Aachen University to show the real-time hardware-in-the-loop capabilities.

1. Introduction
Drivetrain failures state a significant reason for horizontal axis wind turbine (HAWT) downtime and thus reduce their availability. To improve drivetrain technology for HAWT, wind turbine drivetrain test facilities are commissioned in several countries viz. Denmark, Germany, Great Britain, Norway, and the United States [1]. Although drivetrain test facilities have been commonly used for fatigue analysis in the past, a new aspect is their specialization to wind turbines. The latter requires multiaxial loading and real-time hardware-in-the-loop (HIL) capabilities, i.e., a real-time simulation tool which accounts for the aeroelastic rotor loads of HAWTs. In this context, a new integrated simulation environment called rotor-aerodynamic-integrated-simulation-environment (RAISE) has been developed.

Unlike already available codes for the aeroelastic simulation of HAWTs (see e.g. [2]), the application of RAISE is focused on simulations for drivetrain test facilities. Thereby, the computation of accurate wind turbine loads is enhanced by providing a real-time and robust simulation for HIL capabilities. Because of the hardware’s feedback on the aerodynamic loads pre-computed time series are not sufficient to improve the understanding of fatigue and damage processes of wind turbine drivetrains. It goes without saying that an HIL simulation has to be prevented from abnormal termination or unexpected actions since computed loads are directly...
applied to the drivetrain using a multiaxial load application unit. Due to the fact that drivetrains of different size and power may be tested, a sudden breakdown due to arbitrary loads must be avoided. This aspect has to be taken into consideration for the hardware and software of the test rig and the novel simulation tool. Especially during longterm simulations, numerical instabilities are likely to occur. The reason for this are presumably numerical schemes used in the program corresponding to various wind turbine parametrizations. Consequently, in the case of an unexpected program execution error, opportunities to detect and react to those failures are mandatory. Therefore, proper event triggering and zero-crossing detection require either the application of a variable-step solver or a sufficiently small step size for a fixed-step solver. Moreover, the real-time applicability requires the program to execute while fulfilling real-time constraints, i.e., the simulation matches the sample rate for updating input and output. Significant speedup is achieved by vectorization and usage of bus-objects such that user-defined controllers can be coupled to the simulation. No previous code has been found to comply with the specified requirements.

A further and entire new aspect in this context is the capability of online simulation. So far, aeroelastic wind turbine simulations have been conducted such that all parameters and input were available in advance due to the necessity of a pre-generated stochastic 3D wind field. However, a recently developed synthetic turbulence generator offers the opportunity for real-time wind field generation [3] of which RAISE can make use. Though, simulations are not longer limited to the length of a predefined wind field and adjustments can be scheduled. In the following Sections a brief overview of the RAISE implementation is given and results to the commonly used (FAST)-Code are compared.

2. Methods
RAISE has been implemented in Matlab/Simulink [4]. Similar to most available codes, the blade-element-momentum theory (BEM) constitutes the fundamental routine in RAISE. Modifications of its in- and output by various submoduls account for different flow physics in various operational states. Table 1 shows the chosen models in comparison to FAST. A detailed explanation of the respective models can be taken from Burton et al. [5].

| Model   | FAST[6]/Aerodyn [7] | RAISE |
|---------|---------------------|-------|
| Inflow  | GDW                 | TUDk  |
| Induction | GDW                 | Glauert |
| Yaw     | GDW                 | Spera |
| Tip-losses | Prandtl            | Prandtl |
| Hub-losses | Prandtl            | Prandtl |
| Dynamic stall | Beddoes-Leishman  | Beddoes-Leishman |

While tip-losses, hub-losses, and dynamic stall in FAST and RAISE are based on the same models, a distinction is drawn in the inflow, the induction, and the yaw model. While FAST uses the generalized dynamic wake model (GDW) for all of these physical phenomena, RAISE applies engineering models as independent routines. The GDW which is based on the potential flow solution to Laplace’s equation and is preferred to the Glauert model [5] by NREL due to its physically more meaningful interpretation of the wake in yaw operation [8]. The TUDk induction model [9] and the yaw model by Spera [5], however, are engineering models, which have been developed in the course of the JOULE project.
3. Code comparison

Several code validation strategies have been pursued in the past during the development of RAISE beginning with simple test cases and increasing the complexity of the setup gradually. Differences in the results could be accounted for the various underlying models in the simulation. This paper focuses on time series evaluations of the aerodynamic forces, since stress-cycle evaluations are more suitable for fatigue analysis. To generate those time series, a similar test case has been conducted with RAISE and FAST. FAST is a certified simulation tool for HAWTs and hence a commonly used reference. Some results of the simulations which granted FASTs certification are reported in [10]. However, it is necessary to point out, that FAST could not serve as a stringent reference for any test case.

For the test case model setup, NREL’s well documented 5-MW reference wind turbine [11] is selected. This minimizes the uncertainties in the model setup which can easily dominate all uncertainties and errors in the simulation [2]. Since upwind tower influence is not set in the default configuration of the turbine model, it has been left out. Like in FAST a user-defined model file provides all relevant parameters in RAISE. The temporal fluctuating wind field is simply discretized by its axial component such that the ambient wind speed at each blade element is the same at each time step for both programs. Consequently, the comparison allows for the deterministic components of the simulation. The wind speed time series has been obtained by the 3D wind field generator of RAISE. It has been stored in a wind-input file and used in both simulation tools afterwards. The generated wind field is based on the Kaimal spectrum and respective coherence function for 3D spatial resolution with a turbulence intensity of $I_{ref} = 14\%$ at a mean wind speed of $U_\infty = 11.4 \text{m/s}$. The obtained wind speed at hub height of the wind field time series is shown in Figure 1. To eliminate problems in the controller design [2; 10], the turbine runs at a constant rated rotational speed of $\omega = 1.27 \text{rad/s}$ for this test case.

Analogous to the model setup the most possible agreement in the simulation setup was intended for comparability. Therefore, the same discretization has been applied. The simulation time step comprises 0.01s and the aerodynamic forces are evaluated at 17 blade elements. Moreover, FAST's default aerodynamic blade coefficients are used in RAISE. The time series comprises 600s to be in compliance with the International Standard [12]. For a first validation, the rotor is assumed to be rigid.

In addition to the wind speed at turbine hub height, a comparison of the most important rigid rotor results by FAST and RAISE are depicted in Figure 1. These quantities are the total thrust force and the total axial torque acting on the drivetrain. From a visual examination, it is nearly impossible to tell the FAST and the RAISE results apart. For further quantitative analysis, the root-mean-square (RMS) value is calculated from the difference between FAST and RAISE at each time step for a moving time window of 60s. The RMS value time series can be found in Figure 2.

The RMS value time series for the axial rotor torque is located between 0.8% and 12% of the total rotor torque and exhibits a mean value of 2.9%. The corresponding range for the rotor thrust force lies between 2.5% and 7.5% with a mean value of 3.8%. Furthermore, RAISE overpredicts thrust force and axial torque. An in depth analysis shows that these differences are mostly caused by phase shift, not by amplitude. The biggest influence on the aerodynamic forces is due to the inflow model. Thus, the high turbulence intensity leads to a high wind speed gradient for the regarding time series resulting in the observed RMS values.

The following second validation stage considers an entire elastic rotor. In so doing, the influences of centrifugal and gravitational loading are taken into account. The coupling of torsion and bending is modelled in neither simulation environments and hence not discussed within the results. The new results for the elastic rotor and the above wind field time series are now analyzed at a single blade. The respective quantities are the blade root forces and blade root moments. The adopted coordinate system is similar to [13], but different to the blade root
Figure 1. Ambient wind speed (top) at turbine hub height and comparison of rigid rotor results by FAST and RAISE: thrust force (center) and axial torque (bottom) acting on the drivetrain.

coordinate system in [6]. The x-axis of the Cartesian coordinate system points in the direction of the drivetrain shaft rotational axis. The orientation of the y-axis arises from the right-hand
Figure 2. RMS values from the difference between rigid rotor results by FAST and RAISE: thrust force (top) and axial torque (bottom) acting on the drivetrain.

rule and the z-axis points in the direction of the pitch axis. The results of the blade root forces and moments for the elastic rotor are presented in Figures 3 and 4.

The juxtaposition of the blade root forces and moments time series from Figures 3 and 4 again reveals a perfect match. The RMS value time series fluctuate between 2.7% and 7.9% of the total blade root forces at a mean value of 4.2% and 1.9% and 4.9% at a mean value of 2.9% for the blade root moments. Consequently, the results of the novel real-time aeroelastic rotor simulation environment RAISE matches convincingly concerning the presented test case taking NREL’s FAST-Code as a reference.
Figure 3. Comparison between elastic rotor results by FAST and RAISE: blade root force x-component (top), y-component (center), and respective RMS values from the differences between FAST and RAISE for $F_{b,x}$ (bottom left) and $F_{b,y}$ (bottom right).
Figure 4. Comparison between elastic rotor results by FAST and RAISE: blade root moment x-component (top), y-component (center), and respective RMS values from the differences between FAST and RAISE for $M_{b,x}$ (bottom left) and $M_{b,y}$ (bottom right).
4. Conclusion

A robust and accurate real-time aeroelastic rotor simulation environment (RAISE) to predict loads of horizontal-axis wind turbines depending on the turbulent wind field and turbine operating conditions has been developed, tested, and compared to NREL’s FAST-Code. Moreover, it has been successfully implemented at the wind turbine drivetrain test facility at the Center for Wind Power Drives, RWTH Aachen University. In this regard, RAISE allows real-time hardware-in-the-loop testing of complete wind turbine drivetrains accounting for all physical meaningful spectra.

Unlike FAST, the implementation of RAISE offers easy applicability to different test setups for drivetrain test facilities. The graphical programming facilitates interchangeability of the different routines used. Neither further programming of interfaces nor additional compiling of sub-routines is needed. Direct target deployment promotes HIL capability. Furthermore, simple signal processing facilitates rapid integration of external devices.

Future work will focus on further validation and code comparisons. Moreover, the capability of online-simulation using a synthetic turbulence generator will be exploited.

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