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Fully coupled co-simulation of a wind turbine emergency brake maneuver

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ABSTRACT

Co-simulation is a popular numerical method to solve complex multiphysics problems. The co-simulation method has an intrinsic advantage: it allows well-established and specialized simulation tools to be reused and combined with minor adaptations, in contrast to the monolithic approach.

We employ a novel co-simulation approach to simulate a fully-coupled emergency brake maneuver scenario of the National Renewable Energy Laboratory (NREL) Unsteady Aerodynamics Experiment (UAE) Phase VI wind turbine. Within this simulation the acceleration and deceleration of the turbine are a result of the interaction of the blades, generator/gearbox, control unit and the flow field.

The simulation results are validated against measurement data from the NREL UAE Phase VI performed in the NASA AMES wind tunnel.

Using the co-simulation approach, in contrast to the investigations of various other research groups, this work provides a methodological framework to perform simulations much closer to real physics. This is realized by taking into account the interaction of blades, generator/gearbox, control unit and fluid at the same time. Thus, the usual approximations and assumptions on the single fields, which become necessary due to the artificial decoupling, are not needed, e.g. prescribing certain behavior. Moreover, the full flexibility of co-simulation is combined with the stability of a monolithic approach applying the novel Interface Jacobian-based Co-Simulation Algorithm (IJCSA).

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1. Introduction

Renewable and clean energy methods are increasingly becoming more popular as our fossil fuels diminish and more environmentally friendly methods are sought. Wind energy harvesting with wind turbines is such a renewable energy source gaining widespread popularity. More effective wind turbines are being designed, with the next generation wind turbines having blade lengths exceeding 100 m. This poses many challenges in the design and operations of these structures. Scalable multiphysics simulation tools are required in order to design and judge performance, durability and safety of these machines.

We present a simulation of a wind turbine involving the interaction of the blades, generator/gearbox/rotor, control unit and the three-dimensional flow field. We employ the co-simulation approach by coupling three codes: OpenFOAM modeling the air flow around the structure, an in-house multibody dynamics code modeling the generator/gearbox and an in-house code modeling the control unit. In contrast to contemporary simulations of wind turbines (Sezer-Uzol and Long, 2006; McTavish et al., 2009; Chao et al., 2008; Mo and Lee, 2012; Yelmule and Anjuri VSJ, 2013; Anjuri VSJ, 2012; Hsu and Bazilevs, 2012; Lindenburg, 2003; Mo et al., 2013; Sørensen et al., 2002; Tongchitpakdee et al., 2005; Wang et al., 2012; Potsdam and Mavriplis, 2009; Hsu et al., 2012; Zahle et al., 2009; Li et al., 2012) the rotational velocity of the turbine is the result of the solution of a coupled problem and does not need to be prescribed in the presented approach, resulting in a more physical representation.

The presented CFD simulation results were validated against measurement data from the National Renewable Energy Laboratory (NREL) Unsteady Aerodynamics Experiment (UAE) Phase VI performed in the NASA AMES wind tunnel (Hand et al., 2001; Simms et al., 2001).

By using the numerical model of the NREL UAE Phase VI a fully-coupled co-simulation of an emergency brake maneuver scenario is presented within this work. For this loading scenario it is essential to model the control system taking into account the interaction of the turbine components with the environment (air flow).

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A novel co-simulation algorithm (Sicklinger et al., 2014) is used that guarantees both, accuracy and stability, and captures the realistic behavior by appropriately modeling the interaction of various components. One of the advantages of the co-simulation approach is that it allows combining different fidelity models during the various design and development stages, thus helping to improve technical system evaluation at every stage of the design process.

2. NREL UAE Phase VI

In order to be able to perform a validation of the simulation, experimental data needs to be available as basis. The National Renewable Energy Laboratory (NREL) Unsteady Aerodynamics Experiment (UAE) Phase VI is a widely used experiment for validation purposes as it is a full scale wind tunnel experiment. This allows that all needed parameters for the simulation are precisely known.

The major advantage for validation is "the presence of strictly controlled inflow conditions" (Simms et al., 2001) which "were met by testing the NREL UAE in the NASA-Ames 24.4-m (80 in) by 36.6-m (120 in) wind tunnel" (Simms et al., 2001). Zell and Flack (1989) state that the inflow speed of the wind tunnel deviates less than 0.25% from the nominal value, the flow velocity vector diverges less than 0.5° from the test section (*y*-) axes and the achieved turbulence intensity in streamwise direction is no more than 0.5%. Thus, stochastic atmospheric wind behavior is not of concern in this experiment and the inlet velocity is modeled as a steady-state block profile, i.e. all velocity vectors of the inlet plane only have a constant component in the *y*-direction. Nevertheless, the extension of the simulation to consider Atmospheric Boundary Layer (ABL) profiles would be straightforward, like it is shown in Michalski et al. (2011), Andre et al. (2014) and Wüchner et al. (2014).

Furthermore, this experiment is a very well documented case and investigated by many other research groups (Sezer-Uzol and Long, 2006; McTavish et al., 2009; Chao et al., 2008; Mo and Lee, 2012; Yelmule and Anjuri VSJ, 2013; Anjuri VSJ, 2012; Hsu and Bazilevs, 2012; Lindenburg, 2003; Mo et al., 2013; Sørensen et al., 2002; Tongchitpakdee et al., 2005; Wang et al., 2012; Potsdam and Mavriplis, 2009; Hsu et al., 2012; Zahle et al., 2009; Li et al., 2012). A lot of different numerical methods were validated by using the experimental data. This additionally leads to a lot of available simulation data. However, none of the given references takes into account the interaction of the blades, the generator/gearbox, the control unit and the fluid at the same time.

In the following a comprehensive description of the experiment is given.

The UAE, initially named "Combined Experiment", was started in 1987 by the National Renewable Energy Laboratory to provide detailed information on the full-scale 3D aerodynamic behavior of wind turbines.

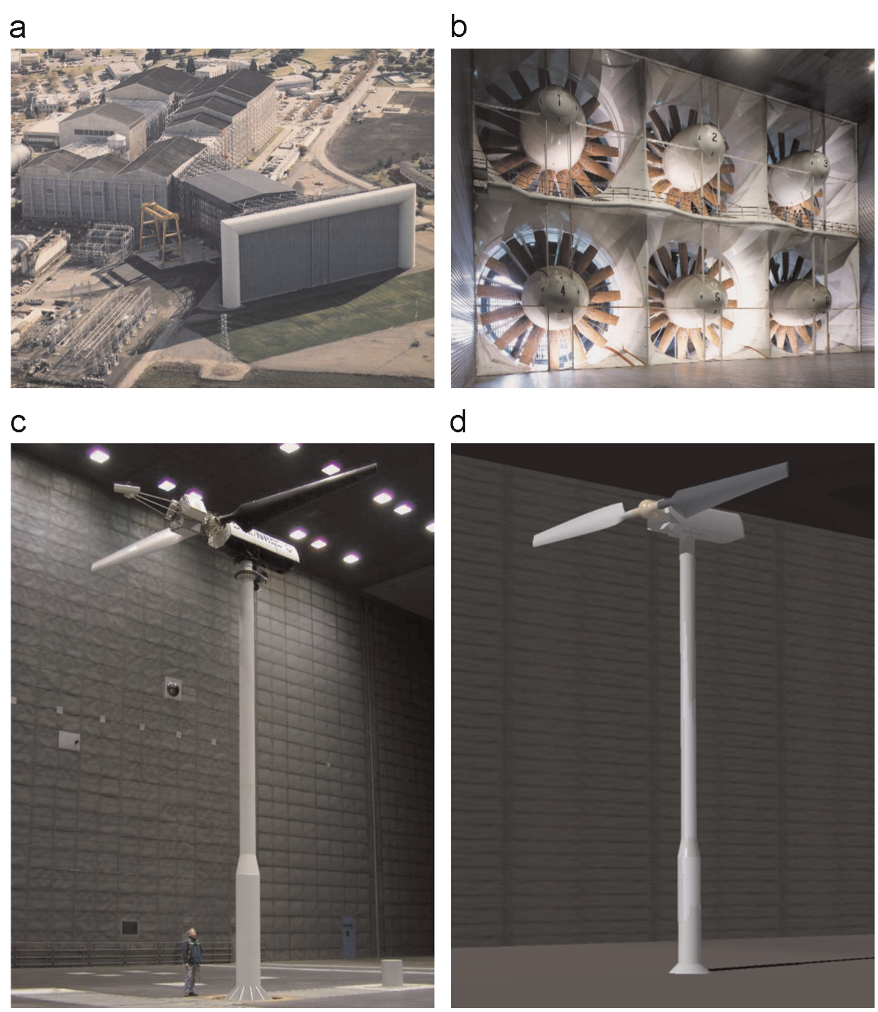

Fig. 1. NASA's wind tunnel and NREL UAE Phase VI wind turbine (Hand et al., 2001). (a) Wind tunnel aerial view (NREL, 2014). (b) Six wind tunnel fans (NREL, 2014). (c) Experiment (NREL, 2014). (d) CAD model.

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