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# Wind tunnel testing of scaled wind turbine models: Beyond aerodynamics

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ABSTRACT

An aeroelastically scaled model of a wind turbine is described, featuring active individual blade pitch and torque control. The model, governed by supervision and control systems similar to those of a real wind turbine, is capable of simulating steady conditions and transient maneuvers in the boundary layer test section of the wind tunnel of the Politecnico di Milano. Expanding the classical scope of wind tunnel models, the present experimental facility enables applications ranging from aerodynamics to aeroelasticity and control.

After a description of the model design and of its main characteristics, several applications are presented. Results are shown for the validation of a wind misalignment observer, for the optimization of the open-loop pitch profile used during emergency shutdowns, for the control in wake interference conditions of two models, and for active load alleviation by higher harmonic individual blade pitch control. Results demonstrate the potential of the proposed experimental facility to enable non-standard observations in the controlled environment of the wind tunnel, beyond the classical purely aerodynamic ones.



## 1. Introduction and motivation

The understanding and simulation of the wind energy conversion process for single wind turbines and wind farms requires the ability to model multiple complex interacting physical processes taking place at diverse spatial and temporal scales. Clearly, the ability to effectively design wind energy systems ultimately relies, apart from an appropriate knowledge of the physics, on the fidelity to reality of the mathematical models used in simulations. Consequently, there is a need to validate such models and to calibrate their parameters so as to maximize their accuracy.

Validation and calibration can be performed with the help of experimental observations, conducted either on the full system or on its sub-components. When looking at the full wind turbine or wind farm system, testing and measurements conducted in the field, although invaluable, present some hurdles. First, it is usually difficult to have complete and accurate knowledge of the environmental testing conditions, which by the way cannot in general be controlled, and, secondly, costs and testing time are often quite relevant.

To complement, support and, when possible, replace field testing, one can resort to the use of scaled models. In such testing conditions it is usually impossible to exactly match all relevant physics due to limitations of the scaling conditions, because of the frequent impossibility of assuring the same full scale and scaled values for all non-dimensional parameters. On the other hand, one has in general a better control and knowledge of the testing conditions, errors and disturbances. Furthermore, it may be possible to perform measurements which might not be feasible at full scale, and the testing typically incurs in much lower costs. Therefore, scaled testing does not replace simulation or field testing, but works in synergy with both towards the goal of delivering validated and calibrated numerical simulation tools, as well as an improved knowledge of the problem at hand.

In the area of aerodynamics, wind tunnel testing of wind turbine models has been reported by, among others, Oku et al. (1996), Hand et al. (2001), Vermeer et al. (2003), Snel et al. (2007) and Schepers and Snel (2007). These and similar studies have produced valuable information and measurements regarding the performance of rotors and the behavior of airfoils, blades and wakes, helping not only with the understanding of the aerodynamical physical processes, but also with the validation and calibration of suitable mathematical models.

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**Nomenclature**

| | |
|---|---|
| $a$ | speed of sound |
| $c$ | blade chord |
| $g$ | gravitational acceleration |
| $i$ | current intensity |
| $n$ | scale factor |
| $n_t$ | time ratio |
| $r$ | radial position |
| $t$ | time |
| $t_f$ | fault time instant |
| $A$ | rotor area |
| $C_D$ | drag coefficient |
| $C_F$ | thrust coefficient |
| $C_L$ | lift coefficient |
| $C_P$ | power coefficient |
| $C_T$ | torque coefficient |
| $C_{L,\alpha}$ | lift curve slope |
| $I$ | blade flapping inertia |
| $J$ | optimization cost function |
| $R$ | rotor radius |
| $T_a$ | aerodynamic torque |
| $T_g$ | generator torque |
| $V$ | wind speed |
| $V_r$ | rated wind speed |
| $\boldsymbol{a}$ | vector of model coefficients |
| $\boldsymbol{m}$ | vector of blade harmonics |
| $\boldsymbol{p}$ | vector of unknown parameters |
| $\beta$ | blade pitch angle |
| $\lambda$ | tip speed ratio |
| $\mu$ | air viscosity |
| $\omega$ | pulsation |
| $\phi$ | wind misalignment angle |
| $\rho$ | air density |
| $\tau$ | non-dimensional time |
| $\Omega$ | rotor angular speed |
| Fr | Froude number |
| Lo | Lock number |
| Ma | Mach number |
| Re | Reynolds number |
| $(\cdot)^T$ | transpose |
| $(\cdot)^{\mathrm{IP}}$ | rotor in-plane component |
| $(\cdot)^{\mathrm{OP}}$ | rotor out-of-plane component |
| $(\cdot)_M$ | quantity pertaining to the scaled model |
| $(\cdot)_P$ | quantity pertaining to the physical full scale system |
| $(\cdot)_{1c}$ | first cosine harmonic |
| $(\cdot)_{1s}$ | first sine harmonic |
| $(\cdot)_{fa}$ | fore-aft component |
| $\check{(\cdot)}$ | experimentally measured quantity |
| $\hat{(\cdot)}$ | quantity obtained by simulation |
| $\dot{(\cdot)}$ | derivative w.r.t. time, $\mathrm{d}\cdot/\mathrm{d}t$ |
| ADC | actuator duty cycle |
| BEM | blade element momentum |
| CAN | controller area network |
| CFD | computational fluid dynamics |
| DLC | dynamic load case |
| EOG | extreme operating gust |
| FBG | fiber Bragg grating |
| FEM | finite element method |
| IPC | individual pitch control |
| LES | large eddy simulation |
| PID | proportional integral derivative |
| RANS | Reynolds-averaged Navier–Stokes |
| TSR | tip speed ratio |

Nonetheless, aerodynamics is only one of the coupled phenomena that take place in the wind energy conversion process and whose understanding is crucial for the most effective design and operation of wind turbines. In fact, design loads on wind turbines are dictated by transient phenomena, where the effects of inertial and elastic loads, as well as of the closed-loop control laws used for a variety of tasks onboard the machine, play a very major role.

In this paper we propose to expand scaled wind tunnel testing beyond the sole domain of aerodynamics. To this end, we describe an aeroelastically scaled model of a multi-MW wind turbine, featuring active individual blade pitch and torque control. The model was designed so as to deliver realistic aerodynamic performance, and can be used for aerodynamic investigations, for example regarding wakes, their characteristics and their modeling. However, the model was also conceived for conducting experimental investigations on the aeroservoelasticity of wind turbines in the controlled environment of a wind tunnel. As such, it can be used for studying the machine response in extreme operating conditions (e.g., emergency shutdowns, operation at high yaw angles, response following failures of onboard sub-systems, etc.), something that is difficult to do in the field. The model can also support research on advanced pitch-torque control laws, on load and wind observers, as well as a variety of other aeroelastic investigations such as the study of the effects of loads induced within a wind farm by wake impingement caused by upstream wind turbines.

The paper is organized according to the following plan. Section 2 describes the scaled wind turbine model characteristics. At first, Section 2.1 describes the wind tunnel of the Politecnico di Milano where the model is typically operated. Next, Section 2.2 states the design requirements that stem from the diverse non-standard applications that need to be supported by the model, while Section 2.3 formulates the scaling laws. The general configuration of the model is given in Section 2.4, followed by Section 2.5 that describes the aerodynamic design, while Sections 2.6–2.8 describe sensors and the pitch and torque systems. The description of the model is complemented by Section 2.9 that discusses the real-time control and model management system, Section 2.10 that defines support tools that were designed for the testing, calibration and maintenance of the models and of their principal sub-components, and finally Section 2.11 that describes a comprehensive aeroservoelastic simulation environment of the experimental facility. Next, a number of non-aerodynamic and non-standard applications are presented in Section 3. A wind misalignment estimator, used in support of active yaw control, is validated in Section 3.1. Next, Section 3.2 describes the optimization of emergency shutdown maneuvers, including the calibration of a suitable mathematical model. Finally, Section 3.3 describes active control applications, focusing on regulation in wake interference conditions, as well as higher harmonic individual blade pitch control. Conclusions and an outlook to future work end the paper at Section 4.

## 2. Scaled wind turbine model

### 2.1. The Politecnico di Milano wind tunnel

The wind tunnel of the Politenico di Milano, which was used for all tests carried out during this project, is a closed-return configuration facility arranged in a vertical layout with two test rooms in the loop, as depicted in Fig. 1.

The wind tunnel features 14 driving fans for a total installed power of 1.4 MW, and has two test sections.