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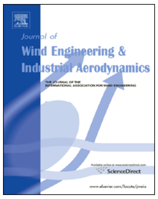

Calibration of wind turbine lifting line models from rotor loads

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ABSTRACT

This paper is concerned with the calibration of lifting line models of wind turbine rotors. In fact, properly tuned lifting lines are key for the accurate simulation of wind energy systems, for example in the areas of performance, aeroelasticity and wake aerodynamics.

The problem is formulated as the constrained optimization of a maximum likelihood cost function, driven by measurements of the rotor loads at the hub and possibly along the blades. Additive functions that correct the lift and drag characteristics of the blade airfoils are identified; such functions depend on the angle of attack and on the spanwise location along the blade, dependence that is approximated using suitable shape functions and their associated nodal parameters.

The estimation problem expressed in terms of the physical nodal parameters is shown to be difficult and typically ill-posed, because of low observability and collinearity of the unknowns. To overcome this difficulty, a novel method is proposed that uses a singular value decomposition of the Fisher information matrix. By this decomposition, the problem is recast in terms of a new set of variables that are statistically independent; in turn, this is used for readily selecting only those parameters that are associated with a sufficiently high level of confidence. The mapping between the new statistically independent and the original physical parameters is expressed by eigenshape functions, whose inspection clarifies which parameters are observable in which ranges of the angle of attack and blade span domain.

The paper is complemented by examples that illustrate the main features of the proposed method. At first, a scaled rotor model is tested in a wind tunnel, and hub measurements are used for the calibration of its lifting line model, whose nominal characteristics appear to be largely in error. Much improvement in the fidelity of the lifting line is observed after calibration by the procedure described here. Next, a simulation study is conducted that illustrates the effects of multiple blade load measurements in the ability to spanwise localize the contributions of different airfoils.

1. Introduction and motivation

At present, several aerodynamic models for wind turbine rotors are based on the coupling of a lifting line with a model of the wake and of the surrounding flow. A lifting line describes a blade as a spanwise sequence of two-dimensional airfoils, typically characterized by their chord, twist and aerodynamic center position with respect to an arbitrary reference curve. Each airfoil is in turn characterized by its lift, drag and moment coefficients, which vary as functions of the angle of attack, Reynolds and possibly Mach numbers. The aerodynamic coefficients are either obtained experimentally from ad hoc wind tunnel tests (Althaus, 1988; Abbott and von Doenhoff, 1959) or computed numerically with specialized codes (for example, see Drela and Giles, 1987).

Different models are available for the coupling with lifting lines, depending on trade-offs among accuracy, modeling complexity, computational cost and final scope of the simulation. Possible choices range from blade element momentum (BEM) theory (Hansen, 2008; Schepers, 2012), dynamic and free wake models (Peters, 2009), or computation fluid dynamics (CFD) approaches, such as the ones based on large eddy simulation (LES) techniques (Wu and Porté-Agel, 2011; Churchfield and Lee, 2012). Such models currently cover many of the very different needs arising in the study and design of wind energy systems. These range from the computation of load spectra on a machine, typically implying in excess of 10^7 time steps and presently routinely carried out by using sophisticated variants of the BEM

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Notation

A	rotor area
C_D	drag coefficient
C_F	thrust coefficient
C_L	lift coefficient
C_P	power coefficient
C_{Mx}	in-plane bending moment coefficient
C_{My}	out-of-plane bending moment coefficient
F	aerodynamic thrust
J	cost function
N	number of samples
P	aerodynamic power
R	rotor radius
V	wind speed
m	number of outputs
n	number of parameters
s_i	ith singular value
$\boldsymbol{F}$	Fisher information matrix
$\boldsymbol{G}$	sensitivity matrix of outputs with respect to parameters
$\boldsymbol{M}$	square root of Fisher matrix
$\boldsymbol{R}$	error covariance matrix
$\boldsymbol{S}$	square matrix of singular values
$\boldsymbol{U}$	matrix of left singular vectors
$\boldsymbol{V}$	matrix of right singular vectors
$\boldsymbol{\Sigma}$	rectangular matrix of singular values
$\boldsymbol{n}$	vector of shape functions
$\boldsymbol{p}$	vector of physical parameters
$\boldsymbol{r}$	residual vector
$\boldsymbol{y}$	output vector
$\boldsymbol{z}$	measurement vector
$\boldsymbol{\psi}$	vector of eigenshapes
$\boldsymbol{\theta}$	vector of statistically independent parameters
Δ	corrective function
Ω	rotor speed
α	angle of attack
β	blade pitch
$\chi_{p,q}$	correlation between pth and qth parameters
η	non-dimensional spanwise coordinate
λ	tip speed ratio
ρ	air density
σ	standard deviation
$d_{p,q}$	element p, q of Fisher matrix inverse
$(\cdot)^*$	estimated quantity
$(\cdot)^0$	nominal quantity
$(\cdot)^T$	transpose
$(\cdot)_{\mathrm{ID}}$	identifiable quantity
$(\cdot)_{\mathrm{NID}}$	non-identifiable quantity
$(\bar{\cdot})$	true (unknown) quantity
BEM	blade element momentum
CFD	computational fluid dynamics
LES	large eddy simulation
ML	maximum likelihood
RANS	Reynolds averaged Navier–Stokes
SQP	sequential quadratic programming
SVD	singular value decomposition
TSR	tip speed ratio

approach, all the way to the generation of turbulent flow fields within a wind farm, for which LES methods are the current method of choice (Churchfield et al., 2012; Fleming et al., 2013).

In all these lifting-line-based approaches, the coupled model provides for a description of the flow field around the rotor. This, in addition to the knowledge of the instantaneous environmental wind and blade-motion-induced speed, allows for the computation of the local angle of attack and of the relevant fluid dynamic parameters at any point along the lifting line. From this information, using the available airfoil aerodynamic coefficients, one can generate the local lift, drag and moment at the corresponding blade cross section, which are in turn fed back as driving forces to the coupled flow model. Iterations are carried out between the coupled flow model and the lifting line, until the flow kinematics is coherent with the loading, according to the used model.

The ability of such approaches to accurately compute all quantities of interest relies on whether the models are capable of capturing the relevant physics, on an adequate spatial and temporal resolution of the solution scales, and on the correct tuning of all physical parameters. System identification (or, more precisely, parameter estimation) techniques are available to calibrate parameters in mathematical models of physical systems from available experimental observations of relevant quantities (Ljung, 1999).

This work deals with the calibration of aerodynamic models for wind turbine rotors, and it is in particular concerned with the estimation of lifting line airfoil aerodynamic characteristics. These may differ from nominal assumed ones for a variety of reasons: shape defects due to manufacturing imperfections, erosion, dirt or ice formation; imprecisions during their two-dimensional characterization because of experimental or numerical defects; lack of two-dimensionality, uncorrected by other means in the model (on account for example of Coriolis effects in the root region, cross-flow due to blade sweep, or other reasons).

Goal of this work is the development of methods that can correct available baseline airfoil characteristics, using measured rotor data. In fact, it is clear that the loads generated on a rotor, at the hub and along the blades, depend on the aerodynamic characteristics of the airfoils. Hence one can hypothesize that, by using measured quantities such as rotor power and thrust and blade loads, the local characteristics of its airfoils could be inferred. The problem is difficult because of the possible low observability of the parameters of interest, since airfoil characteristics in some sections of the blade might have small effects on the measured quantities. Furthermore, as it is often the case in identification problems, some parameters may have effects on the measurements that are similar to the ones of other parameters, so that their respective characteristics may be difficult to discern and separate from one another.

To deal with these problems, the method presented in this work has been designed accordingly. To account for the inevitable presence of various sources of errors and noise in the measurements, the approach is based on a maximum likelihood formulation that can account for sensor and process noise. Furthermore, to ease the understanding of the well posedness of the problem and the choice of a set of identifiable parameters, the method makes use of a singular value decomposition (SVD) approach (Golub and van Loan, 1996; Lancaster and Tismenetsky, 1985). By this method, the physical parameters of interest, which represent corrections to the baseline lift and drag characteristics of the airfoils, are recast in terms of a new set of statistically independent parameters. This reformulation of the problem presents two key advantages: first, one has a simple way of selecting only those parameters that are associated with a desired level of confidence; second, by visual inspection of the eigenshape functions associated with the new parameters, one can understand which physical characteristics of the blade airfoils can be reliably identified from a given set of available measurements.