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RESEARCH ARTICLE

Bayesian calibration of AeroModule code using DanAero data

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Abstract

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Bayesian calibration, BEM models.

1 | INTRODUCTION

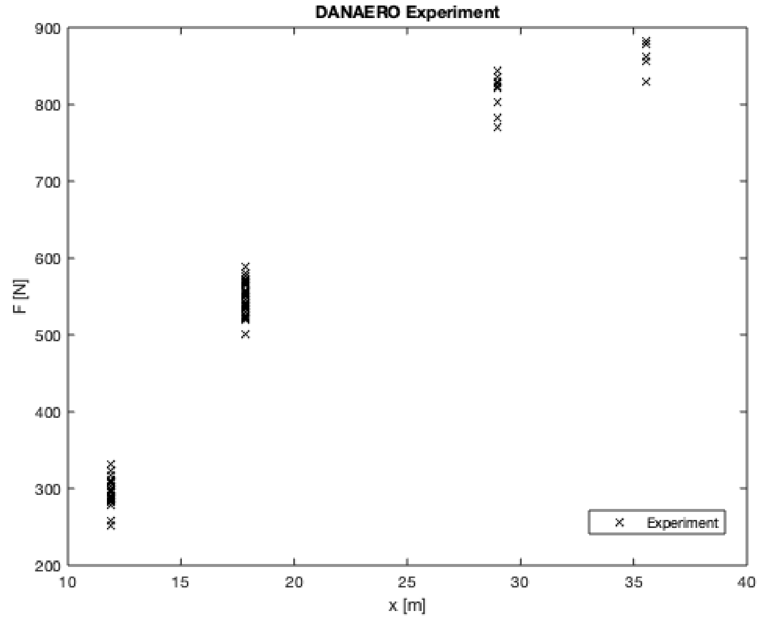
The wind energy industry is experiencing remarkable growths annually. Despite the great progress made, further cost reductions in wind turbine technology are necessary for wind energy to reach its full potential in terms of the large-scale supply of electricity. Improving the reliability of aerodynamic models embedded in the design software currently used in industry is indispensable to guarantee reductions in the cost of wind energy.

Due to its relatively high computational efficiency compared to free-wake vortex methods and CFD, the Blade-Element-Momentum (BEM) theory still forms the basis for many aerodynamic models. Yet various experimental campaigns have demonstrated that BEM-based design codes are not always sufficiently reliable for predicting the aerodynamic load distributions on the wind turbine blades [1]. In many situations, the reliability of such codes was found to be unacceptable, in particular when comparing the predicted results by different aerodynamics/aeroelastic codes from various universities/institutions with the measurement data obtained from the UAE experimental campaigns. In some cases, deviations of the BEM predictions from the measurements exceeded 200%, even though the simplest operating conditions of a wind turbine were being considered (i.e. uniform wind-speed and constant rotor speed, blade pitch and yaw angle).

Wind tunnel tests on model turbines are indispensable to have a better understanding of the underlying physics and to improve engineering models for design codes. The controlled environment offered by a wind tunnel provides a set of measurements that is free from the uncertainties caused by the different atmospheric effects that are always present in open field tests of turbines. To improve the predictions of BEM-based design codes, more reliable airfoil data models and inflow correction models are required. However, using the experimental data to improve these models is not an easy task. Two major problems are encountered: Firstly, measurement data is usually rare and limited. Secondly, there is a difficulty in determining accurately the angle of attack for the operating turbine.

In this investigation, we describe an approach for combining observations from DanAero field experiments with predictions obtained using the TNO's Aero-Module aeroelastic (BEM) code to carry out statistical inference. Of particular interest here is determining uncertainty in the resulting predictions. This typically involves calibration of parameters in the computer model in response to the sensitivity analysis study carried by Kumar et al. [2].

In recent times, there has been increasing efforts in using Bayesian approach for the calibration of computer models. This is because of its ability to quantify uncertainties in input parameters while at the same time reducing discrepancies between simulation output and physical measurements. In the Bayesian calibration of computer models, Markov Chain Monte Carlo (MCMC) methods are a common way for sampling from the posterior distributions of the calibration parameters. Its widespread use can be attributed to its ease of use in a wide variety of problems.



2 | DANAERO EXPERIMENT

A measurement campaign was carried out as part of the DanAero MW experiment[3]. A 2.3MW NM80 turbine located at the Tjæreborg Enge site and a nearby met mast were both instrumented with various sensors. ScaniValve system was used for the surface pressure measurements on the turbine blade.

Besides the data obtained directly from the Tjæreborg Enge site, a number of wind tunnel tests on different airfoils of NM80 turbine were also carried out in different wind tunnels[4]. The objective of the wind tunnel tests was to measure the lift, drag, moment, normal force coefficient and tangential force coefficient at four blade sections (11.87 m, 17.82 m, 28.97 m, and 35.53m) of the LM38.8 blade (38.8m) which were instrumented with pressure taps.

The Tjæreborg experiment database contains 35 Hz measurements and 10 minute statistics (mean, minimum, maximum and standard deviation) of all the data acquired by the DaqWin system as well as down sampled surface pressure measurements from five selected pressure taps at each of the four blade sections. All the data from the experiments are available in data files with formats as explained in[3,4]

3 | BEM MODEL - AEROMODULE

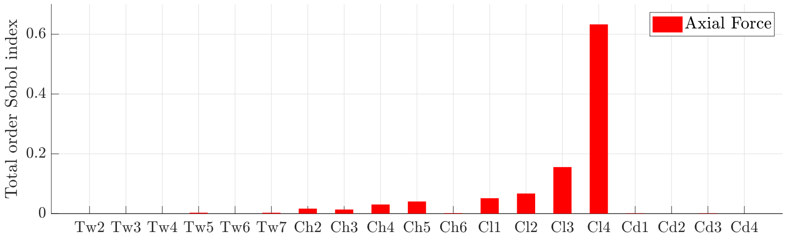
The aeroelastic BEM code - AeroModule is used to model the aerodynamic and aeroelastic behaviour of wind turbine blades by combining the concept of momentum conservation of the flow (aerodynamic analysis) with the equations of motion (structural analysis). In this work, we focus on the first aspect, namely the prediction of aerodynamic blade forces as given by the BEM method. For the purpose of calibration, normal aerodynamic forces measured under non-sheared and non-yawed inflow conditions has been selected from the measurements as described in[3]. The normal aerodynamic force on the blade surface is calculated based on the following equation:

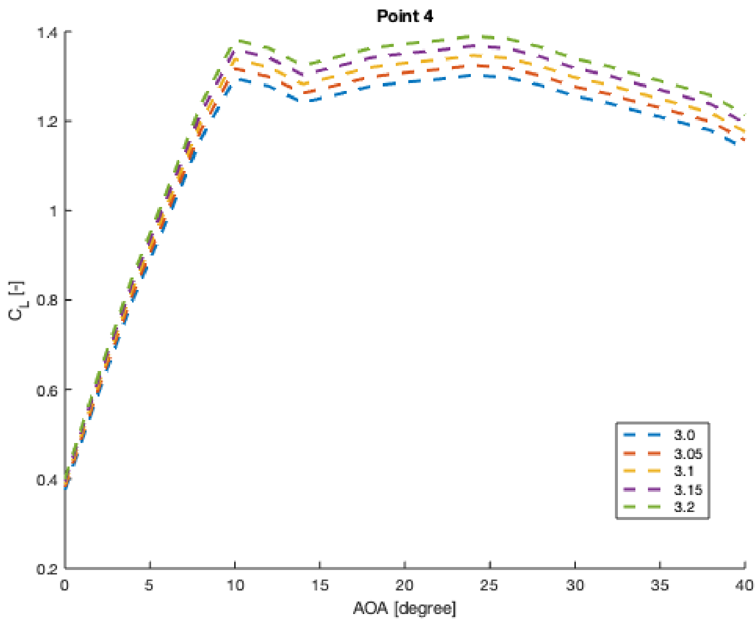
$$F_n = 0.5\rho W^2 c(C_l sin\beta + C_d cos\beta), \tag{1}$$

where ρ is the fluid density, W is the relative flow angle, c is the chord length and β is the relative flow angle. The 3D correction model as developed by Snel has been applied to account for the effects of rotation on the lift and drag coefficients (C_l and C_d). Then, the lift coefficient in equation 1 takes the following form:

$$C_{l3D} = 3.1(\frac{c}{r})^2(\frac{\Omega r}{W})^2(C_{l_{pot}} - C_{l2D}) \tag{2}$$

where r is the local radius, Ω is the rotational speed of the rotor, $C_{l_{pot}}$ is the potential flow lift coefficient and C_{l2D} is the 2D lift coefficient.





4 | SENSITIVITY ANALYSIS

Before calibrating the BEM model, sensitivity analysis was performed to identify the parameters that have the most influence over the model's output (F_n). The objective is to reduce the number of calibration parameters and choose only important parameters in the calibration process. This not only reduces computation cost but also helps mitigate over-fitting. Kumar et al. observed that the model's output is basically only sensitive to the lift coefficient C_l at the outward blade sections.

5 | LIFT COEFFICIENT PARAMETRIZATION

Snel derived a so-called '3D correction' method that gives an increase of the aerodynamic lift coefficient for the effects of rotation. The Snel factor 3.1 was originally used to fit with the DanAero measurements. Following the comparison of the UAE rotor experiment with the BEM code predictions, Snel concluded that this factor could as well be reduced to 3. Because it is known that the term $(\frac{c}{r})^2$ is an empirical fit which gives a stronger dependency on $(\frac{c}{r})$ than what is found from theory, it was decided to calibrate the the Snel factor; viz. a constant value for the range of α considered. Assuming a constant value of k, the C_l curve at point 4 is parametrized:

$$C_{l3D} = k(\alpha)(3.1 \pm \Delta) \tag{3}$$

where k = $(\frac{c}{r})^2(\frac{\Omega r}{W})^2(C_{lpot} - C_{l2D})$ as a function of angle of attack α.

6 | BAYESIAN CALIBRATION

Bayesian methods are used to estimate model parameter θ by combining two sources of information: prior information about θ and observations D on output variables x. The prior information of θ is based on expert knowledge, literature review or by measuring parameters directly in the field or laboratory. In our case, D as a function of x are field measurements from the DanAero experiment. Bayes theorem makes it possible to combine the two sources of information in order to calibrate θ. The first step is to assign a probability distribution to θ, representing our prior uncertainty about the value. In our case, we specified lower and upper bounds of the θ's uncertainty, defining the prior parameter distributions as uniform. The aim of Bayesian calibration is to reduce this uncertainty by using the D, thereby producing the posterior distribution for θ. This is achieved by multiplying the prior with the likelihood function, which is the probability of the D given the θ. The likelihood function is determined by the probability distribution of errors in observations. To generate a representative sample of θ from the posterior distribution, we used Markov Chain Monte Carlo (MCMC) methods.

Symbol	Description
D	Axial force at corresponding radial locations
x	Angle of attack
θ	Snel factor

6.1 | Metropolis-Hastings algorithm

It consists of three steps:

- Randomly generate a new 'candidate' parameter
$$\theta^* = \theta_{i-1} + \delta$$
where δ is a random vector generated using a multivariate normal distribution.
- Calculate the ratio of the posterior probability of the candidate vector over the posterior probability of the current candidate:
$$a = \frac{p(\theta^*|D)}{p(\theta_{i-1}|D)}$$
- Accept θ^* if a $\geq$ u, where u is an uniform random variable from an uniform distribution on the interval (3.0, 3.2), else reject and θ_i = θ_{i-1}

The new point θ^* is always accepted if its posterior value is no lower than the posterior value of θ_{i-1}. Once the chain has attained the N iterations, the chain must have converged to the target distribution which is the posterior θ distribution.

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