Renewable Energy 90 (2016) 352–361

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Uncertainty in wind climate parameters and their influence on wind turbine fatigue loads

Henrik Stensgaard Toft [a, *], Lasse Svenningsen [b], John Dalsgaard Sørensen [a], Wolfgang Moser [c], Morten Lybech Thøgersen [b]

[a] Aalborg University, Department of Civil Engineering, Sofiendalsvej 11, 9200 Aalborg SV, Denmark
[b] EMD International A/S, Niels Jernes Vej 10, 9220 Aalborg Ø, Denmark
[c] Nordex Energy GmbH, Langenhorner Chaussee 600, 22419 Hamburg, Germany

ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form
6 December 2015
Accepted 1 January 2016
Available online 14 January 2016

Keywords:
Wind turbine loads
Uncertainty modelling
Site assessment
Fatigue loads
Reliability analysis

ABSTRACT

According to the wind turbine standard IEC 61400-1, structural integrity of wind turbines is determined either by direct reference to wind data or by load calculation. In both cases, deterministic values are applied and uncertainties neglected for the wind climate parameters and the structural resistance.

The uncertainty related to the wind climate parameters depends highly on the presence, duration and quality of on-site wind measurements, and the perturbations introduced by flow modelling. For the wind speed distribution, the uncertainty is considered in assessment of the annual energy production. For other wind climate parameters which potentially have a large influence on the wind turbine loads, the uncertainty is often not well investigated.

This paper presents a probabilistic framework for assessment of the structural reliability level of wind turbines in fatigue loading. Uncertainty of the site specific wind climate parameters at each turbine position is estimated based on the local wind measurements, speed-up factors and the distance between the wind turbine and the measuring position. The framework is demonstrated for a wind turbine project in flat terrain. The results show that the uncertainty in the site specific wind climate parameters normally accounts for 10–30% of the total uncertainty in the structural reliability analyses.

1. Introduction

The general workflow in the assessment of site specific wind turbine loads is presented in Fig. 1. The site specific wind climate parameters are normally determined based on short-term measurements from one or several meteorological masts, or remote sensing devices, located within the wind farm area. In order to obtain an accurate assessment of the power production, the wind speed time series is normally long-term corrected using measurements from metrological stations, wind statistics or mesoscale data [1]. The local wind climate at each wind turbine position is determined using a micro-scale flow model which, besides using the wind speed, also uses information about the terrain, roughness and local obstacles [2,3]. In addition to annual wind speed distribution, micro-scale flow models can also estimate the wind speed standard deviation (i.e. turbulence) and wind shear at each wind turbine position. The estimated wind climate parameters are, for load calculation purposes, combined into an equivalent wind climate for each wind turbine position. This should according to IEC 61400-1 [4] consist of the annual omnidirectional wind speed distribution, average wind shear and air density along with the 90% quantile of the wind speed standard deviation and the maximum inflow angle. Together, these wind climate parameters form the simplified "equivalent wind climate".

The site specific wind turbine loads are determined based on aero-elastic simulations using the equivalent wind climate parameters and information about the geometry and stiffness of the individual wind turbine components along with the control system. The design iterations during development of new wind turbine types involve laboratory and full-scale tests, especially of blade and drivetrain components along with measurements from prototype wind turbines. This leads to an updated knowledge about the accuracy of the calculation models. However, uncertainty is still present for e.g. the wind turbine structure, aero-elastic model, wind climate parameters and turbulence simulation [5,6].

* Corresponding author. Sofiendalsvej 11, 9200 Aalborg SV, Denmark.
E-mail address: hst@civil.aau.dk (H.S. Toft).

http://dx.doi.org/10.1016/j.renene.2016.01.010

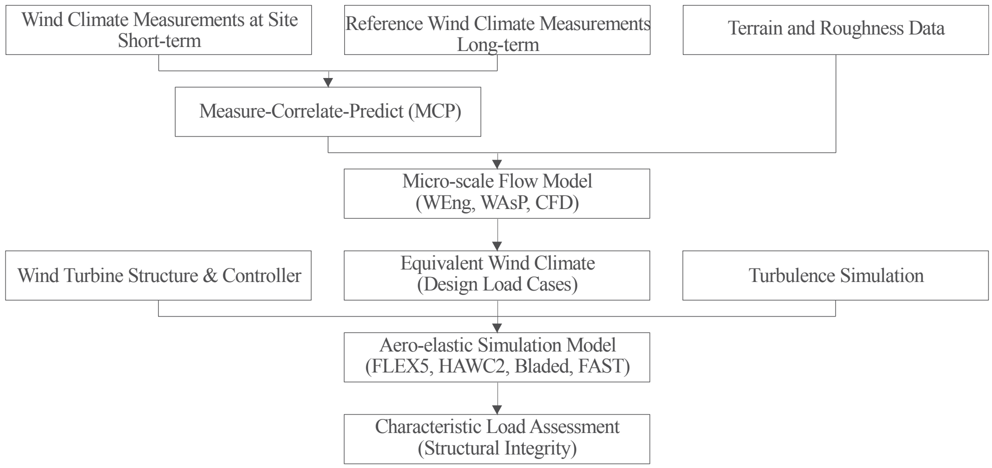

Fig. 1. Workflow in assessment of site specific wind turbine loads.

The uncertainty related to site specific wind climate conditions have been investigated in e.g. Refs. [7–10] in order to determine the resulting uncertainty in the wind resource. For these investigations, the uncertainty in the wind speed distribution is normally dominant. General uncertainty models for the wind climate parameters, with focus on wind turbine loads and reliability assessment, have been developed in e.g. Refs. [11,12]. This work was extended in Ref. [13] focusing on site specific uncertainties in the wind climate parameters and their influence on the reliability level for different wind turbine components.

The purpose of this paper is to propose a systematic and practical probabilistic framework for the assessment of uncertainty in the site specific wind climate parameters and assessment of structural reliability. A practical assessment of the uncertainties will allow for a broader application of probabilistic models in wind turbine site assessment and enable project developers and wind turbine manufacturers to account for uncertainties in site suitability analysis directly. Thereby, it is possible to develop layouts which are not only optimal with respect to energy production, but also optimal with respect to reliability level and operation & maintenance costs. The probabilistic framework follows the same workflow as shown in Fig. 1, but includes a modelling of the uncertainties related to each step.

The probabilistic framework for the assessment of site specific wind climate parameters is based on the assumption that the spatial uncertainty in the wind climate parameters can be estimated based on the modelled wind speed-up factors (i.e. flow perturbations) between the metrological mast and the wind turbine position along with the distance between these.

The remainder of this paper is organized as follows: section 2 describes the framework for probabilistic modelling of the uncertainties related to the wind climate parameters, section 3 describes the traditional deterministic approach for assessment of the structural integrity, section 4 presents the probabilistic design approach for structural reliability assessment, section 5 presents a numerical example with wind turbines in flat terrain, and finally conclusions are given in the last section.

2. Modelling of uncertainties in wind climate parameters

According to [14] and [15] uncertainties can be categorized as follows:

- Physical uncertainties (aleatory)
- Model uncertainties (epistemic)
- Measurement uncertainties (epistemic)
- Statistical uncertainties (epistemic)

The physical or aleatory uncertainties correspond to natural variations in physical quantities which cannot be reduced. The model, measurement and statistical uncertainties are epistemic and relate to uncertainties in mathematical models, uncertainties in measurements and the number of experiments. Epistemic uncertainties can be reduced by e.g. adopting better models, better measurement equipment and by using more data.

Aleatory uncertainty is in general introduced by modelling a variable x as a stochastic variable with mean value μ_x and standard deviation σ_x. Generally, the epistemic uncertainties are introduced by multiplicative stochastic variables or by modelling the statistical parameters in the distribution functions for the physical uncertainties as stochastic variables (typically by a Normal distribution). Often the former approach is used for model and measurement uncertainties, whereas the latter approach is used for the statistical uncertainty.

Uncertainties in wind climate parameters are often characterised based on their variation in time:

- Short-term uncertainties – between 10 min periods.
- Mid-term uncertainties – between days, months and seasons.
- Long-term uncertainties – between years.

The short-term and long-term uncertainties may be characterized as physical uncertainties. Medium-term uncertainties corresponding to daily and seasonal variations or different atmospheric conditions are not considered in this paper, because these are assumed described by the short-term uncertainties, and only complete annual dataset are used. In IEC 61400-12-1 [16] type A and B uncertainties are defined in relation to power curve assessment. In this context type A uncertainties correspond approximately to aleatory uncertainties, whereas type B corresponds approximately to epistemic uncertainties.

The long-term and epistemic uncertainties for the site specific average wind speed, wind speed standard deviation, wind shear, inflow angle and air density are estimated based on the available literature and summarized in Table 1. The physical and short-term uncertainties associated with the wind climate parameters are estimated based on site specific measurements. Seasonal variations in the short-term measurements should be considered if a non-