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2014 J. Phys.: Conf. Ser. 555 012033

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Effect of Geometric Uncertainties on the Aerodynamic Characteristic of Offshore Wind Turbine Blades

Benedikt Ernst, Henning Schmitt, and Jörg R. Seume

ForWind - Center for Wind Energy Research, Leibniz Universität Hannover,
Institute of Turbomachinery and Fluid Dynamics - TFD,
Appelstr. 9, 30167 Hannover, Germany

E-mail: ernst@tfd.uni-hannover.de

Abstract. Offshore wind turbines operate in a complex unsteady flow environment which causes unsteady aerodynamic loads. The unsteady flow environment is characterized by a high degree of uncertainty. In addition, geometry variations and material imperfections also cause uncertainties in the design process. Probabilistic design methods consider these uncertainties in order to reach acceptable reliability and safety levels for offshore wind turbines. Variations of the rotor blade geometry influence the aerodynamic loads which also affect the reliability of other wind turbine components. Therefore, the present paper is dealing with geometric uncertainties of the rotor blades. These can arise from manufacturing tolerances and operational wear of the blades. First, the effect of geometry variations of wind turbine airfoils on the lift and drag coefficients are investigated using a Latin hypercube sampling. Then, the resulting effects on the performance and the blade loads of an offshore wind turbine are analyzed. The variations of the airfoil geometry lead to a significant scatter of the lift and drag coefficients which also affects the damage-equivalent flapwise bending moments. In contrast to that, the effects on the power and the annual energy production are almost negligible with regard to the assumptions made.

1. Introduction

For the development of cost optimized offshore or onshore wind turbines with high reliability and low probabilities of failure, probabilistic design methods become increasingly important in order to consider several types of uncertainties. Uncertainties can be categorized into inherent (basic) uncertainties, model uncertainties as well as human and organisation errors [1]. Inherent uncertainties are related to the randomness of environmental variables (e.g. turbulence or wind shear). Model uncertainties can be subdivided into statistical uncertainties due to limited sample sizes of observed quantities and physical model uncertainties due to assumptions and simplification in the design models. These also include dimension uncertainties related to imperfect dimensions (e.g. geometrical quantities). In order to consider uncertainties, traditional deterministic or semi-probabilistic designs use partial safety factors, while probabilistic methods use full statistical distributions of the uncertain design variables. In the IEC standard 61400-1 [2] the partial safety factors for fatigue design of wind turbine blades are $\gamma_m = 1.20$ for material properties, $\gamma_n = 1.15$ for the consequences of failure, and $\gamma_f = 1.00$ for the load. These correspond to a



target probability of failure $P_f = 10^{-3}$ and a reliability factor of $\beta = 3.09$. The estimation of failure probabilities caused by ultimate or fatigue loading as well as the calibration of partial safety factors for wind turbines has been in the focus of numerous studies (e.g. [3, 4, 5, 6, 7]). However, no detailed information about geometric uncertainties of the rotor blades and how these can be modeled are available. Wind turbine blades are typically made of composite materials and molded in two halves which are bonded together. Due to the manufacturing process and due to the large dimensions of the rotor blades, significant variations of the airfoil and blade geometry can arise. Furthermore, there are unknown deformations during operation. These influence the aerodynamic loads which also affect the reliability of other wind turbine components.

In the design process, aeroelastic simulation tools are commonly used to calculate the aerodynamic loads by means of Blade Element Momentum (BEM) methods. In doing so, unsteady aerodynamic effects are taken into consideration by semi-empirical models. BEM methods require lift and drag coefficients as a function of the angle of attack for the different blade segments, while the airfoil geometry itself is not a direct input. Loeven and Bijl [8] investigated the effect of geometric uncertainties of the thin NACA 5412 airfoil by means of the probabilistic collocation method. They varied the maximum camber, maximum camber location and the thickness. Their results show a significant effect on the lift and drag coefficients due to geometry variations of the airfoil. For the NACA 64-618 and DU 93-W-210 airfoils, which are used in the DOWEC design study and the NREL 5 MW reference wind turbine, Demuijnck and Kooij [9] examined worst-case scenarios of certain airfoil deviations. They varied the leading and trailing edge as well as the thickness of the airfoils. It is shown that these variations affects the lift and drag coefficients as well as the power production of the DOWEC 6 MW blade. Petrone et al. [10] analyzed the effect of uncertainty on the performance of a small 50 kW wind turbine. They considered variability in the wind conditions, manufacturing tolerances, and insect contamination as sources of uncertainties and treat them within a probabilistic framework using Latin hypercube sampling and a stochastic simplex collocation. They varied the twist angle of the rotor blade as the only uncertain geometry parameter.

The objective of the present study is to investigate the effect of geometry variations of wind turbine airfoils on the lift and drag coefficients. Furthermore, the resulting effects on the loads and the performance of an offshore wind turbine are analyzed. For the investigations, the airfoils and the aeroelastic model of the NREL 5 MW reference wind turbine [11] are used. In order to use only a limited number of uncertain parameters, the geometry variations of the airfoils, are described by five characteristic parameters: the maximum thickness, the location of the maximum thickness, the maximum camber, the location of the maximum camber, and the trailing edge thickness. In order to investigate combined effects on the lift and drag coefficients, the parameters are varied simultaneously by means of Latin hypercube sampling. The Latin hypercube sampling is a statistical method to generate constrained sampling schemes of the uncertain parameters. The large number of required samples causes enormous simulation efforts. Therefore, lift and drag coefficients are calculated as a function of angle of attack with the panel code XFOIL [12]. Then, the aeroelastic simulation software FAST [13] is used to determine the loads and the performance of the offshore wind turbine.

2. Uncertain Airfoil Geometry

The rotor blades of the NREL 5 MW reference wind turbine are composed of a cylinder at the blade root, five different DU (Delft University) airfoils and the NACA64 airfoil at the outer part of the blade. The airfoils have a relative thickness between 18% and 40% which decrease with increasing blade length. A detailed description of the blade aerodynamic properties are given in [11] and the airfoil geometries as well as the corresponding lift and drag coefficients are given in

[14]. Except of the cylinder, the effect of geometric uncertainties is investigated for all airfoils. In order to avoid confusions, Table 1 shows the full name of the airfoils and the abbreviations used in the present paper. Furthermore, the maximum relative thickness and the relative radial positions of the airfoils are given.

Table 1. Airfoils used for the NREL 5 MW reference wind turbine

Full name	Abbreviation	Relative thickness	Rel. radial position
DU 99-W-405LM (adjusted)	DU40	40%	≥ 0.19
DU 99-W-350LM (adjusted)	DU35	35%	≥ 0.25
DU 97-W-300LM	DU30	30%	≥ 0.38
DU 91-W-250LM	DU25	25%	≥ 0.45
DU 93-W-210LM	DU21	21%	≥ 0.58
NACA 64-618	NA64	18%	≥ 0.71

As far as the authors know, information about manufacturing tolerances or differences between the real and the design geometry of wind turbine rotor blades are not available in the open literature. For this reason, some assumptions about geometry variations have to be made. Based on the baseline airfoil geometry, the geometry variations are performed in XFOIL [12]. There, the shape of the airfoils are described by cubic splines and characteristic airfoil parameters can be changed directly. The leading edge radius cannot be changed independently. A change also affects the maximum thickness or the location of the maximum thickness and vice versa. Due to this, only the maximum thickness t , the maximum thickness location x_t , the maximum camber w , the maximum camber location x_w , and the trailing edge thickness t_{TE} are varied independently to create geometry variations of the airfoils. These parameters are all normalized with respect to the chord length. Figure 1 shows the baseline geometry, the camber line, and the varied parameters of the DU25 airfoil.

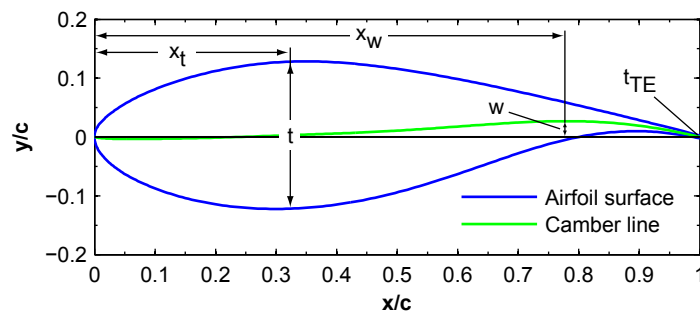


Figure 1. Geometry parameters of the DU25 airfoil

The parameters are varied relatively with respect to the original ones of the baseline geometry. For the variations truncated normal distributions are used. This is a reasonable assumption to model geometry tolerances in a production process [8, 15]. Except of the variations of the trailing edge thickness, all distributions have a mean value of 0% and a standard deviation of 10%, as it was also assumed by Loeven and Bijl [8]. In their work, the variation of the uncertain parameters are limited up to $\pm 30\%$. In terms of the DU40 airfoil with a chord length of 4.557 m and a relative thickness of 40%, this would lead to maximum thickness changes of ± 0.55 m. These large changes seems to be very unrealistic, therefore the lower and upper limits are assumed to be $\pm 5\%$. This leads to thickness changes, along the rotor blade of the NREL 5 MW reference wind turbine, between ± 0.091 m and ± 0.013 m. The relative trailing edge thickness of the DU

airfoils is between 0.0038 and 0.007 and of the NACA64 airfoil it is 0. These values are very small and therefore also the relative changes of $\pm 5\%$ would be negligible small. In the present paper, it is assumed that the relative trailing edge thickness can vary between 0 and 0.01. For reasons of simplification, the relative trailing edge thickness for all baseline airfoils is set to 0.005. Then, the lower limit of the relative changes is -100% and the upper limit is +100%. In order to ensure that also realizations at the lower and upper limit are possible, the standard deviation is set to $2/3$ of the upper limit.

3. Latin Hypercube Sampling

Uncertainty and sensitivity analyses are often performed by means of Monte Carlo simulations. These methods require a sampling procedure to create various sets of deterministic input parameters which describe the variability of these parameters. The simplest procedure is the simple random sampling. Based on a given probability distribution function, all random samples are generated independently from each other. This requires a large number of samples to reach a good approximation of the original distribution function. In order to reduce the number of required samples N , a very efficient and practical sampling procedure is the Latin Hypercube Sampling (LHS) [16, 17]. LHS divides the cumulative distribution function for each random variable into N equiprobable, non-overlapping intervals (see left diagram in Figure 2). Then, within each interval i a value is randomly selected. The random number in the i th interval is

$$u_i = \frac{u}{N} + \frac{(i-1)}{N}, \quad (1)$$

where $i = 1, 2, \dots, N$ and u is a random number in the range between 0 and 1. The random numbers u_i are transformed into the variable space by means of the inverse cumulative distribution function F_X^{-1} in order to obtain the random input variables [18]

$$x_i = F_X^{-1}(u_i). \quad (2)$$

The segmentation of the cumulative distribution function with a probability of $\Delta P = 1/N$ and the allocation of a sample within each interval lead to a good approximation of the tails of the original distribution function. In addition, there is also a good agreement of the mean value as well as the standard deviation of the samples with the original distribution. Due to the characteristic of this procedure, the values of the samples are sorted in ascending order and are not random [19]. Therefore, if more than a single variable is varied simultaneously, the correlation between the variables (correlated or uncorrelated) has to be taken into consideration. In the present paper, it is assumed that all variables are independent. In order to reduce the correlation between the realized variables, a single-switch-algorithm [20] is used which changes the order of the samples until the correlation between the input variables reaches a minimum. The single-switch-algorithm performs well for a small number of simulations and random variables. Figure 2 shows a schematic example of a LHS for two independent random variables X and Y .

In the present study the random input variables are the relative variations of the 5 characteristic airfoil parameters. These are varied simultaneously and independently from each other by means of the LHS. Based on the relative variations, the resulting airfoil geometries are created and the lift and drag coefficients are calculated with XFOIL. A description of the simulation settings is given in the next section. In order to ensure that the number of samples N has no significant effect on the distributions of the input and output parameters, different sample sizes are investigated. In every case, all 5 characteristic airfoil parameters are varied and the LHS is repeated 100 times to reduce effects of the randomly selected values within each non-overlapping interval. Figure 3 shows the mean value of the 100 mean values of the relative variations of the maximum thickness (left), which is used as an input parameter, and

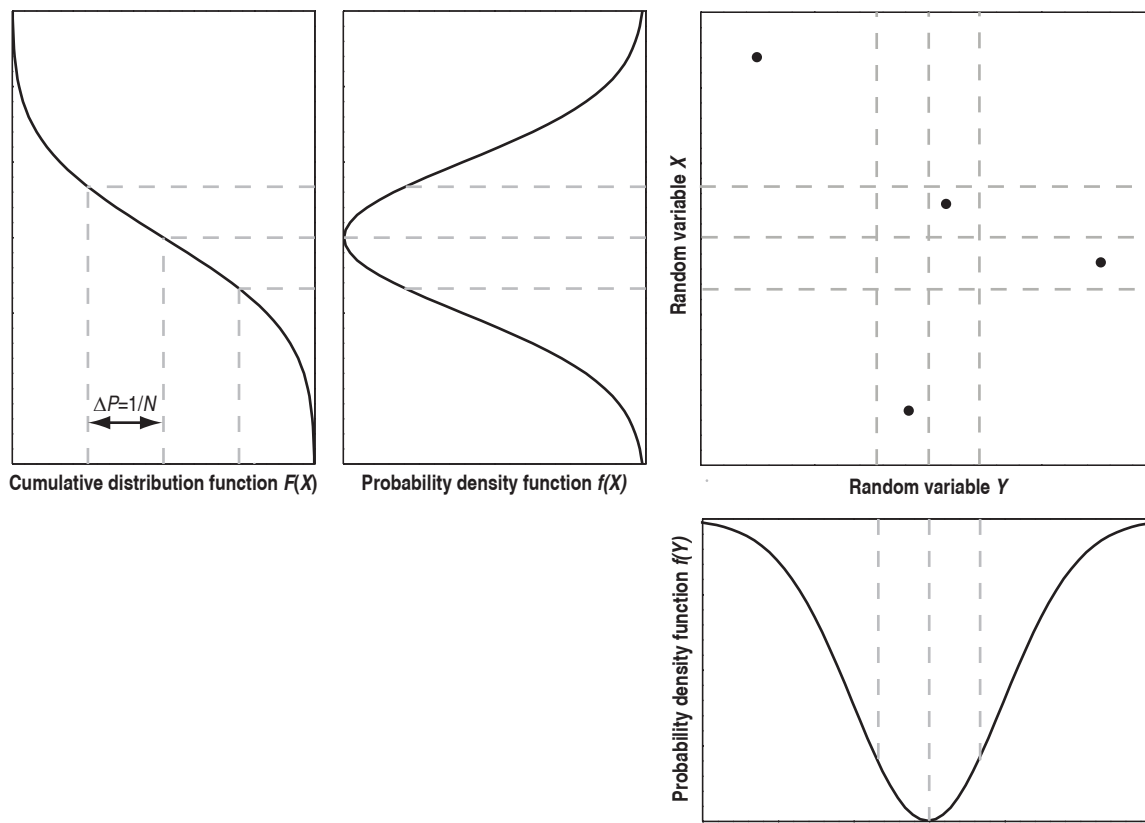


Figure 2. Schematic example for a Latin hypercube sampling with two normally distributed random variables and $N = 4$ samples

the mean value of the mean lift coefficient for an angle of attack of $AoA = 5^\circ$ (right) of the DU25 airfoil. The 95% confidence intervals of the input variable decrease significantly between the number of samples of 50 and 150. However, the confidence intervals are generally small. The effect of the sample size on the lift and drag coefficients is also very small. As a compromise between accuracy and simulation effort, 150 samples are selected for each airfoil. This results in correlation coefficients of all realized input variables lower than $1.3 \cdot 10^{-4}$.

4. Effect on Lift and Drag Coefficients

The aerodynamic lift and drag coefficients of the six different airfoils are calculated by means of the simulation tool XFOIL [12]. XFOIL is based on a panel method which also includes the e^n transition model. For all simulations free transition is assumed and the standard exponent of $n_{crit} = 9$ is used [12]. In accordance to [14], the flow around all airfoils is set to a Reynolds number of $Re = 7 \cdot 10^6$ for standard atmosphere conditions at sea level. Except of the stall region, the simulation results are in a good agreement with the lift and drag coefficients given by [14]. In the stall region the lift coefficient is typically over predicted by XFOIL while the drag coefficient is typically too low. Based on the assumptions, described in the previous sections, 150 geometry variations are simulated for each airfoil. The LHS creates samples of the relative changes of each uncertain input parameter. Therefore, the same sampling can be used for all airfoils. For example, Figure 4 shows the resulting variations of the lift and drag coefficients of the DU25 airfoil.

Due to the estimation errors in the stall region and due to the fact that at pitch-regulated

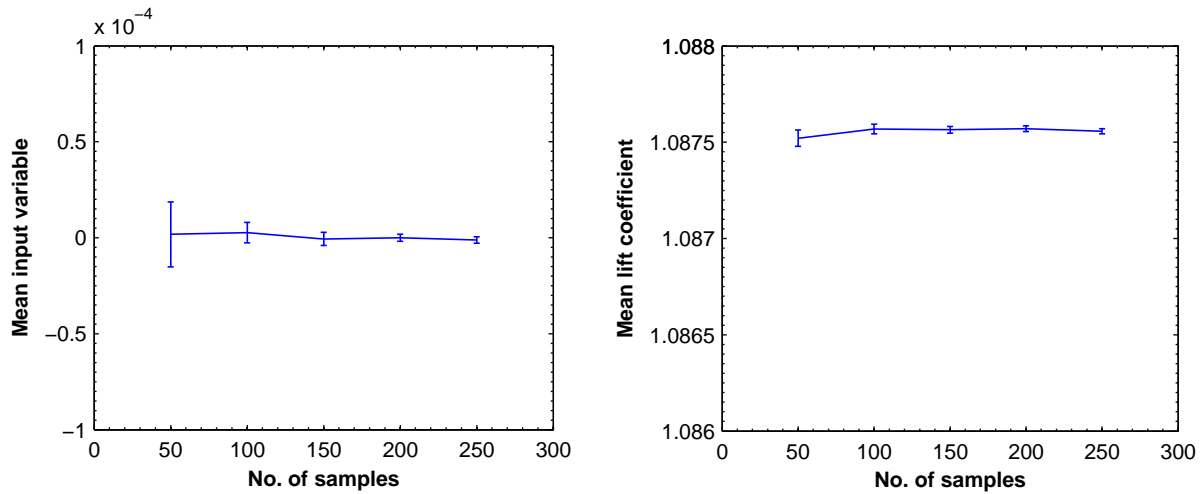


Figure 3. 100 repetitions of the LHS: mean of the relative variations of the maximum thickness (left) and mean lift coefficient of the DU25 airfoil (right) with 95% confidence intervals

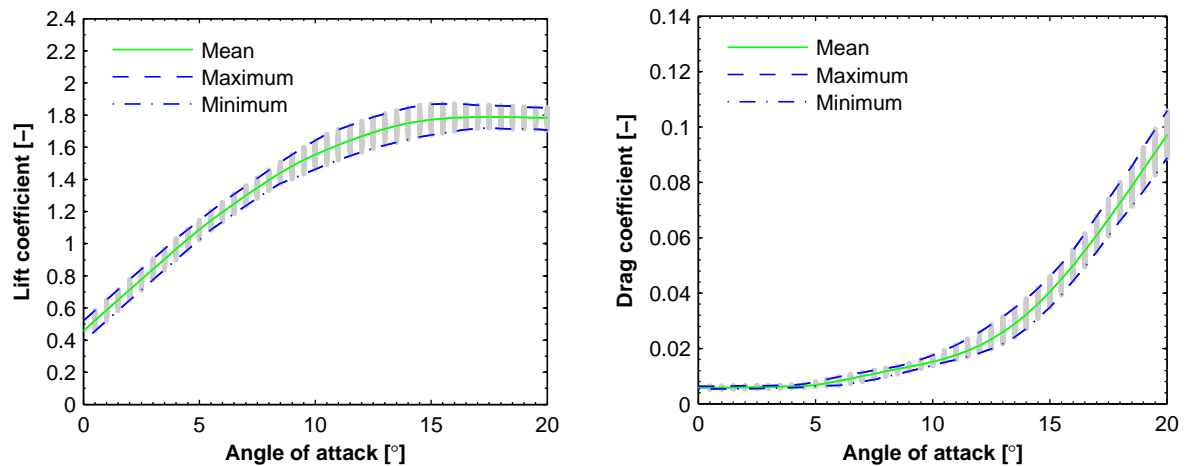


Figure 4. Lift coefficients (left) and drag coefficients (right) of the varied DU25 airfoil geometries

wind turbines typically no stall occurs, the focus is on angles of attack with attached flow (linear region of the lift coefficient). There, the scatter of the lift coefficient is almost constant as well as the slope of the curve. The slope of the DU25 lift coefficient has a coefficient of variation of $CoV = 0.019$. Based on the input uncertainty, the resulting coefficients of variations of the lift coefficients (left) and the drag coefficients (right) are shown in Figure 5. All airfoils have a nearly similar characteristic but on different levels. Except of the DU35 airfoil at high angles of attack, the geometric uncertainty of thinner airfoils leads to a lower coefficient of variation of the lift coefficient. A reason for this is for example the smaller changes of the dimensional thickness. The characteristic of the resulting effects on the drag coefficient are different compared to the lift coefficient. In the stall region of the thick airfoils, the coefficients of variation are significantly higher. In order to get an idea how the lift and drag coefficients are distributed, a Kolmogorov-Smirnov goodness-of-fit hypothesis test is used. For angles of attack with attached flow the scatter of the lift coefficient follows a normal distribution and the scatter of the drag coefficient

follows a shifted lognormal distribution. In both cases a significance level of 5% is chosen. Figure 6 shows the resulting probability density functions exemplarily for an angle of attack of $AoA = 5^\circ$. In the stall region the tested null hypothesis is not accepted for all situations and no consistent characteristic can be observed.

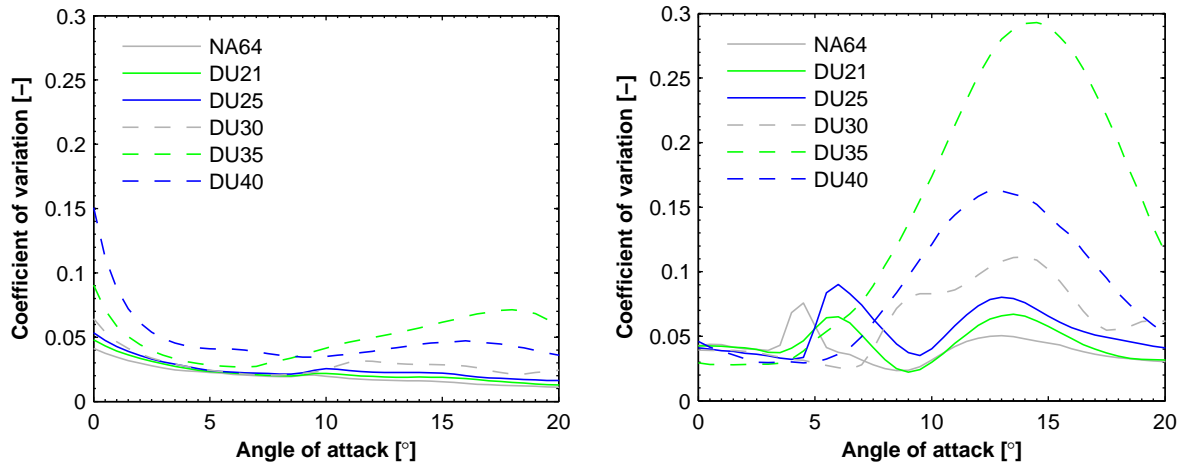


Figure 5. Coefficient of variation of the lift coefficients (left) and the drag coefficients (right)

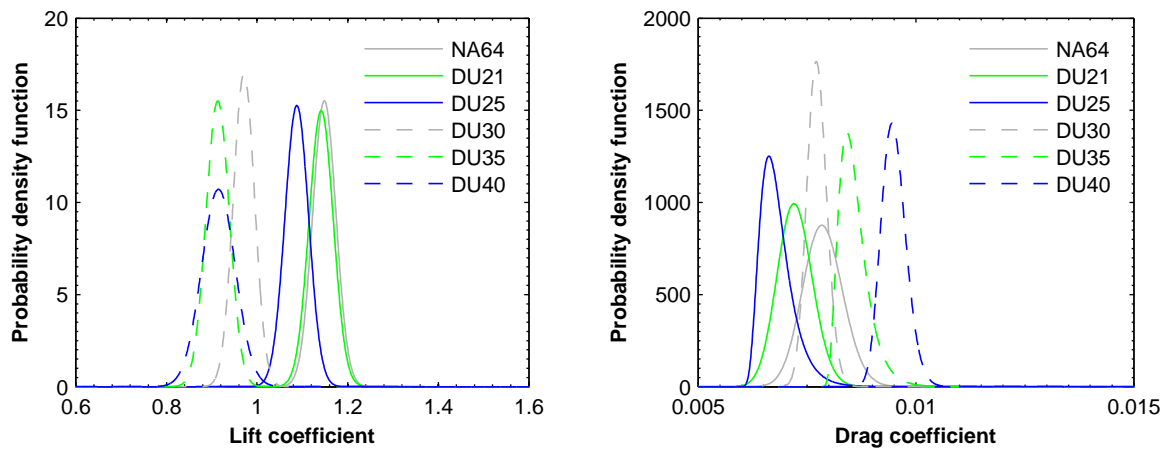


Figure 6. Probability density distribution function of the lift coefficients (left) and the drag coefficients (right) for an angle of attack of $AoA = 5^\circ$

5. Effect on Wind Turbine Performance and Loads

In order to investigate the effect of uncertain airfoil geometries on the performance and the loads, the aeroelastic model of the NREL 5 MW offshore wind turbine (OWT) with a rotor diameter of 126 m and a hub height of 90 m is used [11]. The OWT is pitch regulated and operates with variable speed. The rated wind speed is $v_{rated} = 11.4$ m/s and the maximum rotor speed is 12.1 rpm. Along the rotor blade the geometry can vary in many different ways. In the present study, it is assumed that the relative variations of the characteristic airfoil parameters are uniformly distributed (constant) along the blade length. Due to this, the relative variations, created by means of the LHS, are used for all airfoils which are given in Table 1. Furthermore, it is

assumed that the geometry variations of all three rotor blades are identical. In order to simplify the model and to focus on effects due to geometry variations, constant wind fields without turbulence and shear are used. Wave loads are also neglected. The aeroelastic simulations are performed by means of the simulation software FAST [13] which includes the blade element momentum code AeroDyn [21]. AeroDyn requires additional corrections of the 2D lift and drag coefficients from XFOIL. In order to consider 3D rotational effects, the lift coefficients are corrected by the method described in Du and Selig [22] and the drag coefficients by the method described in Eggers and Digumarthi [23]. Furthermore, an extrapolation of the lift and drag coefficients to angles of attack in the range $-180^\circ \leq AoA \leq +180^\circ$ is done using the Viterna method [24]. For all 150 geometry variations, aeroelastic simulations are performed between the cut-in wind speed $v_{in} = 3$ m/s and the cut-out wind speed $v_{out} = 25$ m/s, with 12 different mean wind speeds (3 m/s, 5 m/s, ..., 25 m/s). In total, each simulation has a duration of 430 seconds but due to transient effects in some simulations, only the last 30 seconds are analyzed. If the lift coefficient has no certain maximum, it is not possible to clearly identify the stall angle in the automated simulation process. Then, the Beddoes-Leishman dynamic stall model leads to unexpectable high loads and a large scatter. Therefore, for the results presented below, no dynamic stall model is used.

Wind Turbine Performance

The geometry variations assumed in the present study, have only small effects on the power curve of the OWT. The largest variations are observed near the rated wind speed. At a wind speed of $v = 11$ m/s the coefficient of variation is $CoV = 0.0021$. The variations of the power curve results also in small variations of the annual energy production with a coefficient of variation of $CoV = 0.0012$. The annual energy production is determined based on a Rayleigh-distributed wind speed with a mean value of $v_{mean} = 10$ m/s and a shape parameter of $k = 2$.

Fatigue Loads

The fatigue loads are analyzed by means of the damage-equivalent load-range approach. For the time series, rainflow counting is used to determine the amplitudes R_i and the corresponding number of load cycles n_i . Based on the IEC standard 61400-13 [25], the damage-equivalent load is defined as

$$R_{eq} = \left(\frac{\sum_i R_i^m \cdot n_i}{n_{eq}} \right)^{1/m}, \quad (3)$$

where m is the Wöhler curve exponent and n_{eq} is the equivalent number of load cycles. The damage-equivalent flapwise and edgewise bending moments at the blade root are calculated with $m = 10$ and $n_{eq} = 30$ for each 30 seconds time series. This results in an equivalent frequency of 1 Hz. Figure 7 shows the scatter of the damage-equivalent flapwise and edgewise bending moments. In addition, in Figure 8 the coefficients of variation of both bending moments are presented. Near the rated wind speed of the OWT, the largest variances of the flapwise bending moments are observed. There, the coefficient of variation is up to $CoV = 0.044$. The coefficients of variation of the edgewise bending moments are about one magnitude lower ($CoV = 0.004$). The reason for this is that these are mainly caused by gravity forces and hardly affected by geometry variations. The distribution of the loads are also tested by means of the Kolmogorov-Smirnov test, but no clear and consistent distribution functions are found which can be accepted with a significance level of 5%.

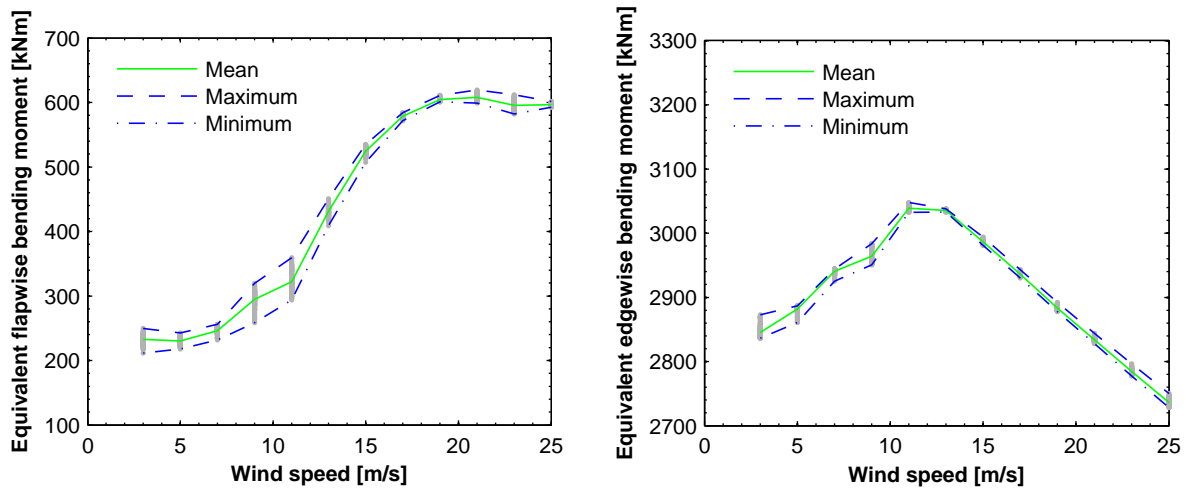


Figure 7. Damage-equivalent flapwise bending moment (left) and edgewise bending moment (right)

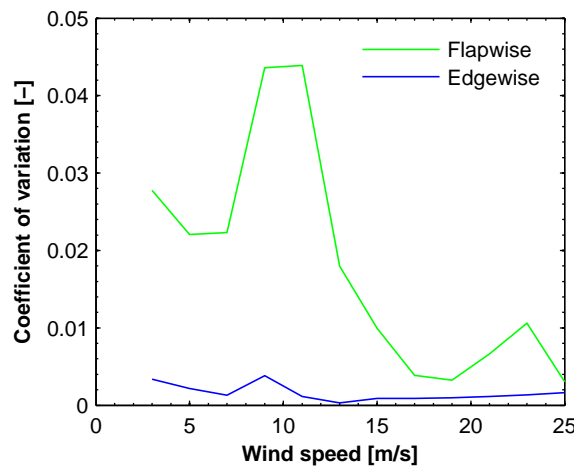


Figure 8. Coefficient of variation of the damage-equivalent flapwise and edgewise bending moments

6. Conclusions

The present paper has investigated the effect of geometric uncertainties on the aerodynamic lift and drag coefficients as well as on the performance and loads of an offshore wind turbine. As a basis, the airfoils and the aeroelastic model of the NREL 5 MW reference wind turbine are used. In order to use only a limited number of uncertain parameters, the geometry variations of the airfoils, are described by only five characteristic parameters: the maximum thickness, the location of the maximum thickness, the maximum camber, the location of the maximum camber, and the trailing edge thickness. It is assumed that the uncertainty of these parameters can be modeled with a truncated normal distribution. In order to investigate combined effects on the lift and drag coefficients, the parameters are varied simultaneously by means of a Latin hypercube sampling. The variations of the airfoil geometry lead to a significant scatter of the lift and drag coefficients which gives an idea about the robustness of the airfoil design. For angles of attack with attached flow, it is shown that the scatter of the lift coefficient follows a normal distribution and the scatter of the drag coefficient follows a shifted lognormal distribu-

tion. These distributions can serve as a direct input for future aeroelastic simulations to model geometric uncertainties directly and to determine their effects on the wind turbine blade loads.

In the present study, it is assumed that the relative changes of the characteristic airfoil parameters are uniformly distributed along the radius. Furthermore, it is assumed that the geometry variations of all three rotor blades are identical. Based on these assumptions, the calculated lift and drag coefficients are used for the aeroelastic simulations. The results show only a small effect on the power curve and the annual energy production. The largest variations of the damage-equivalent flapwise bending moment occur near the rated wind speed of the turbine and has a coefficient of variation of up to $CoV = 0.044$. By comparison, the variation of the edgewise bending moments are hardly affected by geometry variations.

Due to manufacturing tolerances, the rotor blade geometries can vary in many different ways. In future work, the influence of the radial distribution of the airfoil variances and the interdependence between each of the blade segments will be investigated. In addition, variations of the chord and twist distributions along the blade radius will be examined. The quality of the results of probabilistic simulations highly depends on the assumptions made for the input variables and the physical model used. Therefore, if information about more realistic geometry variations are available, these should be considered. Additionally, Computational Fluid Dynamics (CFD) will be used to get a better estimation of the stall behavior of the airfoils, although CFD requires higher computational effort. In order to consider more realistic wind conditions, the effects of turbulent wind fields with shear will be investigated.

Acknowledgements

The authors wish to thank the Ministry for Science and Culture in Lower Saxony, Germany for financing this work within the ForWind joint research project *Probabilistic Safety Assessment of Offshore Wind Turbines*.

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