Advanced investigation into the influence of high frequency turbulence on wind turbine blades

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Abstract

In order to design wind turbines knowledge of the flow field including the high frequency part and the boundary layer at the rotor blade is important. Due to the complexity of the experimental setup, only few results exist. For this reason two research projects are conducted at the University of Applied Sciences in Kiel:

The objective of the first project is the examination of onshore / offshore wind fields and the measurement of high frequency aerodynamic turbulence by a piezo electric transducer. Onshore measurements show that time-averaged parameters like the turbulence intensity are comparable to those of cup anemometers and that there is no clear difference between the measurements from sea- and landside. The decrease of the obtained power spectral density follows a power law with a comparable exponent as those of Kolmogrow. The offshore measurements will be realized at FINO3, a research measurement platform, which will start operating in summer 2010.

By means of a so called aerodynamic glove the boundary layer at a wind turbine blade during rotation under normal working conditions is investigated. The purpose of this project is to develop and install the measuring setup, which consists of pressure taps in circumferential direction and a hot-film to determine the state of the boundary layer: laminar or turbulent. The experimental results shall at first enlarge the experimental database.

Both measurements are accompanied by CFD calculations of two-dimensional blade profiles and stability analysis of the boundary layer by a simplified e^N-method. Initial calculations point up the influence of the N-factor on the results and the need of its accurate determination.

Keywords: atmospheric turbulence measurement on- and offshore, piezo sensor, boundary layer, rotor blade, wall shear stress, transition, hot-film

1 Introduction

During the design process of wind turbines it is essential to consider many parameters and influencing variables for example wind velocity, rotational speed, engine performance as well as the resulting drag and lift. Especially the last three parameters are dependant on the surrounding flow field. The turbulence level of the wind field, including the high frequency part, influence the transition of laminar to turbulent flows in the boundary layer. High frequency (> 10 Hz) wind field measurements are difficult to perform and are therefore very rare. An exception is made by Sreenivasan et al. [1], who examined the transverse structure of atmospheric turbulence by acquiring velocity data using hot wire probes mounted on a meteorological tower.

As for the wind field only few results of boundary layer investigation exist under realistic conditions: in the field during rotation. As the experimental set-up is rather complex, most research is conducted in wind tunnels. Due to the lack of detailed experimental results for the flow field including the boundary layer, transition and the influence of high frequency turbulence, simplified and empirical methods are used for the performance prediction of wind turbines. In order to obtain more data of the flow field and wind turbines aerodynamics two research projects are conducted at the University of Applied sciences Kiel:

1. FINO3 to investigate the turbulence level of wind fields.

2. The so called aerodynamic glove to determine the boundary layer shear stress distribution of the rotor blade on a wind turbine during rotation.

The long-term objective of these two projects is blade profile optimization by using measurement results and combining them with the CFD calculations. If it is possible to prolong the laminar inflow zone, drag on the blade can be reduced.
The following chapter deals with the wind field measurement at an onshore test side, first results of the measurement and the planned measurements at the offshore research platform FINO3. In chapter 3 the measuring setup for the boundary layer investigation and the results of initial simulation calculations are explained.

2 Wind field measurement

A major objective of the FINO3 project is the investigation and comparison of onshore and offshore wind fields by measuring high frequency fluctuations of wind speed with a robust piezo sensor [2],[3]. Therefore onshore measurements are conducted at a test site in Kaiser-Wilhelm-Koog, Germany. This test site is also used as test environment for the sensor under realistic conditions before installing it at the offshore research platform FINO3 (see Figure 1).

Figure 1: Offshore measurement platform FINO3

The platform is located 80 km west of the island of Sylt. The construction of the platform was finished in summer 2009, so that in summer 2010 the offshore measurement will start.
The second aim is the study of the turbulence energy spectrum and the resulting influence on transition of laminar to turbulent flows at wind turbine blades. For this reason the measurement is accompanied by CFD calculations of two-dimensional blade profiles and stability analysis of the boundary layer by a simplified e^N-method with FLOWer (DLR). The results of the measurement will be used to define input conditions of CFD calculations.

2.1 Measuring setup and realization

The measurements are conducted using a piezo-electric sensor, which was tested against hot-wire in a wind tunnel at the University of Oldenburg, Germany. The sensor is able to determine high frequent pressure fluctuations which are for low frequency fluctuations directly related to velocity fluctuations. The applicability of this relation for high frequency fluctuations in the boundary layer has not yet been proven. Pressure changes force displacements of a thin membrane. The displacements cause a mechanical deformation of the piezo crystal, which results in an electric charge on the surface of the crystal. The measured voltage as the primary quantity is proportional to the pressure fluctuations [4]. The sensor is mounted at a pylon about 60 m above ground level onshore and 80 m above sea-level offshore. The onshore measurement is realized for different averaged wind velocities: 6, 12 and 16 m/s and for different wind directions: from seaside/ from landside. The above-mentioned measurement parameters are identified by additional measuring devices like cup anemometers. The measurement is started over a period of 100 seconds, when the parameters are in the desired range.

2.2 Results

The measured data, in this case the pressure fluctuations, is evaluated by frequency analysis with TISEAN, which was developed by MPI Institute of Physics for Complex Systems [5]. An example of obtained power spectral density, *PSD*, is given in Figure 2 for different wind directions. There is no significant difference for spectra of wind fields from the land or seaside. The power spectral density describes how the energy content of the pressure fluctuations is distributed with the frequency. Low frequency fluctuations have the hiqhest energy content. The decrease of the energy spectrum with the frequency *f* follows a potential law with the exponant *a*:

$$PSD(f) \sim k^{-a} \qquad (1)$$

Kolmogorov and Obukov [6] proposed different exponents -3.3 resp. -2.3 for the decrease and their results are also presented in Figure 2. The value of -3.3 is obtained by using the known factor of -5/3 for velocity fluctuations from Kolmogorow and by adapting it by Bernoulli's Law to pressure fluctuations. Assuming that the spectral power can bee converted using the ratio of velocity to pressure as defined in Bernoulli's Law leads to an adaption as shown in equation (1)-(3).

$$PSD(f, \Delta v) \sim k^{-5/3} \qquad (2)$$

$$\Delta v \sim \Delta p^{2} \qquad (3)$$

$$PSD(f, \Delta p) \sim k^{\left(-5/3\right)^{2}} = k^{\left(-10/3\right)} \qquad (4)$$

Both spectra show striking peaks at about 300 Hz. Apart from the pressure fluctuations the acceleration in two directions of the measuring tower is recorded. The analysis of this data leads to the assumption that the peaks are caused by vibration of the tower. Furthermore it was found, that the piezoelectric-sensor is able to resolve fluctuations up to 3 kHz. This limit is in accordance with a general estimation of the frequency resolution for structural Eigen frequencies.

It is possible to compare time averaged parameters like turbulence level and standard deviation to those of cup-anemometers. As defined in equation (5) the turbulence level I_v is the ratio of the standard deviation σ_v to the averaged wind velocity $\bar{v}$.

$$I_v = \frac{\sigma_{\mathrm{v}}}{\bar{\mathrm{v}}} \qquad (5)$$

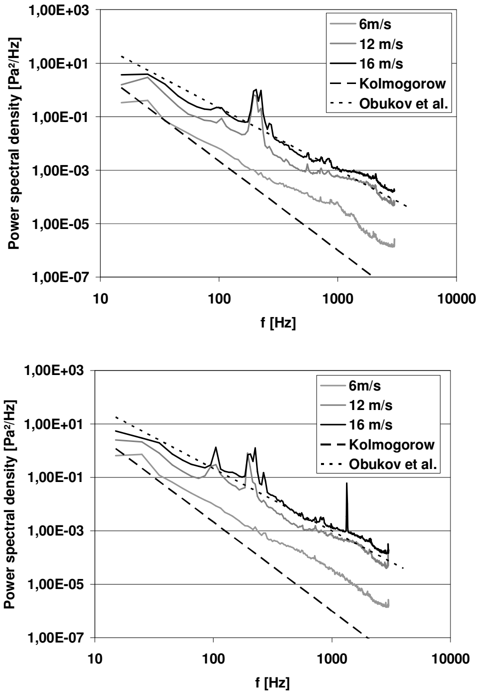

Figure 2: Energy spectra for averaged wind velocities 6, 12, 16 m/s, from seaside (above) and from landside (below)

The averaged wind velocity and the standard deviation can be calculated according to equation (6) and (7) from the measured velocity v_i, the sampling time *T*, the number of measuring points *N* and the sampling interval *Δt*.

$$\bar{v} = \frac{1}{T} \sum_{i=0}^{i=N} v_i \, \Delta t \qquad (6)$$

$$\sigma_v = \sqrt{\frac{1}{T} \sum_{i=0}^{i=N} \left(v_i - \bar{v}\right)^2 \Delta t} \qquad (7)$$

Some modifications are necessary to compare the piezo electric measurements to cup anemometer measurements. The standard deviation is calculated with velocity fluctuations, obtained from pressure fluctuations. The estimation of the turbulence level is carried out according to equation (5) using an averaged velocity, which is defined by cup anemometers. Figure 3 shows the estimated turbulence intensity as function of the averaged wind velocity from the piezo sensor (PS) and the cup anemometers (AN) for several measurements. As for the energy spectra there is no clear difference between the land and seaside. Except for the measurement at a velocity of 16 m/s, landside turbulence intensities lie in the same range for the piezo sensor and the cup anemometer. There is only a small dependency of the wind velocity. For small velocities the values and the deviation of the values are the highest. This result is similar to common observations. Contrary to the results of the Risø National Laboratory, which deals with low frequency turbulence measurements at an onshore and an offshore location, [7] there is for two reasons no clear difference in our results for landside and seaside wind. Firstly both measurements of the FH Kiel were conducted at the same onshore location but with different wind directions. Secondly even the wind from the seaside is influenced by the landscape because the test side is located about 2 km inland.

In a preliminary analysis of the standard deviation as a function of the wind velocity is a slight difference in the shape of both curves for land- and seaside measurement.

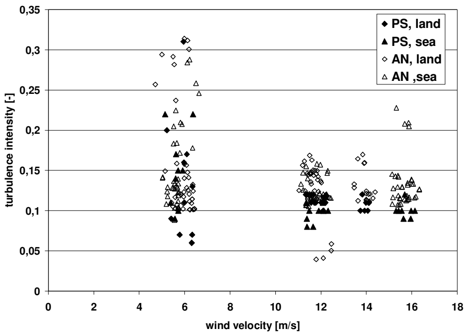

Figure 3: Turbulence intensity from piezo-sensor (PS) and cup anemometer (AN) as function of the averaged wind velocity

2.3 Further Investigation

For further investigation a new sensor, a LCA (Laser Cantilever Anemometer) will be added to the equipment. This sensor was developed by the Hydrodynamic Group of the Carl von Ossietzky University of Oldenburg and is able to resolve higher frequency than the piezo-sensor. Figure 4 gives an impression of the LCA layout. The microscopic cantilever bends when exposed to a flow. The cantilever displacement is detected by a laser beam [8]. After calibration the velocity can be directly calculated. This sensor also will be tested onshore and after that will be installed at the research platform FINO3 in summer 2010. A comparison of the onshore to offshore wind field will then be possible.

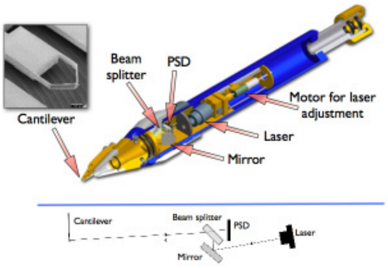

Figure 4: Layout of the LCA (University of Oldenburg)

3 Boundary layer investigation on a rotating blade

The intention of the aerodynamic glove is the installation of measurement equipment, allowing boundary characterization of a rotating blade. The measurement will be performed on a research wind turbine, an E 30 from Enercon under normal operation conditions. The experimental setup is based on the work of Seitz [9] and is adapted to a wind turbine. Seitz investigated the boundary layer of an air wing of a small airplane during flight. He was able to characterize the boundary layer and to detect and describe Tollmien-Schlichting waves, which induce transition. In addition he estimated wave parameters like the wave number and discovered a domination of the wave packet in the main flow direction. Comparable aerodynamic measurements are ongoing at Risø DTU National Laboratory for Sustainable Energy, Denmark. There a rotor blade is instrumented with microphones in order to determine high frequency surface pressure fluctuations [10].

3.1 Measurement setup

The measurement equipment consist of two main components, which will be placed at midspan of the blade: Firstly 64 pressure taps will be installed in circumferential direction to measure the pressure distribution. Secondly a hot-film will be attached at the upper side of the blade. The measuring principle is similar to constant hot-film anemometry. Only the sensor is much smaller in order to not disturb to flow field. By measuring the wall shear stress it is possible to verify, if the boundary layer is turbulent or laminar. Contrary to the work of Seitz it will not be possible to determine wave parameters. Because of the measurement under ordinary working conditions no stable conditions can be guaranteed for calibration. In Figure 5 the hot-film is shown. It has 24 sensors, which will be arranged in flow direction in order to monitor the propagation of the Tolmien-Schlichting waves.

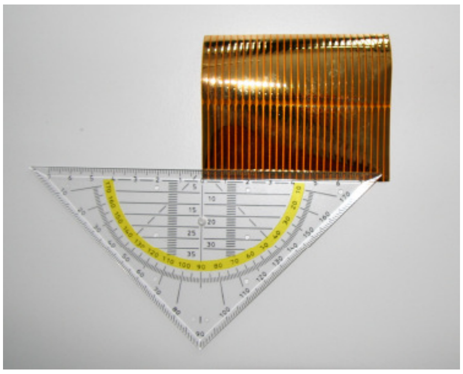

Figure 5 Layout of the Hot-film

As planned the measurement will start in summer 2010. Similar to the wind field investigation the measurement is accompanied by a CFD stability analysis of the boundary layer. In chapter 3.2 first results of this calculation are shown.

3.2 Simulation

In order to answer the question of existence and location of transition it is necessary to consider perturbations of the inflow, the velocity profile in the boundary layer and the pressure gradient. Assuming that the perturbations of the inflow can be described in form of Tollmien Schlichting waves, the stability of the waves determines the stability of the boundary layer. In general the e^N method, based on linear stability theory, is used to predict the point of transition [11], [12]. e^N describes the fraction of the critical perturbation amplitude to the inflow perturbation and characterises the transition from laminar to turbulent flow. Furthermore N, dependent on turbulence level, is often estimated using Mack's correlation [13] according to equation (8), which was developed for flow conditions in wind tunnel tests and is limited for turbulence levels below 3 %. This correlation has not yet been validated or modified for atmospheric flow conditions.

$$N = -8.4 - 2.4\ln\left(I_v\right) \tag{8}$$

The research code FLOWer, developed by DLR, combines the solution of the Reynold's averaged Navier-Stokes equations including turbulence models with a simplified e^N-method for two-dimensional, incompressible boundary layers [14], [15]. Instead of conducting the stability analysis for every cfd calculation, solutions for different velocity profiles and pressure gradients are stored in a database. For a given N-factor and velocity profile the point of transition can be calculated.

3.3 Results

The stability analysis is conducted for an Althaus 206 blade profile of the research turbine with a chord length of 0.95 m for angles of attack between 0 and 7 degrees. The boundary layer is resolved up to $1 \cdot 10^{-6}$ m and the grid consists of 30 000 cells. Results of the stability calculation for the chosen settings and boundary conditions, a Reynold's number of $2.7 \cdot 10^{6}$, the Spalart Almaras turbulence model and an angle of attack of five degrees are shown in Figure 6. The N-factor is displayed as a function of the dimensionless chord length and different perturbation frequencies. The envelope is the critical N-factor and determines the point of transition. For example an N-factor of 4 leads to a point of transition of 0.33 x/c. For this profile mainly perturbations in a range between 1 and 5 kHz induce transition for usual N-factors, which range between 5 and 8. As our measured turbulence intensities according to Figure 3 range above 3 %, Mack's correlation is not applicable. Limiting the energy range of the spectra to the range between 1 and 5 kHz a lower turbulence level is received. This leads to a higher N-factor, which is dependant of the turbulence level. Figure 6 shows that for an increasing N-factor the point of transition moves downstream, so that a larger range of laminar flow is expected at the rotor blade.

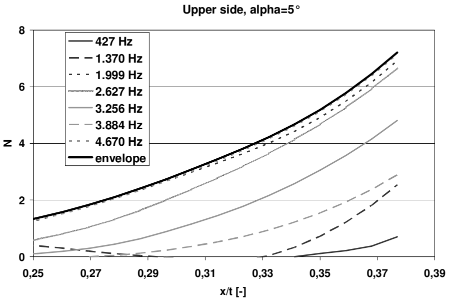

Figure 6: N-Factor as function of the dimensionless chord length for perturbations of different frequencies in the range between 427 and 4670 Hz

In Table 1 the calculated points of transition are listed as a function of the angle of attack. The calculation is accomplished with a N-factor of 6. As expected the point of transitions at the upper side moves upstream with increasing angle of attack.

Angle of attack [degree]	0	3	5	7
Point of transition [x/c]	0.64	0.42	0.38	0.32

Table 1: Point of transition as a function of the angle of attack

4 Conclusions

Concerning the FINO project an experimental set-up to measure high-frequency wind-speed fluctuations is defined, installed and verified. The chosen piezoelectric sensor is able to resolve fluctuations up to 3 kHz and shows reasonable results for the onshore measurement: Time averaged parameters are comparable to those of cup anemometers, the characteristics of the spectral power density are as expected and there is no clear difference between the results of different wind directions. In order to determine fluctuation higher than 3 kHz a laser cantilever anemometer will be developed and installed.

The measuring setup for the aerodynamic glove is defined and will be installed in summer 2010. By means of a hot-film the boundary layer of an rotor blade during rotation will be investigated. A further objective is the analysis of the resulting influence of the turbulence level on the transition of laminar to turbulent flows. Results from measurement and CDF calculations will be combined for blade optimization. For this reason the analysis of the experimental findings is accompanied by stability investigation which is able to identify relevant frequencies for transition. In order to predict the point of transition more precisely the N-factor must be related to the inflow conditions. The applicability of Mack's correlation for atmospheric flows has not yet been proven. Research is ongoing how to modify it for atmospheric wind flows.

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