Pressure and hot-film measurements on a wind turbine blade operating in the atmosphere

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Abstract. In the present study the aerodynamic boundary layer at a rotor blade is investigated while the turbine is working under real operating conditions in the atmosphere. Owing to the complexity of the experimental set-up, up to now most research on transition is conducted in wind tunnels and field measurements are rare. Hence important effects such as the unsteady behavior of the inflow are not taken into account. For the current measurements the blade is equipped with a hot film at the most interesting part of the upper side midspan of the blade in order to detect non-laminar structures in the boundary layer. Furthermore, 34 pressure tubes are installed along the chord length in order to gain information about the flow field. A preliminary analysis of the hot-film measurements combined with a CFD calculation and a stability analysis based on the $e^N$ method leads to two results. Firstly it is possible to determine the state of the boundary layer (laminar or turbulent) and secondly we propose to discuss our findings in case of medium rotational speed within so called Tollmien-Schlichting scenario.

1. Introduction

In this study the results of a detailed investigation of the aerodynamic boundary layer on a rotating wind turbine blade are described. During the measurements the wind turbine is working under ordinary conditions in the atmosphere. As the experimental set-up is rather complex, most previous research studies on this topic were conducted in wind tunnels. A recent exception are the Dan-Aero-experiments, for which high frequency pressure measurements at a blade working under ordinary conditions are conducted [1]. In the wind tunnel measurements important effects such as the rotation of the rotor and the unsteady behavior of the inflow are not taken into account. Due to the lack of detailed experimental results for the flow field, simplified and empirical methods are typically used for the performance prediction of wind turbines and blade designs. However, a detailed knowledge of the flow field including the boundary layer behavior at the rotor blade is essential to design wind turbine blades since the energy yield strongly depends on this issue. Blades, whose boundary layers have an extended laminar zone, offer a higher energy yield. Up to now most transition predictions under low inflow-turbulence conditions have been realized within the so-called $e^N$ method for transition, which assumes a certain exponential growth of an initial disturbance until fully developed turbulence is reached. Common values for N range around 9. An empirical criterion relates this growth exponent to the inflow turbulence. This correlation [2] was developed for wind tunnel tests and has neither...
been validated nor modified for atmospheric flow conditions, which significantly differ from wind tunnel data. In addition to that, in-flight measurements at airplanes show that transition following different scenarios may occur and that only for some scenarios the $e^N$ method is applicable [3].

2. Transition scenarios and stability analysis

This section covers a short overview of possible transition scenarios and the stability analysis based on the $e^N$ method. The above-mentioned natural transition according to the TS scenario follows different steps which have been described in detail by White [4] at the example of a flat plate. Near the leading edge of the plate there is a stable laminar flow. The first instability occurs after a certain length in form of two-dimensional waves. These are the so-called TS waves, which in case of amplification develop to unstable three-dimensional waves and vortices. These vortices later break down to turbulent spots which pass on to a fully turbulent flow. For transition predictions the stability of the TS waves, which denote the beginning of the process, must be considered. This is done by the $e^N$ method [2, 5], which is based on the linear stability theory relying on the Orr-Sommerfeld equation. It evaluates the development of disturbances in the boundary layer. The amplification rate $N$ for disturbances with different frequencies is calculated for each position at the profile. The critical $N$-factor, for which transition occurs, depends on the inflow turbulence and is commonly estimated using Mack’s correlation [2]. As already mentioned, this correlation is limited to wind tunnel flows and to turbulence levels of the free stream lower than 3%. For unknown $N$-factor the transition point cannot be calculated but the frequencies of the most strongly amplified disturbances can be estimated. Another important transition scenario is the bypass transition, which takes place for high inflow turbulence [6]. In this scenario the steps with the unstable waves are bypassed, so that streaks and turbulent spots are directly formed. A significant difference between the two transition scenarios is the occurrence of amplified disturbances in case of the natural transition. On the contrary, the energy spectra should possess no maxima for transition following the bypass scenario, so that this difference can be used to interpret the hot-film measurements [1, 7–9].

3. Equipment for Measurements

3.1. General set-up

A blade of an E30 wind turbine from Enercon GmbH with a rotor diameter of 30 m is equipped with a hot film and pressure tubes in order to investigate the boundary layer and especially the transition process on the blade. The measurement devices are installed at a rotor diameter of 8 m and are shown in Fig. 1. The measurement set-up is based on the in-flight measurement of Seitz [9], who investigated the laminar-turbulent transition with an aerodynamic glove at a small airplane. His measurement equipment consisted also amongst others of a hot film and pressure tubes. The most important results of his investigation were the existence of amplified disturbances in the boundary layer and the occurrence of transition after the TS scenario.

3.2. Measurement of the pressure

In the present study 34 pressure tubes are installed along the chord length in order to gain information about the flow conditions. Due to structural mechanical stability reasons of the blade it was not possible to incorporate pressure tubes in the region of the leading edge as well as the trailing edge and in the region of the shear-web. Unfortunately, the calibration of the pressure transducer went lost during a severe break-down of the transmission cables. Furthermore, a Pitot tube is installed at the leading edge to estimate the free-stream conditions.
3.3. **Hot-film measurement**

Additionally hot-film is attached at the upper side midspan of the blade, covering a profile depth from 25 to 34%. Since the hot film is placed directly on the surface, no velocity but wall shear stress fluctuations can be measured. The hot film consists of 24 sensors, which are arranged in flow direction in order to monitor the propagation of disturbances in the boundary layer. Since the intent of the hot-film measurement is the analysis of the disturbance development in the boundary layer, it is not necessary to calibrate the hot film [8]. The measurements are conducted with a sampling rate of 5 kHz for the hot film and 330 Hz for the pressure tubes over a time interval of 10 seconds. Measurement parameters like the rotational speed of the wind turbine, the engine output and the wind velocity determined by a cup anemometer are sampled with a frequency of 3 Hz. Further measurement equipment like the control units are placed in the nacelle. Unfortunately, measurement parameters like turbulence intensity, wind velocity and resulting rotational speed cannot be chosen freely. Nevertheless, more than 700 measurements, covering a wide range of inflow conditions, have been conducted.

| Re      | $v_{\text{wind}}$ | $v_{\text{rot}}$ | Tu  | N  |
|---------|-------------------|------------------|-----|----|
| -       | m/s               | RPM              | -   | -  |
| $0.14 \cdot 10^6$ | 3.24         | 0.33             | 0.227 | - |
| $1.09 \cdot 10^6$ | 3.02         | 20.86            | 0.028 | 0.16 |
| $2.62 \cdot 10^6$ | 12.57         | 45.35            | 0.02  | 0.97 |

Three measurements are chosen for the present analysis. Their inflow parameters, the calculated Reynolds number (Re), the turbulence level Tu and the N-factor predicted according

![Figure 1](image1.png)

**Figure 1.** Measurement set-up including the hot film and the pressure tubes. The smaller sub-images show the hot-film (upper right, length about 100 mm), the pressure tubes inside a test-section (lower left, about 500 mm) and the data-acquisition system inside the hub (ca. 500 mm)

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to Mack [2] are shown in Table 1. The turbulence level was calculated based on the resulting velocity of the wind velocity and the rotational velocity. In case of $\text{Re} = 0.14 \cdot 10^6$ the wind turbine was shut down. As the rotor is coasting freely in this case, the rotational speed was greater than zero. Since the turbulence level is higher than 3%, it is not possible to calculate an N-factor for the Reynolds number. For $\text{Re} = 1.09 \cdot 10^6$ and $\text{Re} = 2.62 \cdot 10^6$ the wind turbine was working with medium or nearly maximum rotational speed, respectively.

4. Results

In this section the results of the preliminary analysis of the measurements listed in Table 1 are discussed. The first subsection will consider the pressure measurements and is followed by the hot film measurements and CFD calculation with the FLOWer-Code which will help to interpret the measurement results and especially those of the hot-film measurements.

4.1. Pressure Measurements

As already mentioned in Section 3 the pressure measurements do not cover the whole profile, because in some regions of the profile it is not possible to place pressure tubes. In Fig. 2 the measured pressure coefficients (depicted as points) are shown as a function of the chord length. For comparison the corresponding results of the CFD calculations (displayed as lines) are included. For the simulation, the angle of attacks are estimated by the so-called inverse BEM-method. The accordance between the measurements and calculation - due to the lost calibration - is qualitative only.

4.2. hot-film measurements

In Fig. 3 the time signals and calculated energy spectra are shown for the measurements listed in Table 1. The measurement signals are superimposed by noise in the frequency range of about 1000 Hz. We assume that this noise is caused by an auxiliary system of the wind turbine like the ventilator of the nacelle. As this noise is dominating the time signal, it was band filtered. The energy spectra are calculated from the non-filtered signal. The number of the shown hot-film sensors differs for the three measurements since during the measuring period the sensors stopped.

Figure 2. Pressure distribution for the measurements and simulations at $\text{Re} = 1.09 \cdot 10^6$ (a) and $\text{Re} = 2.62 \cdot 10^6$ (b). Notice that scaling of CFD (coloured) and measured (black) values do not coincide because of lost transducer calibration. A correlation is nevertheless possible using the location of the pressure minimum on the suction side. The angle of attack for $\text{Re} = 1.1M$ seems to be around 4 degrees whereas for $\text{Re} = 1.6M$ it seems to be much higher (> 7 degrees).
Figure 3. Time series and energy spectra for hot-film measurements at Re = 0.14 \cdot 10^6 (above), Re = 1.09 \cdot 10^6 (middle), and Re = 2.62 \cdot 10^6 (bottom). Notice that the sharp peaks around 1 kH (energy spectra on the right side) are from unknown reasons and are assumed to be artefacts.

working consecutively. After a measurement period of four month only four working sensors are remaining.

The displayed time signals differ strongly for varying inflow conditions. In case of shut down (Re = 0.14 \cdot 10^6) all channels show a rather smooth time signal with only small disturbances. In case of Re = 1.09 \cdot 10^6 the first channels show a similar behavior, but the disturbances are obviously amplified with increasing chord length. For Re = 2.62 \cdot 10^6 all channels show
a time signal with strong disturbances. Further measurements with similar Re numbers show comparable results.

The right graphs in Fig. 3 depict the energy spectra of four hot-film channels, which are numbered in flow direction. The energy spectra are calculated from the time signal via fast Fourier transformation (FFT). As expected, the decrease of the energy density as a function of the frequency follows a potential law with a linear decrease in the double-logarithmic graph. Similar to the time signals the energy spectra illustrate a strong dependency on the inflow conditions. For increasing Re the levels of the energy spectra increase for all channels. In addition to that the graphs in Fig. 3 show strong maxima at 1000 Hz. As already explained, up to now these maxima have been categorized as noise. Only in case of the medium rotational speed the energy spectra of the four hot-film channels show a characteristic behavior depending on the sensor position at the blade. The energy spectra for channel 5, 12 and 16 are at low level which is similar to the behavior of the measurements at shut down. The energy spectra of channel 20 has a higher level and is comparable to that of the measurement at $Re = 2.62 \cdot 10^6$. Furthermore, a small maximum can be observed for channel 12 and 16 at 300 Hz. The maximum is not as obvious as in the examples in the given references [7–9]. Nevertheless the behavior of the time series is regarded as a hint for the existence of amplified disturbances in the boundary layer and transition according to the TS scenario. Taking all measurement results into account we assume that there is a laminar boundary at $Re = 0.14 \cdot 10^6$; at $Re = 1.09 \cdot 10^6$ the boundary layer seems to be in a transitional state and at $Re = 2.62 \cdot 10^6$ a fully turbulent boundary layer exists [1, 7–9].

### 4.3. Stability Analysis with FLOWer

The research code FLOWer [10], developed by DLR, combines the solution of the Reynolds-averaged Navier-Stokes equations including statistical turbulence models with a simplified $e^N$ method for two-dimensional, incompressible boundary layers [11]. Instead of conducting the stability analysis for every CFD calculation, solutions for different velocity profiles and pressure gradients are stored in a database. Here the stability analysis is conducted for the inflow conditions of the three measurements relying on RANS simulations based on the Spalart-Allmaras turbulence model [12]. The boundary layer is resolved up to $1 \cdot 10^{-6}$ m and the grid consists of 60,000 cells. In Fig. 4 the N-factor is displayed as a function of the dimensionless chord length and different perturbation frequencies. The CFD calculations show that only for $Re = 1.09 \cdot 10^6$ and $Re = 2.76 \cdot 10^6$ amplified disturbances exist in the region of the hot-film. If the N-factors listed in Table 1 for these two cases are taken into consideration, transition occurs for $Re = 1.09 \cdot 10^6$ in the region of the hot-film and for $Re = 2.76 \cdot 10^6$ before the hot-film. For $Re = 1.09 \cdot 10^6$ the frequency range of the most strongly amplified disturbances coincides with those of the measurements. Thus the results of the CFD calculations support the assumption that in case of a medium rotational speed transition occurs according to the TS scenario.

### 5. Discussion

Fig. 3 summarizes our main findings. The spectra and even more the time-signals indicate much stronger variations when crossing a certain local Reynolds number. A comparison with CFD simulations enhanced by a boundary-layer stability module (see Fig. 4) shows that the TS-scenario offers frequencies which are much higher than those detected by our hot-film array. No wave-packets like in [9, 13] seem to occur. We therefore seem to see no genuine transition from that scenario. A possible alternative could be the bypass-szenario [14].

### 6. Conclusions

Measurement equipment, consisting of a hot-film array and pressure tubes, are successfully installed on a wind turbine blade in order to investigate the boundary layer state. During
Figure 4. Stability analysis and N-factor as a function of the chord length at Re = 1.09 \times 10^6 (a) and Re = 2.62 \times 10^6 (b) for an angle-of-attack of 4 degrees.

the measurements our turbine works under ordinary production conditions sustaining 5 - 15% ordinary inflow turbulence. We covered a wide range of inflow conditions. Due to the lost pressure-calibration there are difficulties to locate the actual lift-coefficient to be used as input for our CFD simulations. A preliminary analysis of our hot-film measurements shows that it is possible to gain information about the state of the boundary layer, i.e., whether it is more laminar or more turbulent. A clear indication for a TS-scenario nevertheless seems to be difficult and calls for more measurements.

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References
[1] Madsen H A and et al 2010 Proceedings of the 48th AIAA Aerospace Science Meeting (American Institute of Aeronautics and Astronautics)
[2] Mack L M 1977 Transition and laminar instability Tech. rep. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
[3] Schrauf G 1994 12th AIAA Applied Aerodynamics Conference, Colorado Springs, CO, USA, June 1994 AIAA-94-1848-CP (AIAA) pp 367–375
[4] White F M 2006 Viscous fluid flow International edition 2006 ed (McGraw-Hill)
[5] Reed H L, Saric W S and Arnal D 1996 Ann. Rev. Fluid Mech. 28 389–428
[6] Kachanov Y S 1994 Ann. Rev. Fluid Mech. 26 411–482
[7] Peltzer I 2008 Experiments in Fluids 44 961–972
[8] Peltzer I, Nitsche W and Suttan J 2008 Journal of Aircraft 45 1937–1944
[9] Seitz A 2007 New Res. in Num. and Exp. Fluid Mech. 96 260–267
[10] Kroll N FLOWer Installation and User Handbook Release 116 Institut fü Entwurfsaerodynamik, Deutsches Zentrum für Luft-und Raumfahrt e.V.
[11] Stock H W and Degenhart E 1989 Z. Flugwiss. Weltraumforsch. 13 16–30
[12] Spalart P and Allmaras S 1994 La Recherche Aérospatiale 1 5–21
[13] Reeh A, Weismüller M and Tropea C 2013 Proceedings of the 51th AIAA Aerospace Science Meeting (American Institute of Aeronautics and Astronautics)
[14] Suder K, O'Brien J and Reshotko E 1988 Experimental study of bypass transition in a boundary layer Tech. rep. NASA, Lewis Research Center, Cleveland, Ohio 44135