New anemometer for offshore use

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Abstract. We present a new type of a highly resolving anemometer to perform long-term measurements of turbulent wind flows. The sensor has been designed for rough environments and thus can operate under offshore conditions. The resolution goes down to about 1mm and above 1kHz, thus resolving fluctuations in a wind field of about 1cm. Its measuring principle, based on the atomic force microscope, allows for simultaneous measurements of the horizontal and transversal velocity component within a volume of < 1 mm³.

1. Introduction

Wind energy is the one of the most accepted renewable energy source in Europe. Therefore it gains more and more importance for the industry and the research sector. During the last few years a lot of effort was undertaken in order to get a better understanding of the nature of wind fields. New measurement technologies like LIDAR systems (5) or improved CFD tools helped characterizing the boundary layer. The quantification of turbulence within the boundary layer is extremely important for wind turbines and concerns also performance and safety issues. The actual interest in details of wind turbulence of the wind energy community is mainly focused on structures of the size of the turbine and larger, i.e. the spatial resolution is above 10m (for wind speed of 10m/s this corresponds to frequencies above 1Hz).

One approach in this area of research is the possible existence of universal small-scale turbulence properties. It is assumed in (3) that evidence of small-scale turbulence could be the cornerstone for a better understanding of turbulence and thus could be helpful in many practical fields of application such as CFD. In (4) it could be shown that under certain conditions the statistics of atmospheric turbulence coincide with isotropic laboratory turbulence and thus show the same behavior. However, it is also noted that these results were obtained for only one set of data. Still there is a challenge to achieve a comprehensive and consistent understanding of small scale turbulence for different free field wind conditions (6; 7; 8). In particular up to now there has been not much effort in getting a good characterization of the complexity of wind turbulence on scales below 10m. The overall power production of wind turbines with diameters of 100m and more may be taken not to be effected by these small scale structures, but definitely the aerodynamics around rotor profiles with depth down to some tenth of cm. In recent works we could show from data analysis and from modeling, that 1 sec wind fluctuations definitely will have an impact on largest wind turbines (9; 10). Small scale turbulent fluctuations in the inflow conditions are likely to have an impact on the formation of dynamic stall events, leading as seeds to larger scale aerodynamic loads. On these grounds it is necessary to provide higher resolved data of wind turbulence for further investigation.

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So far, most measurements of atmospheric turbulence have been performed using standard sensors like cup or ultrasonic anemometers. These sensors resolve up to spatial scales of meters (cup anemometer, sampling 1Hz) or ten of cm (ultrasonic anemometer, max sampling 50Hz). In order to characterize turbulent flows on a millimeter-scale and a temporal resolution of beyond 10kHz different anemometers are needed. To fill this gap we have developed a new sensor for atmospheric flows, the so called 2d Atmospheric-Laser-Cantilever-Anemometer (2d-ALCA). It was was optimized to meet the mentioned demands concerning performance and field of application. Its sensitive measuring principle was adopted from the 2d-Laser Cantilever Anemometer for laboratory use (2d-LCA) (2; 11) and allows for highly resolved measurements. The measuring method will be explained further below in detail. The main difference between the 2d-LCA and the 2d-ALCA is the design of the sensing element, i.e. the cantilever. The setup of the 2d-ALCA and the design of the cantilever are shown in fig. 1. The 2d-ALCA is currently undergoing the last testing phase and is now installed on a offshore met mast.

**Figure 1.** The 2d-Laser Cantilever Anemometer for atmospheric use (2d-ALCA) together with a sketch of the cantilever.

### 2. Measuring principle

The used measuring method is based on the laser pointer principle, which is also adopted in atomic force microscopes (AFM). The sensitive component of the sensor is a cantilever made of stainless steel and measuring only 1.5mm in length and 0.4mm in width. Its thickness is only about 30µm. The largest dimension, i.e. the length, gives the limitation for the spatial resolution. When exposed to flow the cantilever experiences a deformation due to the acting force $F$:

$$F = \frac{1}{2} \cdot c_d \cdot \rho \cdot A \cdot v^2 \cdot f(\alpha),$$

(1)

where $c_d$ is the drag coefficient, $v$ is the velocity of the fluid, $\rho$ is the local density, $A$ the cross section of the cantilever and $f(\alpha)$ a function, which depends on the angle of the inflow $\alpha$. A laser beam provided by a laser diode is pointed at the tip of the cantilever and causes a reflecting spot, which again is routed on a 2-dimensional position sensitive detector (2d-PSD) using some optical devices (see fig. 2).
Figure 2. The setup of the 2d-Atmospheric Laser Cantilever Anemometer (2d-ALCA). The laser beam hits the cantilever and is then reflected towards the 2d-PSD element where its position is captured.

The signal provided by the reflecting spot on the 2d-PSD is directly connected to the deformation of the cantilever and is proportional to $F$. The total deformation is a superposition of bending and twisting, whereas twisting only occurs if the cantilever is exposed to a flow coming from angles of attack different from $0^\circ$. For a straight inflow the term $f(\alpha)$ from equation 3 becomes 1. These two bending modes of the cantilever allow for measurements of velocity components in two dimensions (2). Figure 3 shows an exemplary time series for the horizontal signal component of the 2d-ALCA. One can see the fast response of the sensor to a gust event. The signal was sampled at a frequency of 10kHz and the resolution is about 1ms.

Figure 3. Short section of a time series for the horizontal velocity component of the 2d-ALCA at a sampling frequency of 10kHz. The main peak corresponds to a velocity of about 10m/s.

As mentioned before the 2d-LCA is equipped with a different cantilever, which is a smaller micro-structured cantilever measuring only few ten micrometers. The small dimensions of the cantilever and an eigenfrequency far beyond 100kHz allow for even higher temporal and spatial resolutions. However the cantilever was designed and optimized to meet the requirements under laboratory conditions only. To show results obtained with the new measuring principle, we present some measurement data of turbulence obtained with the 2d-LCA. For these measurements a commercial x-wire was used as a reference. The measurements were carried out in the wake of a cylinder of 2cm in diameter. Both sensors were aligned in a distance of 66cm behind the cylinder. At the used mean inflow velocity of 8m/s this corresponds to a Reynolds number of $Re \approx 10000$. Figure 4 illustrates a comparison of the power spectra between both sensors for the longitudinal and transversal velocity components. The comparison shows that the spectra of the 2d-LCA (black) and the x-wire (red) for the longitudinal velocity component
match to a very high degree. The data provided for this velocity component corresponds to the bending behavior of the cantilever. From the power spectra of the transversal velocity component, which is related to the twisting behavior of the cantilever, one can see that the dynamical range is weaker by 2 orders of magnitude compared to the x-wire.

![Power spectra comparison](image)

**Figure 4.** Comparison of power spectra for the longitudinal (left) and transversal (right) velocity component of the 2d-LCA (black) and an x-wire (red) for turbulent flow in the wake of a cylinder.

This effect is caused by the given geometry of the cantilever and has up to now not been optimized with respect to the highest achievable resolution. This longitudinal / transversal resolution behavior can be observed for the 2d-ALCA, too. A solution to this problem will be discussed later. It is also worth mentioning that both sensors detected the detaching frequency of the flow at about 80Hz in both velocity components. Although the cantilever is not equally sensitive to both velocity components, the measurement results clearly show that the concept of the sensor is capable of providing highly resolved measurement data by all means.

3. Challenges

The cantilever used for the 2d-ALCA must meet certain criteria in order to sustain rough offshore conditions and changing weather situations. Stainless steel turned out to be an appropriate material for the cantilever with a view to elasticity and heat expansion properties. The cantilever was realized using wire erosion technology. This very accurate technology allows for creating structures made of steel with a tolerance of only a few \( \mu \text{m} \). However, after the erosion process the cantilever surface becomes rough, which results in a diffuse reflection spot on the 2d-PSD. To get an optical reflectivity the current prototype of cantilever was equipped with a tiny mirror measuring about 0.3 x 0.3mm. Nevertheless, in order to reduce the weight of the cantilever and thus increase the resonance frequency (i.e. temporal resolution), one task for the future will remain to improve the surface. A second main challenge concerns the weak sensitivity towards cross winds as mentioned already. One idea to increase the twisting of the cantilever is to equip it with a additional fin at the tip (1). Figure 5 shows a FEM-simulation for the total deformation of a cantilever due to oblique inflow with and without a fin under same conditions. The total
deformation is indicated by the color levels. The simulation and first experimental tests confirm that the amount of twisting can be raised significantly.

**Figure 5.** FEM-simulation of the total deformation of a cantilever with and without fin. The deformation is indicated by the color levels.

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