Correlation of amplitude modulation to inflow characteristics

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ABSTRACT

Amplitude modulation (AM) of noise from wind turbines and its more extreme version named "other amplitude modulation" OAM have been investigated intensively during the last few years due to the additional annoyance impact this type of noise has compared to broad band noise. In a recent published research by RenewableUK the hypothesis has been that one of the causes of OAM is transient stall on the blade due to non uniform inflow such as shear. Part of the RenewableUK research work was a contribution by DTU on analysis of data from the DANAERO MW experiment from 2009. In the DANAERO experiment a new 38.8m test blade for a 2MW NM80 turbine was manufactured and equipped with a massive instrumentation comprising flush mounted surface microphones, pressure taps and five hole pitot tubes. The correlation of the spectra from the surface microphones and the measured inflow angle (IA) confirmed the strong increase in the noise source for high IA. As only few 10min data sets were measured in the DANAERO project a data set with measured inflow angle from 2003 on the same turbine has been used to explore the statistical properties of AM and OAM based on assumed correlation to IA.

Keywords: Wind turbine, Noise, Amplitude modulation

I-INCE Classification of Subjects Number: 14.5.4

1. INTRODUCTION

During the last years there has been an increasing concern about the annoyance of people by amplitude modulation (AM) of wind turbine noise (1) and the more extreme version of modulation named "other amplitude modulation" (OAM). On that background RenewableUK initiated in March 2011 a comprehensive research study to explore OAM such as characteristics, causes, annoyance etc. The work was organized in 8 work packages and together the reporting from the study (1) published in December 2013 comprises a considerable up-to-date information on different aspects of AM and OAM and has been an important basis for the present study. At a late stage (early 2013) the authors of the present paper were involved in the RenewableUK AM/OAM study and the research work (2) is reported as phase 2 in the RenewableUK report (1).

The present paper contains some results from the work conducted for RenewableUK but the main part is based on new recent research work. The background for the involvement in the RenewableUK research was available, detailed high frequency surface pressure data and inflow data measured on a 2MW 80m diameter turbine within the DANAERO MW project. The DANAERO MW project conducted in the period from 2007 to 2010 in cooperation between Vestas, Siemens, LM Wind Power, DONG Energy and the Technical University of Denmark DTU had the main objective to provide an experimental data base to study fundamental aerodynamic and aero acoustic phenomena on full scale turbines. For the RenewableUK study the data base provided information on the variations of the angle of attack (AOA) on the blade and how the surface pressure spectra at the trailing edge which are the source of trailing edge (TE) noise vary as function of AOA.

However, due to the sensitive instrumentation like flush mounted surface microphones the DANAERO measurements were only carried out in dry weather during daytime and only for a limited period. It was therefore not possible to derive reliable statistics of the AOA variations and therefore the

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analysis of the DANAERO data have been combined with an older data base from 2003 with inflow data measurements on the same turbine.

The structure of the paper is such that the mechanisms and characteristics of AM and OAM are shortly discussed in section 2 based on published research work and not least the information presented in (1). The two experiments, the DANAERO setup from 2009 and the older inflow experiment in 2003 are presented and described in section 3. Then follows the result section and finally the conclusions.

2. AM and OAM

2.1 How to define AM and OAM

Bullmore and Cand present in (4) a comprehensive discussion of the definition of AM and OAM as this was found important for reaching clear conclusions in the RenewableUK study (1) on OAM. Bullmore and Cand use the following definition where the normal version of AM is named NAM: *"…. the definitions of NAM and OAM adopted are those based on the physical source generation mechanisms involved, with NAM being defined as that capable of being fully described in terms of „standard" models of trailing edge noise and OAM being any form of AM lying outside this definition of NAM "*. AM is often characterized as blade *swish* and from the above definition the source is the noise generated at the trailing edge of the airfoil. This noise varies in level and character over time with the turbine blades passing frequency (BPF) for an observer on the ground close to turbine (e.g. for a distance less than 3D) and most pronounced for an observer on the ground in the plane of rotation of the blades. This variation has been shown to be due to a combination of the specific directivity of the radiation of trailing edge noise which is towards the leading edge, coupled with the fact that the turbine blades are moving relative to the listener (4).

As the trailing edge (TE) noise is generated by the turbulent boundary layer on the airfoil passing over the trailing edge, the TE noise is a function of the boundary layer (BL) thickness at the trailing edge. The BL thickness is again a function of the angle of attack (AoA) and it means that TE noise is dependent on the AOA along the blade span. Therefore two main parameters for AM is the directivity characteristics of TE noise and the variation of AoA at the rotor blades e.g. caused by wind shear, the big scales in the atmospheric inflow, operation in yaw or operation in the wake from an upstream turbine (3,5). Depending on the observer position the AoA effect and the directivity influence may be both at a maximum or they may counteract each other.

Following the above definition OAM is now a modulation with characteristics differing from those of AM. Bullmore and Cand (4) mention that OAM could be characterized by one or more of the following features:

- the modulation depth (the difference between the levels of adjacent peaks and troughs in the noise signal) can be significantly greater than that of normal blade swish, with differences in level of up to 6 to 10 dB having been measured, and subjective descriptions of "impulsivity";
- the effect is generally strongest in the downwind direction and has also been reported (less frequently) in the upwind direction of turbines, but it has not been recorded in the cross wind direction in which normal blade swish is most prevalent;
- the dominant frequency characteristics are sometimes lower than for normal blade swish, with a shift in the dominant frequency range to typically around 400 Hz;
- the effect is more dominant in the far field (typically 10 rotor diameters or more from the turbine) and may not even be simultaneously discernible in the near field (typically less than 3 rotor diameters) of the turbines; close to the turbine, substantial swish (2 – 6 dB) is perceived in all directions

2.2 Potential causes of OAM

The main hypothesis for the cause of OAM in the RenewableUK study (1) has been that it is due „transitory stall" on the blades. Oerlemans (5) developed a rotor simulation model including a noise model for a partially stalled airfoil and the model results showed the general observed characteristics of OAM. The source directivity characteristics of the stall noise are such that it is preferentially radiated upwind and downwind of the wind turbine and not in the cross wind direction as characterizes AM. An additional characteristic is that the dominant acoustic frequencies of this stall noise being lower than those resulting from NAM.

In the simulations by Oerlemans (5) wind shear was used in the simulations to trigger transient stall but it was mentioned that non-uniform inflow conditions may also be caused by e.g. yaw (wind veer), topography, large-scale turbulence, or the wake of other turbines.

2.3 Contribution from the present study to understanding causes of OAM

The present work has two main contributions to exploring the mechanisms and causes of OAM. Surface pressure spectra on the blade on a full scale 2MW turbine operating in real inflow have been derived and correlated to instantaneous inflow measurements providing AoA variations. Next the statistical properties of AoA variations and in particular max AoA´s from measurements on the same turbine over a period of three weeks have been conducted.

3. Description of the two experiments

3.1 Inflow measurements

Inflow measurements to the rotating blade on a wind turbine using a five hole pitot tube has been conducted by DTU Wind Energy in several measurements campaigns since it was used for the first time back in the period from 1987-1993 (6). On one of the blades on the 19m diameter rotor the five hole pitot tube was mounted at the leading edge with the head of the probe positioned about one chord length in front of the leading edge and with the supporting tube bend slightly to the pressure side of the blade Figure 1. The tube, typically used on aircrafts, was of the manufacture "Rosemount Model 858AJ" with a diameter of one inch. With the four pressure transducers positioned close to the probe inside the blade the frequency response was tested and showed an almost undisturbed response for frequencies below 10-15Hz (6).

The same tube was used for the inflow measurements on the NM80 80m diameter turbine in 2003 as shown in the right part of Figure 1. The tube was attached to the blade at radius 26.2 m (66% radius) with a small housing with an aerodynamic shape. The housing contained also the four pressure transducers and the signals were transmitted to the hub through a small wire glued to the trailing edge of the blade.

Figure 1 In the left figure is shown the first use in 1987 of the five hole pitot tube on a 19m diameter rotor. To the right, the same tube was mounted at radius 26.2m (66% radius) on the 80m rotor for the campaign in 2003 in the Tjaereborg wind farm. These data are used for the analysis in the present paper.

With a five hole pitot tube two flow angles and the flow velocity can be measured (6). The one angle is called the inflow angle (IA) which can be converted to the angle of attack (AoA) by removing the upwash effect which is due to the influence of the bound circulation around the blade (3).

3.2 The DANAERO MW experiments 2007-2010

The DANAERO MW experiments were conducted in the period from 2007 to 2010 in a project cooperation between Vestas, Siemens, LM Wind Power, DONG Energy and the Technical University of Denmark DTU (7,8). In a follow up project DANAERO MW II with the same partners except DONG Energy, the data were calibrated and checked and finally stored in a suitable data base (9).

The overall objective of the DANAERO experiments was to provide experimental insight into fundamental aerodynamic and aeroacoustic phenomena on full scale turbines. A particular objective was to investigate the influence of the atmospheric flow on the aerodynamics and aeroacoustics. The project comprised a series of coordinated experiments but only the one of them providing input for the present study will be shortly described here.

A new LM38.8m test blade for the NM80 turbine was manufactured during the project and instrumented with pressure taps at four radial stations Figure 2. Adjacent to each of these four radial stations a five hole pitot tube was mounted to measure the local inflow to the blade.

For studying the aeroacoustic noise sources and the boundary layer transition characteristics about 50 flush mounted surface microphones were installed at the outboard radial station 3m from the tip and close to the pressure taps as shown in Figure 2 and 3.

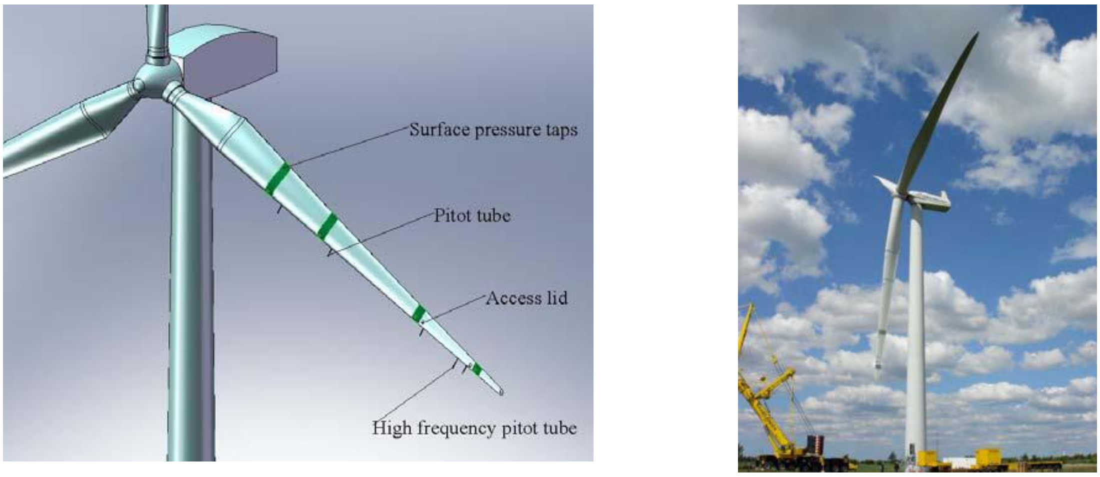

Figure 2 In the left figure is shown an overview of the instrumentation of the test blade. To the right the test blade has been installed on the turbine in May 2009 and replacing one of the original blades.

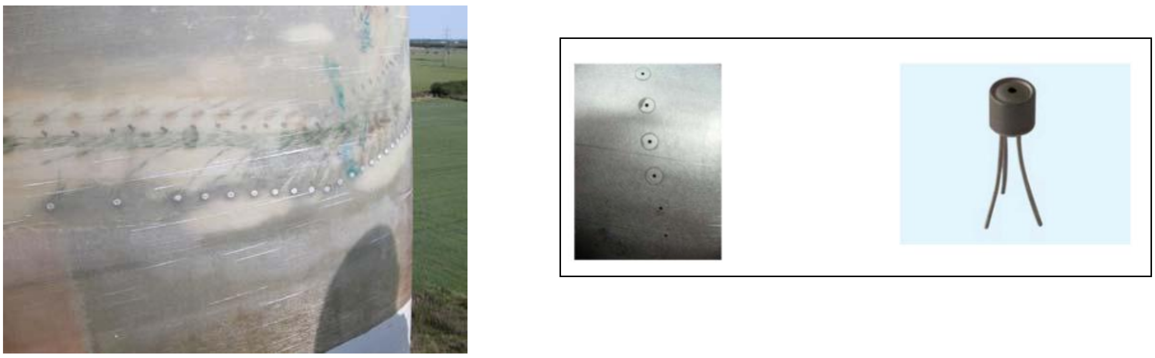

Figure 3 About 50 microphones with a diameter of around 4 mm installed 1 mm below the blade surface and connected through a boring of 1.5 mm. The pressure taps can be seen on the left photo above the row of microphones

The microphones were scanned with a frequency of 50 kHz, the pressure taps with 200 Hz and the rest of the sensors comprising turbine operational parameters and meteorological data in a nearby mast were scanned with 35Hz.

The measurements were conducted over a 2½ month period in 2009 but only as campaign measurements. It means that measurements were carried out only during daytime and in dry weather conditions. Each night all the pressure taps and microphone taps were covered with tape. It should also be noted that in most cases the turbine was run at a constant speed instead of the normal variable speed mode. Further the blades were pitched negatively about 4.5deg. in many of the campaigns in order to get measurements close to stall on the blade.

3.3 Inflow measurements on the 2MW NM80 turbine in 2003

Because the DANAERO MW measurements were only conducted in campaigns during daytime the present analysis has been extended to include inflow measurements conducted on the same turbine in 2003 over a continuous period of about 3 weeks with the turbine in normal operation. Only inflow data from the five hole pitot tube shown in Figure 1 were measured together with turbine parameters including strain gauge measurements at the blade root. During that experiment no measurements from a meteorology mast were available but two nacelle anemometers and wind direction vanes were sampled. The data acquisition rate was 35 Hz and in total about 2000 ten minutes time series were acquired in October to November 2003 and available for the present analysis.

The turbine is situated in a small wind farm with a total of eight 80m diameter turbines in the southwest part of Denmark about 1 kilometer from the North Sea coast as shown in Figure 4. The terrain is flat and the turbines are aligned in two rows with the actual turbine named WT3 in Figure 4. It means that for different wind direction intervals the turbine is operating in the wake of varying downstream distances from upwind turbines. The closest turbine is in a distance of about 3.6D for a wind direction of 201 deg. Figure 4. It should also be noted that considerable differences in the inflow are expected depending on inflow from the sea or inflow or inflow over land.

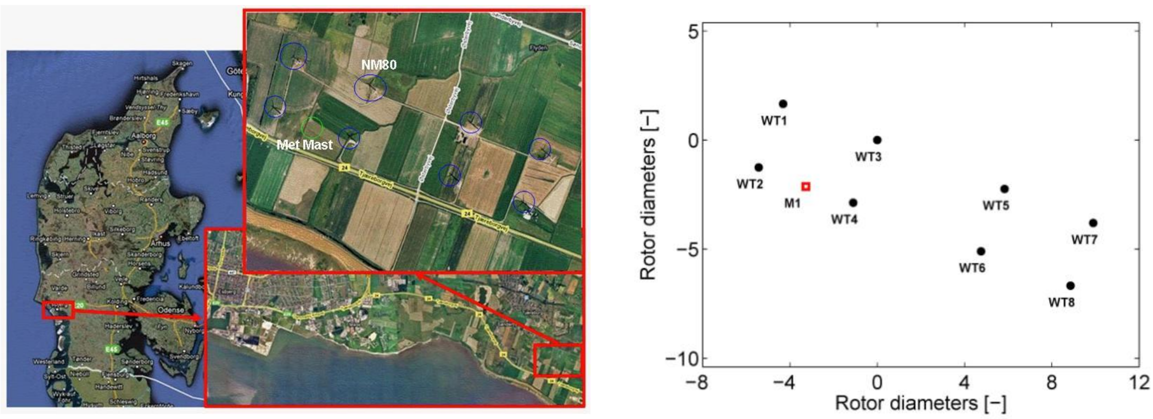

Figure 4 The Tjaereborg wind farm is situated in the South East part of Denmark about one kilometer from the cost to the North See. The actual turbine used for the measurements is WT3 as shown in the sketch of the layout of the wind farm. The met mast M1 shown on the sketch was not erected in 2003.

4. Results

4.1 Measured surface pressure spectra during the DANAERO experiment

In the RenewableUK study on AM and OAM carried out by DTU (3), the DANAERO data base provided information on the variation of the surface pressure spectra as function of AoA. In particular the focus was on the change in spectra at high AoA where trailing edge stall appears and as discussed previously expected to be one of the main causes of OAM. The surface pressure fluctuations in the turbulent boundary layer are not the TE noise but its source as it appears from the modeling of TE noise with e.g. the TNO model (10). However, it should be noted that the TNO model is not expected to be valid for separated flow where other prediction models have been proposed (5,11).

As an example from the study reported in (3) is shown a measurement from September 1st 2009 where there was a strong shear in the inflow on the bottom part of the rotor plane as shown in Figure 5 left. However, on the top part from a height of 60m and above the wind speed is almost constant. This indicates two layers in the atmospheric boundary layer probably caused by the inflow from the sea and the associated change in roughness when the flow reaches the land.

The wind shear causes a considerable variation of measured AoA on the blade as shown on the right part of Figure 5. The AoA was measured at radius 31m was used in this case to correlate with the surface pressure spectra as the most outboard inflow sensor was not working properly at that time.

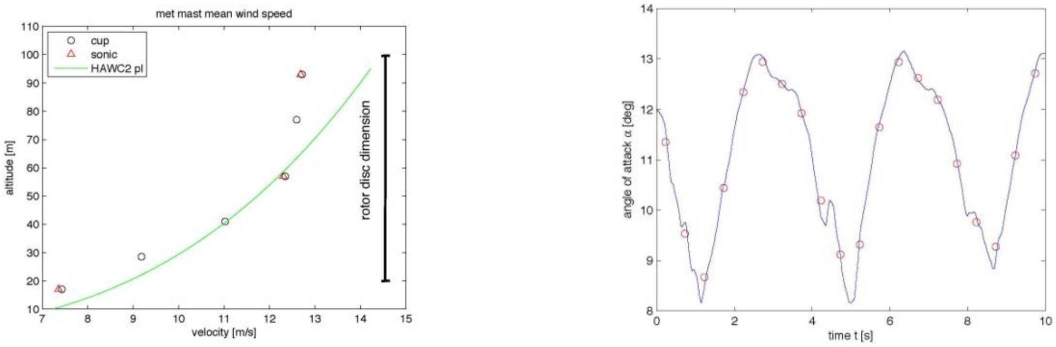

Figure 5 To the left the wind profile measured in the met mast close to the turbine on Sept. 1st, 2009 at 11:40. To the right measured angle of attack at a radial position r = 31m. The red dots indicate the center of the ½ second intervals where spectra of the surface pressure fluctuations were derived. Both figures from (3)

Spectra from a microphone close to the trailing edge were derived for time periods of ½ s interval and the center of the intervals are shown with the red circles in Figure 5. The corresponding contour plot of the surface pressure spectra, Figure 6 left, shows a very strong amplitude modulation in the low frequency range (f < 200Hz). The difference in level in the low frequency range in time is up to 14dB and the contours show a very steep change which could be the source of the „whoosh" or „thump" as has been used to characterize OAM (4). The high levels occur when the AoA is around 13°. The results of binning the data on the AoA and computing the spectra are shown in the left part figure 6. The energy in the spectrum is shifted gradually from high to low frequencies when going from AoA= 8 to AoA = 12. Comparing the spectrum for the AoA equal to 12° and AoA equal 13° one can see a very strong increase in the low frequencies. This abrupt strong increase in the low frequency range due to beginning trailing edge stall is expected to be a main contributor for AOM in the far field.

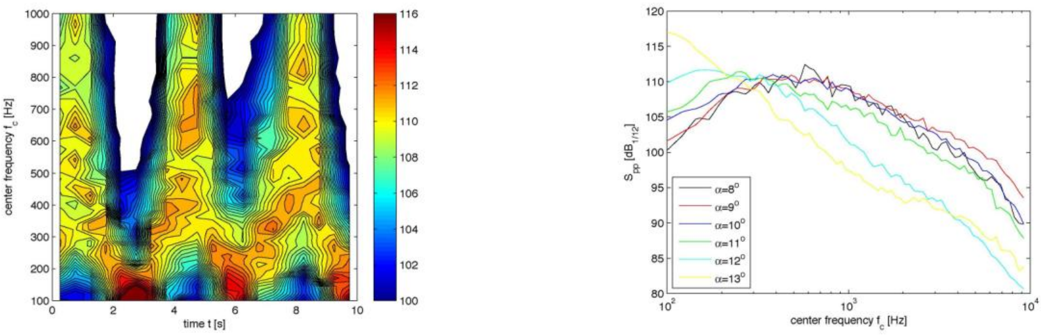

Figure 6 To the left narrow band spectra of surface pressure at radial position r=37m measured on Sept. 1st, 2009 at 11:48. SPL in dB (1/12th octave). To the right narrow band spectra of surface pressure binned on angle of attack measured on Sept. 1st, 2009 at 11:48. SPL in dB(1/12th octave). Both figures from (3)

4.2 Statistics of AoA variations from the 2003 experiment

As OAM seems to be linked to AoA variations and in particular events where the max AoA is so high that initial TE stall is expected, examining the statistics of AoA variations will contribute to the understanding of the occurrence of OAM and the causes. Therefore an analysis of the AoA data from the 2003 measurements on the 2MW NM80 turbine in the Tjaereborg wind farm was carried out.

A correction of the measured inflow angle (IA) for the influence of upwash was carried out based on a similar procedure to the one described in (12). Before the AoA signal was processed to find the amplitude during each rotor revolution a running average over six data points was applied in order to reduce the impact of possible noise in the signal.

To include an analysis of the impact of wake operation compared with free inflow the data were sorted in two groups depending on the yaw position of the turbine used as indicator of the wind direction Figure 7. A simple model of the wake expansion was used to estimate the wind direction interval around each wake generating turbine. For the nearest turbine WT4 in direction 201 the width of the wake when the wake flow hits the considered turbine WT3 is seen to be estimated to about 40^o.

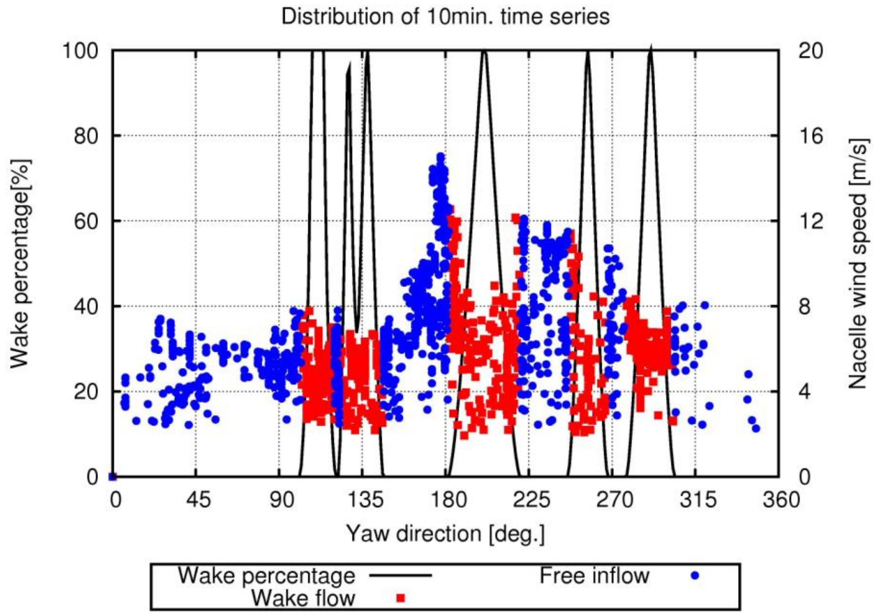

Figure 7 The data were sorted in two groups where the red squares indicate that the inflow to the considered turbine WT3 has passed through the rotor of one of the other turbines in the wind farm. The blue circles indicate free inflow.

The ten minutes statistics of the AoA and the relative velocity (Vrel) are shown in Figure 8 as function of the mean electrical power (Pe) for free in flow and for wake operation, respectively. The variable speed range for the turbine from about 250kW to 1000kW is clearly seen in the way that the mean AoA is almost constant whereas Vrel increases. Below 250kW the turbine runs at its minimum speed and above 1000kW it reaches its max rotational speed. In both regions the AoA increases and there is a slightly increase in Vrel due to the increase in the wind speed through the rotor plane.

The interesting characteristics of AoA with respect to OAM are the distribution of the max values. Most of the highest values are seen for a rotor power of about 500kW just at the beginning of the variable speed operation. The 500kW corresponds to a wind speed of 6-8m/s. Of confidential reasons the absolute values on the AoA scale is not shown but the AoA range between the major grid lines is 5^o. It is seen that for some cases the max AoA values are more than 10^o above the mean value which for most rotor designs will cause operation in some degree of stall. Comparing the free inflow case with the wake case it can be seen that in general higher max AoA are seen during wake operation.

The major influence of wake operation is shown by the derived AoA amplitudes (min to max) over each rotor rev as presented in the two graphs Figure 9 by integrated probability curves. As an example, operation at 284kW the AoA amplitudes for free inflow are above 4^o at 10% of the time but for wake operation it is about 8^o for 10% of time. This is also what is expected as the wake flow causes an increased non-uniform inflow to the rotor.

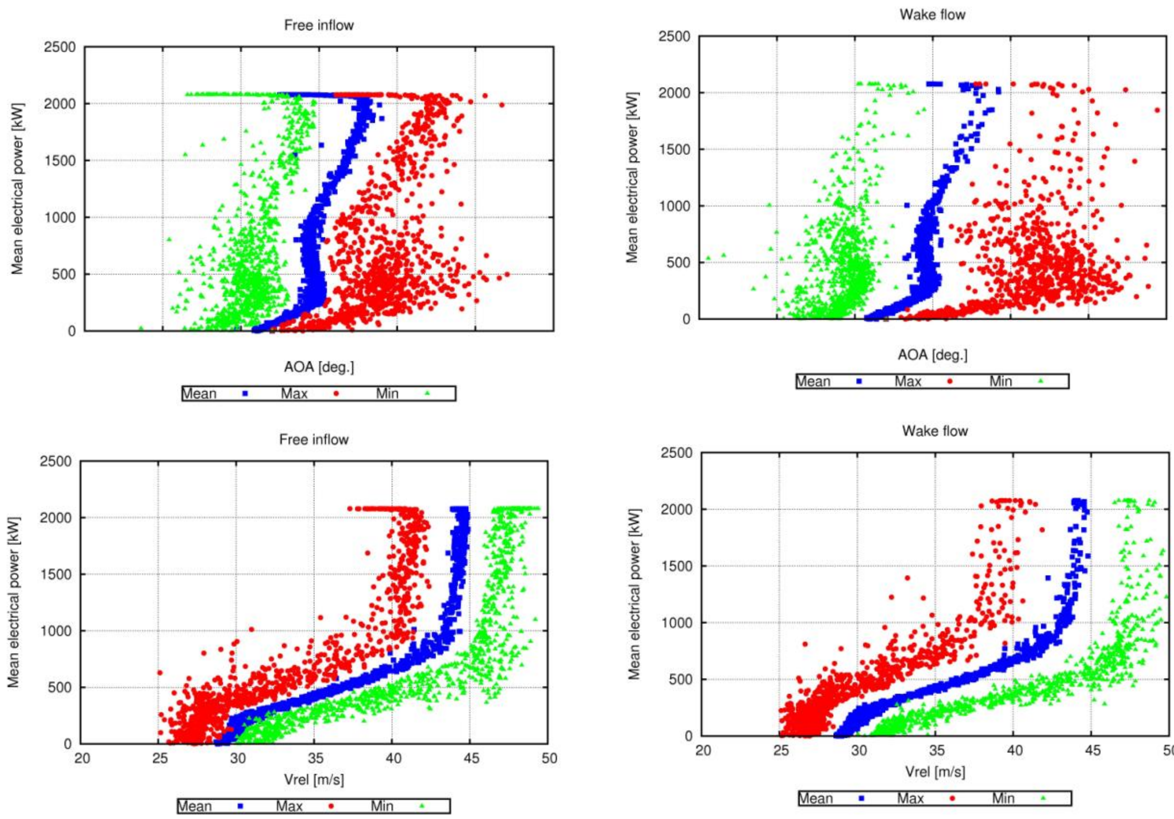

Figure 8 The 10min statistics of AoA and Vrel as function of rotor power. For confidential reasons the absolute values on the AoA axis are not shown but the interval between the major grid lines on the AOA curves is 5°.

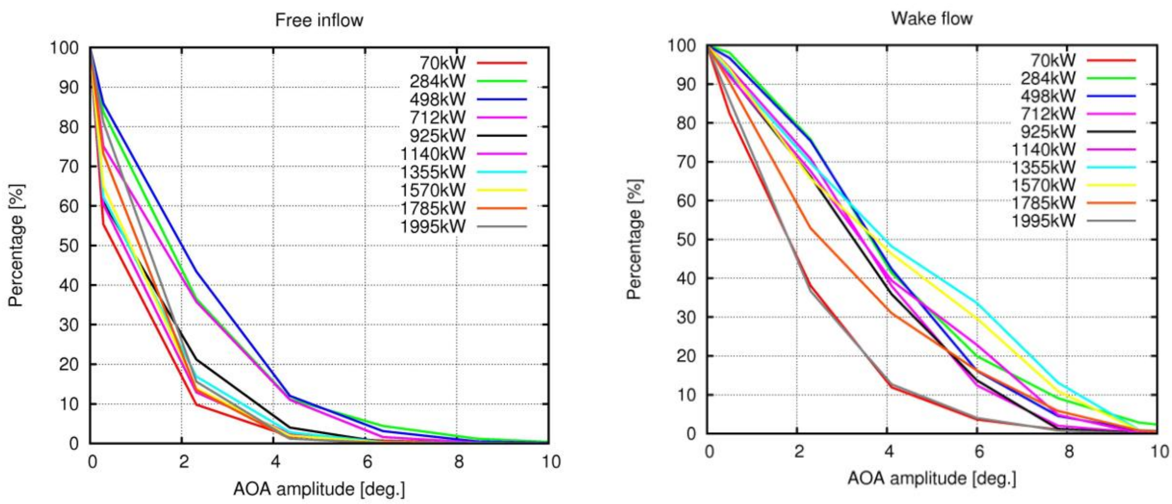

Figure 9 The two graphs show the 10min statistics of integrated probability functions of AoA amplitudes over each rotor rotation.

4.3 Selected cases with extreme max AoA

Some of the 10 min. time series with the most extreme max AoA's as shown in Figure 8 were selected for a closer examination to explore the details of the mechanisms behind these extreme events. Examining the cases for free inflow it turned out that they all were close to the wake regions in Figure 7 so it can be concluded that a wider wind direction interval around the wake generating turbines has to be selected to have completely free inflow. The so-called wake-meandering mechanism (13) can explain that. Wake meandering means that the wake flow with the velocity deficit embedded

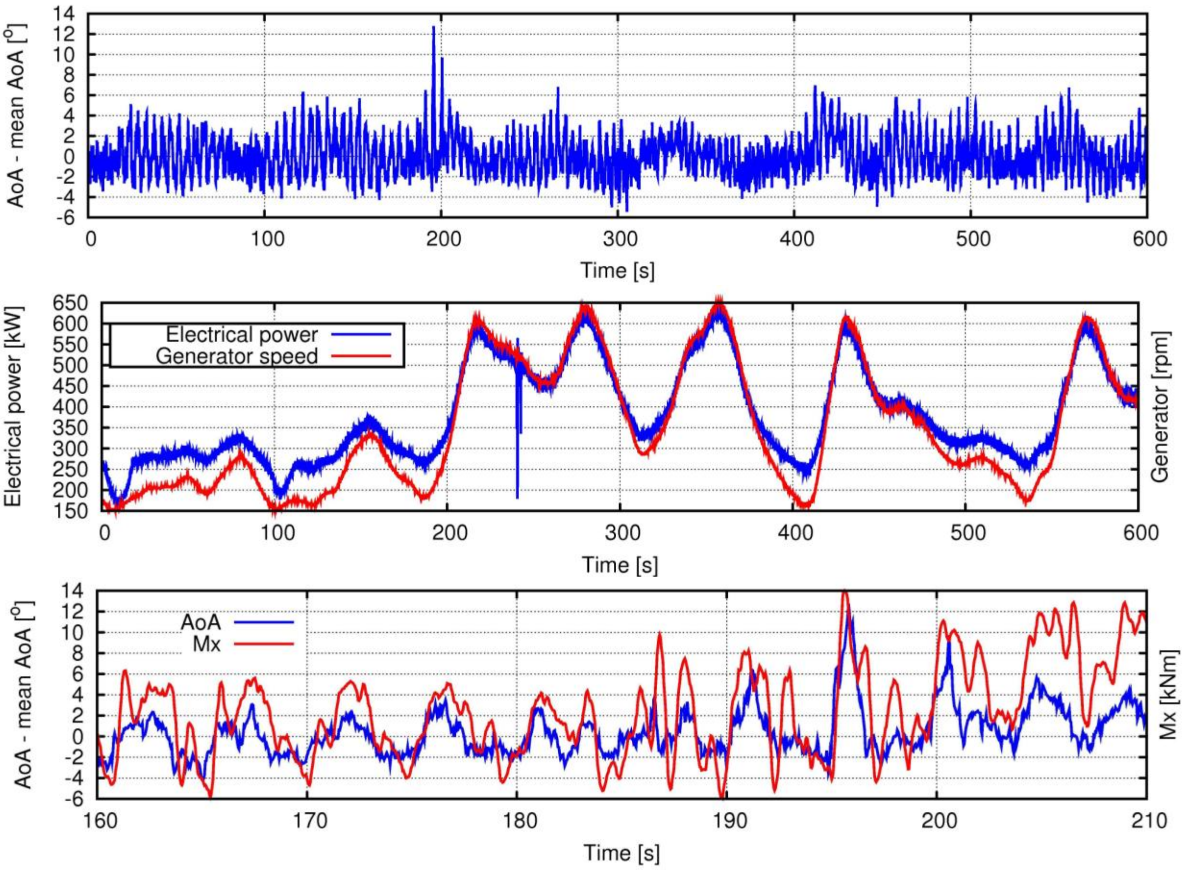

Figure 10 The upper graph shows the AoA variation (AoA – mean AoA) for an operation in partial to full wake. The yaw position is 298^{o} which means wake inflow from WT2. Mean Pe is 381 kW. The lower graph shows the electrical power and the generator rpm. The bottom graph shows the AoA and the flapwise moment.

follows the instantaneous wind direction and although a downstream turbine as a mean over 10 minutes is outside the wake it can for shorter periods be in half wake or maybe even in full wake.

The presented case in Figure 10 shows the intermittent occurrence of extreme AoA as often is mentioned as a characteristic of OAM. This intermittency can be explained by the meandering of the wake which means that the rotor can experience the full velocity deficit in the wake for a short period and afterwards for another period the deficit moves in horizontal or lateral direction and the conditions change to partly wake or even free inflow. This combined with the variable speed operation which means that the rotor cannot accelerate fast enough to follow the abrupt wind speed increase over the rotor disc can cause a transient stall over a part of the rotor for a few revs as seen just before time 200 in Figure 10. The abrupt increase in AoA is confirmed by the measured flapwise moment as shown in the lower graph of Figure 10. For more steady wind conditions with lower atmospheric turbulence the meandering which is controlled by the two lateral turbulence components will be less and such conditions were found in some of the cases with extreme AoA's and then several rotor rotations can contain high AoA's.

Alleviation of the occurrence of transient stall at low unsteady wind as wake flow could be to increase the lower limit of the variable speed. A method to decrease the AoA variations over one rotor revolution could be cyclic pitch or individual pitch based on strain gauge measurement of the flapwise moment as a strong correlation between variations of the flapwise moment and the AoA has been shown.

5. CONCLUSIONS

The analysis of the spectra from flush mounted surface microphones on a 2MW turbine conducted in the DANAERO experiment shows a strong increase at low frequencies when the AoA reaches 12-13^{o} where trailing edge stall initiates. For the turbine operating in a strong wind shear a modulation of the surface spectra for frequencies below 200Hz is 14dB. This is expected to generate AM or OAM in the far field.

The statistics based on an analysis of about 2000 10min time series of measured AoA on the same turbine over a period of three weeks has shown that transient stall over part of a rotor revolution is likely to occur and in particular during wake operation. The meandering of the velocity deficit in the wake can cause abrupt changes in wind speed over the rotor disc and for a variable speed turbine the rotor might not be able to accelerate fast enough to avoid transient stall for a few revolutions. This intermittent occurrence corresponds well to the reported typical characteristic of OAM and the mechanism might explain many of the occurrences of OAM.

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