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A novel full scale experimental characterization of wind turbine aero-acoustic noise sources - preliminary results

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Abstract

The paper describes a novel full scale experiment on a 500 kW wind turbine with the main objective to characterize the aero-acoustic noise sources. The idea behind the instrumentation is to study the link and correlation between the surface pressure (SP) fluctuations in the boundary layer of the blade and the noise on the ground in a distance of about one rotor diameter. In total six surface microphones were used to measure the SP at the leading edge (LE) and trailing edge (TE) of the blade. In parallel noise was measured by eight microphones placed on plates on the ground around the turbine in equidistant angles on a circle with a radius of about one rotor diameter. The data were analyzed in segments of 2.2 s which is the time for one rotor revolution. The spectra for the TE microphones on the suction side of the blade show a characteristic roll-off pattern around a frequency of 600-700 Hz. For increasing wind speed the spectral energy increases below this point and the same is seen on the ground microphones spectra. The decrease in the spectral energy above this point is also found for the blade surface microphones but not on the microphones on the ground. An interesting spectrum was observed for the microphone on the pressure side close to the TE. For increasing wind speed the spectra show a very distinct increase in spectral energy up to about 300 Hz after which the spectra collapse. As the boundary layer is laminar it is thought that this spectral energy is due to sound waves from the TE noise on the suction side.

Keywords

Wind turbine aeroacoustics — surface microphones — noise sources

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INTRODUCTION

Over the last 10 years The Technical University of Denmark (DTU) has worked on experimental characterization of the aero-acoustic noise sources of wind turbines and in parallel developed aeroacoustic modelling. In particular the trailing edge (TE) noise; the turbulent inflow (TI) noise and the stall (ST) noise have been explored as they are the dominant noise sources for wind turbines. The basic source of all three noise types are the high frequency surface pressure (SP) fluctuations in the boundary layer on the blade. TE noise is linked to the SP fluctuations near the airfoil trailing edge [1, 2, 3, 4, 5] produced by turbulent vortices geneated within the turbulent boundary layer (BL) developing on the airfoil surface itself. The convection of these vortices past the sharp TE of the airfoil results in a scattering phenomenon causing the far field noise. Turbulent inflow (TI) noise is produced by atmospheric turbulence vortices that upon impingement on a wind turbine blade generate SP fluctuations on the blade, subsequently radiating as sound. TI noise is predominantly generated in the area of the airfoil section near the leading edge (LE) [6, 7] where the boundary layer typically is laminar. Finally, ST noise is closely linked to the SP fluctuations on the suction side of the airfoil where the flow is separated due to the adverse gradient at a high angle of attack (AoA) [8, 9]. From the above it is clear that characterization of the SP on an airfoil is an important step to understand the far field noise of a wind turbine. However, most experimental data on wind turbine noise are in the form of far field noise measurements according to the International Electrotechnical Commission (IEC) standard [10]. This works well for determining the sound power level of the turbine which normally is needed for certification of the turbine. However, for a closer insight in the noise generation mechanisms on the turbine the method is not well suited. This has recently been demonstrated by the detailed investigations of the causes of amplitude modulation (AM) [11]. The AM was measured in several cases on the ground at different turbines and in the far field but the main generating mechanisms on the turbine could only be described on basis of hypotheses. The close link between SP fluctuations and the far field noise was the main reason that DTU in 2006 began to explore and develop the techniques for measuring SP fluctuations on wind turbine airfoils and blades. The work was in particular conducted within the DANAERO project [12, 13] 2007-2010, the DANAERO II project from 2011-2013 [14] and in the PhD study by Fischer [5]. One of the main objectives of the DANAERO projects was to characterize the noise sources on a fullscale megawatt (MW) turbine with an 80m diameter rotor and compare with the noise mechanisms on a blade section in a wind tunnel. The work led to new insight into wind turbine aeroacoustics in real atmospheric turbulent inflow [15] and has contributed to the understanding of the mechanisms behind AM [16, 17]. One of the shortcomings in the above experimental set-up has been that no measurements of the noise on the ground near the turbine and further away was carried out. This means that it has not been possible to study the link or correlation between the detailed noise source characterization on the blade and the far field noise. Also the directivity of the different noise sources could not be investigated. Further, a shortcoming in the DANAERO measurements was that the surface microphones used could not withstand any moisture as they were installed in a cavity about 1 mm below the airfoil surface. To overcome these limitations a new experimental set-up has been developed in 2015 at DTU with the overall aim to characterize the noise sources on a wind turbine by measuring SP fluctuations on the blade and in parallel the noise on the ground around the turbine. A further objective has been to develop an instrumentation that is transportable so it can be used on turbines at different sites with e.g. different inflow conditions. In the present paper this new set-up is first described followed by presentation and discussion of initial results.

1. EXPERIMENTAL SET UP

The main elements of the instrumentation are six surface microphones on one of the turbine blades and a five hole pitot tube for measuring the inflow angle (IA) to the blade and relative velocity. Further, eight microphones are placed on the ground in a circle around the turbine in a radius of one rotor diameter. Measurements of wind speed and direction with anemometers and a sonic anemometer at different heights in a nearby meteorological mast were also carried out. Finally, a number of microphones were placed in a line on the ground in the far field for propagation studies but they were not used in the campaigns for the present study. The overall set-up is shown in Fig. 1

1.1 Turbine and test site

The turbine used for the measurements is a Nordtank 500 kW turbine with a rotor diameter of 41.1m, shown in Fig. 2, situated at DTU Wind Energy, Campus Risoe. The site as shown in Fig. 3 is relatively flat and close to Roskilde Fjord (200-300m), Fig. 4. The site is not ideal for noise measurements as a road is close to the site as seen in Fig. 4. However, the turbine was chosen as it is owned by DTU and close to the DTU Wind Energy Labs. The main data of the turbine are presented in Table 1.

1.2 Blade surface microphones

The six surface microphones were G.R.A.S. 40LS 1/4" CCP Precision Surface Microphone with a thickness of just 2.5mm and a 7.4mm diaphragms. They were delivered with a supple detachable silicon-rubber fairing and attached to the blade surface with tape as shown in Fig. 5. The connecting cables were also taped to the blade surface and first directed towards the TE and then led to the hub along the TE. In the hub the data aquisition system was mounted, scanning the microphones with 50 kHz (measurements on 15/10) and 25kHz (measurements on 23/10). Results from the microphone set-up shown in Fig. 5 will be shown later. On each side of the blade two microphones were positioned close to the LE and one close to the TE. The TE microphones were 0.5m in spanwise distance to the tip brake (closed during operation with very small gap) and the LE microphones at an additional distance of 0.5m inboard as shown in Fig. 5. The microphones were calibrated individually by the manufacturer in laboratory conditions. During calibration, the sensitivity was measured with a 114.00

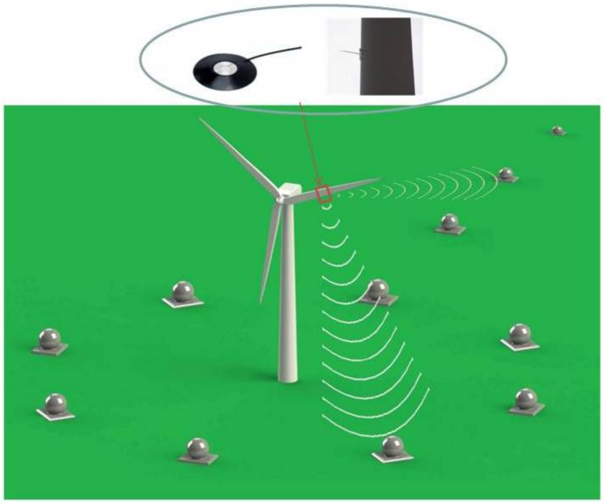


Figure 1. Sketch of the experimental set-up. Surface microphones on one of the blades and a five hole pitot tube for inflow measurements. On the ground eight microphones on plates at equidistant angle intervals around the turbine in a radius of one rotor diameter. Finally, a number of wireless microphones in the far field beyond one rotor diameter for noise propagation measurements (not used in the present campaign).

Table 1. NTK 500kW Specifications

Rotor	
Rotor diameter	41.1 m
Swept area	1320 m^2
Rotational speed	27.1 rpm
Tilt	2^o
Coning	0^o
Blades	
Blade type	LM 19.1
Blade profiles	NACA-63-4xx* & FFA-W3-xxx*
Blade length	19.04 m
Blade chord	0.265 - 1.63 m
Blade twist	$0.02 - 20.0^o$
Air brakes	Pivotal blade tips
Drive train	
Power regulation	Passive aerodynamic stall
Gearbox	Flender, ratio 1:55:35
Generator	Siemens 500 kW, 4 poles, 690 V
Tower	
Type	Conical steel tube, height=33.8 m
Hub height	36 m

* ‘xx’ and ‘xxx’ denote the varying airfoil thicknesses along the span

Figure 2. The 500kW Nordtank turbine situated at DTU Wind Energy, Campus Risoe, is used for the measurements.

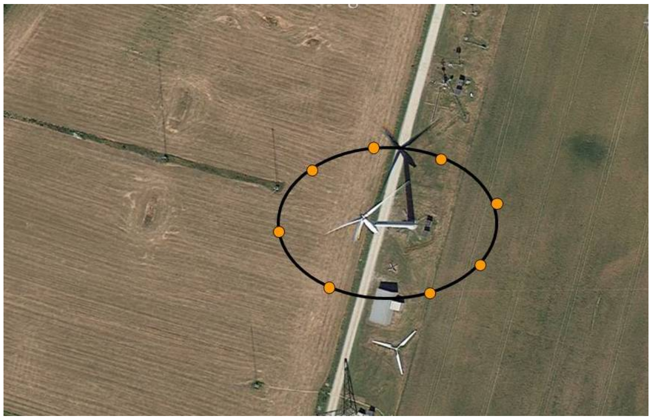


Figure 3. The 8 microphones on the ground positioned around the turbine on a circle at equidistant angle intervals.

dB at 250 Hz acoustic input signal, generated by a G.R.A.S. 42APPistonphone with adaptor RA0202, and is traceable to National Physical Laboratory, UK. The uncertainty of the sensitivity measurement was less than ±0.1 dB for each microphone. The frequency response is flat. The variation is less than 0.1 dB in the frequency range between 20 Hz and 20000 Hz.

Figure 4. The test site with a road east of the turbine position and Roskilde Fjord to the west.

1.3 Microphones on the ground

Eight microphones were placed around the turbine at equidistant angle intervals and at a radius of 45m from the tower which is a distance equal to one tower height plus a half rotor diameter according to the IEC 61400- 11 standard for wind turbine noise measurements [10]. Microphone setup was manufactured by BSWA Technology Co. and comprises a ½” microphone connected to a preamplifier. The microphones have a nearly flat frequency response within a range varying between 20 Hz to approximately 10 kHz. The microphones are placed under half-spherical wind shields and attached to a 1.2m diameter circular plywood board as seen in Fig. 6.

1.4 Inflow measurements with a five hole pitot tube

In the above mentioned DANAERO experiments the inflow measurements played an important role in determining the exact, instantaneous inflow angle (IA) to the blade and the relative velocity [12, 13, 14]. The TE noise is closely linked to the boundary layer thickness at the TE which again is correlated with the angle of attack (AoA) or IA. The terminology IA is used here as the AoA in principle only can be uniquely defined for a blade section in 2D flow. On MW turbines with rotor diameters above 100m the IA can vary considerably during one rotor revolution (rev.) due to e.g. wind shear or big turbulent eddies. This can cause amplitude modulation (AM) of the noise and combing IA measurements with measurements of SP fluctuations have provide a detailed insight into the mechanisms of AM [17].

1.5 Data acquisition

Three different data acquisition systems were used for the present set-up. The surface microphones were sampled via a 24 bit ±5V A/D converter and a National Instrument system cRIO-9033 in the hub. We used a sampling rate of 50kHz in the campaign on the 15/10 but found out that we could go down to 25kHz which was used in the campaign on the 23/10. The system features a combination of analog and digital low pass filters with a cut off frequency of half the

Figure 5. Photos showing one of the surface microphone set-up´s as used in the measurement campaign II. Two microphones close to the LE.(5 and 10 chordwise position) and one microphone close to the TE (95 chordwise pos.) on both the pressure and suction sides of the blade.

Figure 6. One of the eight microphones around the turbine on the plywood board and with a wind shield.

Figure 7. The autonomous inflow sensor unit mounted on the blade.

sampling frequency to avoid aliasing. The 8 microphones on the boards on the ground were recorded with a National Instruments PXI acquisition platform sampling at 50 or 25 kHz, respectively. A third PC-based data acquisition system was used to sample the data from the wind turbine and meteorology mast sensors. The sampling rate was 35Hz. The two systems sampling the microphones on the blade and on the ground were synchronized with a GPS clock.

2. POSTPROCESSING

The time-series for the microphones on the blade and on the ground were split into 2.2 s sub-series as this corresponds to the time of one rotor rev. The 2.2s time-series were divided into 20 sub-series and spectral averaging performed subsequently. Windowing was performed using a standard Hanning window. Then all the above calculated spectra were binned according to chosen conditions based on an arbitrary sensor but in the present case the nacelle wind speed sensor was used. All the spectra within each bin were finally averaged together. It was also investigated what impact it has using 10s time series. The overall trend for how the spectra change with wind speed were the same but the curves were smoother for the shorter time series than for the 10s series. It should be noted that the turbine is running at constant speed and therefore the IA and thus also AoA will increase with wind speed. The same will be the case for the TE noise correlated with AoA and this motivates the above post processing. The most important parameters for TI noise is the inflow turbulence intensity and the length scale [6, 7]. This could be investigated by looking at the influence of turbulence intensity in the inflow (the nacelle wind speed) and look at the variation in the spectra for a fixed wind speed bin.

The first attempts in this direction have been carried out with the present data set but to reach some conclusive results the data base should be bigger. Background noise measurements were carried out while the turbine was stopped at different times during the campaign. The background noise comes mainly from the nearby road. But also the noise created at the wind shields due to the flow speed above the ground plays a role. For the present analysis we show the uncorrected spectra and the background noise spectra in the same plots so it can be seen at what frequencies the uncorrected spectra might be influenced by the background noise.

3. EXPERIMENTAL RESULTS AND INTERPRETATION

Results will be presented from two campaigns I and II with different surface microphones arrangements, each of them carried out within one day over a few hours. In campaign I all the six microphomes were placed close to the trailing edge as shown in Fig. 8. The focus was TE noise characterization and the reason to use six microphones at the same chordwise position was to get a data set from which the spanwise length scale in the boundary layer can be derived. The results on this were not ready for the present paper. In campaign II, two microphones were positioned at the LE and one at the TE on each side of the blade, respectively. The arrangement is shown in Fig. 9. Unfortunately, two microphones indicated with red in Fig. 9 were malfunctioning in this campaign.

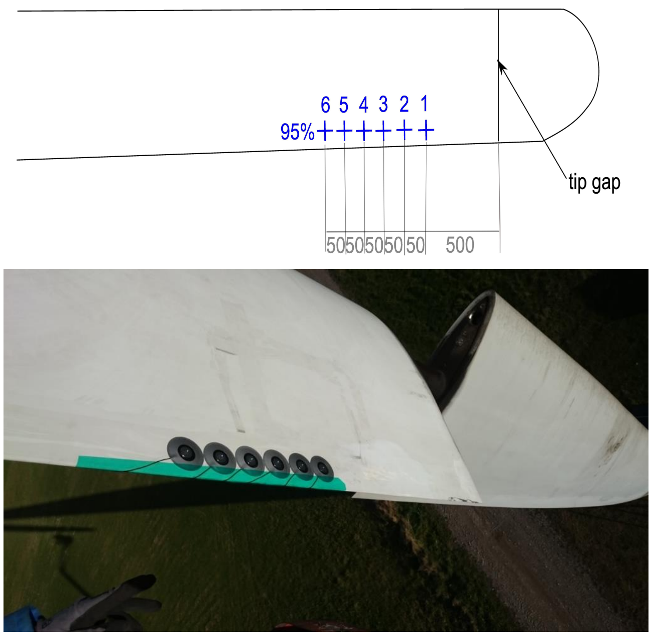


Figure 8. In campaign I the six microphones were positioned on the suction side 500 mm from the tip brake attachment and with 50mm between the individual microphones.

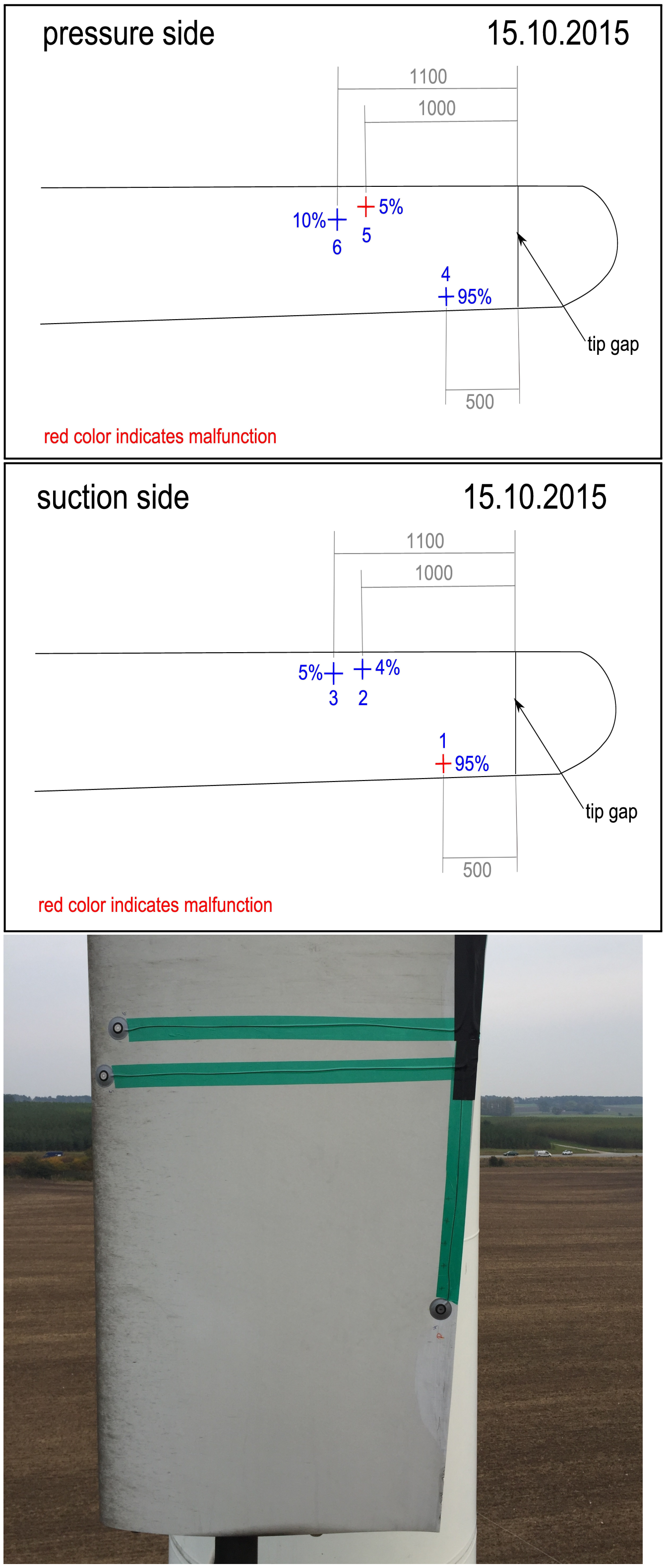


Figure 9. The microphone positions in campaign II. Two microphones were at the LE and one at the TE on each side of the blade. The photo shows the microphones on the pressure side.

3.1 Results from campaign I with surface microphones close to the TE

In this campaign carried out on one day, all the six blade surface microphones were mounted at the TE as shown in Fig. 8. The spectra from the six microphones are shown in Fig. 10 for 1m/s wind speed bins of Vn from 4.5m/s to 10m/s. Unfortunately, microphone no. 1 was malfunctioning. However, the spectra from the other microphones show a very clear dependency on Vn and thus on AoA. They all have a turning point at 600-700Hz where the spectrum is independent of Vn. Above this frequency the spectral energy increases for decreasing Vn and above the opposite trend is the case. Exactly the same was seen in the DANAERO experiments [14] although this neutral frequency was at a slightly lower value. Now correlating with the spectra of two microphones on the ground it can be seen that they have somewhat the same changes in spectral shape for frequencies below 400-500Hz as function of changes in nacelle wind speed. However, for the ground microphones it is now more a band of neutral frequencies from 500-1000Hz than a specific neutral frequency as seen in the SP spectra on the blades. For frequencies above 1000-1100Hz the changes in shape of spectra of the ground microphones are almost the opposite of the blade SP microphones. For increasing Vn the spectral energy on the ground microphones increases whereas the opposite tendency is found for the spectra from the blade surface microphones. A peculiarity is found in the spectra of microphone 5 and 6 which are the two most inboard of the six. The spectra indicate separation on the blade by the strong increase in spectral energy at the low frequencies. The same characteristics of the spectra as found at stalled conditions in the DANAERO experiments [17]. However, why it only occurs for the 6.5 and 7.5m/s bin and only on the two inboard microphones remains unexplained.

3.2 Results from campaign II with surface microphones at LE and TE

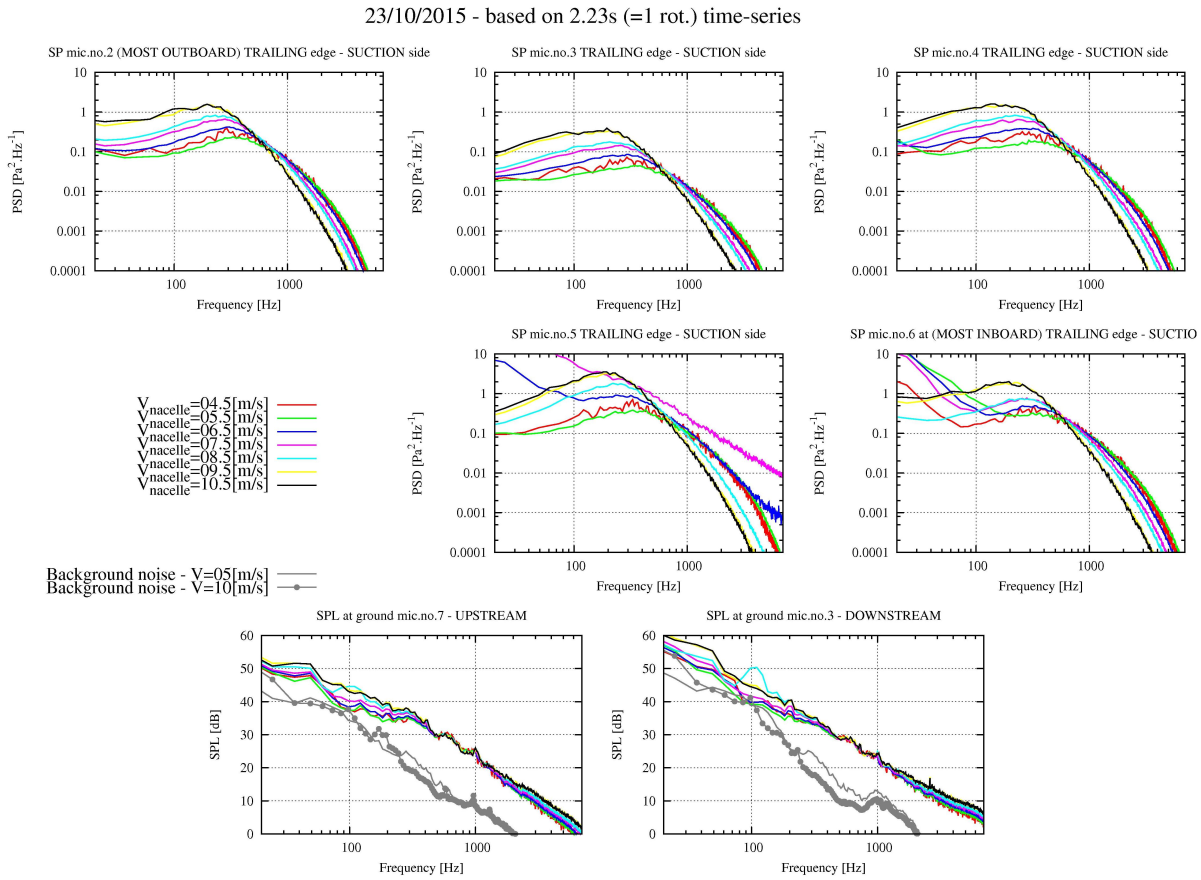
In this campaign there were two microphones at the LE and one at the TE on each side of the blade, respectively. The arrangement is shown in Fig. 9. Unfortunately, two microphones indicated with red in Fig. 9 were malfunctioning in this campaign. Spectra from three of the blade surface microphones; 95% position pressure side; 4% suction side and 10% pressure side are shown in Fig. 11 together with the spectra from the upstream and downstream microphone on the ground. The most remarkable result from this set-up is from the microphone on the pressure side close to the trailing edge. The spectra have a very distinct dependence on the wind speed up to about 300 Hz after which all the curves are collapsing indicating no dependence on wind speed. The spectra from the two ground based microphones show the same dependence on the wind speed but up to a slightly higher frequency that is the turning point frequency mentioned above. The mechanism behind the spectrum of that microphone is thought to be the scattering of the noise from the suction side boundary layer at the TE and reflecting around the TE and back to the airfoil surface. So it is not a self generated noise at this position as the boundary layer according to the spectral characteristics is laminar due to the accelerated flow on the pressure side. The 10% LE suction side microphone spectra increases also very distinctly with wind speed up to 300-400Hz after which the spectra are influenced by the increasing Tollmien–Schlichting instability waves at 2-3 kHz. The peak of instability is more broad banded than seen in wind tunnels but the same characteristics has been measured on an 80m diameter rotor in the DANAERO project [13]. The 10% LE pressure side microphone shows very little dependence on wind speed up to 300 Hz after which the Tollmien–Schlichting instability waves again change the spectrum, however now with decreasing effect as function of increasing wind speed as the pressure gradient becomes more favorable for increasing AoA. From this microphone set-up it can be concluded that the spectra from the microphone on the pressure side and the spectra from two ground based microphones show a similar development in spectra shapes up to 200-300Hz for a change in wind speed from 4-11m/s.

3.3 Results on directivity

As a last result is shown data on the directivity of the wind turbine noise campaign I. The basic data processing is the same but the spectra shown are now the difference with the spectrum of the downstream microphone, Fig. 12. The overall tendency is a lower level of the noise from the four microphones closest to the rotor plane in the frequency range up to about 1 kHz. There is also a tendency to higher levels when just moving slightly to the side from the upstream or downstream position. All this seems to be as expected according to the modeling of directivity of TE noise. For higher frequencies between 1-3 kHz there is another pattern with almost constant levels of the different microphones. However, a new tendency above 3 kHz is seen where two upstream microphones are decreasing and two downstream decreasing. Finally, directivity polar plots for the same data set are shown for a few frequency bands in Fig. 13. The figure displays 1/3rd oct. band integrated SPL at chosen 1 octave band center frequencies. Up to about 1kHz there is a clear asymmetry of the noise levels relative to a line aligned with the wind direction. For frequencies between 3.5 and 4.5 kHz the highest levels are downstream the turbine.

CONCLUSIONS

A novel full scale experimental set-up for detailed characterization of noise sources on a full scale turbine operating in the atmospheric environment has been presented. The main elements are six microphones mounted at the LE and TE of the blade, eight microphones on boards on the ground and an inflow instrument mounted on the blade close to the leading edge. The analysis of the first experimental data shows qualitatively the same change in spectra for the TE microphones on the blade and in the spectra from the microphones on the ground for frequencies up to about 500Hz. A very distinct dependence on the wind speed was found for the spectra measured on the pressure side close to the TE. A conjecture is that it is not due to SP generated in the boundary layer but TE noise from the


23/10/2015 - based on 2.23s (=1 rot.) time-series

SP mic.no.2 (MOST OUTBOARD) TRAILING edge - SUCTION side

SP mic.no.3 TRAILING edge - SUCTION side

SP mic.no.4 TRAILING edge - SUCTION side

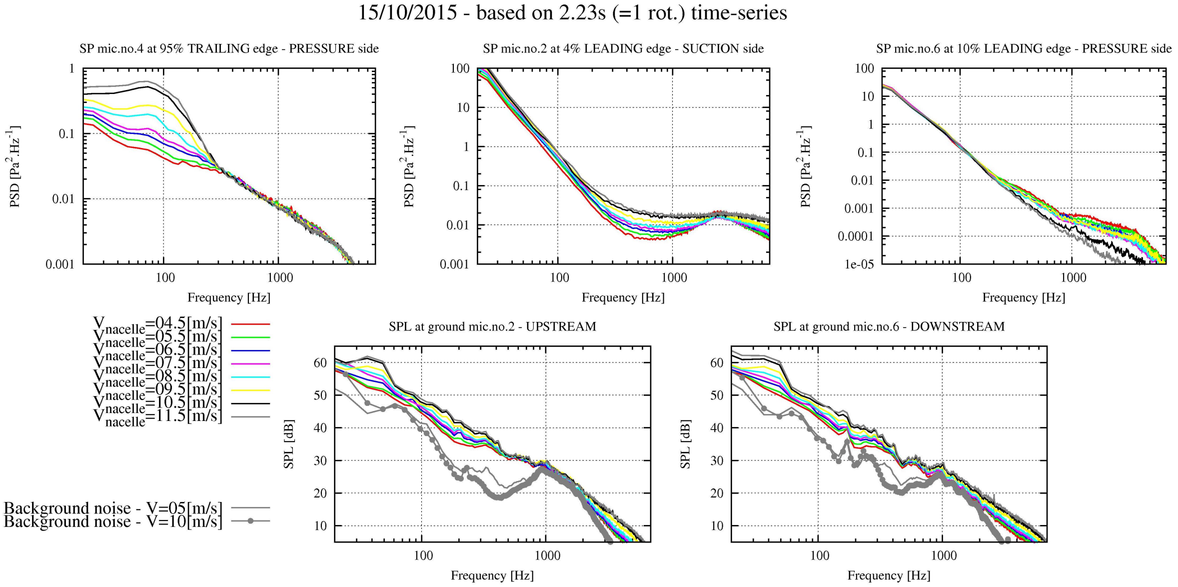
SP mic.no.5 TRAILING edge - SUCTION side

SP mic.no.6 at (MOST INBOARD) TRAILING edge - SUCTIO

SPL at ground mic.no.7 - UPSTREAM

SPL at ground mic.no.3 - DOWNSTREAM

Figure 10. Spectra of 5 TE surface microphones in upper two rows. Bottom row with the spectra from the ground based microphones.


15/10/2015 - based on 2.23s (=1 rot.) time-series

SP mic.no.4 at 95% TRAILING edge - PRESSURE side

SP mic.no.2 at 4% LEADING edge - SUCTION side

SP mic.no.6 at 10% LEADING edge - PRESSURE side

SPL at ground mic.no.2 - UPSTREAM

SPL at ground mic.no.6 - DOWNSTREAM

Figure 11. Spectra of 5 TE surface microphones in upper two rows. Bottom row with the spectra from the ground based microphones.

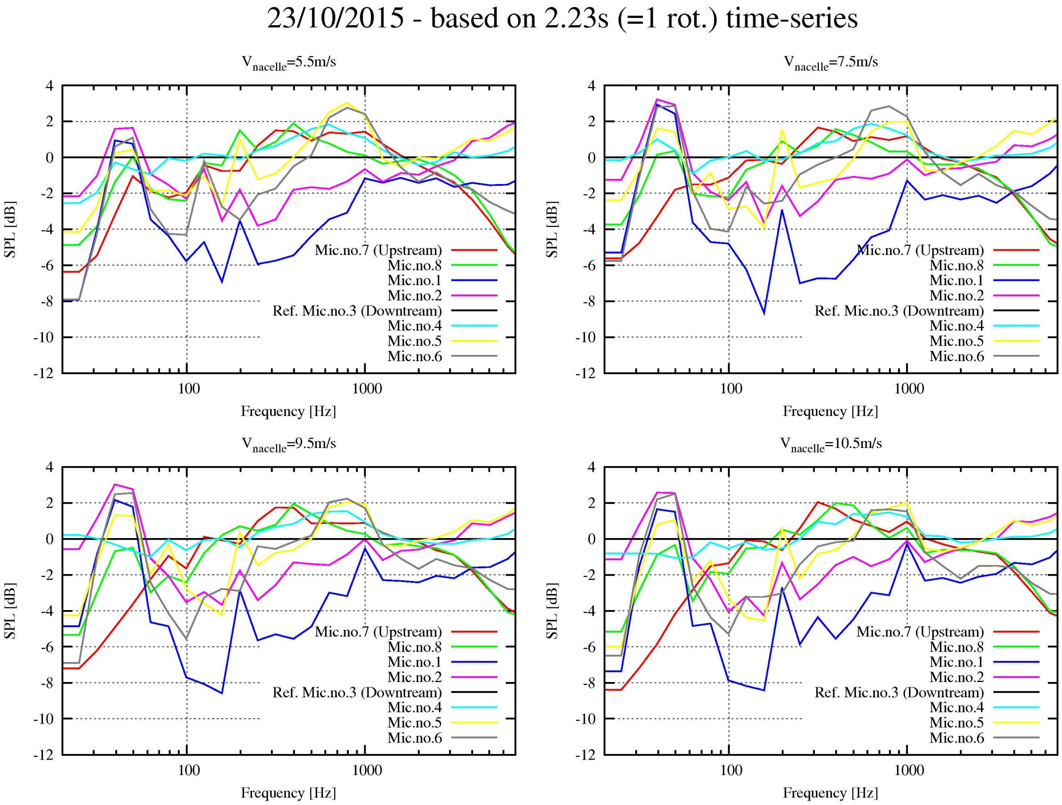


Figure 12. Measured relative microphone response (Mic. no. 3 downstream reference) during campaign I for different wind speeds.

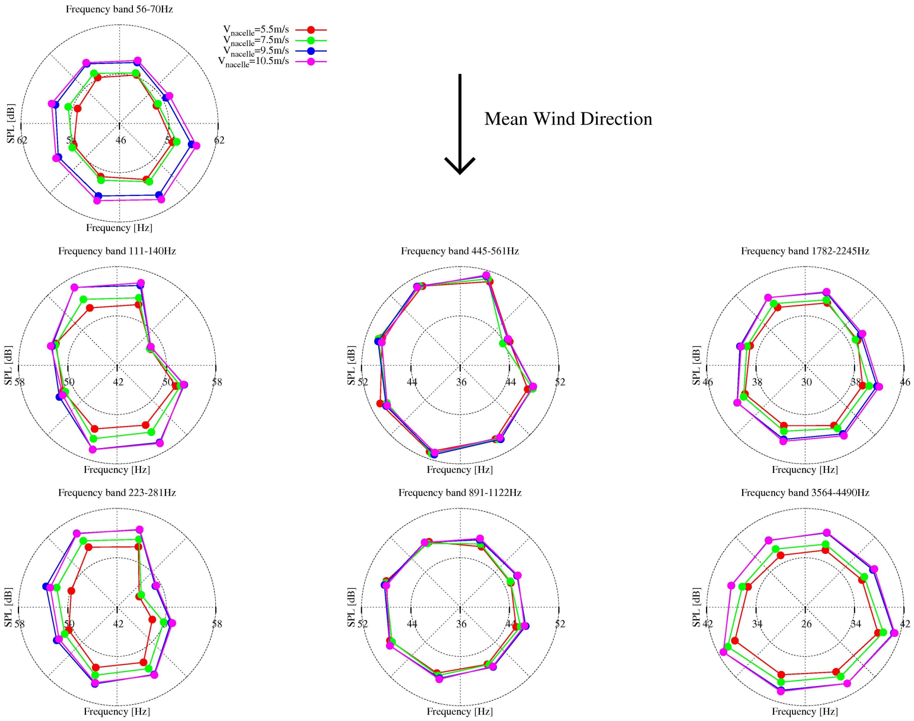


Figure 13. Measured directivity during campaign I shown as polar plot of microphone readings, for different wind speeds.

suction side of the blade scattering around the TE. Finally, the set-up shows that detailed information about directivity can be derived from the eight microphones on the ground.

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