Noise Source Identification with Blade Tracking on a Wind Turbine

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Manufacturers of wind turbines often use simulation techniques such as Computational Fluid Dynamics to analyse noise radiation from the blades. Although simulations are very attractive during the design phase, they do not take all mechanisms from the real life into account, and therefore real measurements will also be necessary for validation during development. Beamforming is a measurement technique for decomposing the sound into directions of incidence. Measurements are performed with an array of microphones and the output is typically visualized as a contour plot showing the noise contribution on the surface of interest. In this paper a tracking beamforming approach is applied on an operating wind turbine. Knowing the position of the turbine and measuring the blade(s) azimuth angle, the focus points can follow the movement of the blades, and the noise map can be visualized on the blade(s) for each azimuth angle step. The array used for the measurements consists of 9 lines of microphones lying on the ground (flush mounted in rigid plates) with 12 microphones per line. On one of the blades there was a set of known source locations (whooshing sound from accelerometers mounted on the blade), and the results confirmed their locations.

1 INTRODUCTION

Acoustic measurements on wind turbines are important both for the manufacturers of the turbines as well as for the operators that serve them at a later stage. The manufacturers also use simulation tools to investigate the radiation of sound. Simulations are very powerful, since it is easy to modify the design to obtain an idea of the acoustic consequence of the modification, and thereby iteratively optimize the design before producing a physical prototype. However, all physical phenomena from the real world cannot be taken into account in simulations, which is why real measurements are often used for validation. Therefore the manufacturers also need real measurements as a supplement to the simulated results. To perform such kind of validation it may be desirable to not only measure the sound pressure level on the ground, but also to know the distribution of acoustic sources on the rotor of the turbine and then compare the distribution with for instance results from Computational Fluid Dynamics (CFD) computations. Beamforming is a measurement technique, where a microphone array is used to decompose the sound field into directions of arrival, and the sound can then be visualized on a surface in space.

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By focusing the beamformer on the rotor of a wind turbine, it is possible to obtain a distributional map of the noise sources appearing on the rotor as a function of time and/or frequency, which can then directly be applied for comparison with simulations.

Noise problems can also appear a long time after the turbine has been installed. If for example a crack appears in one of the blades. In such cases the operator of the turbine may not be able to easily localize the position/cause of the noise, which may introduce a long troubleshooting time to make visual inspection of the blades. In such cases beamforming can also be a useful tool, since it can localize the position of the dominant sources.

Beamforming can be processed with or without tracking of the position of the blades. If the blade positions are not measured, the focus points are stationary in space and the beamformer will give an average value over a small time interval for each focus point. The disadvantage is that the result is smeared when the source parses through several reconstruction points in the time intervals: the faster the source is moving, the more smeared the result will be. The optimal results of the beamformer can be achieved if the 3D positions of the blades are known as a function of time. Such a tracking beamforming approach makes it possible to average over the time interval without smeared results, because the focus point follows the position of the source.

Tracking beamforming is a known discipline in the aircraft industry for fly-over noise source identification.[1-4] Applying the technique to wind turbines is not that different from aircraft applications, so findings from aerospace research can also be exploited for wind turbine applications. An interesting analysis is made in Ref. 5, where tracking beamforming is applied on a wind turbine with a rotor diameter of 58 metres using a ground microphone array. In the present paper a similar measurement approach is used on a wind turbine with a rotor diameter of 100 metres, and deconvolution is used in conjunction with the tracking beamforming to improve the spatial resolution.

2 THE MEASUREMENT SYSTEM

2.1 Hardware

The array has an elliptical shape (13.6 m x 8.5 m) as illustrated in Fig. 1, and it consists of 9x12 microphones (with wind screens). The elongated shape is required in order to have approximately the same spatial resolution of the beamformer in both horizontal and vertical direction on the rotor plane. All microphones are flush mounted in rigid plates. The plates of the inner 9x9 microphones constitute a large star-shaped plate, whereas the outer three microphones per line have their own individual plates. The spatial resolution of the beamformer is inversely proportional to the array diameter, and for large arrays it is more practical to place it on the ground. Also, the wind induced noise in the microphones is less significant near the ground. Due to the rigidity of the plates and the fact that they follow the surface of the ground, it is reasonable to assume that the ground acts as an acoustic mirror, and that the pressure at the microphones is simply doubled.

In practice, the ground may not be completely flat, which means that the microphones are not placed in the same plane. The mirror ground assumption mentioned above is not very sensitive to such fluctuations but it still is important to know the actual positions of the microphones. These are measured with a laser that has a distance and tilt output and it is mounted at the centre array. The positions of the plates can be measured by pointing the laser along each line individually and performing a few distance measurements per microphone line. The laser is also used to find the position of the wind turbine relative to the array.

The 108 microphones are connected to a front-end, which is connected to a PC through a LAN cable. The system requires an extra channel to acquire a signal that contains data related to the azimuth angle. This signal can either be a tacho signal or a sawtooth signal with a level that is proportional to the azimuth angle.

2.2 Data processing

The software consists of a measurement application and a post-processing application. The measurement part records the time data from the microphones and the azimuth signal and stores it to the database together with relevant metadata. At the time of calculation, the measured data is then loaded from the database in the post-processing software. After defining a set of the calculation parameters, the software processes the data and displays it as a contour map superimposed on a picture of the rotor/blade.

Apart from the dynamic azimuth signal the user must also specify a few parameters which are assumed to be static. These are the dimensions of the turbine (height, tilt etc.), yaw angle and the bending of the blades. As default, the software assumes that the blades move on a cone shaped surface of which the user can specify the coning angle. It is basically this cone (or a part of it) on which the sound field is calculated. A more complex shape can also be specified by the user through a programmatic interface to the software.

The calculation results shown in this paper do not take account for the wind's influence on the sound propagation. However, there is an option to use a linear wind profile by specifying the wind direction and the wind speed at two different heights. As for the blade bending, the user can also apply a user-defined wind model through a programmatic interface.

With all the above information at hand the software performs beamforming calculations on the rotor surface or a part of it. Diagonal removal is implemented as described in Ref. 6, providing the capability of suppressing the contributions to the averaged spectra from the wind noise in the individual microphones. Instead of having a fixed grid of calculation points a tracking time-domain Delay-And-Sum (DAS) algorithm is applied,[6] where the beamformer's focus points follow the motion of the blade(s). The software also allows for the fact that the sound is delayed relative to the azimuth signal, i.e., a given sample in the acoustic signals corresponds to an earlier time in the azimuth signal. Next, the time signals at each focus point are block wise Fourier transformed and averaged over a set of user-specified angular intervals. If a measurement is performed during more than one revolution the results are also averaged across those revolutions. There will be a set of frequency domain DAS maps on the rotor/blade surface for each of the angular intervals between 0º and 360º. The resulting pressure values on the map are scaled to approximate the sound pressure on the calculation grid by adjusting for the 1/R dependency of the assumed monopoles on the rotor (here, R is the distance from the focus point to the array centre).

Turbulence in the air will introduce a reduction of coherence over distance, and the coherence length will decrease as the frequency increases. This issue is treated by applying a shading filter[6] (area weighting) to the microphone signals so that only the central part of the array is used at high frequencies, and the radius of the shading function is inversely proportional to the frequency. This means that the microphone spacing must be higher at the central part of the array as seen in Fig. 1. As mentioned earlier, the resolution is inversely proportional to the array diameter, but since the density of microphones is much higher near the central part, the effective array size would be smaller, which would impact the low-to-medium frequencies, where the entire array is used. To compensate for this resolution loss, an additional weighting factor is applied to ensure constant effective weight per unit area over the active part of the array.

The effective frequency-dependent shading to be applied to each microphone signal is implemented as a zero-phase FIR filter, which is applied to the signal before the DAS calculation.

The resolution of the DAS maps can be further improved by applying deconvolution.[7] In deconvolution it is assumed that the source can be represented as a set of incoherent monopole sources on the mapping surface. This is a reasonable assumption when dealing with aerodynamic noise due to the uncorrelated nature of turbulence excitation. The output of DAS beamforming at a given frequency will be approximately equal to the true source power distribution convolved in 2D with a frequency-dependent spatial impulse response, which is called the Point Spread Function (PSF). The idea of deconvolution techniques is to compute the PSF, and deconvolve it with the DAS map to get back to the real sources. There are two deconvolution methods available in the current software: DAMAS2 and FFT-NNLS (see Ref. 7 for further details). In this paper, FFT-NNLS is used for all the calculations. The output from deconvolution is basically the strengths of the monopoles, and these can be scaled in various ways. All deconvolution results in this paper are intensity scaled, i.e., calculating the radiated intensity from a monopole with the evaluated source strength.

3 MEASUREMENTS

3.1 Description of the measurement

The test of the system was carried out on a wind turbine with a rotor diameter and tower height of approximately 100 metres. The array was laid on the ground on the upwind side of the tower at a distance of around 100 m, and with the array's major axis pointing directly towards the tower as illustrated in Fig. 2. The array must not be too close to the turbine, since in that case a small difference in angle seen from the array corresponds to a large distance on the rotor surface. On the other, since the beamformer's resolution is inversely proportional to the measurement distance, the array must not be too far away either. A good compromise between these two issues is to place the array so that the nacelle is at 45° from the ground seen from the array, which is why the array was positioned at 100 m from the tower. A tarpaulin was spread on the ground before deploying the array as shown in Fig. to protect the array from water and dirt. The tarpaulin was fastened at the edges, and it was verified that it did not create disturbing noise. The exact positions of the microphones were measured with a laser as described in the previous section, and the laser was also used to find the coordinates of the tower. There was a signal available from the tower with information about the azimuth angle as a function of time. Its output ranged from approximately 0-5 V and the voltage was directly proportional to the angle.

Several measurements were made – each with slightly different yaw angles due to changing wind direction. The yaw angle was ranging from about -4° to 11°, where 0° is directly upwind (see Fig. 2). Each recording lasted 60 seconds, and it was ensured that the yaw was constant during the recording before storing the data to the database. The wind speed was approximately 6 m/s for all measurements. For other testing purposes there were three accelerometers mounted on the rear exterior surface of one of the blades as shown in Fig. 4. This blade is denoted as "Blade 1" in the results that follow. As the picture also shows, there was a loose wire hanging from one of the accelerometers – this wire created a whooshing sound which was easy to hear. The fact that there was a source with a known location was excellent for this first measurement. All measurements were completed in about 6-7 hours, including setting up the system and packing it away at the end of the day.

3.2 Calculated results

The results presented here are based on two different datasets; one with a yaw angle of 3º and the other at 11º. The calculations performed here do not take into account the refraction of the sound propagation due to the wind profile, and the calculation surface is set to be a cone, which is bended 2º forward (towards the array).

Unfortunately, the azimuth signal was not that "clean". Sometimes a set of samples were missing. Furthermore, the signal was only sampled at around 17 Hz, which corresponds to approximately 3.5º (with a rotation time of 6 seconds). The software has a routine for smoothing the signal, but such inaccuracies can still have an impact on the tracked beamforming result if the focus points are not following the actual source throughout the recording. Instead of trying to smooth the azimuth signal, the signal will be treated as a tacho signal, since the abrupt change in the voltage near 360º can serve as a tacho pulse as well. This will of course introduce an offset error if for instance the RPM changes during a single rotation. On the other hand, the tracking movement will be smooth and stable, which would not necessarily be the case if the true signal was applied (even after treating the signal with a smoothing technique).

The following results concern the measurement with the nacelle at a yaw angle of 3º. Figure 5 shows an example of the pressure at the rotor surface calculated with traditional DAS without blade tracking. It is averaged over 30 seconds (approx. 5 revolutions) and calculated at a grid of fixed focus points. The contour map is overlaid on a picture of the rotor, and knowing that the blades rotate clockwise, it is clear that the highest pressure is generated as the blades sweep downwards. This is also in agreement with the results presented in Ref. 5. This type of map does not require tracking of the blades and it is useful for getting a quick overview of the sound radiation - for instance to separate the contribution from the rotor and the nacelle. If the aim is to investigate the radiation of the individual blades separately, blade position information is required, which in this case was achieved from the azimuth signal logged from the tower. Figure 6 shows the results of a tracking DAS calculation for the same recording as in Fig. 5. Contributions from the tip of the blades dominate as expected due to the higher speed at the end of the blade and the turbulences around it. Inaccuracies in the measurement of the position and orientation of the nacelle could have significant consequences on the maps. For instance if the rotation centre of the tracking motion was offset from the actual rotation centre of the rotor, the focus points would be moving around in the local coordinate system of the rotor instead of being fixed. Fortunately, the hotspots are seen to follow the tips well for all angles, which indicate that the tracking works as intended. It is clearly seen that one of the blades is the dominant contributor at all azimuth angles. As expected this is "Blade 1" due to the noise from the loose wire and the accelerometers. During downwards movement noise from the other blades is also visible in the map, but the strongest source is still "Blade 1" even when it approaches 0º (when the blade points upwards).

DAS results such as those in Fig. 6 are sufficient to get an overview of the radiation from the individual blades, but using deconvolution a more detailed map can be obtained. In Fig. 7 the beamformer is focused on "Blade 1" only as it passes 90º, and it is easy to see the improvement in spatial resolution when deconvolution is applied. From the DAS results there is only one source is apparent at most of the frequencies, but the deconvolved maps clearly show two sources (except at the lowest of the considered frequencies). Only at 4 kHz it is evident from the DAS result that there are two sources on the blade. The left hotspots correspond very well to the position of the loose wire, and the location of the source to the right matches with the outer accelerometer near the tip. The noise from the centre accelerometer can naturally not be separated from the wire noise, since they are so close to each other. On the DAS map there is a small spot at the position of the inner accelerometer at 3.15 kHz. Whether it is a real source or just a side-lobe (a ghost image) is not clear, but the fact that it does not appear on the deconvolution result could indicate that it is a side-lobe from an actual source, which is filtered out in the deconvolution process.

Next, the beamformer is focused at the less noisy blades, “Blade 2” and Blade 3”, and Fig. 8 shows the deconvolution maps at different frequencies at 90º azimuth. There is a tendency that a wider area of the outer region radiates at the lower frequency whereas it is more concentrated near the tip at higher frequencies. Also, it seems that the highest level is closer to the trailing edge at 1.25 kHz, whereas it is on the leading edge at 2.5 kHz and 3.15 kHz. However, it is important to mention that the uncertainties related to the azimuth signal means that the map can be shifted slightly up or down relative to the blade. To investigate whether the leading or trailing edge is the main radiator would require a more accurate measurement of the azimuth angle.

Figure 9 shows the DAS result on the full rotor for another recording (where the yaw angle was 11º). For this measurement – and also other recordings from the measurements – there is a source at the position of the tower (indicated with blue arrows on the plots). In Fig. 10 the same measurement is used without synthesizing to 1/3 octaves. The beamformed FFT spectrum is displayed for two different points on the rotor surface: one at the tower and one at a blade tip. The tower point has a concentration of energy around 1 kHz to 1.5 kHz, whereas the blade has a spectrum that decays gradually with the frequency. The reason for the tower radiation was not investigated further, but a possible explanation could be structural mode excitation in the tower that results in sound radiation.

5 CONCLUSIONS

This paper describes a microphone array system for visualizing the sound field on the individual blades of an operating wind turbine. The system consists of 108 microphones and a reference channel for measuring the azimuth angle of the rotor. The software uses the traditional Delay-And-Sum beamforming to obtain the source map, and on top of that a deconvolution technique is applied to obtain even better spatial resolution. Knowing the orientation of the rotor and measuring the azimuth angle, the focus points of the beamformer are moved continuously during calculation to follow the positions of the blades, thereby avoiding spatial smearing when the results are averaged over small time intervals. The end result is a map of the dominant noise sources visualized as a contour plot overlaid on a picture of the rotor/blade. The results can be displayed as a function of both azimuth angle and frequency.

A set of measurements was performed out on a wind turbine with a rotor diameter of approximately 100 metres. The average wind speed on the measurement day was 6 m/s, and the measurements were performed with the array on the upwind side of the turbine. The purpose of this paper (and of the measurements) has not been to analyze and solve a specific noise problem, but rather to demonstrate that the system works as intended, i.e., produce results that displays the noise distribution on the blades as a function of the blade position within a working day. There were three accelerometers mounted on the exterior surface of one of the blades (used for other purposes), and from one of the accelerometers there were a loose wire hanging, which produced audible noise. This setup was very suitable for validation of the system, and the results presented here show that this blade had the highest noise level, and when applying deconvolution a dominant source is clearly identified at the position of the wire, well separated from another hotspot at an accelerometer near the tip. Finally, the results also revealed noise radiated from the tower approximately ½ a blade length below the nacelle.

6 REFERENCES

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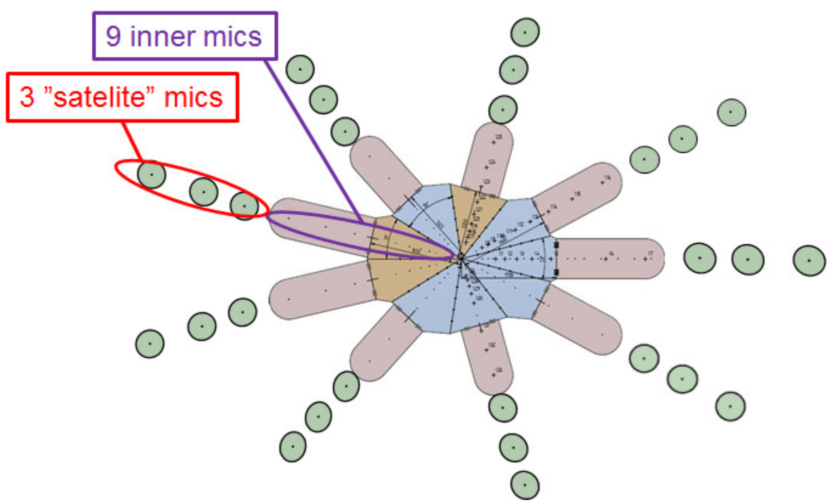

Fig. 1 – Illustration of the 13.6 m x 8.5 m elliptical shaped ground-based microphone array (seen from above).

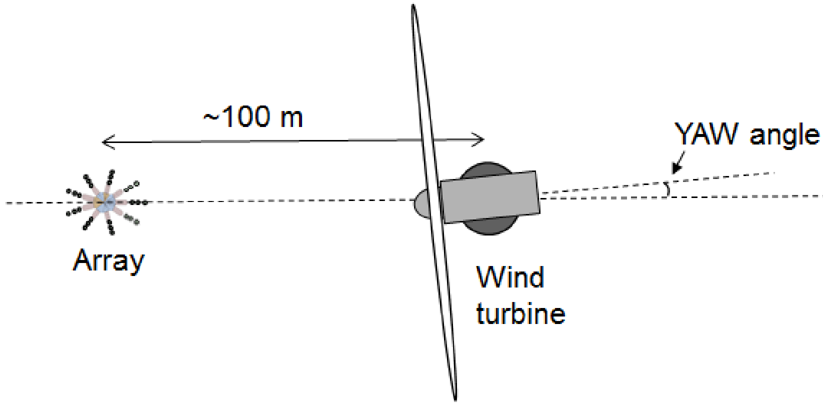

Fig. 2 – Illustration of the array located in front of the wind turbine. In this paper the yaw angle is defined as 0º when the nacelle is pointing towards the array, and this angle is increasing as the nacelle rotates counterclockwise.

Fig. 3 – The ground array seen from the side, with the right hand side pointing towards the wind turbine.

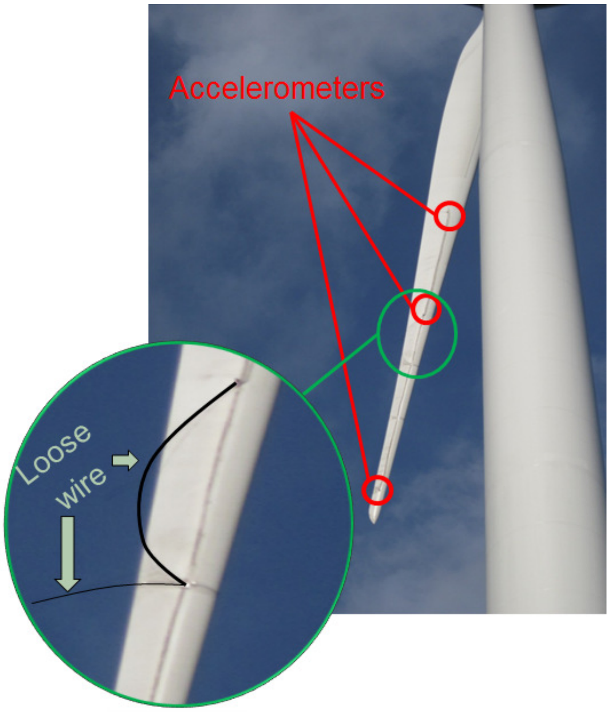

Fig. 4 –Three accelerometers mounted on “Blade 1”. The zoomed picture shows a loose wire near one of the accelerometers.

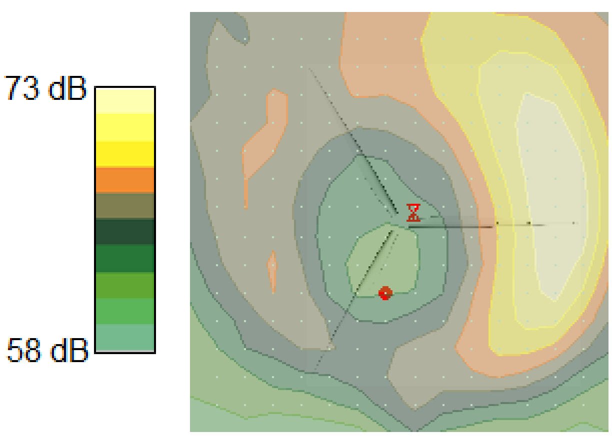

Fig. 5 – Delay-And-Sum map at 1 kHz (1/3 octave band) averaged over 30 sec. (approx. 5 revolutions). The blades are rotating clockwise. The results are scaled to resemble the sound pressure level at the rotor surface.

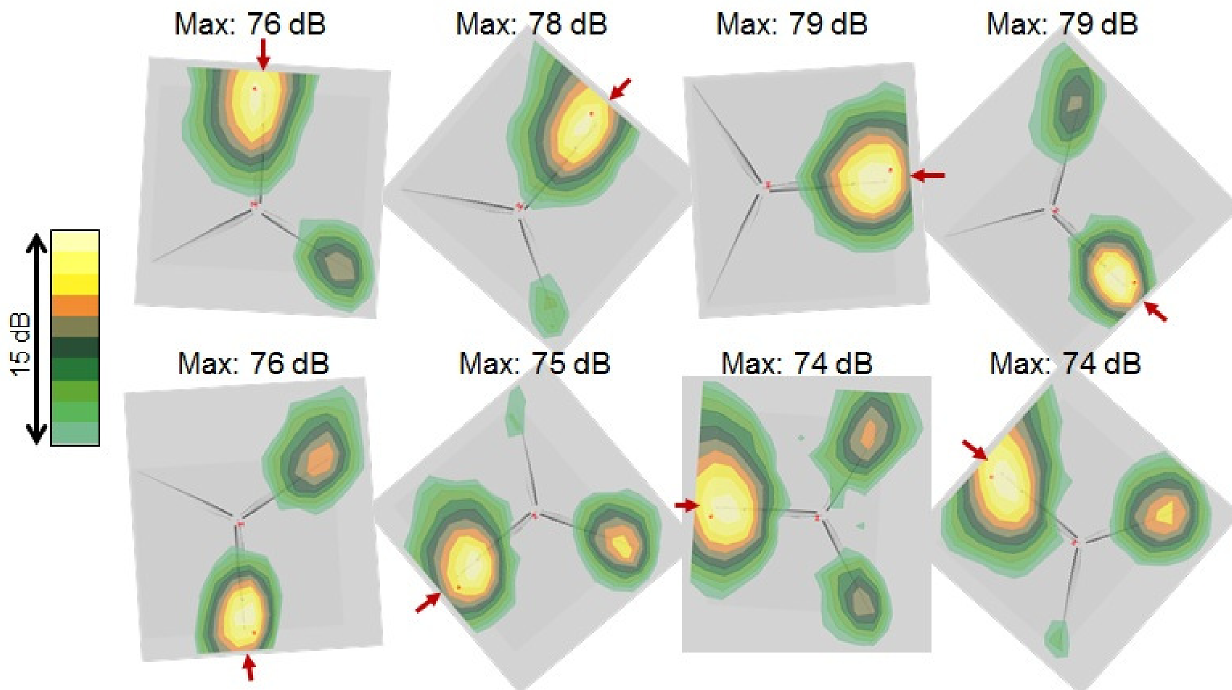

Fig. 6 – Delay-And-Sum beamforming with blade tracking at 1 kHz (1/3 octave band). The plots show the estimated sound pressure level on the rotor surface as a function of the blade positions which rotates clockwise, and the red arrows indicate the position of "Blade 1". On each plot is indicated the maximum level of the map. Yaw: 3 degrees

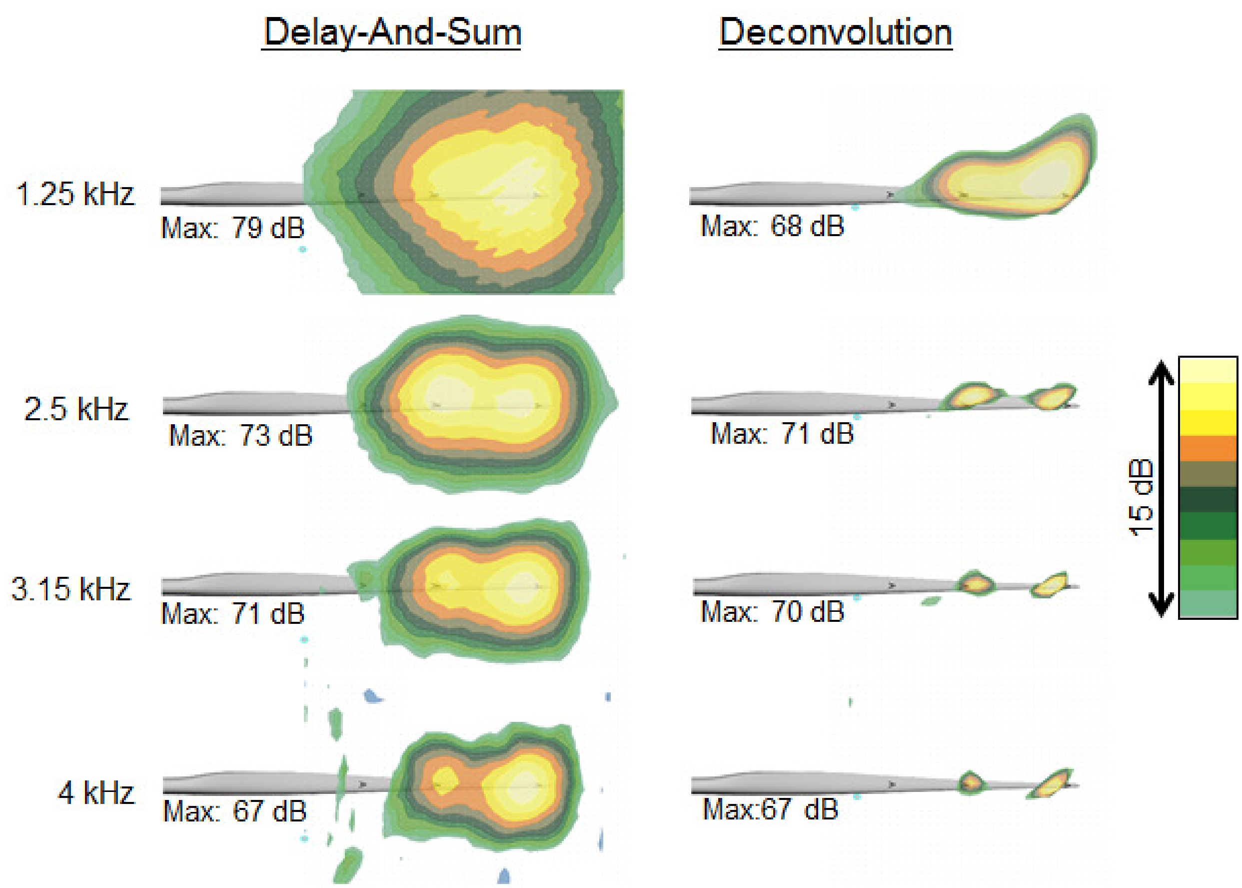

Fig. 7 – Noise source map on "Blade 1" at 90º azimuth. The blade is tracked from 80º-100º and the map shows the average of a single pass through. On each plot the maximum level of the map is denoted. The three small black dots on the blade indicate the positions of the accelerometers. Yaw: 3 degrees.

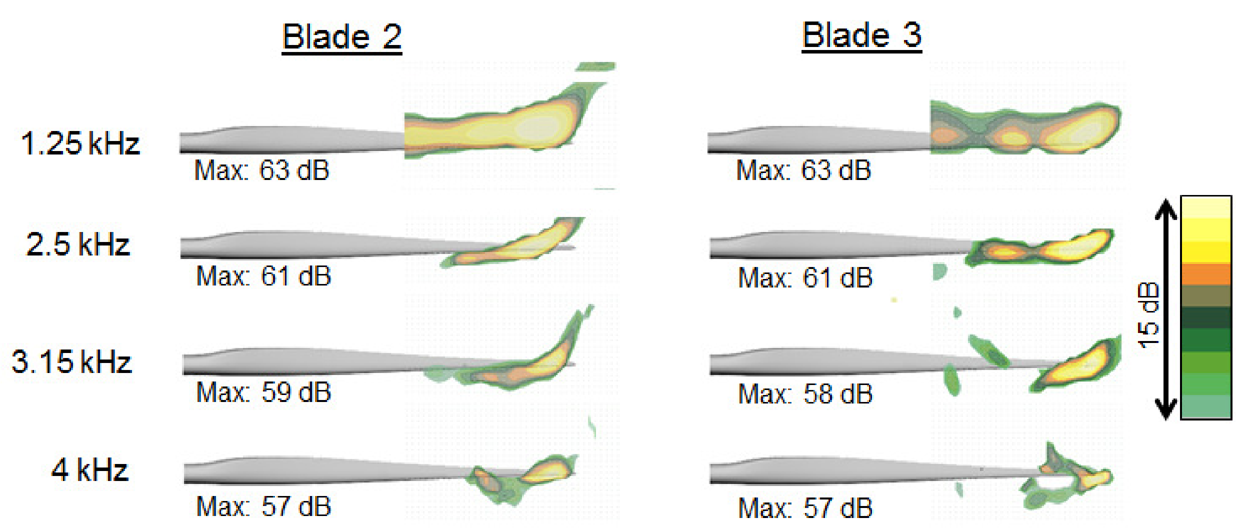

Fig. 8 – Deconvolution on "Blade 2" and "Blade 3" for different third octave bands at 90 degrees azimuth. The blade is tracked from 80º-100º and the map shows the average of a single pass through. Yaw: 3 degrees.

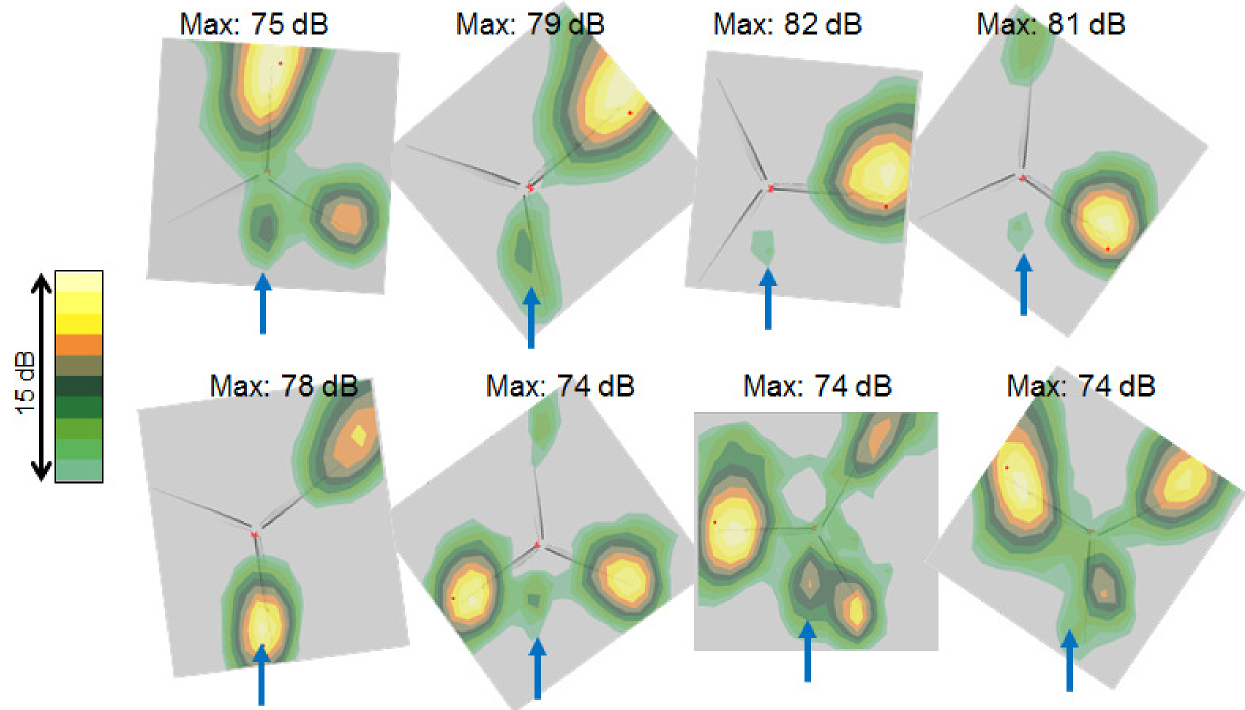

Fig. 9 – Delay-And-Sum beamforming at 1 kHz (1/3 octave band) as a function of blade positions for 11 degrees yaw. The blue arrows indicate contribution around the position of the tower.

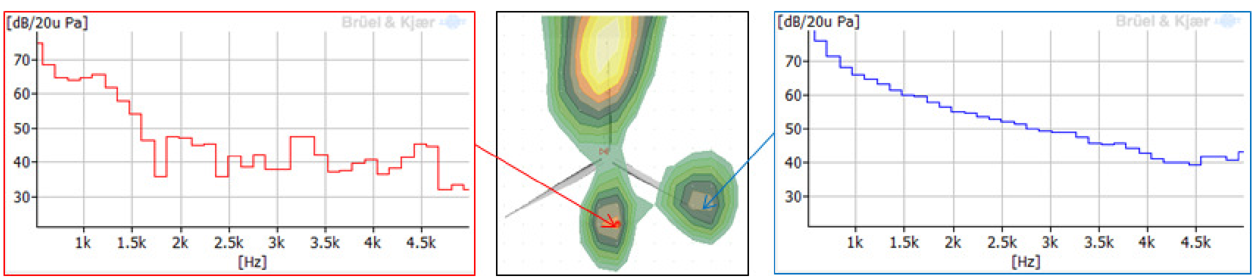

Fig. 10 – DAS spectra at two different points when "Blade 1" is at 0 º. The left spectrum is at the tower and the right spectrum is at the tip of the down-moving blade. yaw: 11º.