

Reduction of Wind Turbine Noise using Optimized Airfoils and Trailing-Edge Serrations

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Acoustic field measurements were carried out on a 94-m diameter three-bladed wind turbine, with one standard blade, one blade with trailing edge serrations, and one blade with an optimized airfoil shape. A large horizontal microphone array, positioned at a distance of about one rotor diameter from the turbine, was used to locate and quantify the noise sources in the rotor plane and on the individual blades. The acoustic source maps show that, for an observer at the array position, the dominant source for the baseline blade is trailing edge noise from the blade outboard region. Due to convective amplification and directivity, practically all of this noise is produced during the downward movement of the blade, which causes the typical swishing noise during the passage of the blades. Both modified blades show a significant trailing edge noise reduction at low frequencies, which is most prominent for the serrated blade. However, the modified blades also show tip noise at high frequencies, which is mainly radiated during the upward part of the revolution, and is most important at low wind speeds (i.e. high tip loading). Nevertheless, average overall noise reductions of 0.5 dB and 3.2 dB are obtained for the optimized and for the serrated blade, respectively.

Nomenclature

2D	=	Two-dimensional
D	=	Trailing edge noise directivity function
ECN	=	Netherlands Energy Research Foundation
f	=	Frequency
GE	=	General Electric
M	=	Local blade inflow Mach number
N	=	number of measurements
NLR	=	National Aerospace Laboratory, The Netherlands
OASPL	=	Overall Sound Pressure Level
P	=	Rotor power
RPM	=	Number of rotor revolutions per minute
SPL	=	Sound Pressure Level

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St	=	Strouhal number: $St=f\delta^*/U$
U	=	Local blade inflow velocity
$U10$	=	Wind speed at 10 m height
α	=	Misalignment angle between array and wind turbine (see Figure 2)
δ^*	=	Trailing edge boundary layer displacement thickness
ε	=	Standard deviation of the mean: $\varepsilon = \sigma/\sqrt{N}$
ζ	=	Angle between blade flow velocity and source-observer line
θ	=	Angle between blade chord line and source-observer line
σ	=	Standard deviation: $\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2}$ with $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$ (or from curve fit through data)
φ	=	Angle between blade plane and plane containing chord line and observer
ψ	=	Rotor azimuth angle

I. Introduction

WIND turbine noise is one of the major issues for the widespread use of wind energy. For a modern large wind turbine, aerodynamic noise from the blades is generally considered to be the dominant noise source, provided that mechanical noise is adequately treated¹. The sources of aerodynamic noise can be divided into airfoil self-noise and inflow-turbulence noise. Airfoil self-noise is the noise produced by the blade in an undisturbed inflow, and is caused by the interaction between the boundary layer and the trailing edge of the blade. Self-noise can be tonal or broadband in character, and may be caused by several mechanisms, such as turbulent boundary layer trailing edge noise (subsequently denoted as trailing edge noise), laminar boundary layer vortex shedding noise, trailing edge bluntness noise, or blade tip noise. Inflow-turbulence noise is caused by the interaction of upstream atmospheric turbulence with the leading edge of the blade, and depends on the atmospheric conditions. It is an open issue to what extent inflow-turbulence noise contributes to the overall sound level of a wind turbine².

Due to the large number of applications (e.g. wind turbines, airplanes, helicopters, fans), the characteristics of airfoil noise have been investigated extensively in both experimental and theoretical studies³⁻¹³. Both inflow-turbulence and self-noise mechanisms were considered and the dependence on parameters such as flow speed, angle-of-attack, radiation direction, and airfoil shape was characterized. These studies formed the basis of several semi-empirical wind turbine noise prediction models, which were validated by comparison to field measurements¹⁴⁻²⁰. Since the field results only provided the overall sound level of the turbine, the relative importance of the different mechanisms was determined mainly on the basis of the predictions. In some studies inflow-turbulence noise was regarded to be the dominant source^{11,14-16,18}, while others considered trailing edge noise to be dominant¹⁷. In another case, the turbine noise in different frequency ranges was attributed to mechanical noise, trailing edge noise, tip noise, and inflow-turbulence noise¹⁹.

In a few studies source location measurements were performed to provide more direct information on the source mechanisms²¹⁻²⁵. The results from Refs. 21-23 were obtained using an acoustic parabola or a linear array of microphones, and focused only on the horizontal blade position. In Refs. 24 and 25, a large two-dimensional microphone array, positioned on the ground about one rotor diameter upwind of the turbine, was used to localize the noise sources in the complete rotor plane and on the individual blades, for two different wind turbines. It was shown that practically all noise (emitted to the array) was produced during the downward movement of the blades. This strongly asymmetric source pattern, which causes the typical swishing noise during the passage of the blades, was explained by convective amplification and trailing edge noise directivity. The following directivity function for trailing edge noise was used²⁶:

$$D = \frac{2\sin^2(\theta/2)\sin^2\varphi}{(1-M\cos\xi)^4} \quad (1)$$

where θ is the angle between the blade chord line and the source-observer line, φ is the angle between the plane of the blade and the plane containing the chord line and the observer, ξ is the angle between the local blade inflow velocity and the source-observer line, and M is the local blade inflow Mach number. The numerator in Eq. (1) describes the directivity of high-frequency trailing edge noise, and indicates that most of the noise is radiated in the direction of the airfoil leading edge. It was analytically derived for edge noise from a semi-infinite flat plate^{6,27}, but was also found to be valid for finite airfoils⁹, provided that the angle θ is not too close to 180°. In the limit for low-frequency dipole noise, where the acoustic wavelength is much larger than the airfoil chord, the $\sin^2(\theta/2)$ term

changes into $\sin^2(\theta)^{5,26}$. Nevertheless, in Ref. 24 Eq. (1) was found to be valid for the whole tested frequency range, including the low frequencies where the acoustic wavelength was of the same order as the blade chord. The denominator in Eq. (1) represents the 4th power convective amplification factor for trailing edge noise²⁸, and indicates that the noise source becomes louder when it is moving towards the observer.

Many studies have addressed the reduction of airfoil or wind turbine noise. Since inflow turbulence noise and trailing edge noise both scale with approximately the 5th power of the local blade inflow velocity^{5,6,24}, an obvious means for noise reduction is to reduce the rotor RPM or rotor diameter. However, these measures also reduce the power output of the turbine¹. The same holds for increasing the blade pitch angle (which reduces the angle of attack). Thus, the challenge is to achieve a noise reduction without a reduction in power output. With regard to tip noise, which depends on the characteristics of the tip vortex, it has been demonstrated in several studies that the tip shape can have a significant influence on the noise from a wind turbine^{1,6}. The importance of inflow-turbulence noise depends on the structure of the atmospheric turbulence and on the shape of the blades. It has been shown both experimentally and numerically that inflow turbulence noise levels increase with increasing 'sharpness' of the airfoil leading edge^{10,13}.

With regard to trailing edge noise, a number of reduction concepts have been investigated. After it had been shown theoretically that the acoustic radiation efficiency of a trailing edge can be reduced by serrations²⁹, this concept was investigated in a number of experimental studies on 2D airfoils³⁰, model wind turbines^{31,32}, and a full-scale wind turbine²⁵. In Ref. 31, serrations were applied to a 16-m diameter model wind turbine, and depending on the flow conditions overall noise reductions of up to 3.5 dB were obtained. In order to prevent increased noise at high frequencies, it was found to be critical to align the plane of the serrations with the trailing edge flow. In Ref. 23, serrations were applied to a 1 MW wind turbine, and an overall noise reduction of 2-3 dB was obtained, despite increased noise at high frequencies. It should be noted that the measurements in Refs. 31 and 23 only focused on the horizontal (downward) blade position, which may give an incomplete picture. An alternative concept for trailing edge noise reduction is the application of flexible trailing edge brushes. The brushes align automatically with the trailing edge flow and have shown significant noise reduction potential in wind tunnel tests on flat plates and on a 2D airfoil^{12,33}. However, a first attempt to apply this concept to a full-scale wind turbine yielded a reduction of only 0.5 dB³⁴, possibly because the improvised brushes were too short. Finally, it has been shown in calculations and wind tunnel tests on 2D airfoils that trailing edge noise can be reduced by a modification of the airfoil shape, without a loss in aerodynamic performance³⁵.

The present study concerns acoustic field measurements on a 2.3 MW, 94-m diameter wind turbine with one standard (baseline) blade, one blade with an optimized airfoil shape and one standard blade with trailing edge serrations. The tests were performed in the framework of the European SIROCCO project (Silent Rotors by Acoustic Optimisation³⁴). Building on the results from earlier wind tunnel studies on a model rotor³², the subject of the project was the design, testing, and full-scale validation of quiet wind turbine blades, without a loss in power performance. In an earlier stage of the project, acoustic field measurements on the baseline turbine²⁵ indicated that trailing edge noise from the outer 25% of the blades was the dominant noise source for this turbine, and that the three blades produced practically the same sound pressure levels: the average OASPL for the three blades differed by less than 0.15 dB, and for the two standard blades that were used again in the present campaign less than 0.05 dB. Subsequently, optimized airfoil shapes were designed and assessed through aerodynamic and acoustic wind tunnel tests on 2D airfoils³⁴⁻³⁶. The principle of the airfoil design was to reduce the dominant low-frequency (<1 kHz) trailing edge noise peak in the spectrum (which is due to the thick suction side boundary layer), by reducing the loading of the suction side, at the expense of an increased pressure side loading (which causes a slightly higher noise level at less important medium frequencies of 1-3 kHz)³⁵. The wind-tunnel tests showed 2-3 dB reduction in OASPL (depending on lift coefficient)³⁴, and an improved aerodynamic performance for the newly designed airfoils, even though severe geometric and aerodynamic constraints had to be considered in the design (to enable implementation in the existing blade structure). The new airfoil was then incorporated in the design of the outer part of the optimized blade (subsequently denoted as 'SIROCCO blade'). In addition to the new blade design, the third rotor blade was used to test a second noise reduction concept, trailing edge serrations. The serrated blade had the same nominal geometry as the baseline blade.

The main goal of the present test campaign was to assess the acoustic performance of the two modified blades versus the baseline blade. In order to assess the effect of blade roughness due to e.g. dirt or insects, the blades were tested in both clean and tripped conditions. A large horizontal microphone array, positioned at a distance of about one rotor diameter from the turbine, was used to measure the distribution of the noise sources in the rotor plane and on the individual blades. Since the array position was fixed and the wind direction varied, both up- and downwind measurements were performed. From power and loads measurements on the baseline and modified rotor, it was found that the in-plane and out-of-plane blade loads on the serrated blade, and to a lesser extent also on the

SIROCCO blade, were slightly higher than on the baseline blade, causing the aerodynamic performance of the modified blades to be similar or slightly better than the baseline blade³⁴.

In the present paper the acoustic array results are presented and analyzed. The noise characteristics for the three blades are investigated as a function of wind speed, rotor azimuth angle, and observer position (upwind or downwind), for clean and tripped conditions. Section II describes the test set-up, test program, and the array processing methods. In Section III the results are presented and discussed. The conclusions of this study are summarized in Section IV.

II. Experimental Method

A. Test set-up

The measurements were carried out in March/April 2007, on the same GE 2.3 MW prototype test wind turbine that was used in the baseline test campaign in 2005. It had a rotor diameter of 94 m, a tower height of 100 m, and was located on the ECN test site in the Wieringermeer (Netherlands). In order to compare the blade performance for identical weather and turbine conditions, the rotor consisted of one standard (baseline) blade, one standard blade with trailing edge serrations, and one SIROCCO blade. The SIROCCO blade was nominally identical to the baseline blade, except for the outer ~30%, where it had a new airfoil. The serrated blade had the same nominal geometry as the baseline blade. The aluminum serrations, with a thickness of 2 mm, were mounted to the outer 12.5 m of the blade (pressure side). The 2 mm step was smoothed using filler material over a few centimeters of chord. Similar to Ref. 32, the length of the serrations was about 20% of the local chord, and varied as a function of radius: the tooth length was about 10 cm at the tip and about 30 cm at the most inboard position. (Figure 1). Using templates for different radial stations, the plane of the serrations was aligned with the flow direction at the blade trailing edge. This trailing edge flow direction is constant in the variable RPM region of the turbine (up to a nacelle wind speed of about 9 m/s). Prior to the acoustic measurements, all blades were cleaned. In order to assess the effect of blade roughness due to e.g. dirt or insects, the blades were tested with and without trips: in State 1 all blades were tripped and in State 2 all blades were clean. The 2D trips, with a thickness of about 0.4 mm and a width of 4 mm, were installed close to the leading edge on both sides of the blade, from the very tip to about half the blade span. The (variable) blade pitch angle was the same for the three blades.

An acoustic array was used to locate and quantify the noise sources on the rotor and on the individual blades. The acoustic array consisted of 148 Panasonic WM-61 microphones, mounted on a horizontal wooden platform of 16x18 m², which was positioned at a distance of about one rotor diameter from the turbine (Figure 2). Since the array position was fixed and the wind direction varied, both up- and downwind measurements were performed. The Panasonic microphones were mounted flush to the surface of the platform, with the membrane parallel to the platform, and were equipped with wind screens. As a reference, two calibrated LinearX M51 microphones equipped with hemisphere wind screens were mounted on the platform as well. The microphone array had an elliptic shape to obtain approximately the same array resolution in the horizontal and vertical direction, thus correcting for the 'view angle' of about 45° (Figure 3). The ellipse was slightly tilted to the right-hand side of the rotor plane, to obtain maximum resolution on the side where the blades move downward (for the standard array position, i.e. upwind of the turbine) and where maximum noise radiation was observed in the 2005 campaign. The array had a high microphone density in the center to ensure low side-lobe levels at high frequencies, and a low-density outer part to obtain a good resolution at low frequencies. The distance and orientation of the array with respect to the turbine were determined using a laser distance meter and a compass.

B. Data acquisition

Acoustic data from the array microphones were synchronously measured using the VIPER multi-channel data-acquisition system³⁷, at a sample frequency of 30.7 kHz and a measurement time of 30 s. The acoustic data were processed using FFT blocks of 1024 samples with a Hanning window and 50% overlap, yielding 1800 averages and a narrowband frequency resolution of 30 Hz. A second-order 500 Hz high-pass filter was used to suppress high-amplitude pressure fluctuations at low frequencies, and thus to extend the dynamic range of the A/D converter, so that low pressure amplitudes at high frequencies are included. The sound levels were corrected for the filter response and for pressure doubling due to reflections at the platform. Prior to the measurements, the sensitivity at 1 kHz was determined for all array microphones using a calibrated pistonphone. The frequency response of the Panasonic microphones was taken from previous calibration measurements. The frequency response of the M51 microphones was taken from calibration sheets. No corrections were applied for microphone directivity, since calibration measurements showed that these effects amounted to less than 2 dB up to 20 kHz, for angles smaller than 75° with respect to the microphone axis. Phase matching of the microphones was checked using a calibration source at known

positions. A trigger signal from the turbine (one pulse per revolution) was recorded synchronously with the acoustic data, in order to determine the location of the blades as a function of time for the source localization on the individual blades (Section IID).

In parallel to the acoustic measurements, several parameters from the turbine and two nearby meteo masts were continuously measured at a sample rate of 4 Hz or higher. These data included wind speed, wind direction, temperature, power production, turbine orientation (yaw angle), RPM, and blade pitch angle.

C. Test program

During the 4-week test campaign, in total more than 600 measurements were taken. Following the IEC norm for wind turbine noise measurements³⁸, it was attempted to obtain measurements at wind speeds (at 10 m height) between 6 and 10 m/s. The wind speed at 10 m height was calculated by multiplying the average nacelle wind speed by 0.70 (according to the standard wind profile from Ref. 38). Since the array position was fixed and the wind direction varied, both up- and downwind measurements were performed. Measurements with a large misalignment angle α (see Figure 2) were excluded from the analysis, because for very oblique view angles the array resolution becomes poor. On the basis of the turbine operational data, the most stable measurements were selected for further analysis. An overview of the selected measurements is given in Table 1. Due to unpredictable weather conditions, it was not possible to obtain measurements in each wind speed bin, and for State 1 only downwind measurements were done. Since the clean rotor is considered to be most representative for the rotor during normal operation, and since the upwind measurements covered all relevant wind speeds, the focus of this paper will be on State 2a. The average turbine and weather conditions for the different rotor states are listed in Table 2 (equal weights per wind speed bin). In order to give an impression of the variation of the parameters within each state, this table also shows the standard deviation for each value. It should be noted that the power, RPM, and blade pitch angle are not randomly distributed around the mean value, but depend on the wind speed according to the turbine control system. Therefore, the standard deviations for these parameters are based on linear curve fits through the measured data as a function of wind speed.

D. Phased array processing

The microphone array data were processed using two different methods. With the first method (SOLACAN-Source Location by an ACOUSTIC ANTenna), noise sources in the rotor plane were localized using conventional beamforming³⁹. Thus, noise from the rotor hub can be separated from blade noise, and it can be seen where in the rotor plane the blade noise is produced. The method shows the integrated effect of the three blades, averaged over the complete measurement time of 30 s (i.e. several revolutions). The first step of this processing involves the calculation of an averaged cross-spectral matrix which contains the cross-powers of all microphone pairs in the array. To improve the resolution and to suppress background noise (e.g. wind-induced pressure fluctuations on the microphones), the main diagonal of the cross-power matrix (i.e. the auto-powers) was discarded. A frequency-dependent spatial window was applied to the microphone signals, in order to improve the resolution at low frequencies and to suppress coherence loss effects at high frequencies (due to propagation of the sound through the atmospheric boundary layer). The scan grid, with a mesh size of 2 m in both directions, was placed in the rotor plane of the wind turbine, and was rotated in accordance with the orientation of the turbine (depending on wind direction). The 4° tilt angle between the rotor axis and the horizontal plane was also accounted for. The effect of sound convection in the atmospheric boundary layer was taken into account by assuming a constant wind speed between the scan location and the microphones. This constant wind speed was calculated as the average wind speed between the rotor hub and the array center, using the standard wind profile from Ref. 38. The narrowband acoustic source maps were summed to 1/3-octave bands, and the source levels were normalized to a constant reference distance. The noise sources in the rotor plane were quantified using a source power integration method⁴⁰. This technique sums the source powers in (part of) the measured source map, and corrects the results with a scaling factor obtained by performing a simulation for a monopole source at the centre of the integration region. The thus obtained integrated sound pressure level of the turbine, as measured at the array position, is similar to the 'apparent sound power level' defined in Ref. 38. All spectra presented in this paper are in 1/3-octave bands.

The second processing method employed three rotating scan planes to localize the (de-dopplerized) noise sources on the three individual blades (ROSI-ROtating Source Identifier⁴¹). This enabled a comparison of the noise from the different blades. The start position of the scan planes was determined using a trigger signal from the turbine that was recorded synchronously with the acoustic data. The mesh size of the scan grid was 1 m in both directions, and the scan plane was placed around the blade, in the rotor plane. Similar to the first processing method, the narrowband acoustic source maps were summed to 1/3-octave bands, and the source levels were normalized to a constant reference distance. The ROSI results show the noise sources on the individual blades, averaged over a

specified part of the revolution. In order to distinguish between the noise production during the down- and upward movement of the blades, separate ROSI scans were done for rotor azimuth angles ψ from 0° to 180° and from -180° to 0° (with 0° the upper vertical blade position). In order to limit processing time, only the first rotor revolution after the start of each acoustic measurement was processed. The noise from the blades was quantified using a power integration method for moving sound sources⁴², which is similar to the above-mentioned integration method for the stationary rotor plane. The thus obtained integrated sound levels represent the contribution of the different blades to the overall sound pressure level of the turbine, as measured at the array position.

E. Accuracy of source localization and quantification

The relative position and orientation of the acoustic array and the wind turbine were determined using a laser distance meter and a compass. Nevertheless, there are a number of uncertainties in the localization method, which may cause a deviation between the measured and actual source position. First, the blades are not located exactly in the rotor plane: the 4° rotor tilt angle is accounted for but the rotor cone angle and the bending of the blades outside the plane not. Second, sound convection by wind gusts is not accounted for; a standard wind profile is assumed according to Ref. 38. Third, the rotor RPM is assumed to be constant within one revolution. Therefore, the accuracy of the source localization technique was assessed by attaching for a short period of time a whistle to one of the blades, at a position unknown to the acoustic test team. After determining to which blade the whistle was mounted, the ROSI source maps were used to estimate the exact whistle position (Figure 4). The thus obtained source radius was found to deviate only 0.5 m from the actual radius, which is considered to be accurate enough for these tests. Figure 4 also illustrates that the scan resolution is sufficiently high to determine accurate integrated blade noise levels: from numerical simulations⁴³ it was found that as long as the distance between adjacent scan points is smaller than the main lobe width (i.e. the width at 3 dB below the peak level), the integrated levels are accurate.

The acoustic source maps were quantified using the power integration method described in the previous section. The accuracy of this method in terms of *absolute* sound pressure levels was verified by comparing the integrated rotor source maps to the measured sound pressure levels at the array microphones. If all the noise measured by the array microphones is due to the turbine rotor, these spectra should coincide. Figure 5 shows the spectra measured by the array microphones ('arraymics') and the reference microphone at the center of the array ('refmic'), versus the integrated spectra for the rotor ('powint') and the three blades ('ROSIpow'). These spectra were averaged over all measurements in State 2a, were corrected for pressure doubling by the array surface, and were normalized to the same reference distance. It can be seen that the average spectrum of the array microphones is practically equal to that on the reference microphone. The small difference at low and high frequencies may be due to wind noise on the array microphones at the edge of the platform. Figure 5 also shows that the integrated spectra for the rotor and the blades have the same shape as the reference spectrum, but are about 3 dB lower over the whole frequency range. Apart from a small effect of certain assumptions and simplifications in the integration method²⁵, this difference may be attributed to coherence loss at the array microphones, due to propagation of the sound through the turbulent atmospheric boundary layer. A similar effect has also been observed in open jet wind tunnel tests⁴⁰. However, coherence loss effects typically increase with frequency, while here a more or less constant offset is found. Furthermore, coherence loss effects would be expected to increase with increasing wind speed, while here the difference between the integrated rotor noise level and the level of the reference microphone remained constant (within about 0.5 dB) for increasing wind speed. An alternative explanation for the lower integrated levels could be that the reference and array microphones pick up some background noise (e.g. from the wind over the platform), which is not present in the integrated rotor noise spectra (no background noise measurements with stopped rotor were performed in the present test campaign). The difference between the two integrated spectra may be due to the different integration regions (complete rotor versus outer part of the blades), and the fact that the ROSI spectrum is dedopplerized and the rotor spectrum is not. Dedopplerization results in reduced frequencies and reduced sound levels for the down-going blade, and vice versa for the up-going blade.

For the evaluation of the noise reduction concepts in the present study, the accuracy of the *relative* sound levels (i.e. level differences between the different blades) was most important. This accuracy was assessed in the baseline test campaign by comparing the individual blade noise spectra for two consecutive revolutions: for each blade the overall sound pressure level (averaged over all selected measurements) differed by less than 0.06 dB for the two consecutive revolutions. This means that the level differences between the blades can be considered to be accurate within 0.1 dB, for the given weather conditions and turbine operation parameters (including misalignment angle).

III. Results and discussion

In this section the results of the acoustic array measurements are presented and discussed. First, the noise source distribution in the rotor plane is analyzed for the up- and downwind array position. Next, the noise sources on the individual blades are investigated, to assess the performance of the SIROCCO blade and the serrations, as a function of array position, wind speed, and rotor azimuth angle. Since the clean rotor is considered to be most representative for the rotor during normal operation, and since the upwind measurements covered all relevant wind speeds, the focus will be on State 2a.

A. Noise sources in the rotor plane

Each 30 s measurement resulted in acoustic source maps, showing the noise sources in the rotor plane as a function of frequency. In order to show the general trends, these maps were averaged over all selected measurements in the respective rotor state (Figure 6 to Figure 8). Thus, these maps show the average effect of all three blades over all revolutions. The black circle indicates the 94-m rotor diameter and the 'X' indicates the center of the rotor plane. The range of the color scale is always 12 dB and the maximum is adjusted for each frequency band. The rotation direction is clockwise (note that the source map in Figure 8 was mirrored to allow easy comparison to the upwind measurements, i.e. an observer at the array position would see the rotor turn in counter-clockwise direction). Similar to the previous results on the baseline turbine²⁵, the upwind measurements (Figure 7) indicate that, for an observer at the array position, most of the noise is produced by the outer 25% of the blades, during their downward movement. This effect, which causes the typical swishing noise during the passage of the blades, can be explained by convective amplification and trailing edge noise directivity²⁴ as described in Eq. (1). For the higher frequencies, minor noise sources can also be observed at the tip of the up-going blades, and at the location where the blades pass the tower. The nature of this 'tower source' is hard to assess on the basis of the present data, but it could originate from (1) reflection of blade noise on the tower, (2) impingement of blade tip vortices on the tower, and/or (3) the upstream influence of the tower on the flow field around the blade.

For the *downwind* measurements (Figure 6 and Figure 8), nacelle noise appears to be more pronounced than for the upwind array position, which may be explained by a combination of two factors: first, the ventilation opening is on the rear side of the nacelle, so that the nacelle noise is radiated mainly in the downwind direction. The nacelle noise level in State 1 is lower than in State 2b, probably because of the misalignment angle of -204° (i.e. a deviation of 24° with respect to -180°) in State 1 (Table 2). Second, on the basis of the ζ -dependence in Eq. (1), the trailing edge noise from the blades is expected to be slightly higher on the upwind side than on the downwind side (due to the wind speed and rotor tilt angle). This was confirmed by comparison of the blade noise spectra in states 2a and 2b for the same wind speed bins (see Section IIIB5). In the downwind plots the nacelle source appears off-centre because it is located in front of the scan plane, which coincides with the rotor plane. Despite the (relatively) increased nacelle noise, the overall turbine noise is still dominated by the noise from the blades. Note that in Figure 6 the source maximum for the down-going blade has shifted anti-clockwise (relative to the State 2 plots), which can be explained by the convective amplification factor in Eq. (1) for the average misalignment angle of -204° in this rotor state²⁵. Also note that in the downwind source maps the noise source at the tip of the up-going blades is more prominent than in the upwind maps. In the next section it will be shown that, besides a small directivity effect, this effect is mainly due to the lower average wind speeds (and thus lower pitch angle and higher tip loading) for these measurements (Table 2).

B. Noise sources on the individual blades

As mentioned in Section I, acoustic field measurements on the baseline turbine²⁵ showed that the average OASPL for the two standard blades that were used again in the present campaign (i.e. the baseline and serrated blade) differed by less than 0.05 dB. Furthermore, it was argued in Section IIE that the average level differences between the blades, as measured with the microphone array, are accurate within less than 0.1 dB. Thus, with the present test set-up it is well possible to assess the acoustic performance of the serrations and the new airfoil.

1. Single-microphone analysis

During the field tests, the difference in noise between the blades could be clearly observed by subjective listening. This can be illustrated by plotting the OASPL measured on a single microphone (i.e. the reference microphone at the center of the array) as a function of rotor azimuth angle (Figure 9). The A-weighted overall levels in this figure were summed between 250 Hz and 800 Hz, to focus on the low-frequency noise of the down-going blade. Furthermore, the levels were averaged over all measurements and all revolutions in State 2a (synchronization was done using the trigger signal from the turbine). As a reference, the result for the test campaign on the baseline

turbine (2005) is shown as well. For the baseline rotor, clearly three humps are observed, representing the swishing noise which is observed when the three blades pass the ‘3 o’clock’ position (see also Figure 7). The amplitude variation during the passage of the blades is about 2.5 dB. If we assume that the noise of the modified rotor is also mainly radiated during the downward movement of the blades, the three ‘humps’ for the modified rotor can be associated to the baseline blade, the SIROCCO blade, and the serrated blade respectively. Thus, it can be estimated that the SIROCCO blade yields a reduction of more than 1 dB, while the serrated blade is about 4 dB quieter than the baseline blade. However, it should be noted that these values only pertain to the low-frequency noise radiated from around the 3 o’clock position, whereas the blades may also produce significant noise during the other part of the revolution (as will be seen below). Moreover, at each moment the single microphone picks up the noise from all three blades, so that the contribution of each blade cannot be extracted from the single-microphone results. Thus, although Figure 9 nicely illustrates subjective on-site observations, a dedicated array processing method (as described in Section IID) is required to obtain a clear picture of the noise radiated by each individual blade during the complete revolution.

2. Average blade noise characteristics

The source maps for the individual blades, averaged over the complete revolution and over all measurements in State 2a, are shown in Figure 10. The source maps run from 15 m to 60 m in radial direction, and have a chordwise extent of 30 m. The black line indicates the outer 32 m of the blade (trailing edge on upper side). The range of the color scale is 12 dB and the maximum is adjusted for each frequency band, so that the colors within one row can be compared directly. First, the source maps show that the differences in source *position* for the three blades are small. The source radial position, defined as the radius at which the maximum level in the source map occurs, is shown in Figure 11 as a function of frequency for the three blades. Since the mesh size of the scan grid was 1 m (Section IID), these source radial positions are multiples of 1 m. For all blades the source radial position increases with frequency, which can be understood using the relation $St=f\delta^*/U\approx const.$ for the trailing edge noise peak^{6,33}: for increasing radius the local blade inflow velocity U increases and the boundary layer displacement thickness δ^* decreases, so that the produced frequencies are higher^{24,25}. Except for the lowest frequencies, where the modified blades have a lower source radius, the differences in average source radial positions between the different blades are small. More importantly, the source maps in Figure 10 show that for low frequencies both modified blades are significantly quieter than the baseline blade, especially the serrated blade. For high frequencies however, both modified blades are noisier than the baseline blade, especially the SIROCCO blade. These trends are illustrated in Figure 12, which shows the average integrated spectra for the three blades. These spectra were obtained by averaging the integrated spectra for all measurements in State 2a, with equal weights per wind speed bin. As mentioned in Section IID, these sound levels represent the contribution of the different blades to the overall sound pressure level of the turbine, as measured at the array position. The integrated spectra confirm the low-frequency noise reduction and high-frequency noise increase for the modified blades. For the serrated blade the A-weighted sound pressure level at high frequencies is even higher than at low frequencies. Based on these average spectra, for the upwind measurements on the clean rotor (i.e. State 2a), which are considered most representative for normal operation and which cover all relevant wind speeds, average overall noise reductions of 0.5 dB and 3.2 dB were obtained for the SIROCCO and serrated blade, respectively. For the other two rotor states, which covered only the lower wind speeds, average noise reductions of 0.0 dB and 1.6 dB (State 1) and 0.2 dB and 1.2 dB (State 2b) were found for the SIROCCO and serrated blade, respectively. The reasons for the lower noise reduction in these states will be discussed in subsequent sections. The measurement uncertainty of the above-mentioned average noise reductions will be discussed below in Section 4.

3. Dependence of blade noise on rotor azimuth

In order to better understand the acoustic behavior of the modified blades, it is interesting to look at the dependence of the blade noise on the rotor azimuth angle (Figure 13). This figure shows the ‘overall source maps’ for the different blades for 12 rotor azimuth intervals of 30°, starting at $\psi=0^\circ$ (‘12 o’clock’). These overall source maps (averaged over all measurements in State 2a) were obtained by summing the source maps between 160 Hz and 5 kHz, after applying A-weighting and a correction for array resolution (which depends on frequency and blade position) to the levels. Thus, the OASPL of the blade is equal to the sum of all scan levels in a given source map. Similar to the previous blade source maps, the black line indicates the outer 32 m of the blade. The range of the color scale is 12 dB and the maximum is the same for all maps, so that the colors can be compared directly. This figure shows that during the *downward* movement of the blades, both modified blades are substantially quieter than the baseline blade. However, during the *upward* movement both modified blades are noisier. These observations are illustrated in Figure 14, which shows the integrated blade spectra for the down- and upward half of the revolution

separately. The high-frequency noise increase for the modified blades occurs mainly during the upward part of the revolution, and for the serrated blade, the increased noise of the up-going blade even dominates the overall average spectrum.

4. Dependence of blade noise on wind speed

Besides the rotor azimuth, the blade noise characteristics were also found to depend strongly on the wind speed. This is illustrated in Figure 15 and Figure 16, which show the integrated blade noise spectra for the 7 m/s and 10 m/s bins of State 2a, respectively (the State 2b spectra in Figure 15 will be discussed below in Section IIIB5). The 7 m/s blade spectra show a high-frequency hump around 1250-1600 Hz, which is absent in the 10 m/s spectra. As seen in the previous section, this high-frequency noise is mainly produced during the upward movement, and originates from the very tip of the blade (Figure 10 and Figure 13). Since the average blade pitch angle was 0° in the 7 m/s bin and higher towards feather in the 10 m/s bin, this suggests that the high-frequency noise at low wind speeds can be associated with the increased tip loading as a result of the lower pitch angle (for wind speeds U_{10} higher than 7 m/s the turbine control system increases the pitch angle, which reduces the local angle-of-attack and thus the blade loading). This also explains the fact that the up-going blades were noisier in States 1 and 2b than in State 2a (Figure 6 to Figure 8), since the average blade pitch angle was lower than in State 2a (Table 2). Apparently this tip noise does not follow the trailing edge noise directivity function described in Eq. (1), since it is mainly radiated during the upward movement of the blades. Figure 15 also shows that the tip noise is much more prominent for the modified blades than for the baseline blade, which is always dominated by trailing edge noise. Thus, the adapted pressure distribution on the modified blades, possibly in combination with the slightly increased blade loading (Section I), changes the tip vortex characteristics such that tip noise increases.

For the baseline and SIROCCO blades the frequency of the low-frequency trailing edge noise peak is higher at 10 m/s than at 7 m/s, which can be explained by the lower blade loading (due to the higher pitch angle), which leads to a thinner suction side boundary layer. This is confirmed in Figure 17, which shows the source radial positions for both blades in these two wind speed bins: for a given radius, the trailing edge boundary layer thickness decreases for the higher wind speed, so that the produced frequencies are higher. For both bins the source radial position of the SIROCCO blade is slightly lower than for the baseline blade, which is consistent with the higher trailing edge noise peak frequency, and which suggests that the main objective of the airfoil design, i.e. to obtain a thinner suction side boundary layer (see Section I), has succeeded. If we suppress the spectral influence of tip noise by considering only the downward part of the revolution (Figure 14), a slight trailing edge noise increase is observed between 1 and 3 kHz for the SIROCCO blade, which, similar to the wind tunnel results, can be attributed to the increased pressure side boundary layer thickness³⁵. However, even if we consider only the downward part of the revolution, the average reduction in OASPL for the SIROCCO blade in State 2a is only 1.0 dB, which is lower than the 2-3 dB found in the wind tunnel tests. The reasons for this discrepancy between wind tunnel and field results are not fully clear yet. Apart from blade quality, a possible explanation could be that instationary inflow conditions in the field lead to lift fluctuations well beyond the prescribed design lift range³⁴.

In terms of A-weighted overall sound pressure levels (summed between 160 Hz and 5 kHz), both modified blades were found to reach maximum noise levels at a wind speed U_{10} of about 7 m/s, where the tip loading and therefore the tip noise are highest (the blade pitch angle only starts to increase significantly for wind speeds higher than 7 m/s). The noise from the baseline blade, which is dominated by trailing edge noise, also peaks around 7 m/s. The corresponding noise reductions (Figure 18) are lowest around 7 m/s and increase for higher wind speeds, for both the serrated and SIROCCO blade. Thus, the results indicate that at high wind speeds the noise from the three blades is dominated by trailing edge noise, which is effectively reduced by the new airfoil shape and the serrations. However, at lower wind speeds (increased tip loading due to lower pitch angle), significant high-frequency tip noise is generated by both modified blades during their upward movement, which partly cancels the trailing edge noise reduction. As a result, the average noise reductions obtained in States 1 and 2b, which had lower wind speeds and therefore lower average blade pitch angles (Table 2), were lower than the 3.2 dB and 0.5 dB found in State 2a for the serrated and SIROCCO blade, respectively.

In order to evaluate these average noise reductions it is important to understand the uncertainty levels associated with the measurement method employed during this study. As argued in Section IIE, for the weather conditions and turbine operation parameters in State 2a, the measurement uncertainty of the average noise reductions is smaller than 0.1 dB. For different turbine and meteo conditions (within the tested range), the uncertainty in the noise reduction can be assessed from the scatter in Figure 18: for the serrated and SIROCCO blade, standard deviations σ of 0.6 dB and 0.4 dB were found, which leads to standard deviations of the mean (ϵ) for the average noise reductions of 0.10 dB and 0.06 dB, respectively. Since these ϵ -values are smaller than the average noise reductions of 3.2 dB and 0.5 dB, the average reductions are significant for the tested range of turbine and meteo conditions.

5. Upwind versus downwind measurements

In order to assess the effect of observer location (i.e. upwind versus downwind array position), Figure 15 compares the blade noise spectra for the 7 m/s bin in States 2a and 2b. The meteo and turbine parameters were similar for both cases. It can be seen that for all three blades the level of the low-frequency trailing edge noise hump is lower on the downwind side. A partial explanation for this could be that the downwind integrated blade noise levels suffer from increased coherence loss (see also Section IIE), because the blade noise propagates through the rotor wake. Indeed, the difference between the integrated rotor noise level and the level of the reference microphone was about 1 dB higher for the downwind measurements than for the upwind measurements in the 7 m/s bin. In addition, the reduced downwind trailing edge noise levels may be explained by the ξ -dependence in Eq. (1), due to the wind speed and rotor tilt angle (see also Section IIIA). In contrast to the low-frequency noise, the high-frequency tip noise peak has approximately the same level for the up- and downwind measurements, which means that the *relative* importance of tip noise is higher on the downwind side. Besides the tip loading effect discussed in the previous section, this increased importance of tip noise on the downwind side is an additional explanation for the lower noise reductions obtained in States 1 and 2b (as compared to State 2a), and for the fact that the up-going blades are noisier in States 1 and 2b than in State 2a (Figure 6 to Figure 8).

6. Baseline blade noise for different rotor states

Figure 19 shows the baseline blade noise spectra for the three different rotor states. With regard to the clean rotor, a number of differences can be observed between states 2a and 2b: first, the low-frequency trailing edge noise peak for State 2a has a higher frequency and higher level than State 2b. This can be explained respectively by the higher wind speed (i.e. lower blade loading and thinner boundary layer) in State 2a, and the difference in directivity for the up- and downwind observer position (see Sections 4 and 5 above). Second, State 2b spectrum shows a high frequency tip noise peak, which is almost absent in State 2a. As mentioned before, this can be explained by the lower average wind speed (and thus higher tip loading) in State 2b (Section 4), and by the increased importance of tip noise on the downwind side (Section 5). Thus, to assess the influence of tripping on blade noise, State 1 should be compared to State 2b. The average conditions for these two states are practically the same, except for the misalignment angle (Table 2). Figure 19 shows that the low-frequency trailing edge noise peak for State 1 has a higher level and lower frequency than in State 2b. This suggests that the trip has increased the trailing edge boundary layer thickness. Furthermore, the high-frequency tip noise peak is slightly lower for the tripped case. Thus, the results do indicate a small effect of tripping (0.6 dB increase in OASPL for the present conditions), but for a conclusive answer measurements should be done with a clean and a tripped blade on one rotor.

IV. Conclusions

Acoustic field measurements were carried out on a 94-m diameter wind turbine, with one standard blade, one blade with an optimized airfoil shape, and one standard blade with trailing edge serrations. The blade modifications had no adverse effect on their aerodynamic performance. In order to assess the effect of blade roughness due to e.g. dirt or insects, the blades were tested in both clean and tripped conditions. A large horizontal microphone array, positioned at a distance of about one rotor diameter from the turbine, was used to locate and quantify the noise sources in the rotor plane and on the individual blades. Since the array position was fixed and the wind direction varied, both up- and downwind measurements were performed.

The acoustic source maps for the baseline blade show that, for an observer at the array position, the dominant source is trailing edge noise from the outer 25% of the blade. Due to convective amplification and directivity, practically all noise is produced during the downward movement of the blade, which causes the typical swishing noise during the passage of the blades. Both modified blades show a significant trailing edge noise reduction at low frequencies, which is most prominent for the serrated blade. However, the modified blades also show a noise increase at high frequencies, which can be associated with the blade tips. This high-frequency tip noise is mainly radiated during the upward part of the revolution, and is most important at low wind speeds (i.e. high tip loading) and for the downwind array position. Nevertheless, for the upwind measurements on the clean rotor, which are considered most representative for normal operation and which cover all relevant wind speeds, average overall noise reductions of 0.5 dB and 3.2 dB are obtained for the optimized and serrated blade, respectively. For both blades the noise reduction increases with increasing wind speed. The downwind measurements on the clean and tripped rotor only cover the lower wind speeds, and show less noise reduction. Comparison of the noise from the baseline blade for clean and tripped conditions suggests a noise increase of 0.6 dB due to tripping.

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Tables

	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
State 1 (tripped rotor; array downwind)	8	8	8	0	0
State 2a (clean rotor; array upwind)	7	8	8	8	6
State 2b (clean rotor; array downwind)	8	8	8	0	0

Table 1. Number of selected measurements per wind speed bin for each rotor state.

	<i>U10</i> (m/s)	<i>P</i> (MW)	RPM	α (°)	blade pitch (°)
State 1	6.9	1.6 (0.1)	14.5 (0.2)	-204 (12)	0.0 (0.1)
State 2a	8.1	2.1 (0.1)	14.9 (0.0)	-2 (4.4)	5.1 (0.6)
State 2b	6.9	1.6 (0.1)	14.6 (0.1)	-183 (2.4)	0.0 (0.0)

Table 2. Average weather and turbine parameters for each rotor state. The standard deviation σ is indicated between brackets.

Figures



Figure 1. Climber removing trips from serrated blade.

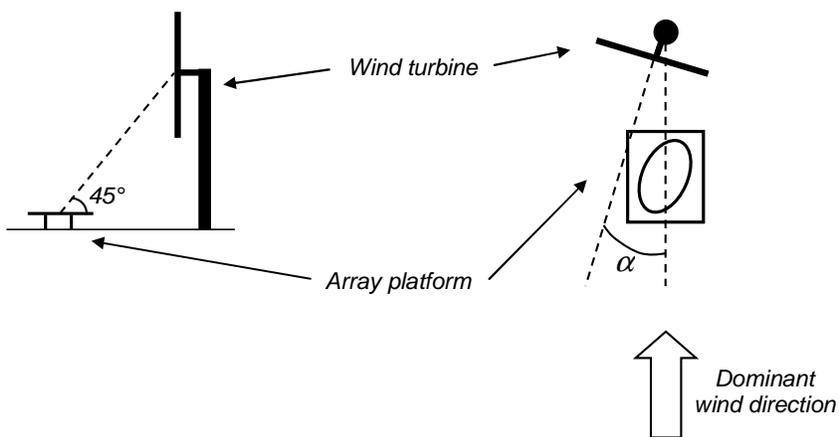


Figure 2. Side view (left) and top view (right) of test set-up. The array microphones were mounted on the platform in an elliptic shape for optimum resolution.

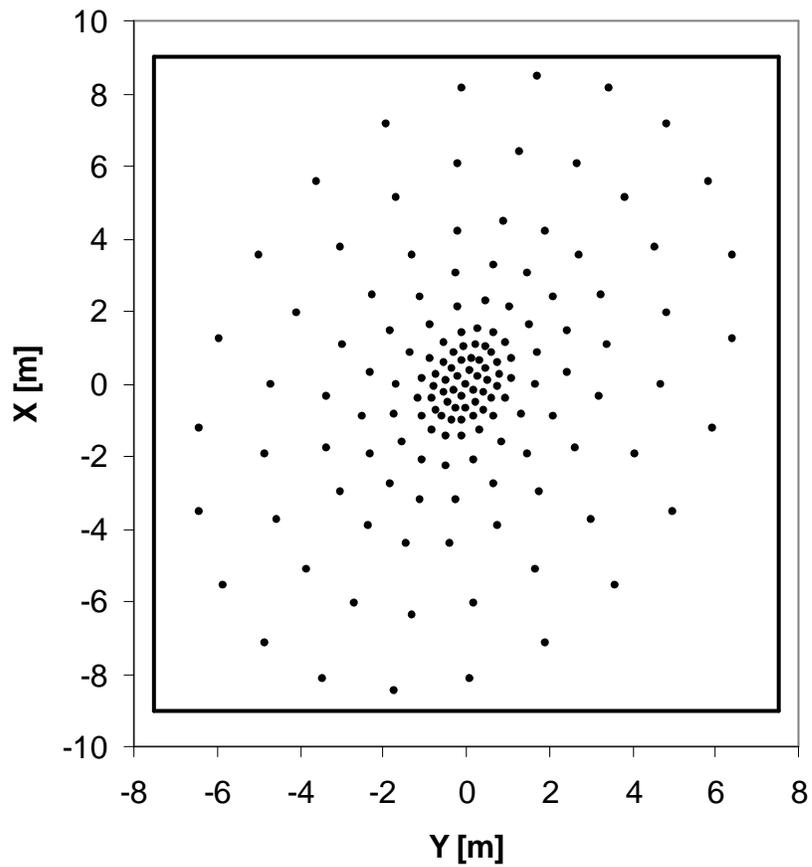


Figure 3. Layout of array microphones. The rectangle indicates the platform dimensions.

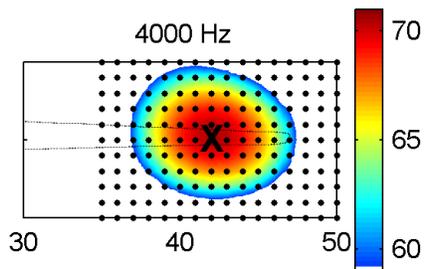


Figure 4. Acoustic source map for whistle measurement. The black dots indicate the scan grid and the cross indicates the actual whistle position.

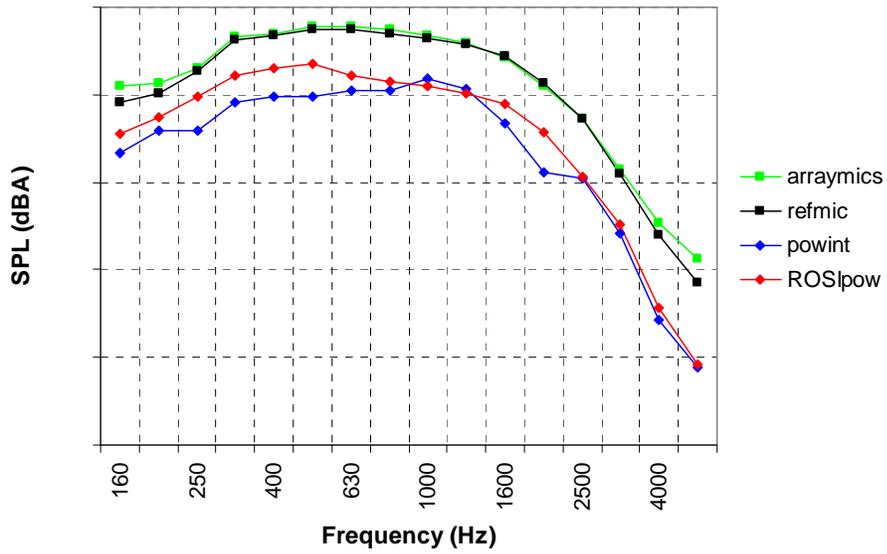


Figure 5. Verification of power integrated method.

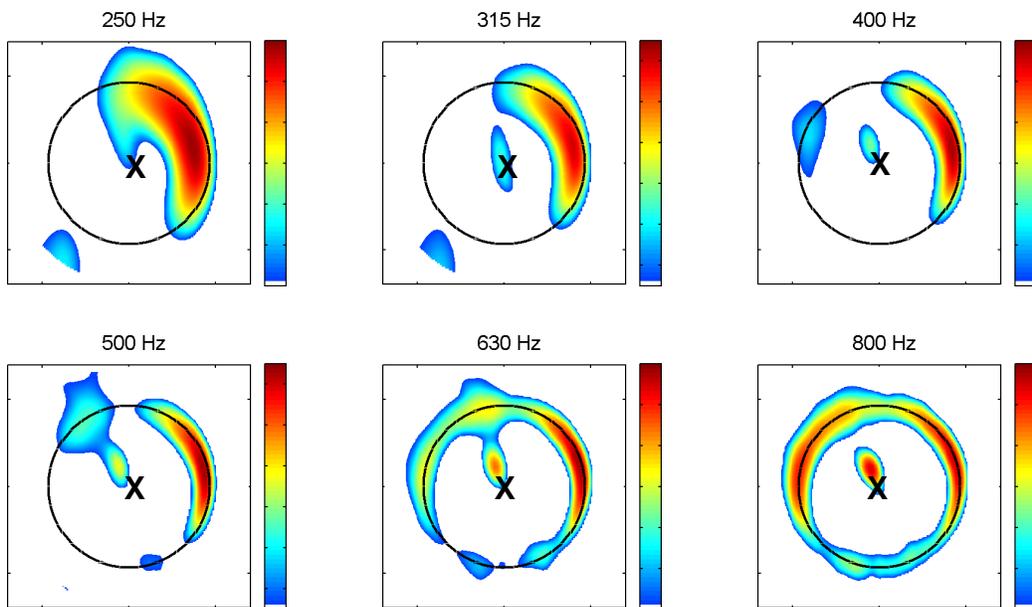


Figure 6. Average source maps for State 1 (tripped rotor, downwind array position).

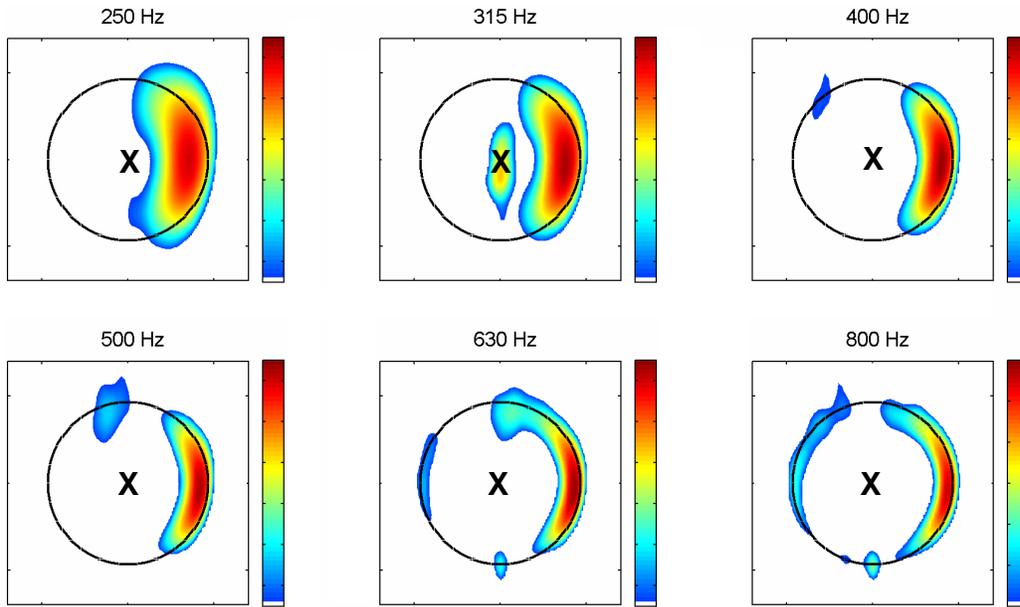


Figure 7. Average source maps for State 2a (clean rotor, upwind array position).

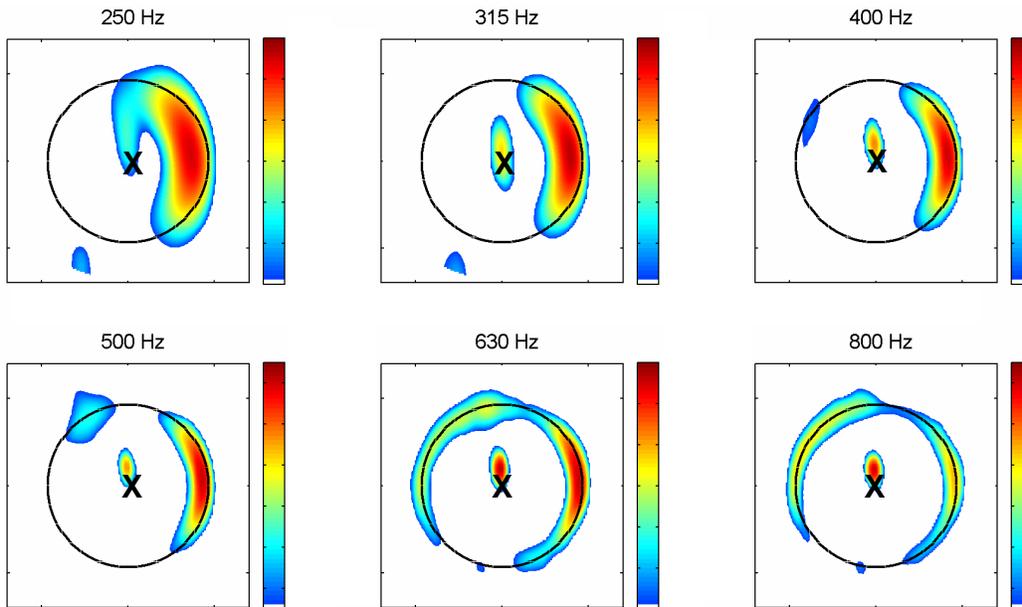


Figure 8. Average source maps for State 2b (clean rotor, downwind array position).

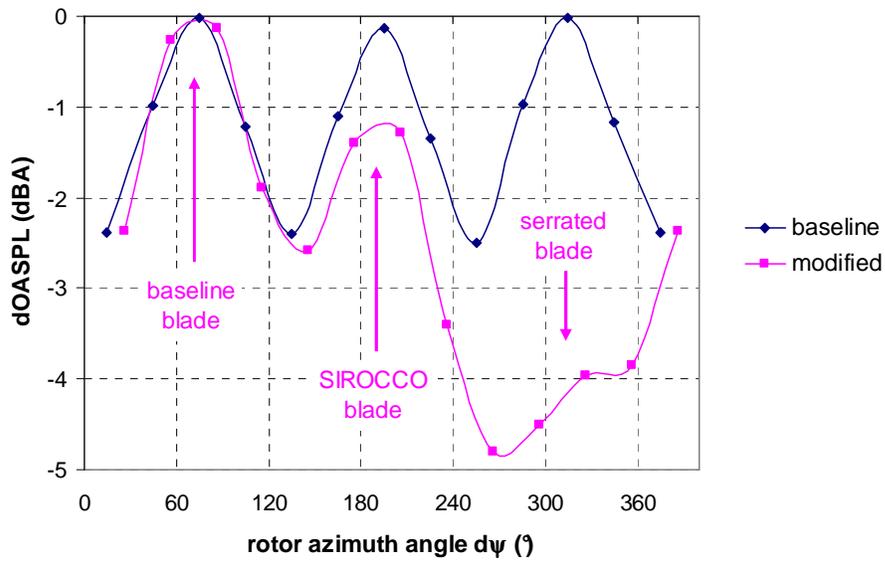


Figure 9. Average sound pressure level on central array microphone as a function of rotor azimuth, for baseline rotor (2005) and rotor with modified blades (State 2a).

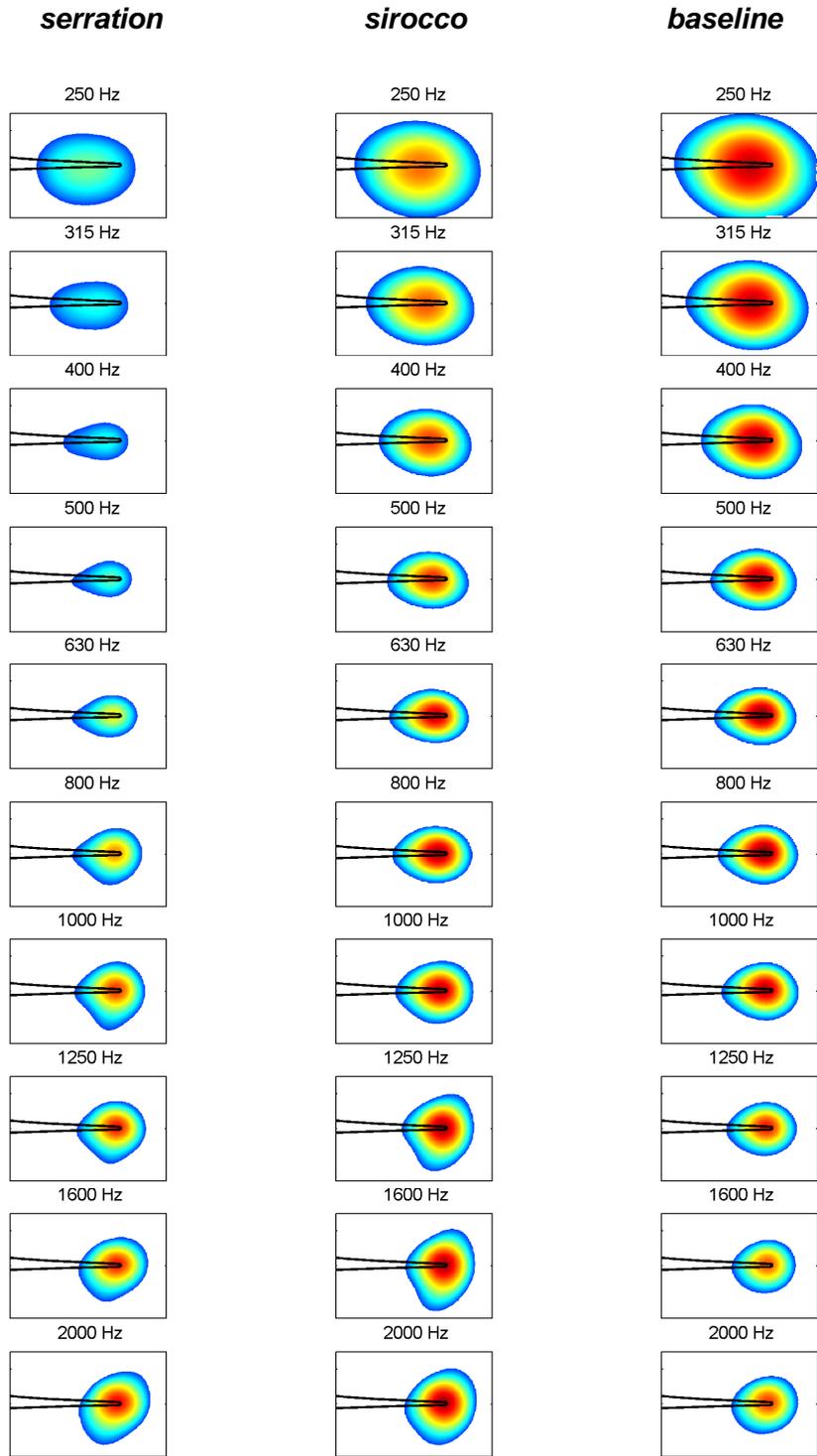


Figure 10. Average source maps for individual blades in State 2a, as a function of frequency.

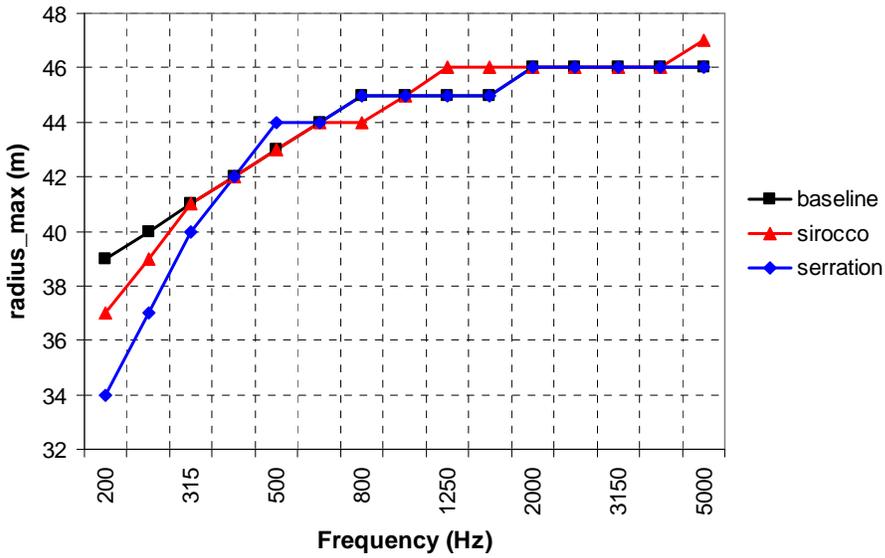


Figure 11. Average source radial position as a function of frequency for the three blades in State 2a.

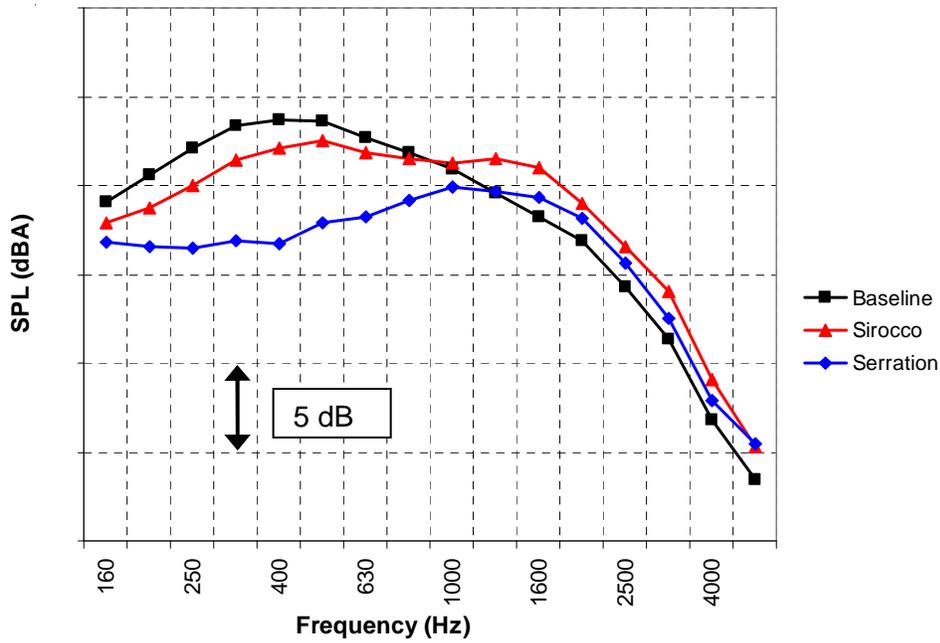


Figure 12. Average blade noise spectra for State 2a.

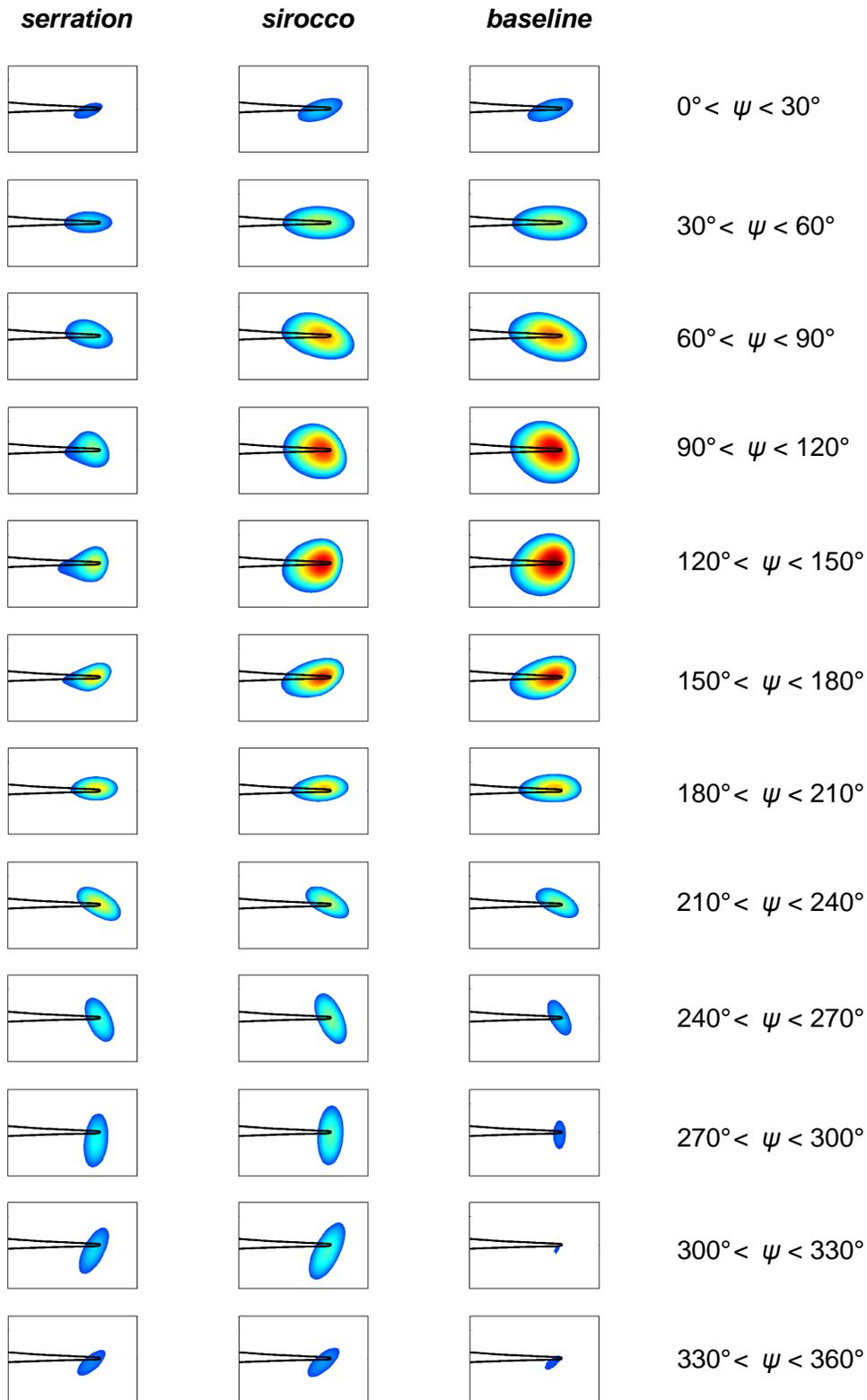


Figure 13. Average overall source maps for individual blades in State 2a, as a function of rotor azimuth.

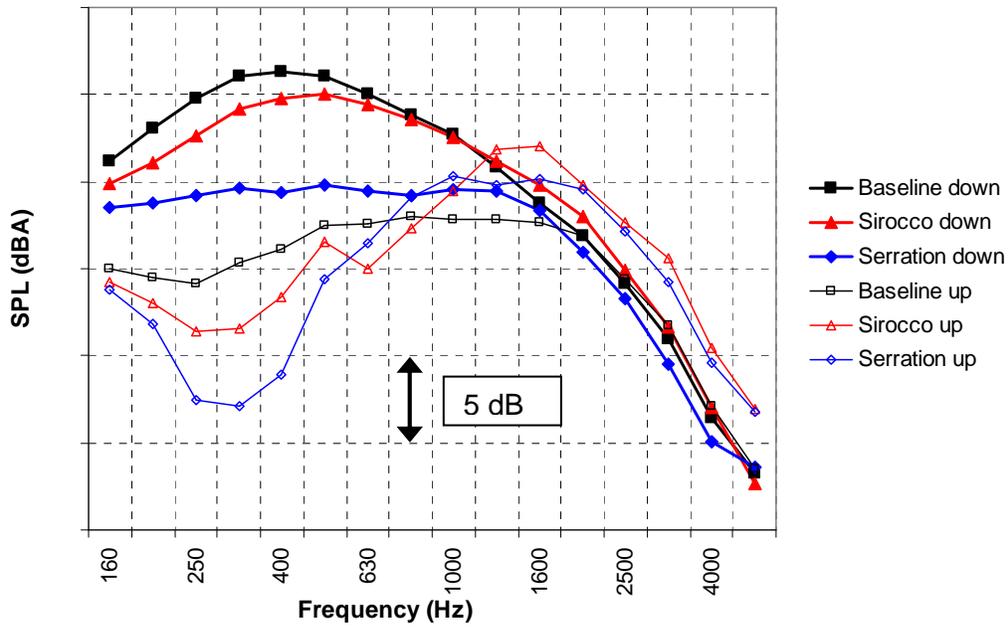


Figure 14. Average blade noise spectra for the upward and downward part of the revolution in State 2a.

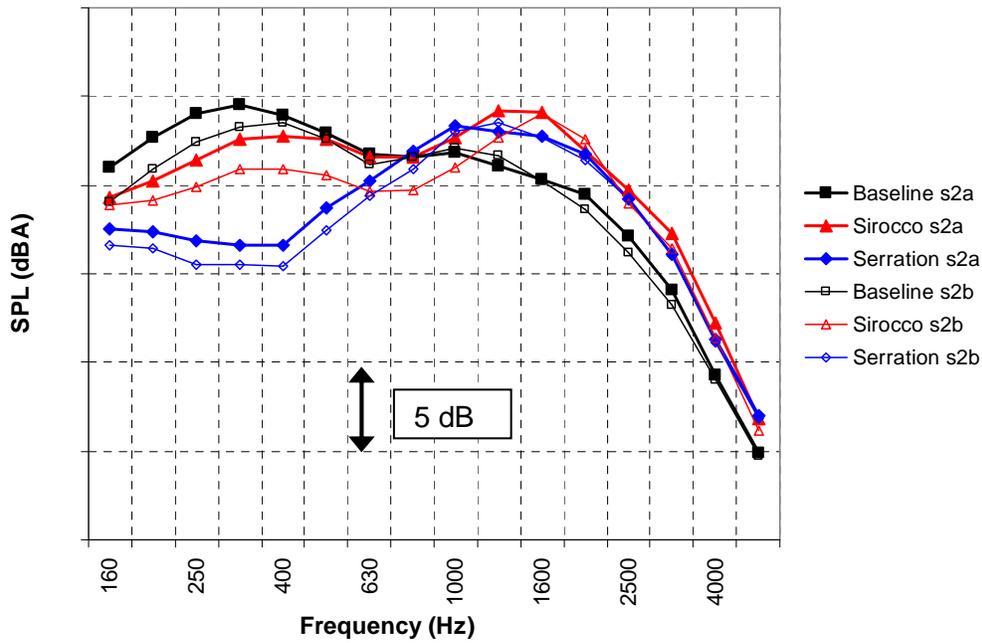


Figure 15. Average blade noise spectra for the 7 m/s wind speed bin of State 2a and State 2b.

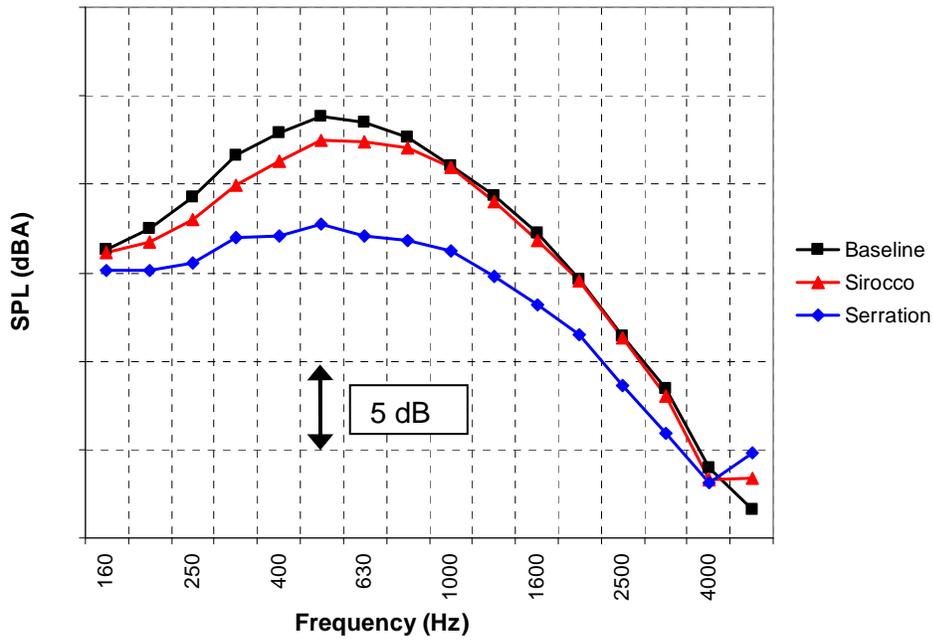


Figure 16. Average blade noise spectra for the 10 m/s wind speed bin of State 2a.

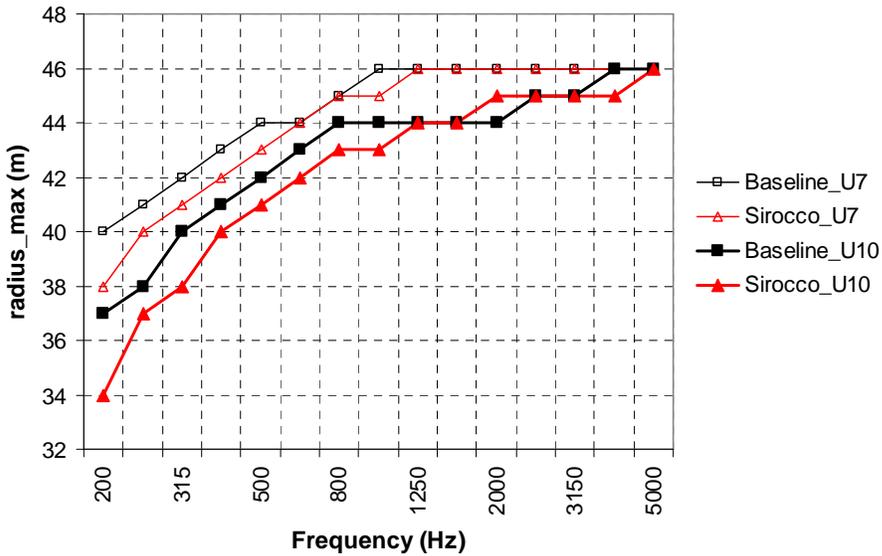


Figure 17. Source radial position as a function of frequency for the baseline and SIROCCO blades in the 7 m/s and 10 m/s wind speed bins of State 2a.

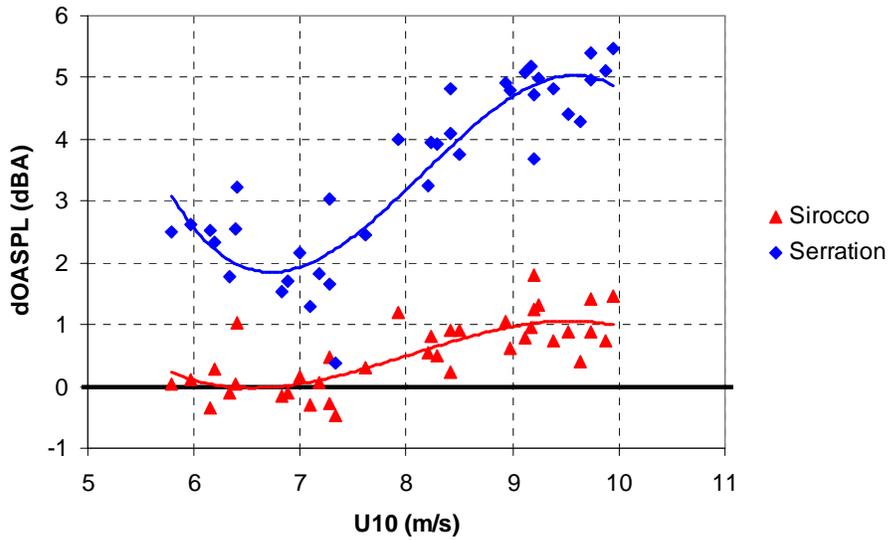


Figure 18. Overall blade noise reduction as a function of wind speed for State 2a. The solid lines are third-order least-squares fits through the measured data.

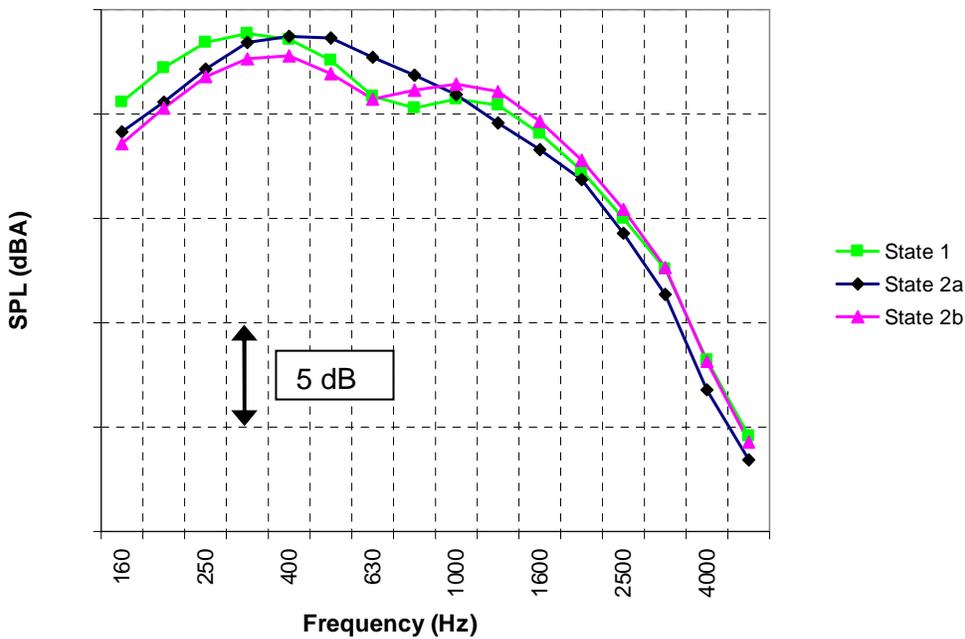


Figure 19. Average baseline blade noise spectra for different rotor states.