AWEA Windpower 2013

Chicago, IL May 6-8, 2013

Concepts for Wind Turbine Sound Mitigation

Dr. Kevin Kinzie[†] , Dr. Roger Drobietz[‡], Dr. Benoit Petitjean[*], Saskia Honhoff[‡]
GE Advanced Technology Operations – Wind Energy
([†]) 300 Garlington Road, Greenville, 29615, SC [USA]
([‡]) Holsterfeld 16, 48499 Salzbergen [Germany]
GE Global Research – Europe
(*) Freisinger Lanstr. 50, 85748 Garching b. München [Germany]

Abstract

An overview of fundamental wind turbine noise sources and their relative importance to overall sound levels is presented as well as methods of managing farm level sound. Several noise reduction concepts are presented followed by a discussion of how wind turbine operation affects far-field sound. First, several blade tip geometries were designed and tested on a 2.5 MW class wind turbine platform. The results show that tip shape can significantly impact the blade noise signature. Low noise tip shapes provide a decrease of 5–6 dB(A) in apparent sound power level (Lwa) compared to a baseline tip. Second, a number of trailing edge noise reduction concepts were screened via extensive wind tunnel testing. Serrations were selected for full-scale field tests and fitted on three different wind platforms with different blade designs and demonstrated a decrease of 2–4 dB(A) in apparent sound power level (Lwa) compared to the original (unserrated) blades. Finally, a general methodology is presented to optimize wind turbine operation in order to meet target noise levels with maximum energy yield. It is then demonstrated how bringing together these noise reduction technologies and operational strategies enable wind farm layouts that meet ever stricter local sound regulations.

Introduction

Wind turbine noise represents one of the obstacles to a more widespread use of wind energy today. As wind turbine rotors become larger and wind farms are located closer to residential areas, innovative approaches to sound reduction, low noise operation, and strategic siting methods can all be used together to provide wind farms that mutually satisfy the interests of operators and the communities that they serve. Manufacturers are able to provide hardware solutions that mitigate noise at the source, but a good understanding of turbine operation and the impact of turbine siting also affords opportunities to control the observed sound at the receptor locations where operators are required to meet local regulations. Figure 1 illustrates the key components and opportunities for wind turbine sound generation starting at the turbine source and ending at the receptor.

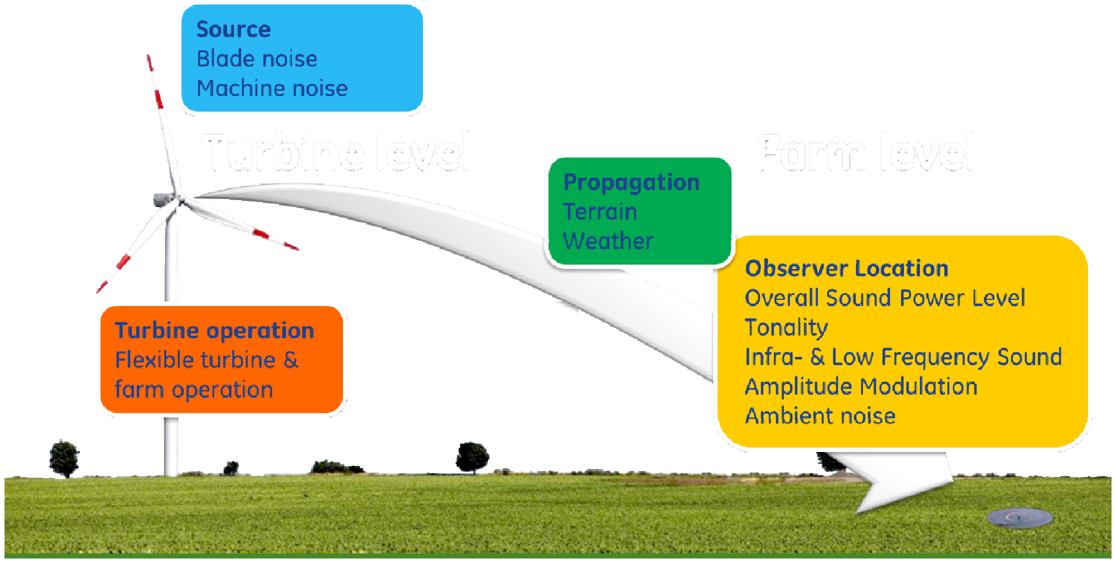

Figure 1. Illustration of key elements of wind turbine farm level sound

The initiation of all wind turbine sound starts with noise source mechanisms located on or near the turbine itself. These noise sources can be highly influenced by turbine operational parameters such as rotational speed and blade pitch angle as well as wind characteristics. Once the sound has been generated at the turbine, it propagates away from the source and is influenced by the local terrain and atmospheric conditions. Finally, the sound reaches the receptor location where it can be quantitatively described by typical sound metrics such as apparent sound power level and spectral levels. However, as is the case with many acoustic applications, perceived sound and annoyance can be very subjective and affected by influences such as ambient background noise, tonal characteristics, and modulation of sound. All of these can be strong drivers of public opinion. This paper explores several turbine source noise mitigation techniques as well as how these technologies and turbine operation can be used to produce quieter wind farms.

Wind Turbine Noise Source Noise Characteristics

The two main sources of sound generated by a wind turbine are mechanical noise and aerodynamic noise. Mechanical noise originates from the various machinery components of a wind turbine, such as the gearbox, the generator or the cooling fans, and is essentially made up of several tones emitted at frequencies that are directly proportional to the rotational speeds of the machinery elements. Today, mechanical noise is not considered to be the dominant source of sound from wind turbines [1, 2].

Aerodynamic (or flow-induced) noise is radiated from the blades and has a broadband character, although in some cases tones can also be present. The main flow-induced noise mechanisms are inflow turbulence noise (or leading edge noise) and airfoil self-noise. Inflow turbulence noise results from the interaction of turbulence in the atmosphere with the leading edge of the blades. Lowson [3] and Zhu *et al.* [4] (among others) have shown that this mechanism radiates predominantly in the low-frequency range – below about 200 Hz.

Airfoil self-noise has been described in details by Brooks *et al.* [5], who suggested that it is in fact a combination of several competing mechanisms that can be more or less dominant for a given airfoil, depending on its aerodynamic state. The mechanisms relevant to a wind turbine blades are: turbulent boundary layer trailing edge noise, flow separation noise, and tip vortex noise. Brooks *et al.* [5] also derived semi-empirical prediction models for each of these mechanisms, which have been used extensively to predict wind turbine noise [4, 6, 7]. Such prediction tools are extremely valuable to wind turbine blade designers, as they provide the relative contributions from each mechanism to the overall blade noise and which ones are most significant – and thus should be tackled first. For illustrative purposes, a typical A-weighted, one-third octave band spectrum from a large, pitch-regulated, upwind turbine is given in Figure 2, along with the contributions from the different flow-induced noise mechanisms.

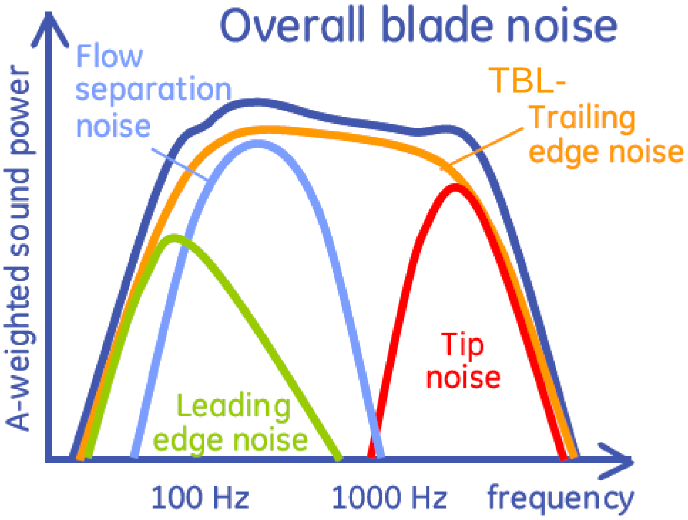

Figure 2. Example A-weighted, third-octave band spectrum from a large, modern wind turbine with relative contributions from flow-induced noise mechanisms.

Several acoustic measurement campaigns [8, 9] have established that turbulent boundary layer trailing edge noise is the dominant mechanism for large wind turbines. Airfoil trailing edge noise itself has been the object of several theoretical [10–12], experimental [13–15] and numerical [16–18] studies, and is relatively well understood. It is caused by the scattering interaction of the pressure fluctuations in the turbulent boundary layer with the sharp trailing edge of the airfoil. Therefore, the exact shape of the trailing edge as well as the physical properties of the material with which it is built can be expected to play a critical role in the efficiency of the acoustic emission. For example, Howe [19] pointed out that the trailing edge cross-section geometry can directly impact the amplitude of the radiated noise. He also showed analytically that serrated trailing edges may provide significant noise reduction over straight edges [20]. Recent experimental studies conducted by Herr [21] emphasized the possible noise benefits using flow-permeable trailing edges.

Tip vortex formation noise is known to contribute mostly to high-frequency broadband airfoil self-noise [4]. Brooks and Marcolini [22] have proposed a prediction model, in which the amplitude of the noise radiated from the three-dimensional flow near the tip is proportional to the so-called vortex ‘wetted length,’ i.e. the spanwise extent at the trailing edge of the separation due to the tip vortex. More recently, Drobietz and Borchers [23] developed a more thorough theory for tip vortex noise emission, according to which tip noise is caused mainly by i) the interaction between the vortical structures and the side edge surface itself, and ii) the interaction between the merged vortex and the upper side edge as well as the suction side surface. Although the importance of tip noise for wind turbine applications can vary with blade design, its contribution could be reduced provided that the aforementioned interactions are minimized.

The present paper focuses on technologies for both tip vortex and trailing edge noise reduction. First, the influence of tip design over wind turbine noise is investigated by means of acoustic measurements performed on a full scale wind turbine platform equipped with three different tip shapes. Second, this work explores various low noise trailing edge concepts, such as flow-permeable edges and serrations. Preliminary noise measurements carried out in a wind tunnel on airfoil scale models are used to downselect the most promising option, which is then validated through field testing.

Influence of Tip Shape On Wind Turbine Noise

Tip Shape Designs

In an effort to assess the influence of tip shape over wind turbine noise, three different tips were proposed for full scale field testing. The ‘slender’ tip and the ‘ogee’ tip were designed to minimize both the vortex ‘wetted length’ and the interaction between the vortical structures and the side edge itself. Further details on the ogee tip shape can be found in reference [1]. A potentially “loud” tip shape was also designed in the form of a ‘blunt’ tip with a much larger chord, and for which no particular attempt was made to minimize the vortex ‘wetted length’. Planforms and photographs of the three tip shapes are shown in Figure 3.

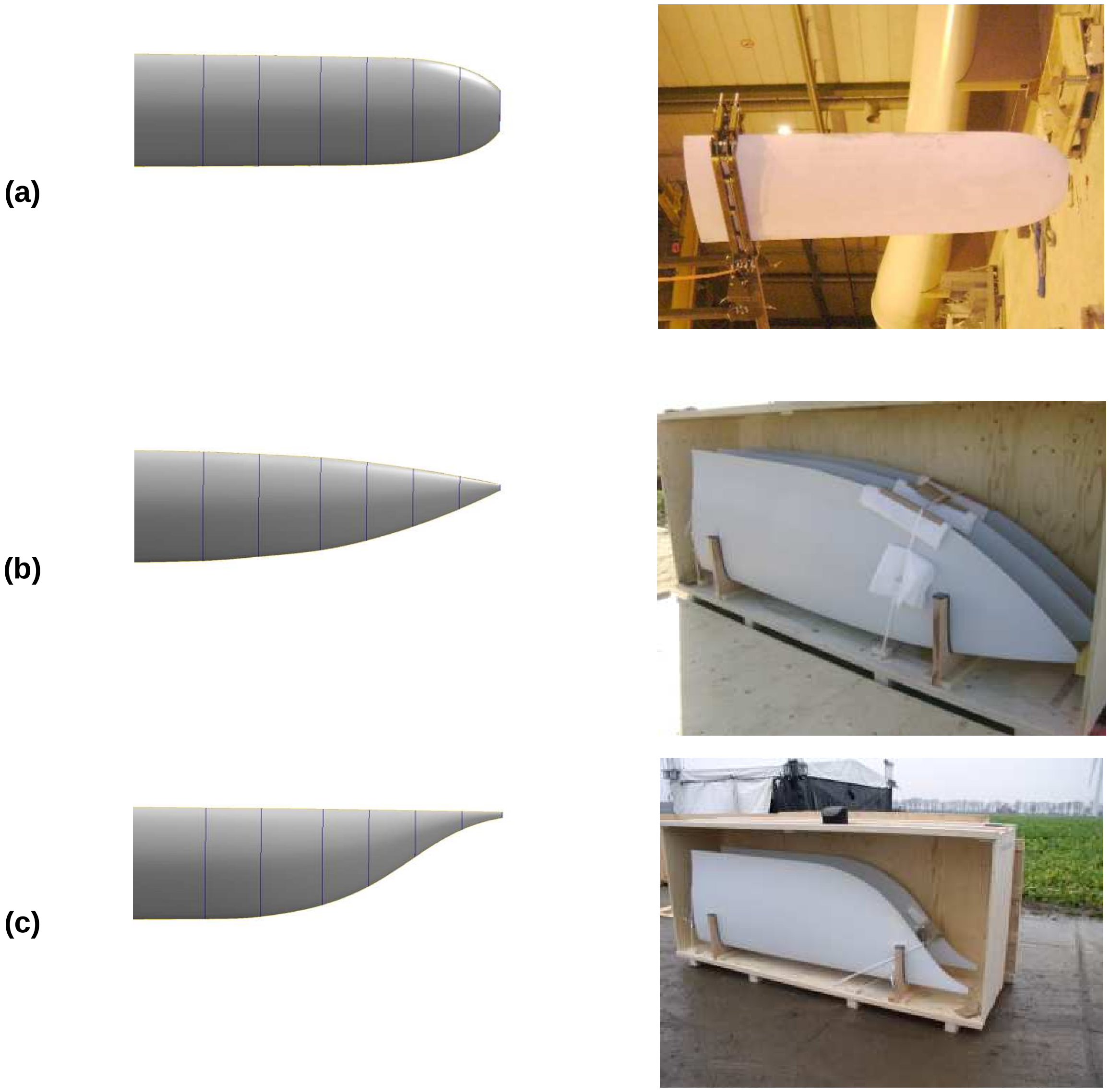

Figure 3. Planforms and photographs of the three tip shape designs **(a)** Blunt tip, **(b)** Slender tip, and **(c)** Ogee tip.

Full Scale Noise Measurements

Three copies of each of the three tip shapes were manufactured, mounted and tested separately on the 2.5 MW class wind turbine. The test turbine had a pitch regulated, upwind rotor with a diameter of 100 m, and a hub height of 85 m. For each tip shape, acoustic data were collected over a period of about one week in order to acquire sufficiently large datasets in the wind speed range [5-10] m/sec (10 m height standardized wind speed) and ensure repeatability. Noise measurements were performed according to IEC standard 61400-11 [24] with a single microphone located approximately 130 m downwind of the turbine.

Results & Discussion

The A-weighted sound pressure levels measured from the various tip shapes are shown in Figure 4 for selected one-third octave band frequencies and for electrical power levels of 60% and 95% of the total rated power. For ease of comparison, the spectral data from the slender and ogee tips are expressed as the difference in sound pressure level with the blunt tip, in such a way that a negative value indicates a noise reduction (compared to the blunt tip), whereas a positive value represents a noise increase.

Overall, both the slender and the ogee tips reduce noise in the frequency range [500-2000] Hz, and over the entire range of turbine operation examined in this work. The noise reduction is most significant at high frequencies, and reaches –12 dB(A) at 2 kHz. This result is consistent with Figure 2, in which tip noise emission is shown to contribute to the overall blade noise for frequencies higher than 1 kHz. At lower frequencies the noise signature of the wind turbine is essentially dominated by noise from the blade trailing edge. As a result modifications of the tip shape have very little influence over the sound levels at these frequencies. Furthermore, there is no remarkable difference between the noise benefits from the slender and ogee tips.

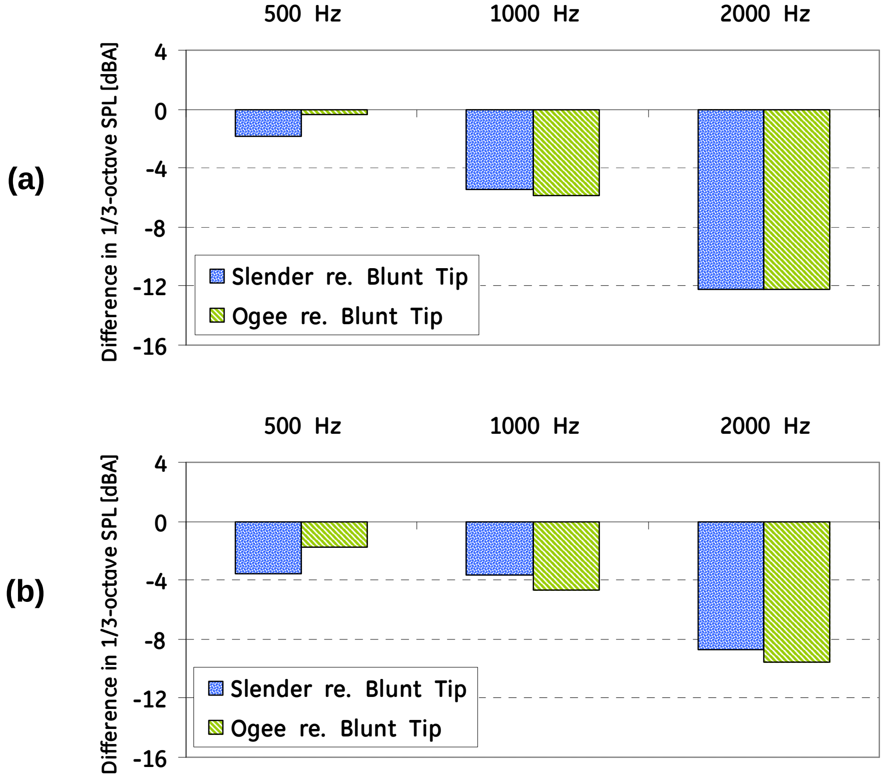

Figure 4. Acoustic results from the field demonstration testing performed with three tip shapes for **(a)** 60%, and **(b)** 95% rated power.

The very significant decrease in noise levels obtained with the slender and ogee tips tends to validate the design philosophy that guided the development of such shapes, which essentially attempts to minimize both the vortex ‘wetted length’ and the interaction between the vortical structures and the side edge itself. On the whole, these low noise tip shapes provide a decrease of 5–6 dB(A) in the wind turbine overall averaged sound power level (OASPL integrated over frequencies from 50 Hz to 10,000 Hz).

Trailing Edge Noise Mitigation

Low Noise Trailing Edge Designs

In an effort to assess the noise reduction potential from various low noise trailing edge concepts, a measurement campaign was carried out by GE Wind Energy in partnership with the German Aerospace Center (DLR) [28]. Tests were conducted on two airfoil scale models, referred to as ‘profile 1’ and ‘profile 2’. The modifications tested included metal serration fixtures (cut in aluminium sheets) as well as trailing edge sections manufactured with materials of various porosities. The airfoil profiles were manufactured with removable trailing edge sections, so that tests could be performed with two trailing edges built out of metallic foam (HOLLOMET, pores size 133, 0.8kg/l) and hollow sphere foam (HOLLOMET HKS-316l). The three low noise trailing edge concepts are shown in Figure 5.

Acoustic Wind Tunnel Measurements

The acoustic measurements took place in the Acoustic Wind Tunnel Braunschweig of the German Aerospace Center (AWB). The AWB is an open-jet, low background noise facility with a rectangular nozzle exhaust of 0.8 m by 1.2 m and a maximum flow speed of 65 m/s. An airfoil profile can be placed in the test section between two acoustically treated side-walls that also allow for variation of the angle of attack relative to the tunnel axis. A photograph of the facility is given in Figure 6.

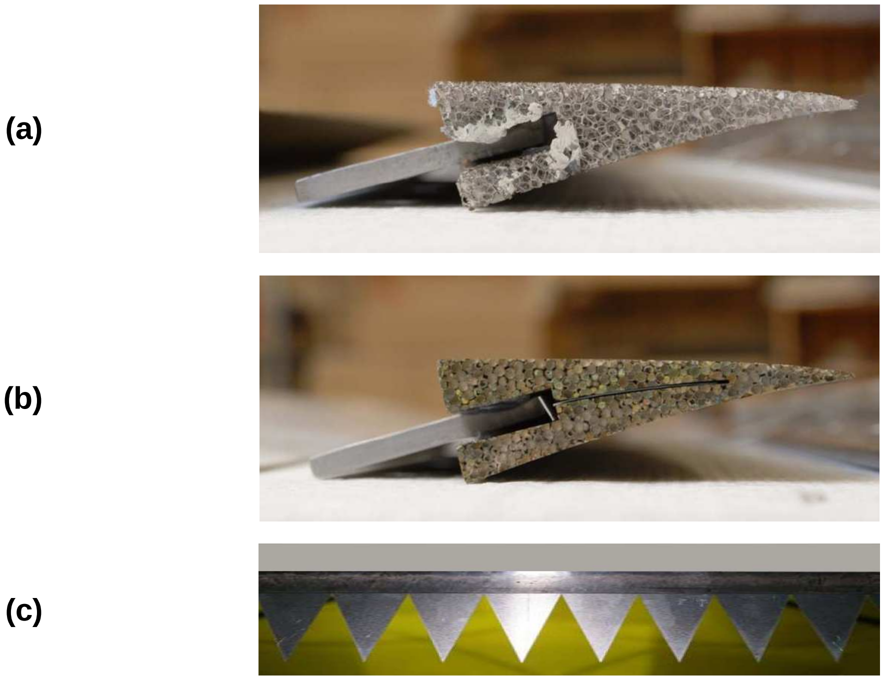

Figure 5. Photographs of low noise trailing edge concepts, namely (a) metal foam edge section, (b) hollow sphere foam, and (c) sawtooth serrations.

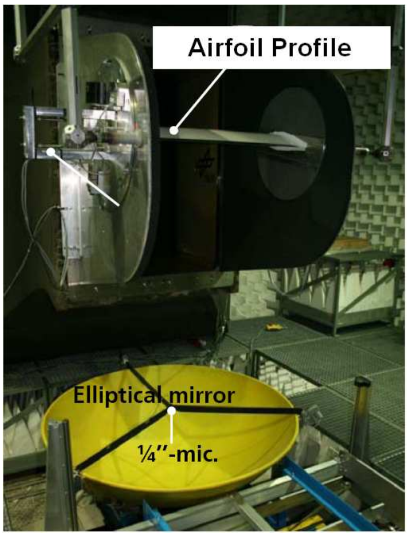

Figure 6. The acoustic wind tunnel at the German Aerospace Center. Notice the elliptical mirror used for trailing edge noise measurements.

The airfoil profiles had a chord length of 0.3 m, and a span of 0.8 m. The inflow velocity was set to 60 m/sec, which corresponds to a Reynolds number of approximately 1.2 million.

Sample results are shown in Figure 7. The far-field, third-octave band spectra for each tested trailing edge modification have been normalized with the reference data acquired with the original, untreated airfoil profile. In the same fashion as in Fig. 4, negative values represent a noise reduction, while positive values indicate an increase.

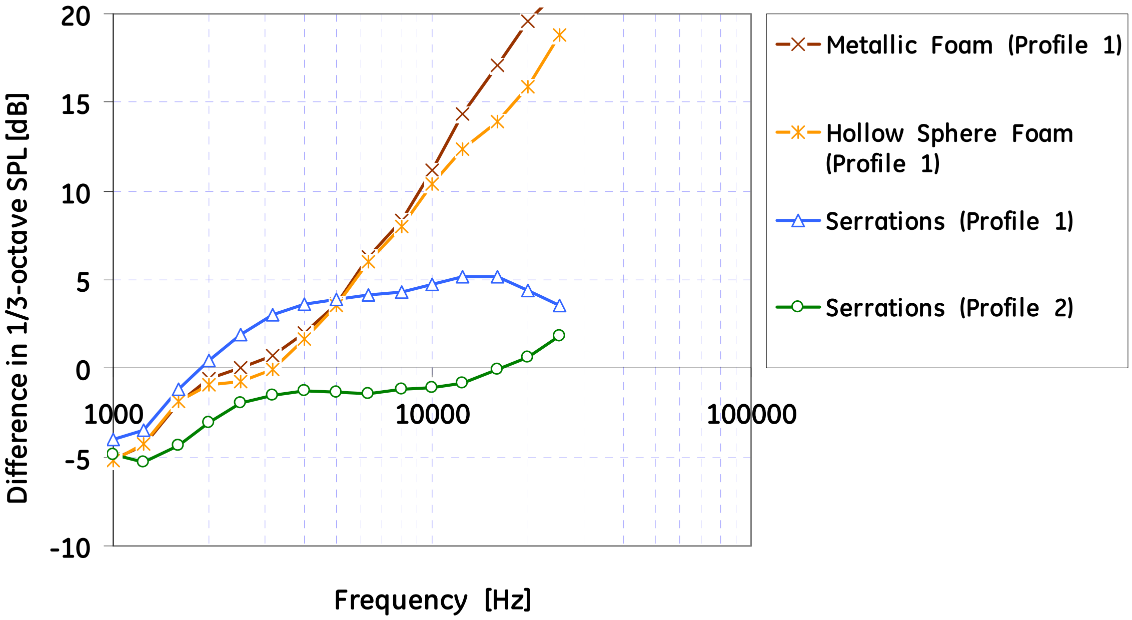

Figure 7. Far-field trailing edge noise spectra for flow-permeable trailing edges and serrations, referenced to the original (untreated) configurations.

All far-field spectra show similar trends, characterized by a noise decrease in the lower frequency range (from 1 to 3 kHz) followed by a noise increase at higher frequencies. Although all trailing edge treatments appear to offer somewhat similar benefits in the low frequency range, significant differences are observed at high frequencies. On the one hand, the porous edges lead to a considerably stronger noise emission beyond 3 kHz where the sound level difference compared to the untreated airfoil increases nearly linearly with frequency and reaches approximately 20 dB at 25 kHz. With serrations, on the other hand, the noise increase is more limited and does not exceed 5 dB for profile 1. For profile 2, the noise benefits extend over a very large frequency range and the noise starts increasing only around 20 kHz. This relationship between the acoustic efficiency of the trailing edge serrations and the airfoil geometry itself is an important result that must be understood for proper serration design. Trailing edge serrations were selected for implementation on full-scale wind turbines and field tested with the results discussed in the next section.

Full Scale Noise Measurements

Trailing edge serrations were manufactured, mounted and tested on three different wind turbine platforms with electrical power ratings 1.5 MW, 2.5 MW, and 2.75 MW, respectively. All test turbines were equipped with pitch-regulated, upwind rotors with diameters 77 m (1.5 MW), 110 m (2.5 MW), and 103 m (2.75 MW). Furthermore, all blades were equipped with the low noise 'slender' tip shape described in the previous section of this paper. For each platform acoustic data were collected over a period of one to several weeks in order to acquire sufficiently large datasets in the wind speed range [5-10] m/sec (10 m height standardized wind speed) and ensure repeatability. Noise measurements were performed according to IEC standard 61400-11 [24] with a single microphone located approximately 120 m to 140 m downwind of the different test turbines.

Results & Discussion

The A-weighted sound pressure levels measured from the three wind turbines equipped with trailing edge serrations are shown in Figure 8 for selected one-third octave band frequencies and for electrical power

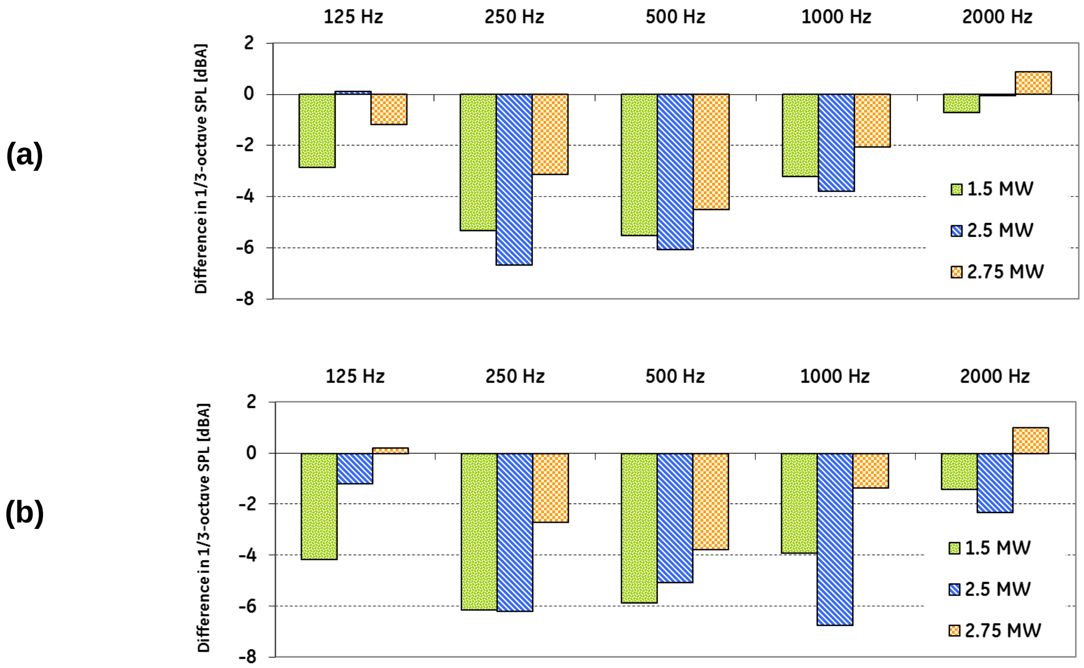

Figure 8. Acoustic results from the field demonstration testing performed with trailing edge serrations at **(a)** 60% and **(b)** 95% rated power.

levels of 60% and 95% of the total rated power. Once again, the spectral data are expressed as the difference in sound pressure levels between the serrated and untreated blades, in such a way that a negative value indicates a noise reduction (compared to the untreated blade), whereas a positive value represents a noise increase.

For all three wind turbine platforms and over the complete range of turbine operation examined in this work, trailing edge serrations provide about 4–6 dB(A) noise reduction at 500 Hz, and about 2–4 dB(A) reduction at 1000 Hz. At 2000 Hz the noise benefits appear to be weaker. This could be interpreted as the full scale equivalent of the noise increase observed at higher frequencies in the wind tunnel data. Most likely, however, this is due to the fact that trailing edge noise is no longer the dominant noise mechanism for frequencies 2 kHz and above, thus making the contributions from serrations less visible (if at all) in the overall blade noise. Finally, the differences in noise benefits observed between the three platforms are certainly related directly to the fact that serrations do not provide uniform noise reduction for the various airfoil profiles used on the blades (as seen in the wind tunnel preliminary study).

On the whole, serrated trailing edges provide a decrease of 2–4 dB(A) in the wind turbine overall averaged sound power level (OASPL integrated over frequencies from 50 Hz to 10,000 Hz), and as such represent a very efficient way to mitigate blade trailing edge noise.

Noise Optimized Wind Turbine Operation

Reducing the blade source noise with technologies such as the low noise tip and serrations is the foundation of a quiet turbine. However, the turbine operating characteristics are just as important in order to achieve the lowest noise possible. Even the best noise reduction technology can be rendered ineffective if the turbine is operated in a way that drives up the noise. Additionally, it is generally true that during normal operational most operating parameters that drive towards higher power also drive towards higher noise. The challenge for the wind turbine manufacturer is to determine how to operate the turbine in a way that noise constraints are met with the highest possible power output. For any given blade design, this objective can be achieved via an optimization that combines a noise response surface (i.e. noise vs. turbine operation parameters) with the corresponding power performance response.

Conceptual diagrams of these response surfaces are shown in Figure 9. The colored curved lines show lines of constant noise as a function of blade pitch and tip speed ratio (TSR) for a given rotational speed. In general, lower pitch values (i.e. higher blade angle-of-attack) and higher TSR (i.e. rotational speed) drive towards higher levels of noise. The blue contours indicate blade power coefficient (Cp) where darker shades indicate higher Cp values. While it’s clear that the Cp contours show a maximum level at only one combination of pitch and TSR, it is also seen that for lower values of Cp there are multiple combinations of pitch and TSR that provide the same Cp level, but the noise is different at each value of pitch and TSR. Therefore, it is possible to find an optimum value of pitch and TSR where the turbine can operate at a given noise level while maximizing Cp. This approach is very important when designing noise reduced operation (NRO) modes that are sometimes necessary to meet noise regulations at wind farm receptor locations. Additionally, in some regions, noise restrictions are a function of wind speed so this optimization can be carried out at every wind speed and thereby provide the best possible power curve given the noise constraints.

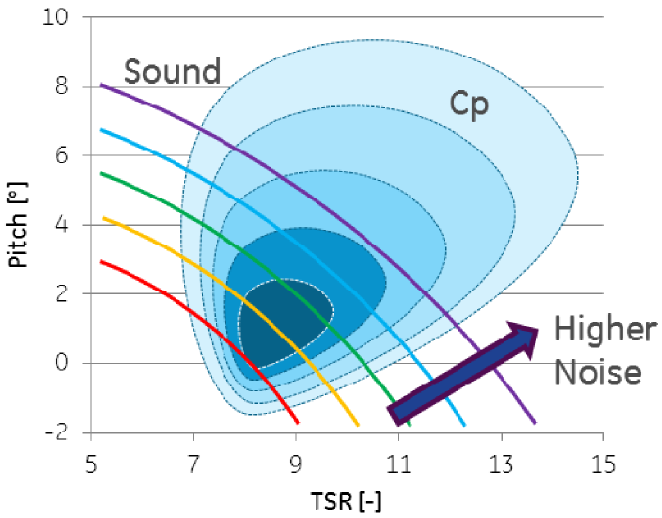

Figure 9. Conceptual response surfaces of (a) sound, and (b) power coefficient superimposed over sound contours

Farm Level Noise Considerations

Once the turbine sound characteristics have been designed by the manufacturer, it is up to the farm operator to provide a site layout that meets the local noise regulations. In practice, this works best as a partnership between the manufacturer, operator and acoustic consultants to maximize the output of the farm while meeting noise constraints. By judiciously selecting the right turbine configuration and operating modes, it is possible to optimize sound and power output without incurring unnecessary operating losses.

Typically, turbine configuration and operating modes are selected based on the worst situation, i.e. maximum noise emission. Noise propagation simulations are carried out using the maximum noise emission of all turbines within a farm as inputs; the noise at observer / residential locations is derived as the sum of all individual contributions and is usually required to stay below a given limit. Depending on the region, this limit can be a single absolute value or wind speed dependent.

Now, noise reduction options such as serrations and a variety of NRO modes provide a great deal of additional flexibility for the farm operator. As stated before, serrated trailing edges provide 2–4 dB noise reduction with no penalty on energy yield, whereas even the most efficient NRO modes lead to a decrease in AEP due to the reduced rated power level. For the sake of example, consider the farm layout of 23 turbines shown in Figure 10a. In the initial, traditional layout, none of the turbines received serrations and nine are operating in some form of NRO in order to meet the noise requirements at the farm boundaries. The layout in Figure 10b shows serrations applied to the strongest noise-contributing turbines. As a result, only three turbines still need to be operated in NRO. Both farms generate the same sound levels and meet the necessary noise requirements, but the farm layout with serrations and fewer NRO modes generates 4.5% more power output than the initial farm layout.

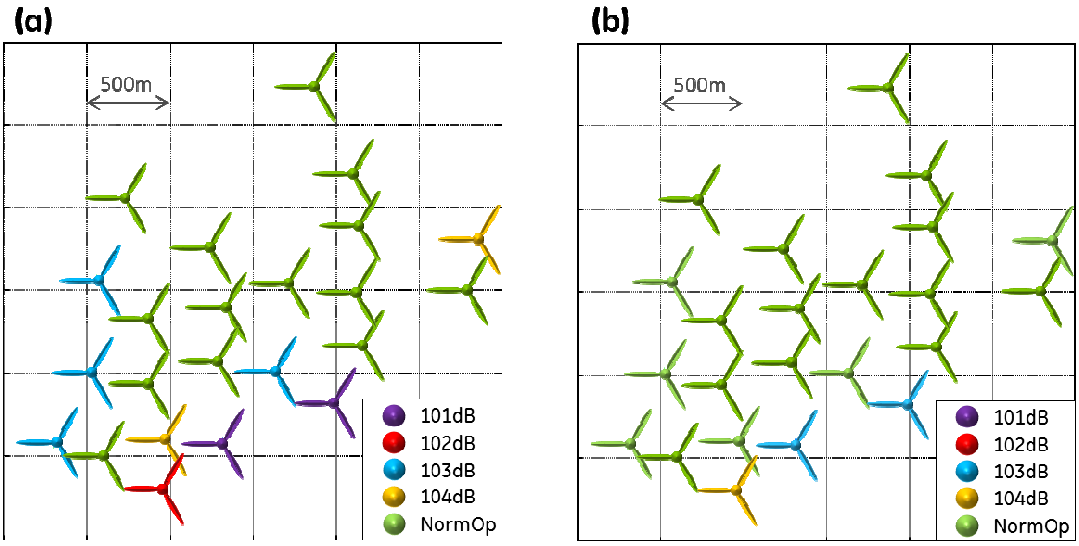

Figure10. Example farm layouts that each meet the same noise constraints. (a) without serrations and only NRO modes; (b) with serrations plus NRO modes. The second layout has 4.5% higher overall output.

Still, even this optimized layout with serrations is based on maximum noise emission inputs and leads to fixed NRO settings. In particular, any time-varying parameters influencing the overall farm noise emission, such as wind speed, wind direction, air density or turbine shut down times for maintenance have not been considered. More sophisticated wind farm layouts with even higher energy yield are therefore possible, because the traditional approach based on worst case conditions usually results in unnecessary margins for situations outside this worst case. With the proper innovative control architecture, such a layout optimization could utilize real-time input in order to operate the turbines in a manner that accounts for conditions that influence the sound received at key receptor locations while meeting all noise constraints.

Conclusions

The present paper reviewed several possible low noise technologies for both tip vortex and trailing edge noise mitigation and discussed the impact of turbine operation on sound at both the turbine and farm levels.

First, acoustic measurements were carried out on a full scale wind turbine platform successively equipped with three different tip shapes. The results showed that such tip shapes can significantly impact the blade noise signature. On the whole, low noise tip shapes provided a decrease of 5–6 dB(A) in apparent sound power level (Lwa) compared to the 'blunt' (loud) tip. Second, several low noise trailing edge concepts were tested on airfoil scale models in the AWB acoustic wind tunnel. These low noise concepts included flow-permeable edges and serrations. Based on the preliminary results, serrations were selected for full-scale field testing, and fitted on three different wind platforms with different blade designs. On the whole, the serrated blades provided a decrease of 2–4 dB(A) in apparent sound power level (Lwa) compared to the original (unserrated) blades. Finally, it was shown how a good understanding of the noise and power characteristics of a turbine can be used to simultaneously optimize turbine operation for low noise and high power. Additionally, an example was provided of how combinations of noise reduction technology and NRO modes can provide wind farm operators with the most flexibility to maximize power output and meet farm level noise constraints. The combinations of such low noise technologies and innovative operational modes represent important progress towards better accepted, quiet wind turbines.

Acknowledgements

Part of this work has been funded by the German Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, FKZ 0325146. The authors are (solely) responsible for the content of the publication.

References

[1] S. Wagner, R. Bareiss, G. Guidati, *Wind Turbine Noise*, Springer Verlag, 1996.

[2] J.N. Pinder, "Mechanical Noise from Wind Turbines," *Wind Engineering*, **Vol. 16 (3)**, pp. 158–168, 1992.

[3] M.W. Lowson, "A New Prediction Model for Wind Turbine Noise," Renewable Energy, Conference Publication No. 385, 1993.

[4] W.J. Zhu, N. Heilskov, W.Z. Shen, J.N. Sorensen, "Modeling of Aerodynamically Generated Noise from Wind Turbines," *Journal of Solar Energy Engineering*, **Vol. 127**, pp. 517–528, 2005.

[5] F.T. Brooks, D.S. Pope, M.A. Marcolini, *Airfoil Self-Noise and Prediction*, NASA RP-1218, pp. 1–137, July 1989.

[6] G. Leloudas, W.J. Zhu, J.N. Sorensen, W.Z. Shen, S. Hjort, "Prediction and Reduction of Noise from a 2.3 MW Wind Turbine," *Journal of Physics*, Conference Series 75, 2007.

[7] S. Oerlemans, J.G. Schepers, "Prediction of Wind Turbine Noise and Validation against Experiment," *International Journal of Aeroacoustics*, **Vol. 8 (6)**, 2009.

[8] S. Oerlemans, P. Sijtsma, B. Mendez Lopez, “Location and Quantification of Noise Sources on a Wind Turbine,” *JSV*, **Vol. 299**, pp. 869–883, 2007.

[9] S. Oerlemans, M. Fisher, T. Maeder, K. Koegler, “Reduction of Wind Turbine Noise using Optimized Airfoils and Trailing Edge Serrations,” *AIAA Journal*, **Vol. 47 (6)**, 2009.

[10] J.E. Ffowcs Williams, L.H. Hall, “Aerodynamic Sound Generation by Turbulent Flow in the Vicinity of a Scattering Half Plane,” *JFM*, **Vol. 40 (4)**, pp. 657–670, 1970.

[11] R.K. Amiet, “Noise due to Turbulent Flow Past a Trailing Edge,” *JSV*, **Vol. 47 (3)**, pp. 387–393, 1976.

[12] M.S. Howe, “A Review of the Theory of Trailing Edge Noise,” *JSV*, **Vol. 61 (3)**, pp. 437–465, 1978.

[13] M. Roger, S. Moreau, “Back-Scattering Correction and Further Extensions of Amiet’s Trailing Edge Noise Model, Part 1,” *JSV*, **Vol. 286**, pp. 477–506, 2005.

[14] T.F. Brooks, T.H. Hodgson, “Trailing Edge Noise Prediction from Measured Surface Pressures,” *JSV*, **Vol. 78 (1)**, pp. 69–117, 1981.

[15] M. Roger, S. Moreau, “Competing Broadband Noise Mechanisms in Low-Speed Axial Fans,” *AIAA Journal*, **Vol. 45 (1)**, pp. 48–57, 2007.

[16] J. Casper and F. Farassat, “A New Time Domain Formulation for Broadband Noise Predictions,” *International Journal of Aeroacoustics*, **Vol. 1 (3)**, pp. 207–240, 2002.

[17] M. Wang, P. Moin, “Computation of Trailing-Edge Flow and Noise using Large-Eddy Simulation,” *AIAA Journal*, **Vol. 38**, pp. 2201–2209, 2000.

[18] J. Winkler, S. Moreau, and T. Carolus, “Large-Eddy Simulation and Trailing Edge Noise Prediction of an Airfoil with Boundary Layer Tripping,” 15th AIAA/CEAS Aeroacoustics Conference, May 2009.

[19] M. S. Howe, *Acoustics of Fluid-Structure Interactions*, Cambridge University Press, pp. 226–231, 1998.

[20] M. S. Howe, “Noise Produced by a Sawtooth Trailing Edge,” *JASA*, **Vol. 90**, pp. 482–487, 1991.

[21] M. Herr, “A Noise Reduction Study on Flow-Permeable Trailing Edges,” in *Proceedings from the World Congress on Computational Mechanics*, 2007.

[22] T. F. Brooks, M. A. Marcolini, “Airfoil Tip Vortex Formation Noise,” *AIAA Journal*, **Vol. 24 (2)**, pp. 246–252, 1986.

[23] R. Drobietz, I.U. Borchers, “Generic Wind Tunnel Study on Side Edge Noise,” 12th AIAA/CEAS Aeroacoustics Conference, May 2006.

[24] IEC Standard 61400-11, *Wind Turbine Generator Systems – Acoustic Noise Measurement Techniques*, 2002.

[25] M. Herr, W. Dobrzynski, “Experimental Investigations in Low Noise Trailing Edge Design,” *AIAA Journal*, **Vol. 43 (6)**, pp. 1167–1175, 2005.

[26] F. R. Grosche, H. Stiewitt, B. Binder, “Acoustic Wind Tunnel Measurements with a Highly Directional Microphone,” *AIAA Journal*, **Vol. 15 (11)**, pp. 1590–1596, 1977.

[27] R. Drobietz, M. C. Brink, I. U. Borchers, P. Boehning, “Jet Noise Source Distribution Measurements with an Acoustic Mirror,” 14th AIAA/CEAS Aeroacoustics Conference, May 2008.

[28] B. Petitjean, R. Drobietz, K. Kinzie, “Wind Turbine Blade Noise Mitigation Techniques,” 4th International Wind Turbine Noise Conference, April 2011