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Wind Turbine Blade Noise Mitigation Technologies

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Abstract

The present paper provides on overview of GE's most recent studies on wind turbine blade low noise technologies for tip vortex and trailing edge noise mitigation. Several tip geometries were noise tested on a GE 2.5 MW wind turbine platform. The results show that tip shapes can significantly impact the blade noise signature, particularly in the higher frequency range. Low noise tip shapes provide a decrease of 5–6 dB(A) in apparent sound power level (Lwa) compared to a 'blunt' (loud) tip. Within extensive wind tunnel tests a number of trailing edge noise reduction concepts were screened. Serrations were selected for full-scale field testing and adapted on three different wind platforms with different blade designs. The serrated blades provide a decrease of 2–4 dB(A) in apparent sound power level (Lwa) compared to the original (unserrated) blades. Both the low noise tip shapes as well as the serration technology have now been implemented in GE's most recent blade designs.

Introduction

Wind turbine noise represents one of the major obstacles to a more widespread use of wind energy today. 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 – say below 200 Hz – and therefore seems to be of lesser importance for large, modern wind turbines, especially when A-frequency weighting is applied.

Airfoil self-noise is produced when an airfoil section encounters a steady, non-turbulent flow field. It 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. These mechanisms are: laminar boundary layer vortex shedding noise (LBL-VS), turbulent boundary layer trailing edge noise (TBL-TE), flow separation noise (SEP), trailing edge bluntness vortex shedding noise (TEB-VS), and tip vortex noise (TIP). 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 allow to identify 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 1, along with the contributions from the different flow-induced noise mechanisms.

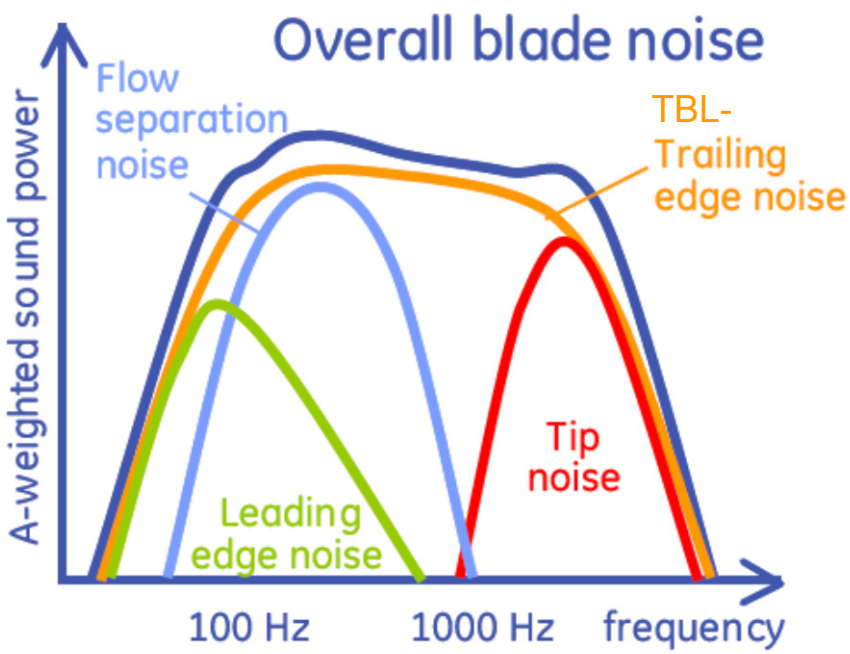

Figure 1. Example A-weighted, third-octave band spectrum from a large, modern wind turbine with relative contributions from flow-induced noise mechanisms.

Note that neither LBL-VS nor TEB-VS are shown in Fig. 1. LBL-VS is irrelevant for large wind turbines, as no boundary layer can remain fully laminar on the blades,

even in perfectly clean aerodynamic conditions. Also, recent measurements by Oerlemans *et al.* [8] have demonstrated that TEB-VS is not an important acoustic source on large wind turbines.

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. But with the exception of Ref. [9], these promising concepts have seldom been applied to full scale wind turbines, and the noise benefits they could potentially provide are mostly unknown.

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 has been a controversial topic, its contribution could be reduced provided that the aforementioned interactions are minimized.

The present paper focuses on possible low noise 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 over 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' as well as the interaction between the vortical structures and the side edge itself. Note that 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 2.

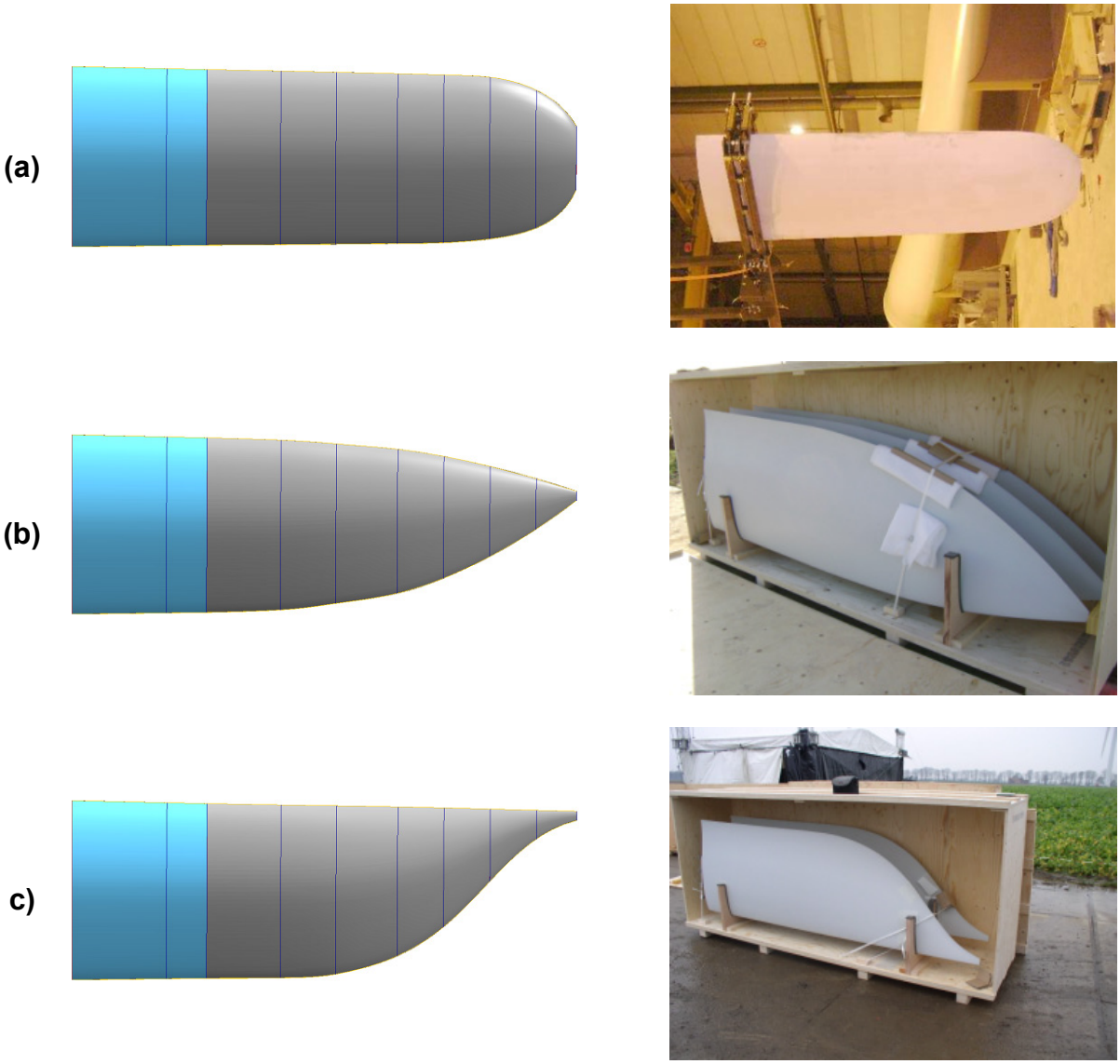

Figure 2. Planforms and photographs of the three tip shape designs **(a)** Blunt tip, **(b)** Slender tip, and **(c)** Ogee tip.

Full Scale Noise Measurements

Three copies of each of the three tip shapes were manufactured, mounted and tested separately on the GE 2.5 MW wind turbine platform. 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. Acoustic pressure signals and turbine operation parameters were recorded simultaneously; one-third octave band spectra were calculated over periods of 10 seconds and averaged following a binning procedure based on electrical power. The frequency-dependent, A-weighting scale was applied to all sound levels in order to account for the sensitivity of the human ear. The results were also corrected for background noise levels and machinery tonality (when present). Finally, the measurement uncertainty was estimated to be ±1 dB.

Results & Discussion

The A-weighted sound pressure levels measured from the various tip shapes are shown in Figure 3 for selected one-third octave band frequencies (namely 500 Hz, 1 kHz, and 2 kHz), and for electrical power levels 40%, 60%, 80%, 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, it appears that 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 2kHz. It is, however, more limited in the mid-frequency range where it drops down to approximately –6 dB(A) at 1 kHz, and –3 dB(A) at 500 Hz. This result is consistent with Figure 1, 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. Furthermore, there is no remarkable difference between the noise benefits from the slender and ogee tips. At 500 Hz the slender tip seems to provide slightly more noise reduction than the ogee tip, but the observed differences in sound pressure levels are of the order of the measurement uncertainty.

It is interesting to note that the noise reduction from the slender and ogee tips appears to be somewhat weaker when the turbine operates at 95% rated power. The difference in sound pressure levels is only –8 dB(A) at 2 kHz, and less than –4 dB(A) for the other two frequencies. This is most likely due to the fact that at such power level the pitch regulation is already operational and acts to reduce the blade angles of attack, which also reduces the tip vortex strength. As a consequence the noise levels from the blunt tip are lower, and so are the differences with the other tips.

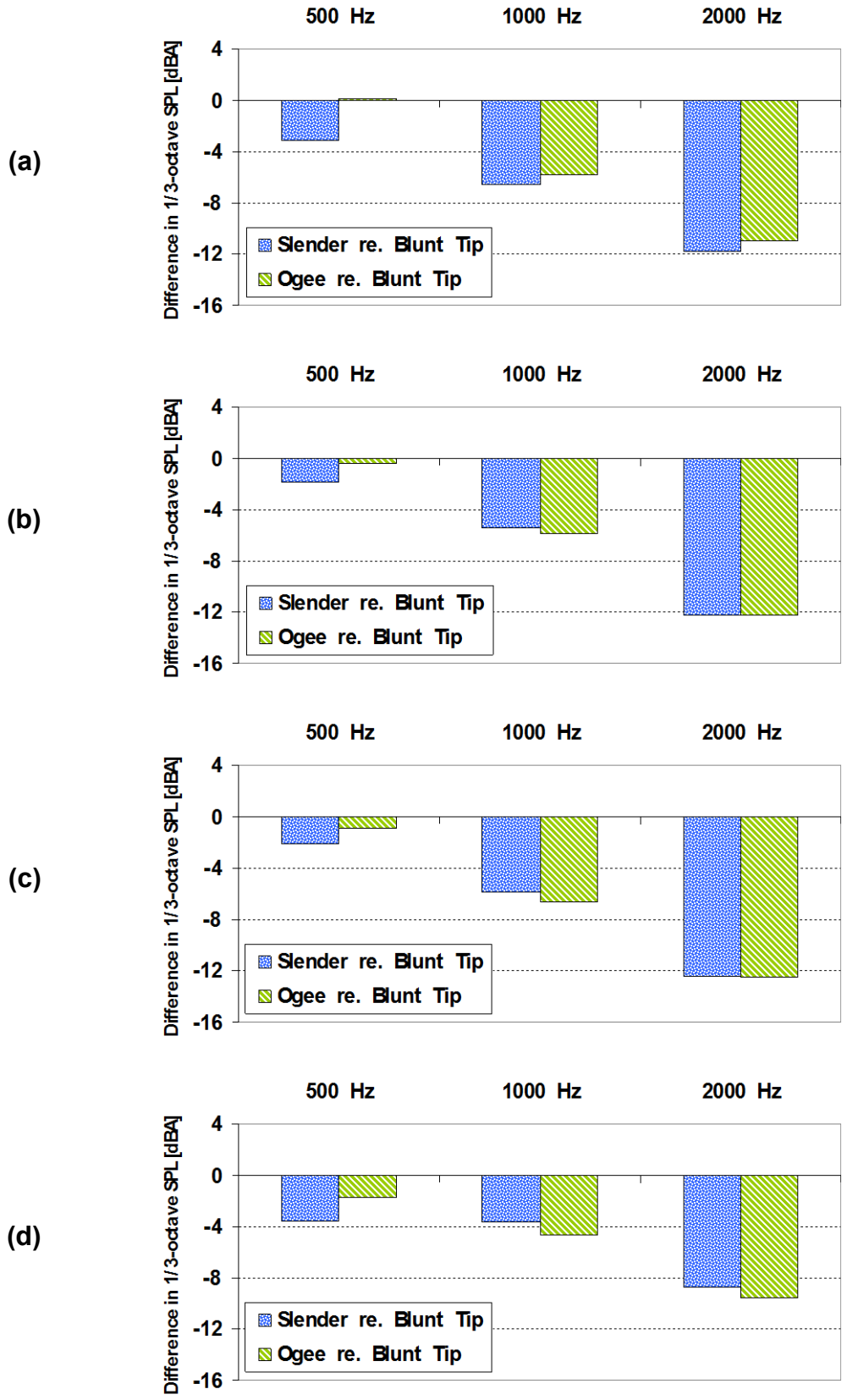

Figure 3. Acoustic results from the field demonstration testing performed with three tip shapes for **(a)** 40%, **(b)** 60%, **(c)** 80%, and **(d)** 95% rated power.

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 large measurement campaign was carried out by GE Wind Energy in partnership with the German Aerospace Center (DLR), and the University of Stuttgart (Institute for Aerodynamics and Gas Dynamics, IAG). Tests were conducted on two GE proprietary 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 different 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 4.

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 5.

As established from previous studies [25], single microphone measurements in the acoustic far field are not suitable for trailing edge noise analyses, even in quiet test facilities such as the AWB. In the present work, an 'acoustic mirror' with elliptical shape is used to separate trailing edge noise from the extraneous contributions due to the test rig and the flow shear layer. The elliptic mirror system has a 1.4 m reflector diameter, and is pointed toward the pressure side (PS) of the airfoil. The mirror is mounted on a traversing device, which allows to perform streamwise acoustic scans in order to locate the dominant noise source areas on the airfoil.

(a)

(b)

(c)

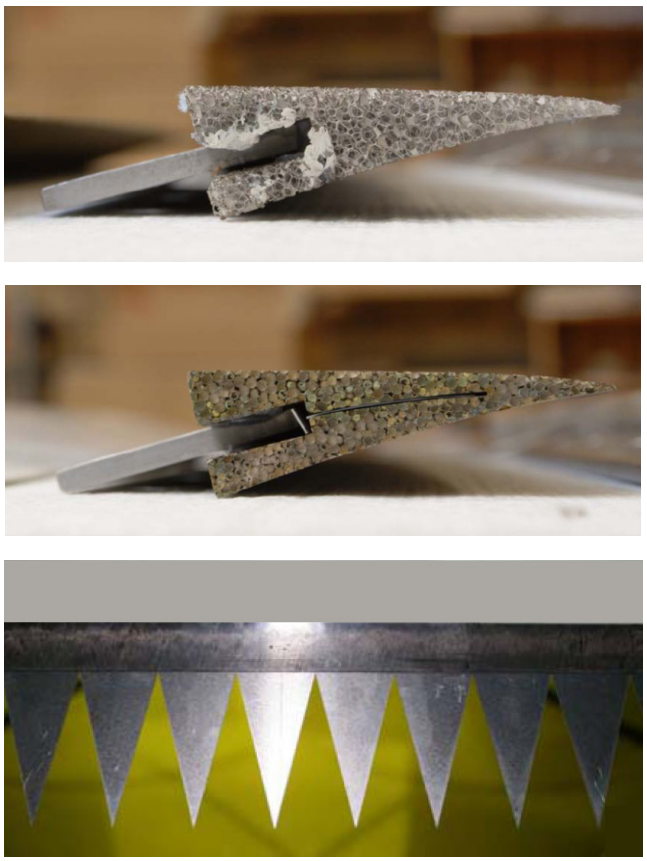

Figure 4. Photographs of low noise trailing edge concepts, namely **(a)** metal foam edge section, **(b)** hollow sphere foam, and **(c)** sawtooth serrations.

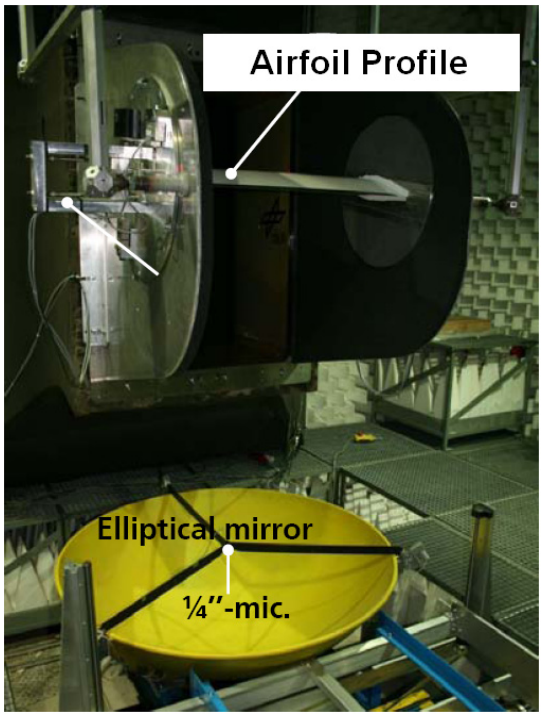

Figure 5. The acoustic wind tunnel at the German Aerospace Center. Notice the elliptic mirror used for trailing edge noise measurements.

For all measurements the acoustic mirror axis is oriented at 90 degrees to the wind tunnel centreline, and a calibrated 1/4-inch (6.35 mm) condenser microphone (Brüel & Kjær type 4136) is placed at one the foci of the ellipse. Noise data are recorded at a sample rate of 100 kHz, and one-third octave band acoustic spectra are produced in a frequency range of [1-25] kHz. Note that extensive corrections must be applied to the data collected with the acoustic mirror system, in order to account for sound wave convection, extraneous noise sources, system response function (spatial resolution and 'gain' of the mirror), and acoustic source distribution. More detailed information on the AWB facility as well as on the acoustic mirror measurement technique can be found in references [26] and [27].

For all measurements performed at AWB, the airfoil profiles had a chord length of 0.3 m, and a span of 0.8 m. The models were designed and manufactured at the University of Stuttgart (Institute for Aerodynamics and Gas Dynamics, IAG). The inflow velocity was set to 60 m/sec, which corresponds to a Reynolds number of approximately 1.2 million. To avoid such phenomena as laminar boundary layer-vortex shedding (not representative of the flow state on a full scale wind turbine blade), zigzag tape was applied on both sides of the airfoil to force early transition to turbulent flow conditions. Finally, the angle of attack was selected to be representative of the variable speed region operating conditions on the outboard section of a wind turbine blade.

Sample results from the measurements carried out with the elliptic mirror are shown in Figure 6. 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. 3, negative values represent a noise reduction, while positive values indicate an increase.

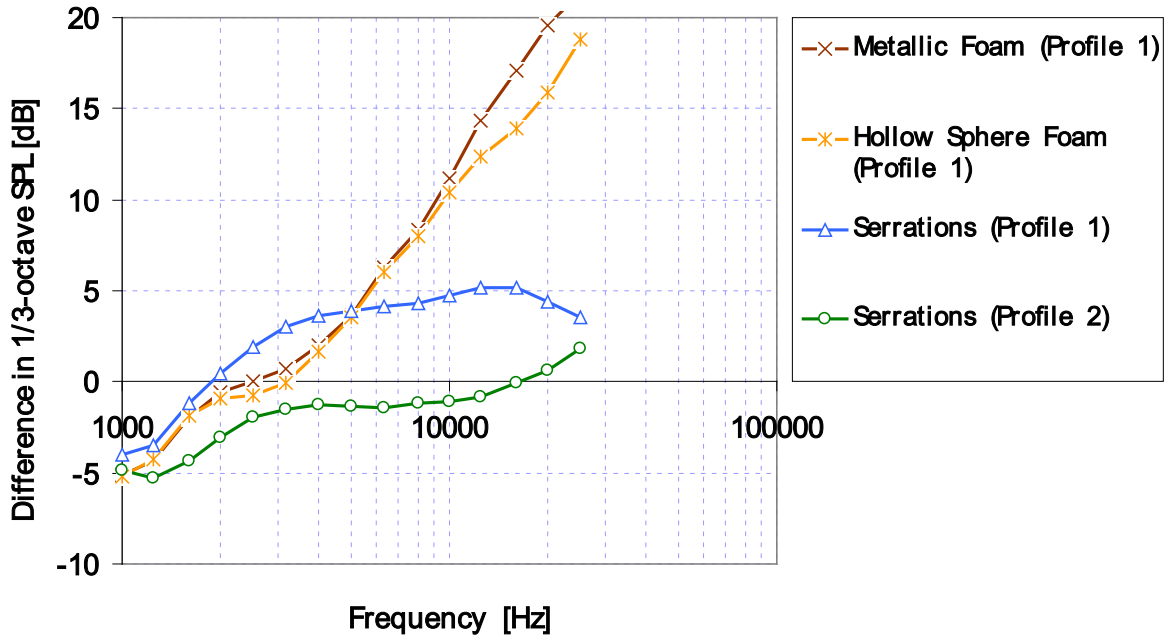

Figure 6. Far-field trailing edge noise spectra for flow-permeable trailing edges and serrations, referenced to the original (untreated) configurations.

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; past this point the sound level difference with 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 deserves further investigation. Trailing edge serrations were down-selected for implementation on full-scale wind turbines and field testing. There are several reasons for this choice. First, the acoustic data collected in the wind tunnel clearly indicate that serrations provide more balanced benefits than porous trailing edges, with limited noise increase at high frequencies (profile 1) and noise reduction over a potentially very wide frequency range (profile 2). Second, porous materials seem not well suited for long-term use in the harsh environmental conditions that wind turbines typically experience over their lifetime. In particular, the danger of clogging due to dust, insects, or ice (to name only a few) could quickly result in a complete loss of the acoustic benefits that flow-permeable trailing edges may provide.

Full Scale Noise Measurements

Trailing edge serrations were manufactured, mounted and tested on three different GE 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 (GE 1.5 MW), 110 m (GE 2.5 MW), and 103 m (GE 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. Acoustic pressure signals and turbine operation parameters were recorded simultaneously; one-third octave band spectra were calculated over 10 second periods and averaged following a binning procedure based on electrical power. The results were A-weighted and corrected for both background noise levels and machinery tonality. Finally, the measurement uncertainty was estimated to be $\pm$1 dB.

Results & Discussion

The A-weighted sound pressure levels measured from the three wind turbines equipped with trailing edge serrations are shown in Figure 7 for selected one-third octave band frequencies (namely 500 Hz, 1 kHz, and 2 kHz), and for electrical power

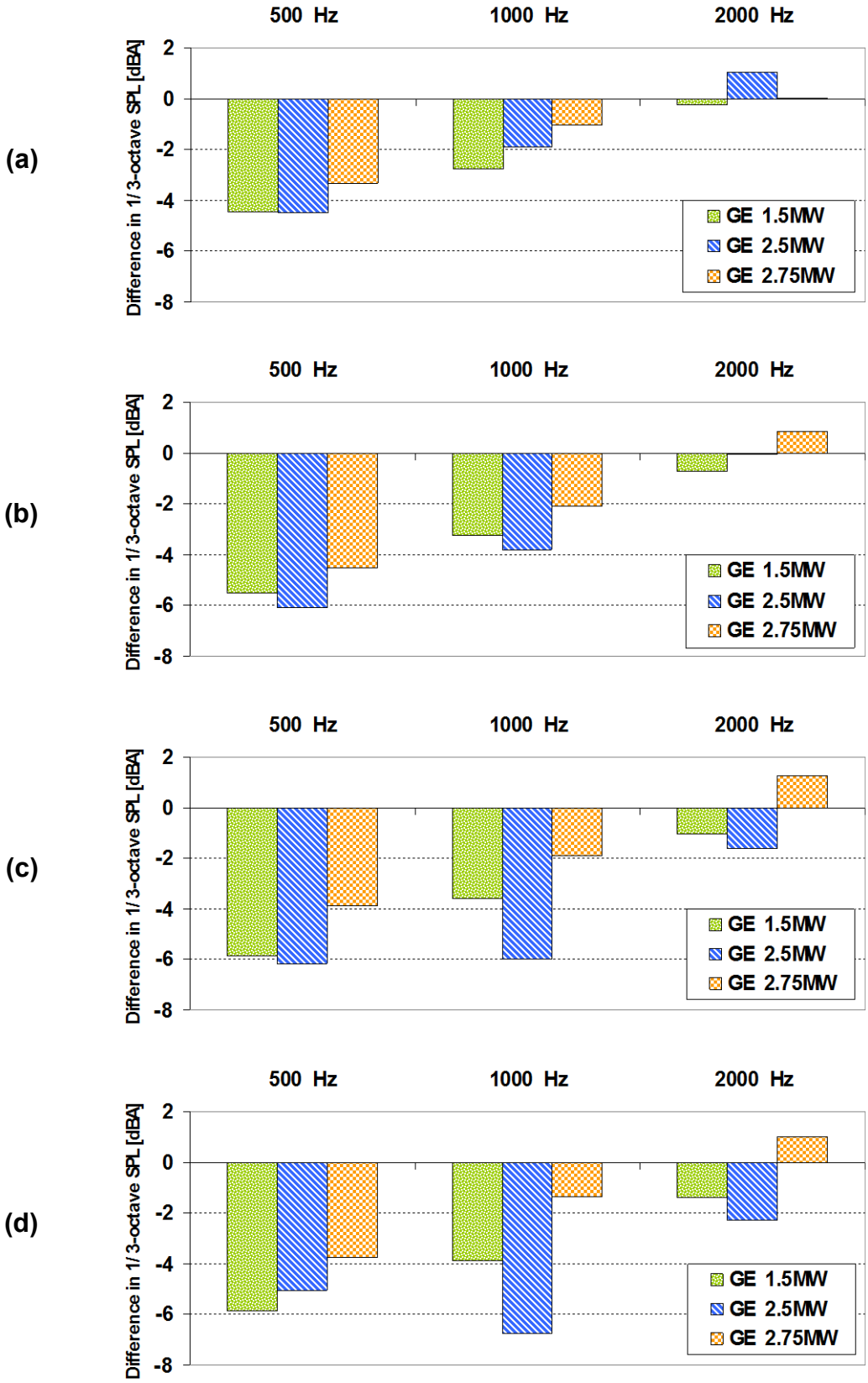

Figure 7. Acoustic results from the field demonstration testing performed with trailing edge serrations at **(a)** 40%, **(b)** 60%, **(c)** 80%, and **(d)** 95% rated power.

levels 40%, 60%, 80%, 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.

Conclusions

The present paper reviewed several possible low noise technologies for both tip vortex and trailing edge noise mitigation.

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.

The combination of such low noise technologies for both tip vortex and trailing edge noise represents an important progress towards better-accepted, quiet wind turbines.

Acknowledgements

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