Serration Design Methodology for Wind Turbine Noise Reduction

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Abstract. Trailing edge serrations are today an established method to reduce the aeroacoustic noise from wind turbine blades. In this paper, a brief introduction to the aerodynamic and acoustic design procedure used at LM Wind Power is given. Early field tests on serrations, retrofitted to the turbine blades, gave preliminary indication of their noise reduction potential. However, a multitude of challenges stand in the way of any proof of concept and a viable commercial product. LM undertook a methodical test and validation procedure to understand the impact of design parameters on serration performance, and quantify the uncertainties associated with the proposed designs. Aerodynamic and acoustic validation tests were carried out in number of wind tunnel facilities. Models were written to predict the aerodynamic, acoustic and structural performance of the serrations. LM serration designs have evolved over the period of time to address constraints imposed by aero performance, structural reliability, manufacturing and installation. The latest LM serration offering was tested in the field on three different wind turbines. A consistent noise reduction in excess of 1.5 dB was achieved in the field for all three turbines.

1. Introduction

In the domain of wind turbine noise, serrations are an accepted method for achieving noise reduction in the field. It has been generally accepted that the serrations, when retrofitted on an airfoil, reduce the noise generated by the turbulent boundary layer on its trailing edge. Although a complete understanding of serration noise reduction physics is still pending, the performance of serrations has been proven both in anechoic wind tunnels, as well as in field measurements. There still exist several gaps in understanding the parameters that drive serration performance. There are also large uncertainties in the procedure of scaling the acoustic performance of serration from a model scale wind tunnel to a full scale field measurement.

In order to convert serration prototype designs into commercially viable products, uncertainties and challenges associated with the design of serrations have to be better understood. LM has been active in the field of serration design since 2009, and has acquired a significant amount of knowledge on the intricacies of serration design and performance [1][2].

This paper will specifically focus on the following:

- The LM serration design methodology
- Prediction and modeling of serrations
- Results of wind tunnel and field measurements

2. Serration Design Methodology
The serration design procedure involves the sizing of serrations, their placement along the span, the material selection, and method of attachment on the blade. Knowledge of the operating condition and blade profile helps in the estimation of serration flap angle.

Figure 1 shows a schematic of the attachment of a serration panel on an airfoil section. It is attached to the pressure side and has a tooth length which is scaled with the airfoil chord. It is further given a flap angle, which is a function of the angle of attack and airfoil shape. Serration placement along the span, shown in Figure 2, targets the regions where noise sources are dominant, which is generally the last 30% span region. Increasing the serrated span beyond 30% is not advisable since it increases the additional loads on the turbine while providing insignificant noise reduction. Each colour indicates a serration panel of different length and flap angle, with longer serrations occupying inboard regions and shorter serrations at the outboard regions. LM design additionally accounts for constraints imposed by lifting and handling locations, fatigue safety factors limits, and the tip curvature of the blade. Material selection should ease manufacturability, and combined with efficient structural design and attachment methods on the blade, the lifetime of serrations will be enhanced.

Figure 1. Side view of the serration panel.

Figure 2. Schematic of sample serration placement on the blade.

In addition to providing noise reduction, the design of serrations should reduce the impact they have on blade aerodynamics and loads while at the same time ensuring that they are reliable enough to last on the blade. The material of the serration and the glue used for attachment of serrations to the blade is carefully selected to maximize the life of serration on the blade.

LM has developed reduced order models to predict the aerodynamic, acoustic and structural performance of the serrations [3]. Models for estimating the serrated polars were developed based on the aerodynamic measurements of various LM airfoils and serrations in the LM wind tunnel. Models
that predict the noise reduction caused by the serrations were developed based on acoustic tests done in the field where various designs of serrations were tested on multiple LM rotors. Models for the bending moment induced by aerodynamic loads on serrations were developed based on measurements from strain gauges attached to the serrations.

3. Validation of Serration Performance

This section describes the test campaigns undertaken by LM to validate serration performance. Aerodynamic tests on serrations were carried out to measure the lift and drag modifications caused by serrations on airfoils. Acoustic emissions of scaled down models were measured in anechoic wind tunnels. Finally field acoustic tests were also carried out, where the full scale serrations were retrofitted to the wind turbine rotors and noise measurements were made to estimate the noise reduction performance.

3.1. LM Wind Tunnel Test Campaign

The aerodynamic tests were performed to measure the polars for the serration designs retrofitted to LM airfoil profiles for various speeds and angles of attack. The measurements were performed in the LM low speed wind tunnel, located in Lunderskov, Denmark. It is a closed test section, closed circuit wind tunnel with test section dimensions 1.35 m width, 2.70 m height and 7.00 m length. The results of the aerodynamic measurements were compared to those measured for the straight edge airfoils to estimate the impact of serrations on lift and drag coefficients. Figure 3 shows the photograph of a serration model retrofitted to an LM airfoil profile of chord 900mm. Two different serrations of length 100mm and 130mm were retrofitted to the LM airfoil and polars were measured. Lift and drag polar measurements were made for three test cases; straight edge airfoil, airfoil with 100 mm serration and airfoil with 130 mm serration for a Reynolds number of 3 million. The lift of the serrated airfoil was measured from wall pressure data which was further correlated by a force balance technique. Wake rake pressure measurements were used to measure the drag. Three dimensional flow effects on the polar were not investigated during measurements. Airfoil chord was used for the normalization. The impact of serrations on lift coefficient is shown in Figure 4. Serrations were found to increase the lift curve slope by ~ 2% and the $c_{\text{max}}$ value compared to the baseline airfoil. Also it was observed that, as the length of the serrations was increased, these effects were increased marginally. Serrations were also found to increase the drag with respect to baseline airfoil, as shown in Figure 5. Longer serrations (130mm) had 3% higher drag than the shorter serrations (100mm).

Additionally, the effect of serration flap angle on aerodynamics is investigated in LM wind tunnel. Three flap angles, 0, 5 and 10 degree were measured and their impact on maximum lift is assessed. Increased flap angle (towards the upper side of the airfoil) reduced the addition lift as shown in Figure 6.
**Figure 3.** Photograph of serrations mounted on an airfoil at the LM wind tunnel.

**Figure 4.** Comparison of straight edge and serrated cl polars measured in the LM wind tunnel for $\text{Re} = 3 \times 10^6$. 
Figure 5. Comparison of straight edge and serrated cd polars measured in the LM Wind tunnel for $Re = 3 \times 10^6$.

Figure 6. Flap angle effect on maximum lift

3.2. Acoustic Wind Tunnel Test Campaign

The acoustic performance of serrations was evaluated in the Virginia Tech stability wind tunnel, as well as the Institute for Sound and Vibration Research (ISVR) anechoic wind tunnel and the TU Delft V-Tunnel.

The Virginia Tech campaign was aimed at understanding the impact of serration length on far field acoustics [4]. An acoustic array was used to measure the far field noise generated by serrations of two
different lengths, retro fitted to an airfoil. This test campaign provided an early glimpse into the wind tunnel performance of serrations.

In 2015, a detailed test campaign was conducted in the ISVR wind tunnel where serrations were tested on an LM airfoil to estimate the impact of various serration design aspects. The ISVR has an open jet wind tunnel with test section in an anechoic chamber with dimensions of $8 \times 8 \times 8$ m $^3$ [7]. The height and width of the exit nozzle are 0.15 and 0.45 m, respectively. The LM airfoil used for the ISVR tests had an 18% thickness, a 0.2 m chord and a 0.45 m span. The trailing edge serrations tested were fabricated using a 3D printer. They were attached to the pressure side of the airfoil with a thin double tape, minimizing the size of the step of the attachment surface. The test cases included serrations with different flap angle, shapes and lengths. In all the cases, a serration teeth width of 20 mm is used. Three serration types were tested, 2D, 3D I and 3D II, referring to flat plate serrations (2D), and serrations with two different 3D geometries. Tapered thickness and its variant makes the geometry 3D. Figure 7 shows the schematic of LM airfoil mounted in the test section with microphones arranged in a circular arc around the airfoil.

Measurements were made using a 16 mic array arranged in an arc, with a radius of 1.2 m from the TE center. However, for processing, only the data from the 90 deg mic (directly above the TE) was used. This was done because the TE noise directivity is maximum in the 90 degree direction. No correlation techniques were used for measurements. Far field noise spectra were computed from time series of 10 s measurements, sampled at 50 KHz. A hanning window with size of 1024 data points, corresponding to a frequency resolution of 48.83 Hz, was used in the processing of the data. Acoustic data were recorded at four freestream flow velocities, 20, 40, 60 and 80 m/s.

The influence of serration flap angle on the self-noise of the LM aerofoil is presented in Figure 8. The difference between noise level for straight edge airfoil and serrated airfoil, denoted as delta SPL is plotted on the y axis. A comparison of the noise reduction spectra between three flap angles, 0 deg, 5 deg and 10 deg is made in the figure. The data is presented at a speed of 80 m/s for 0 deg geometric angle of attack (aoa). The influence of serration flap angle on noise reductions are significant, exhibiting variations of up to 3.5 dB at some frequencies. As the serration flap angle is increased from 0° to 10°, noise reductions increase below about 1.1 KHz and decrease above this frequency.

Figure 9 shows the impact of serration shape on noise. In general, the 3D serrations provide improved noise reduction with respect to 2D design at low frequencies (1.3 kHz at 80 m/s). However no additional noise benefit is observed at higher frequencies.

The impact of serration length on noise reduction is shown in Figure 10. As serration length is increased, the noise reduction at low frequencies increases and noise reduction at high frequencies decreases.
**Figure 7.** Schematic showing microphones arranged in an arc around the airfoil mounted in the test section.

**Figure 8.** Impact of serration flap angle measured as delta SPL between the straight edge and the serrated airfoil.
Figure 9. Impact of serration shape measured as delta SPL between the straight edge and the serrated airfoil.

Figure 10. (a) Impact of serration length measured as delta SPL between the straight edge and the serrated. (b) Overall pressure level comparison

A test campaign was carried out at the TU Delft vertical wind tunnel, V-Tunnel, as a part of an LM led Industrial PhD project. Particle image velocimetry (PIV) was used to interrogate the flow field around the serrations. PIV measurements give a good indication of how the aerodynamics of the straight edge airfoil is impacted by the presence of serrations on the trailing edge. Separately, noise was measured using an acoustic (microphone) array [1][2]. Test setup and position of microphone array is shown in Figure 11 a and b respectively. Noise measurements were referenced to the center of array. Acoustic array based measurements were preferred in order to quantify the impact of serrations on noise levels while avoiding spurious acoustic sources in the untreated test section room, side plates and nozzle exit.
The schematic of the acoustic measurement setup is shown in Figure 11 a. Figure 12 shows the acoustic results measured using the array, showing the impact of serrations on airfoil noise at a velocity of 35 m/s and three different AoA of 0 deg, 6 deg and 12 deg. The serrations are 4 cm long and are retro fitted to a NACA0018 airfoil of 20 cm chord. The serrations were oriented at a flap angle of 0 deg. The serrations used in this experiment are most effective in the 1-4 KHz range with the noise reduction efficiency dropping off at higher frequencies. Increase of angle of attack reduces the noise reduction efficiency of the serrations oriented at a given flap angle. Shown also for reference is the predicted noise reduction from Howe’s model [8], which shows a nonphysical trend of significant increase in noise reduction efficiency of the serrations at higher frequencies.

The acoustic wind tunnel tests clearly indicate that the serrations are effective noise reduction devices. Both 2D and 3D serrations were effective in reducing airfoil noise, with 3D serrations performing slightly better in the lower frequencies. It was also observed that increasing serration length increases the noise reduction efficiency. Flap angle was also found to be a critical parameter that impacts noise reduction.

**Figure 11.** (a) Schematic of the acoustic array setup at TU Delft. The microphone array can be observed in front of the airfoil. (b) Array positions
Figure 12. Noise reduction measured in the Delft wind tunnel using acoustic array at a flow speed of 35 m/s.

3.3. Wind Turbine Field Test Campaign

In 2015, acoustic field tests were performed on three different turbines with blades retrofitted with LM serrations. The tested wind turbines were of 2 to 3 MW rated power, with diameters varying from 90 m to 122 m. The acoustic measurements were carried based on the IEC 61400-11 ed. 3 guidelines [5]. A-weighted sound power levels were obtained from the field measurements for a range of wind speeds. For each field test campaign, at least two sets of measurements were made, a “clean” set where rotor noise alone was measured and a “serrated” set where the serrations were retrofitted to the rotors and the total noise was measured.

Figure 13 shows a comparison of sound power level (PWL) between the clean rotor and the serrated rotor for the 120 m diameter rotor. A noise reduction of 1 to 2 dBA is observed across the wind speeds measured. The uncertainty of the spectra presented in figure 13 and 14 (field test) is +/- 1 dB(A). Serrations are effective in the low to medium frequency range, where the noise peak is observed.

Figure 14 gives the PWL spectral plot for 9 m/s wind speed. Serrations seem to be very effective in reducing noise in the low to mid frequency range (100 Hz to 1000 Hz). At higher frequencies, a slight increase in levels is observed. Figure 15 shows the noise reduction obtained from serrations for the three latest validation campaigns undertaken by LM. In the figure, measured noise reduction is plotted versus wind speed at hub height. The serration designs including the length of serrations, flap angle, and panel placement are different for the three turbines tested. Clean and serrated turbine tests are performed close in time, and it was confirmed that ambient conditions including inflow did not vary significantly.

The field measurement campaign results indicate that serrations are effective in reducing noise for various blade types and operating conditions. A noise reduction in excess of ~1.5 dB is observed across the wind speeds of interest.
**Figure 13.** Comparison of PWL between the clean and the serrated rotor of 120 m diameter plotted versus wind speed at 10m height.

**Figure 14.** Comparison of PWL spectra between the clean and the serrated rotor of 120m diameter for 9 m/s wind speed.
4. Conclusions
A summary of serration design and validation efforts undertaken by LM is described in this paper. Modeling, testing and validation of various serrations designs were carried out to address the impact of different design parameters, and to reduce uncertainty in obtaining a satisfactory and consistent serration performance in the field. Various serration designs tested in the field generated in excess of 1.5 dB noise reduction consistently over three wind turbine noise measurement campaigns. This work has generated adequate validation data from wind tunnel and field tests and has boosted LM’s confidence in the potential of serration for noise reduction.

5. References
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**Figure 15.** Noise reduction measured in the field for 3 different serrated LM rotors.