

An Experimental Parametric Study of Airfoil Trailing Edge Serrations

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Abstract

Self-noise of an airfoil arises due to different mechanisms. In applications such as wind turbines the turbulent boundary layer interacting with the trailing edge is thought to be the dominant mechanism. In this study, a parametric study of add-on sawtooth type trailing edge serrations is carried out for trailing edge noise reduction. The main parameters which are known to control the performance of this trailing edge serrations type are the height and width of the serration teeth (i.e., amplitude and wavelength, respectively). Several parameters have been investigated experimentally in an aero-acoustic wind tunnel at the University of Siegen on a Somers S834 airfoil section. These parameters include the two main parameters mentioned above as well as orientation, thickness and the side on the airfoil, where serrations are attached. The experimental results show a maximum noise reduction for thin, long and narrow serration teeth, attached on the pressure side and oriented along the wake of the airfoil.

Introduction

Wind energy is a renewable source of energy and wind turbines convert energy without causing substantial adverse effects to the environment. However, the wide spread of wind turbines near densely populated regions is restricted partly due to the emitted noise. Studies conducted to identify the noise sources from wind turbines have revealed that the dominant noise source is the flow induced trailing edge noise (TEN) [1].

Considering the practical constraints a noise reduction techniques of current interest for wind turbines are serrations attached to the trailing edge (TES). HOWE [2] contributed to the understanding of the effect of TES by deriving an analytical noise radiation model for low Mach number (Ma) flows to predict the noise reduction caused by saw tooth serrations on an infinite flat plate airfoil at zero angle of attack. JONES et al. [3] conducted direct numerical simulations (DNS) of the flow around a NACA-0012 airfoil with and without TES. Two serration geometries were investigated, one with an amplitude $2h$ (see Fig. 1) equal to the boundary layer thickness δ at the TE (named as short) and another one with an amplitude of 2δ (named as long), with wavelength λ being constant for both designs. Compared to the short TES the long TES provided higher noise reduction for all frequencies. The short TES provided less noise reduction and this only in a finite frequency range, above which the noise level increased.

GRUBER [4], who did an extensive study of TES showed that the noise reduction is due to the reduction of phase speed at which the turbulence is convected near the saw tooth edges. In addition to that, a reduction of coherence of pressure measured along the saw tooth is also reported in the frequency band where noise reduction happens. VATHYLAKIS et al. [5] investigated the effect of flap angles on the noise reduction on a NACA65(12)-10 airfoil, where flap angles from -15° to $+15^\circ$ in steps of 5° have been studied. The flap-up position ($+5^\circ$), which is oriented towards the suction side, resulted in the best noise reduction, the flap-down position (-5°) was the worst configuration.

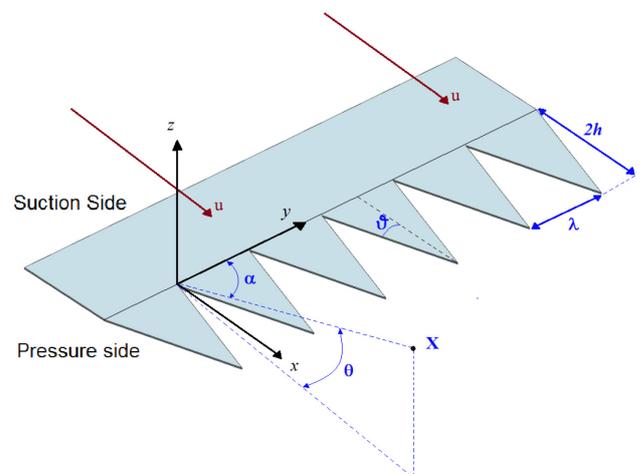


Fig. 1: Geometrical parameters of a serrated trailing edge and the coordinate system.

This paper presents a preliminary experimental model scale study on the acoustic effect of various parameters apart from the classical serration geometry "amplitude" and "wavelength", which could influence the noise reduction capability of TES, and a discussion on some findings of other researchers like deviation between experiment and HOWE's model, effects of flap angle and effects of serration amplitude.

Experimental Setup

Airfoil investigated and aero-acoustic wind tunnel

The experimental investigation was carried out in an aero-acoustic wind tunnel facility at the University of Siegen. The airfoil segment was a SOMERS S834, with a chord length of 0.2 m and a span of 0.266 m. The effective angle of attack (AOA) for this study was 4.7° . For compensation of loss of lift due to finiteness of jet and flow deflection in the wind

tunnel here a geometric AOA of 12.7° is required. The aeroacoustic wind tunnel provides a maximum flow velocity $u = 25.55$ m/s. The chord based Reynolds number (Re) is $3.5 \cdot 10^5$. In order to replicate or mimic the real conditions in a large wind turbine, a ten times higher Re has to be achieved. Hence the airfoil is tripped at the natural transition position that will occur at $3.5 \cdot 10^6$. The tripping positions were calculated using XFOIL. A zig zag trip is applied along the complete span at 34 mm from the leading edge (LE) on the suction side (SS) and 152 mm from the LE on the pressure side (PS).

Acoustic measurement

The wind tunnel exhausts in a semi-anechoic chamber which allows the acoustic measurements. More details about the semi-anechoic chamber can be read in [6]. Three microphones (1/2" Brüel & Kjaer TM, type 4190) are used to measure synchronously the noise being emitted from the airfoil. The microphones are located at a distance of 2.5 times chord (500 mm) from the TE as shown in **Fig 2**. All measurements are captured with a sampling rate of $f_s = 51.2$ kHz. The spectral analysis is based on the power spectral density S_{pp} obtained using the *pwelch* routine in Matlab™ Vers. R2014b ($\Delta f_{ref} = 1$ Hz, $p_0 = 2 \cdot 10^{-5}$ Pa). L_{Spp} is defined as

$$L_{Spp}(f) = 10 \cdot \lg \left(\frac{S_{pp} \cdot \Delta f_{ref}}{p_0^2} \right) \quad [\text{dB}] \quad (1)$$

During TEN measurements the background noise due to the wind tunnel contaminates the acoustic signature of the airfoil. Therefore, the measurements were done once with the reference airfoil and once without. The L_{Spp} spectrum of all three microphones averaged is shown in **Fig 3**. It has to be noticed that the signal to noise ratio is insufficient in frequency ranges above 3000 Hz, i.e., the background noise is too high in these frequency to separate airfoil from background noise. Hence in this study, the investigations of TES will be only displayed in a frequency range from 200 Hz to 3000 Hz.

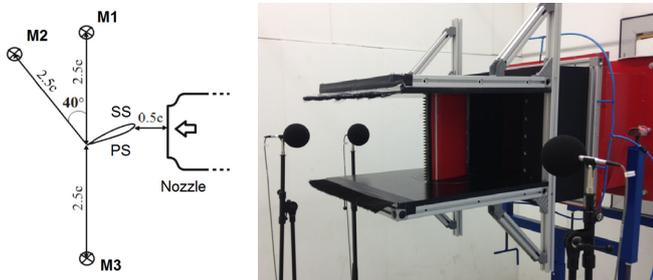


Fig. 2: Left: Schematic diagram of microphone locations, right: Microphones in semi anechoic chamber

Serrations investigated

The following two parameters are defined to design the serration:

- The relative length h/δ , where h is half of serration's amplitude and δ is the boundary layer thickness at the TE, which is obtained from the experimental results of reference airfoil as 9 mm.

- The relative wavelength λ/h , where λ being the serration's wavelength.

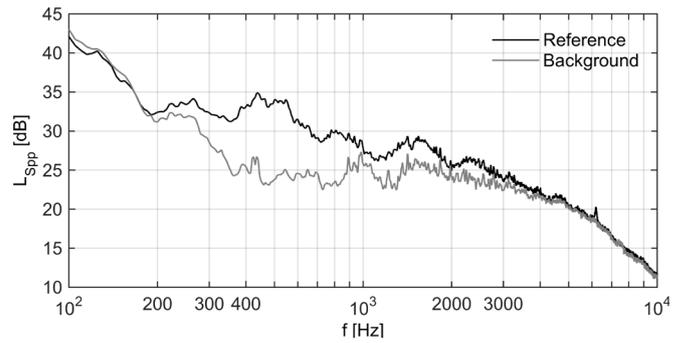


Fig. 3: L_{Spp} of reference airfoil and background noise at microphone locations as shown in Fig. 2 (average of 3 microphones).

Before the various designs were investigated, a parametric study of three following important parameters was carried out:

- Fixation side: The side on which serrations are glued.
- Orientation: The angle φ the serration makes with respect to the camber line of the airfoil. The serrations oriented towards the SS have positive values of φ and the serrations oriented towards the PS have negative values of φ (**Fig 4**). The serration aligned to camber line has $\varphi = 0^\circ$. Orientation angles between $+15^\circ$ and -15° in steps of -5° have been investigated.
- Relative thickness t/δ , where t is the thickness of the serration: the values of $t/\delta = 0.56\%$, 3.30% , 5.60% and 11.00% have been investigated.

After evaluating the results from this parametric study, three sets of serrations incorporated with the best fixation side, orientation and relative thickness are investigated, **Tab. 1**.

Tab. 1: Parameter of serrations investigated

Set #	λ/h	h/δ
1	0.25, 1.00, 5.00	1.00
2	0.25, 1.00, 1.50, 2.00, 2.50, 5.00	3.00
3	1.00	1.00, 1.50, 2.00, 2.50, 3.00

Results

Three main parameters are analyzed one after the other. The best result in each analysis is kept for the next parameter's analysis.

Fixation side

For this investigation, a serration having $h/\delta = 1$ and $\lambda/h = 1$ with a relative thickness $t/\delta = 0.67\%$ and the orientation angle $\varphi = +5^\circ$ is chosen. Measurements are carried out with this serration glued on the SS and PS respectively. It is to be noted that, when the serration is glued on the PS, the orientation angle is naturally $\varphi = +5^\circ$, but when it is glued on the SS, the serration has to be oriented towards the SS to yield the same orientation angle $\varphi = +5^\circ$ (**Fig 4**).

The L_{Spp} spectra for both cases are plotted in **Fig. 5** along with the L_{Spp} spectrum for the reference case without TES. It is observed that the serration when glued on SS results in less noise reduction in comparison to the serration glued on PS. Hence for the following investigations, the serration is glued on the PS.

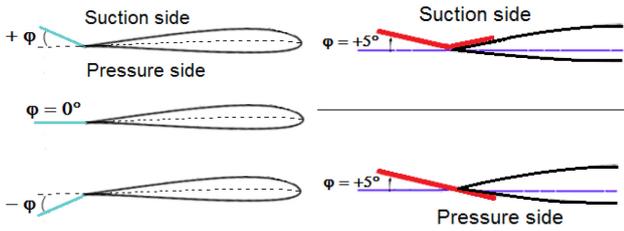


Fig. 4: Left: Schematic diagram of orientation angles φ , right: Schematic diagram of different fixation sides of TES.

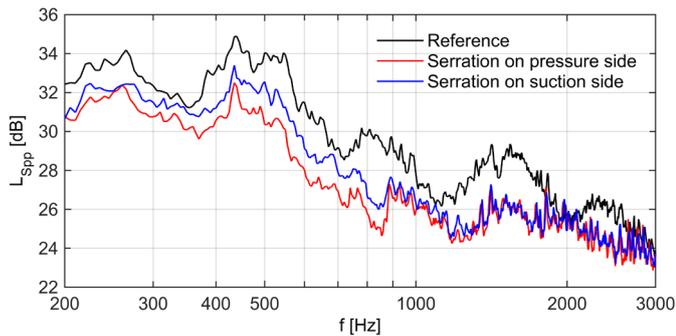


Fig. 5: Effect of fixation side of serrations

Orientation

For this investigation, a serration having $h/\delta = 1$ and $\lambda/h = 1$ with a relative thickness of $t/\delta = 3.3\%$ is chosen and glued on the PS. Measurements are carried out for orientation angles $\varphi = +15^\circ$ to -15° in steps of -5° . First a comparison of $\varphi = +15^\circ$, 0° and -15° is shown in **Fig 6a**. It is to be noted that the serration oriented towards SS ($\varphi = +15^\circ$) brings a potential reduction only beyond 600 Hz. On the contrary, the serration oriented towards PS ($\varphi = -15^\circ$) increases noise emission beyond 600 Hz. The serration aligned with camber line ($\varphi = 0^\circ$) reduces the TEN almost in the entire frequency range displayed. In **Fig. 6b**, the comparison of $\varphi = -10^\circ$, 0° and 10° is shown. The same tendency is observed here except for the fact that the frequency at which the change of behavior happens is shifted to 750 Hz, which was 600 Hz in the previous case. The serration aligned with the camber line ($\varphi = 0^\circ$) seems to be still the best configuration. Finally the comparison of $\varphi = -5^\circ$, 0° and $+5^\circ$ is shown in **Fig 6c**. Here it is observed that, all three orientation angle reduce the noise emission and the best noise reduction is provided by the serration with $\varphi = -5^\circ$. This is contradicting with the results presented by VATHYLAKIS et al. [5]. However, for the next investigations, the orientation angle $\varphi = +5^\circ$ will be implemented, because to achieve $\varphi = -5^\circ$, the serrations have to be bent manually towards the PS and the risks of misaligning some of the tooth is high, whereas with $\varphi = +5^\circ$ the serrations need to be glued on the PS and requires no further bending.

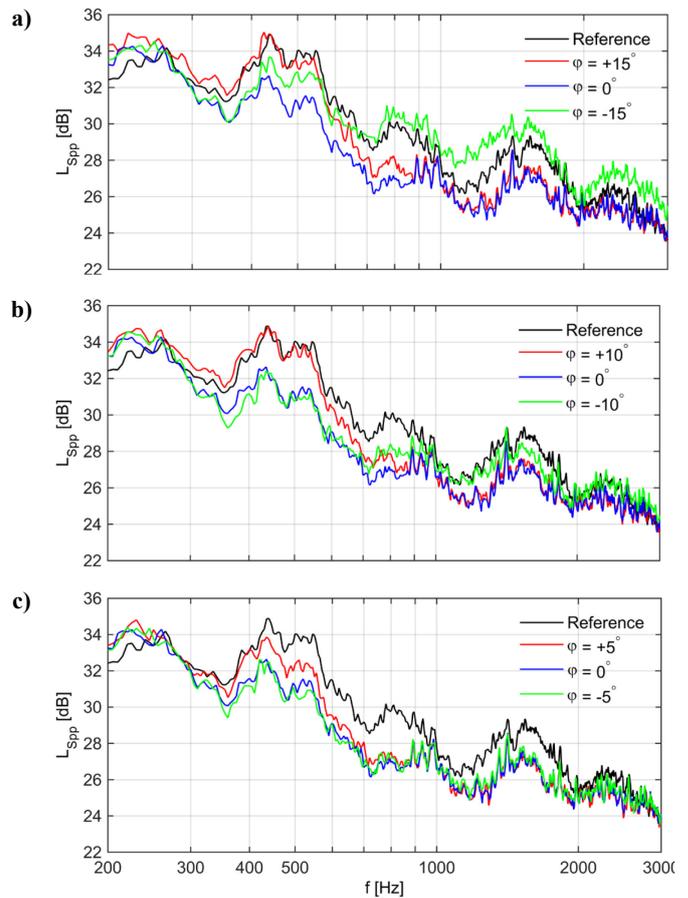


Fig. 6: Effect of orientation angle φ .

Relative thickness

For the investigation of relative thickness, a serration having $h/\delta = 1$ and $\lambda/h = 1$ with the orientation angle $\varphi = +5^\circ$ is chosen and is glued on the PS. Four different relative thicknesses of serration were investigated, $t/\delta = 0.56\%$, 3.30% , 5.6% and 11.00% . The measurement results are shown in **Fig 7** for only three of them. The results show that the variation of thickness does not have a big influence in noise reduction. However it is observed that the thinner the serrations are the higher is the noise reduction. For further investigation, the serration with $t/\delta = 0.56\%$ is chosen.

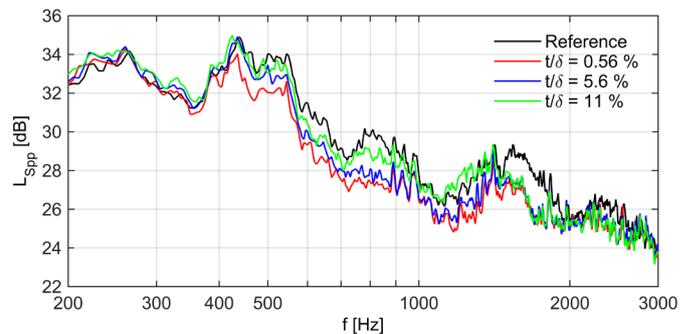


Fig. 7: Effect of relative thickness of serrations t/δ .

Serrations based on HOWE's theory

As already stated, all the serrations investigated in this section are glued on the PS with $\varphi = +5^\circ$ and $t/\delta = 0.56\%$.

At first an analysis is made between serrations which have a constant h/δ (1 and 3) but varying λ/h (0.25, 1, 5), i.e., Set 1 and Set 2. The measurement results are shown in **Fig 8.a** and **Fig 8.b**. The following two observations are made:

- The longer the serrations, the higher the noise reduction. This is in agreement with the observations in simulations by JONES et al. [3].
- According to HOWE, the sharper the serrations, the higher is the noise reduction. But in both cases presented below, the serration with $\lambda/h = 0.25$ causes less noise reduction as compared to $\lambda/h = 1$.

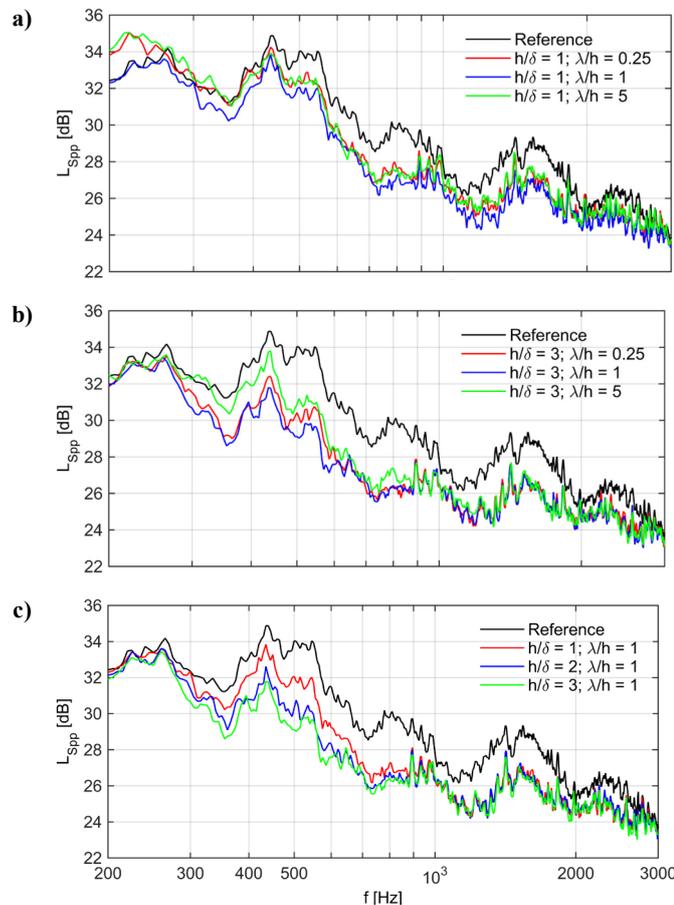


Fig. 8: Effect of "amplitude" and "wave length" of serrations; a) set 1, b) set 2, c) set 3.

Another interesting comparison is presented in **Fig 8.c**, where the serrations are increased in amplitude from $h/\delta = 1$ to 3 in steps of 1 and the wavelength is kept the same of half of amplitude in each case. A clear increase in noise reduction can be seen for the frequency range 300 Hz to 800 Hz, as the serrations become longer and broader.

The results of other investigated serrations are not shown here. The serration which brought about the least noise reduction was $h/\delta = 1$ and $\lambda/h = 0.25$. The best serration is the one with $h/\delta = 3$ and $\lambda/h = 1$. With this geometry a noise reduction of 3 dB was achieved in the frequency range from 300 Hz to 900 Hz with a maximum of 5 dB noise attenuation at the TE peak around 500 Hz. This finding corresponds to GRUBER's [4], who also reported that the serrations with $h/\delta > 2$ yield the maximum noise reduction. However, the

increase in noise beyond $f\delta/u > 1$, as reported by Gruber, was not observed here due to the insufficient signal-to-noise ratio.

Conclusion

In this study a variety of triangular type trailing edge serrations have been designed based on HOWE's theory and eventually investigated in model scale experiments. On top of the classical design parameters h/δ and λ/h , more technological parameters have been investigated. The outcome was that it is beneficial to glue the serration on the pressure side rather than the suction side (which caused a step) and to keep the thickness at 0.05 mm (i.e., $t/\delta = 0.56\%$). The best angle of orientation is $\varphi = -5^\circ$, which means the serration is oriented towards the pressure side, aligning most probably with the wake, which has not been quantified in this study. The investigation of various serrations based on HOWE's theory showed that the serrations having $h/\delta = 3$ and $\lambda/h = 1$ bring best results. Previous predictions that smaller values of λ/h result in better noise reduction could not be confirmed within this study.

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