IEA Task 39: Wind tunnel serration benchmark

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1 Introduction

Trailing edge serrations have been widely used to reduce trailing edge noise of wind turbine blades [1]. However, large uncertainties in terms of analytical and computational modelling as well as testing do persist. The challenges in wind tunnel testing are found in the low signal to noise ratio, because an aerofoil equipped with trailing edge serration is very quiet and background noise in the aeroacoustic test setup can become dominant.

1.1 Objectives

The leading aeroacoustic test facilities in Europe joined forces to quantify these uncertainties in testing. The strategy was to test the same aerofoil model in the different facilities in order to compare results and quantify the spread of the data. Furthermore, the data set should be published as a reference for benchmarking computational models. It is planned to use the BANC framework for this purpose.

1.2 Work Flow

In order to achieve these objectives, two models of the same aerofoil shape but of different size were tested in 5 different facilities. Exchanging the same model reduces the uncertainty in geometry that is usually present when manufacturing different models with the same theoretical geometry. The model were equipped with exactly defined serration geometries that were also produced at one place and shipped to the different facilities. The time line for the experiments is presented in table 1.2.

Institution	Facility	Model chord	Time	accomplished
TU Delft	AT	0.2 m	Nov. 2019, Mar. 2020	yes
DTU	PLCT	0.9 m	April 2020	yes
TU Delft	LTT	0.9 m	July 2020	yes
DLR	NWB	0.9 m	Nov. 2020, Feb. 2021	yes/no
DLR	AWB	0.2 m	mid 2021	no

Most experiments have been completed, but two test campaigns are still pending.
The results of the different test campaigns will be compiled and the uncertainty will be quantified. Scaling laws for the results for the models with different size will be applied. The analysis is not complete. Preliminary results will be presented in this report.
When the data set is analysed a benchmark data set for the validation of noise prediction codes will be released. It is planned to publish the data set and the benchmark formulation in the BANC framework [2] during the AIAA conference in 2021. Due to the COVID-19 situation there is some uncertainty about the date of the conference.

2 Description of the Wind Tunnels and Measurement Setups

3 different institutions and 5 different wind tunnels participate in the benchmark exercise. The German Aerospace Center (DLR) participated with the Low Speed Wind Tunnel (NWB) and the Aeroacoustic Wind Tunnel Braunschweig (AWB) in the project. The Delft University of Technology (TU Delft) participated with the Low Turbulence Wind Tunnel (LTT) and the anechoic vertical wind tunnel (AT). The Technical University of Denmark (DTU) participated with the Poul La Cour Wind Tunnel (PLCT).
The aerofoil model for the benchmark was a NACA63-018. The 5 facilities operate on 2 different scales of size. Hence, a model of 0.9 m chord length was provided by DTU for the larger facilities PLCT, LTT and NWB) and a model of 0.2 m chord was manufactured during the project by TU Delft for the smaller facilities (At and AWB).
In the following, the details of the test facilities and aerofoil models are presented.

2.1 Large NACA63-018 model

The 18% thick NACA63-018 aerofoil model with 0.9 m chord length was made of aluminum, fig. 1. The span of the model was 1816 mm and it included two extension pieces to expand the

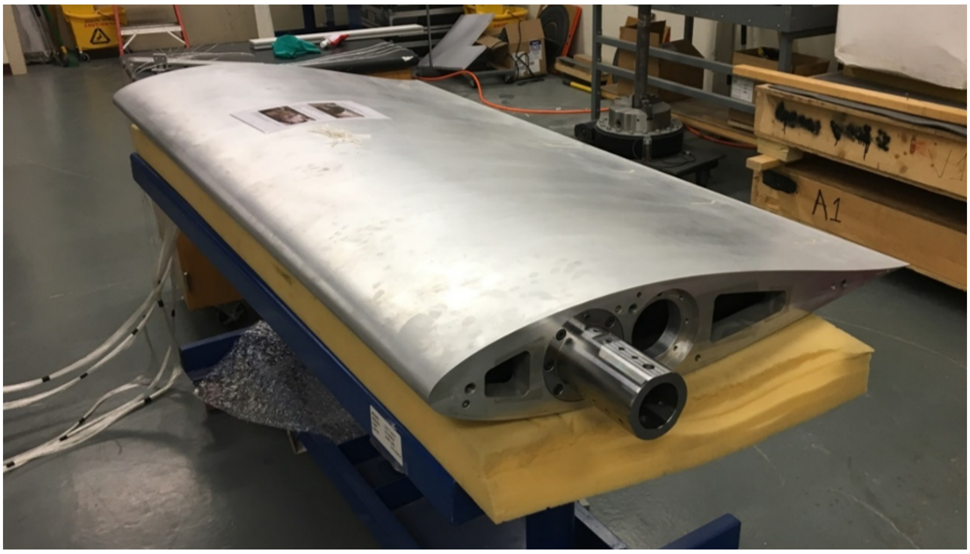

Figure 1: The large NACA63-018 aerofoil model.

span to 1999 mm. The weight of the aerofoil was 122 kg.
It is equipped with 192 port holes for the measurement of the aerofoil surface pressure. The port holes have a diameter of 0.5 mm and are arranged in 7 bands at different spanwise positions. The band at center span contains the highest concentration of ports with a number of 96.
The extensions with serrations are depicted in fig. 2. They are 1980 mm in spanwise extend and were attached to the pressure side of the model.

Figure 2: The extensions with serrations for the large NACA63-018 aerofoil model.

3 Small NACA63-018 model

The 200–mm chord NACA 63018 airfoil model with a span of 400 mm is depicted in fig. 3. TU Delft managed and conducted the production of this model. The airfoil model is made

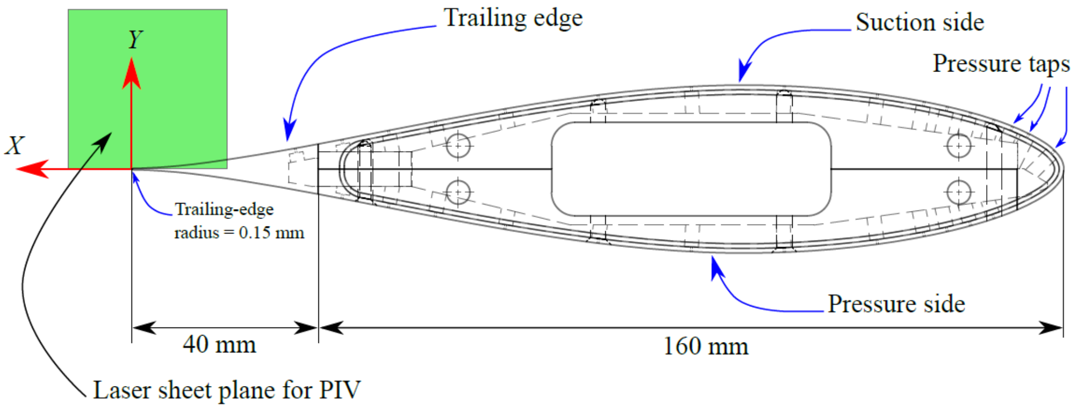

Figure 3: The small NACA63-018 aerofoil model.

of aluminum and the surface of the model is spray–painted in black to minimize reflections. The airfoil model consists of three modules: the suction side, the pressure side, and the trailing–edge. The trailing edge module made up 20% of the chord and the trailing–edge thickness is 0.3 mm. The modular construction assured a precise installation of the serrations, fig. 4. Along the chord distribute 28 0.4–mm diameter pressure tap openings. The minimum and maximum chordwise locations of the pressure taps are 2% and 82.5%, respectively.

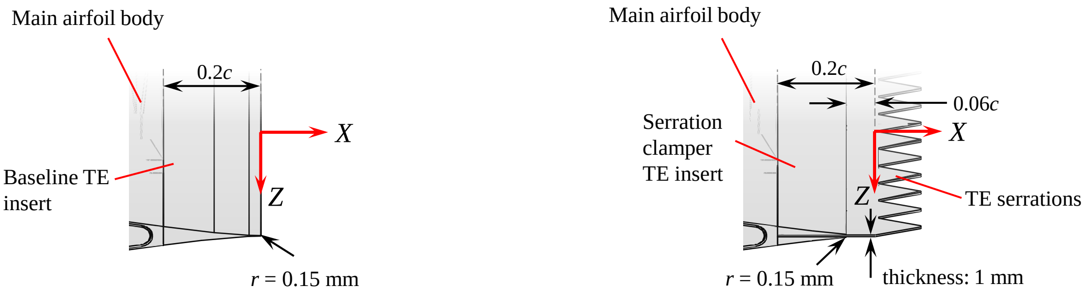

Figure 4: The serrations for the small model.

3.1 Geometry of the trailing edge serrations

Three different serration geometries were developed. The design parameters were serration length, wave length and the flap angle as defined in fig. 5. Two different serration geometries

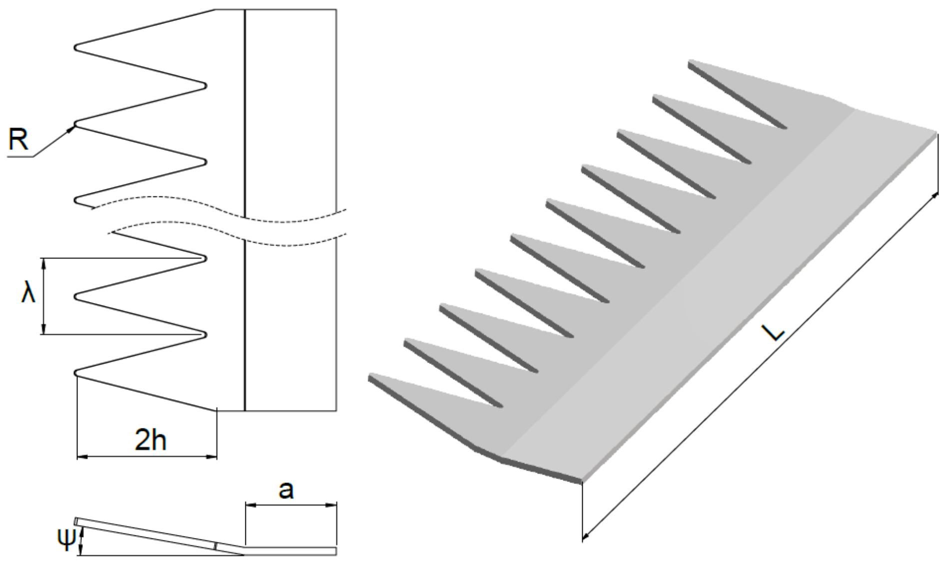

Figure 5: Definition of the design parameters for the serration geometries.

were considered, a standard saw-tooth geometry and a iron shaped geometry according to [3], fig. 6. Considering these parameters, three different geometries for each aerofoil model were manufactured: a saw-tooth configuration with a flap angle $\psi = 0$ deg (S0), the same configuration with a flap angle of $\psi = 4$ deg (S4) and the iron shaped configuration shown in fig. 6 with a flap angle $\psi = 0$ deg (SI). The rounding radius of the tips R was 2 mm for the serrations of the large model and 0.4 mm for the serrations of the small model. The spanwise

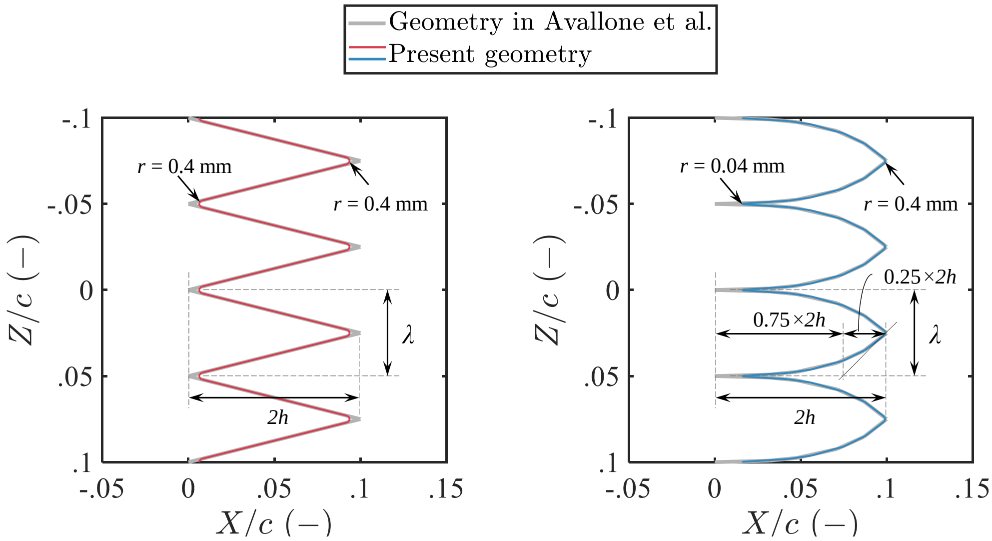

Figure 6: The theoretical serration geometry.

length L was chosen to cover the whole span of the models.

3.2 The PLCT at DTU

The PLCT has a closed loop airline. The flow is driven by a 2.4 MW fan. A top speed of 105 m/s can be achieved. The test section has a cross section of 2 x 3 m and is 9 m long.
The walls of the test section are 6 m long and cover the part of the test section that begins 1 m downstream of the contraction. They are made of Kevlar material that is acoustically transparent but keeps the flow confined, fig. 7. The test section is surrounded by an anechoic chamber. The acoustic field in the anechoic chamber was tested according to ISO 3745 standard. It is close to an ideal free field above frequencies of 125 Hz [4]. However, in the frequency range range between 200 Hz and 3150 Hz the deviation from ideal free field conditions is ± 2 dB which is slightly higher than allowed according to ISO 3745.
The noise emitted from the aerofoil is measured by an 84 microphones phased array. The microphone array is placed in the anechoic chamber with a distance of 1.2 m from the Kevlar wall. It is centered above the trailing edge of the aerofoil and its mid-span, figure 7. The rendering depicted in figure 8 further illustrates the acoustic setup.

3.3 Test facilities at TU Delft

3.3.1 The A-Tunnel

The anechoic vertical wind tunnel (A–Tunnel) at Delft University of Technology (TU Delft) in the Netherlands is an acoustic open jet wind tunnel, fig. 9. Two different exit nozzles were used in the experiment, one with a cross section of 400 mm x 700 mm and one with a cross

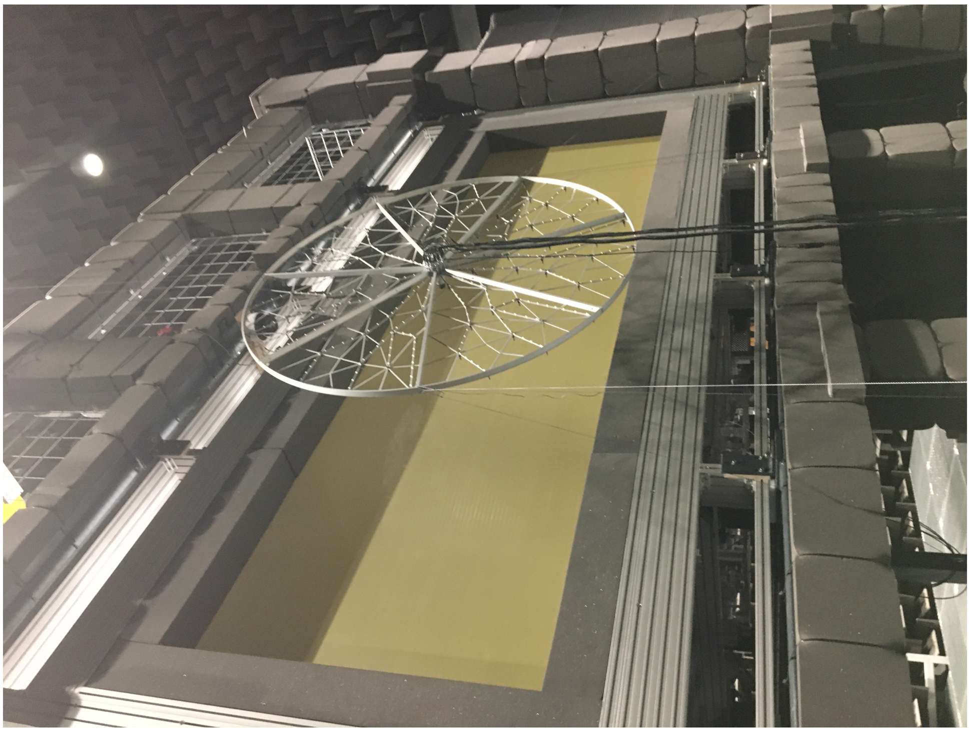

Figure 7: The microphone array and Kevlar wall.

section of 250 mm x 400 mm. With the large nozzle the free–stream flow speed is varied up to the maximum value of 35 m/s, corresponding to the chord–based Reynolds number $4.6 \cdot 10^5$. With the small nozzle the maximum flow speed was 70 m/s corresponding to a chord–based Reynolds number $9.2 \cdot 10^5$. The expected turbulence intensity is below 0.1%.
A microphone array is employed to collect far–field acoustic signal acoustic beamforming technique is applied to isolate and quantify the TBL–TE noise. A microphone array holding 64 GRAS 40 PH microphones (frequency response ± 1 dB, frequency range 10 Hz to 20 kHz, and maximum output 135 dB Ref. 20 μPa [8]) is used. The microphones are arranged in an optimized multi–arm spiral configuration.

3.3.2 The Low Turbulence Wind Tunnel

The Low Turbulence Wind Tunnel (LTT) at TU Delft has a long track record in aerodynamic aerofoil testing aerofoil testing [ref Nando]. The airline of the tunnel is a closed circuit and the flow is driven by a 6 bladed fan with a 525 kW DC motor. The test section of the tunnel is 1.25 m x 1.8 m. It has a length of 2.6m. Recently, one sided of the test section was equipped with a Kevlar wall and a microphone array behind it, fig. 10. Measurements were performed in both hard-walled and Kevlar-walled setup.

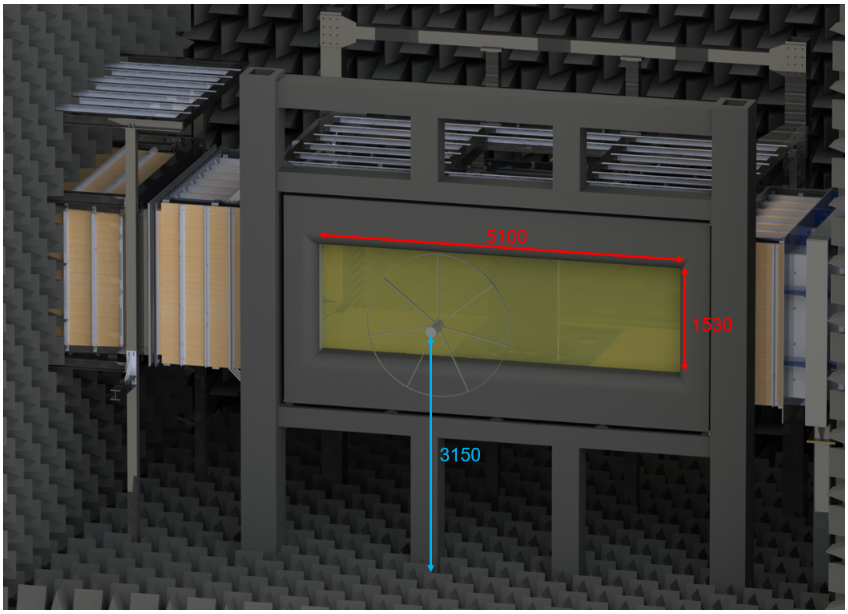

Figure 8: Rendering of the acoustic setup.

3.4 Test facilities at DLR

3.4.1 Aeroacoustic Wind Tunnel Braunschweig

The Aeroacoustic Wind Tunnel Braunschweig (AWB), fig. 11, is a close loop open test section wind tunnel. The inlet nozzle has a rectangular cross section of 2.1 m x 0.8 m. A maximum flow speed of 60 m/s can be achieved. The test section is surround by an anechoic chamber that attenuates acoustic reflection down to the frequency limit of 2000 Hz. There is a microphone array and an acoustic mirror placed at 90 deg. elevation angle above the trailing edge.

3.4.2 The Low Speed Wind Tunnel

The Low Speed Wind Tunnel (NWB) of DLR has been mainly used in the aircraft industry for several decades. In 2009 and 2010 it was refurbished to improve the acoustic properties. The airline of the tunnel is a closed circuit. It operates in two different setups: a closed test section for aerodynamic measurements and an open test section for acoustic measurements, fig. 12. The test sections have a cross section of 3.25 m x 2.8 m. The closed test section is 8 m long and a maximum flow speed of 90 m/s can be reached, the open test section is 6 m long and provides a maximum flow speed of 80 m/s.
The test section is surrounded by an anechoic chamber of the dimension 14 m x 16 m x 8 m. It is certified for 99% acoustic damping in the frequency range between 100 Hz and 40 kHz according to the ISO 3745 standard. A microphone array of 140 microphones and a diameter of 3 m together with an elliptic mirror are placed in the anechoic chamber for acoustic measurements.

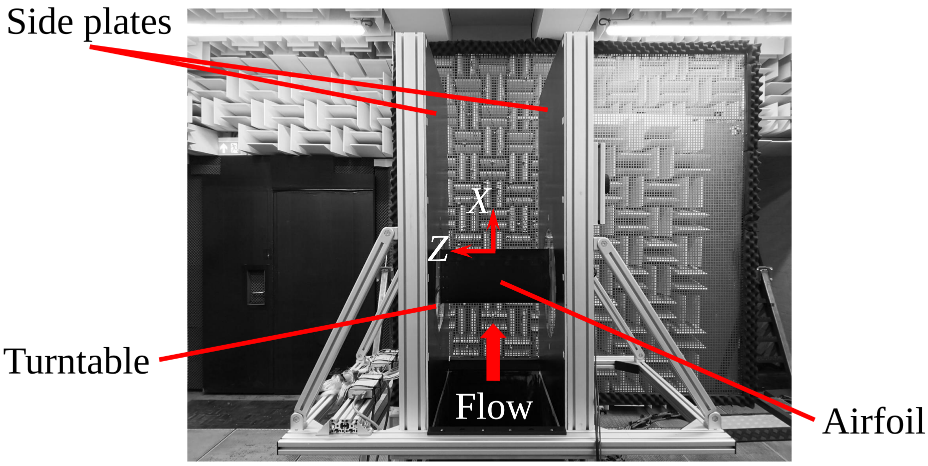

Figure 9: The A tunnel.

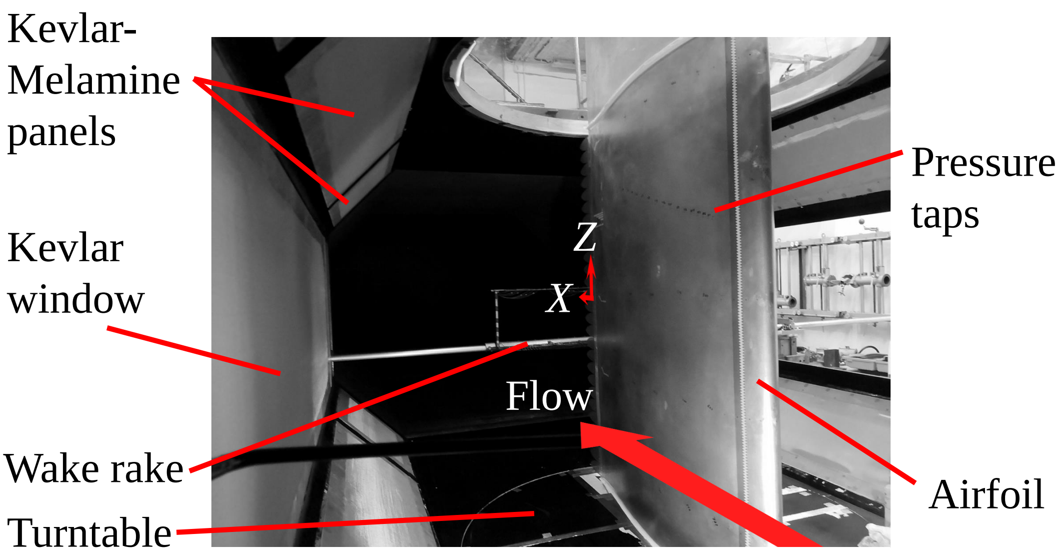

Figure 10: Acoustically treated test section for the LTT.

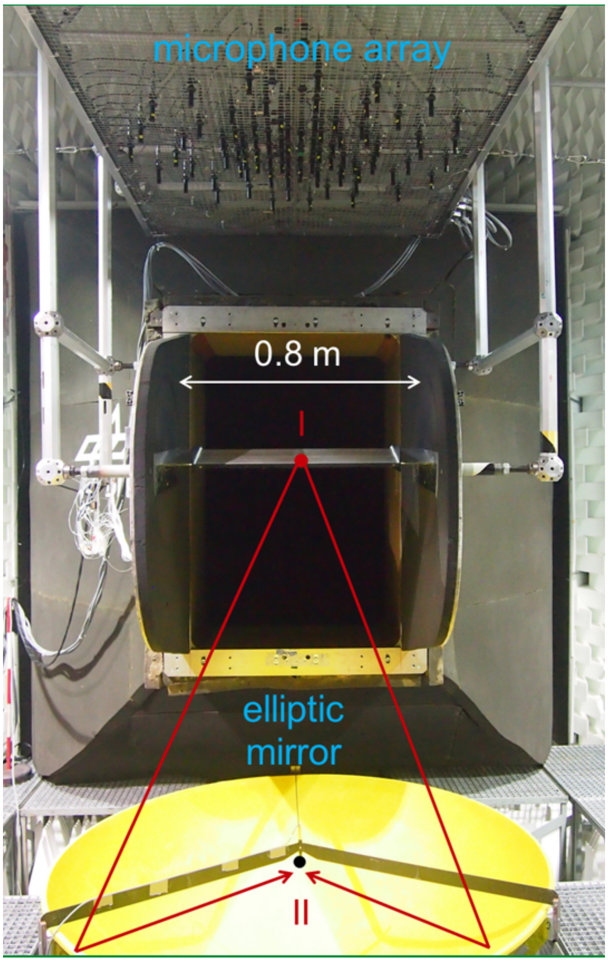

Figure 11: The AWB.

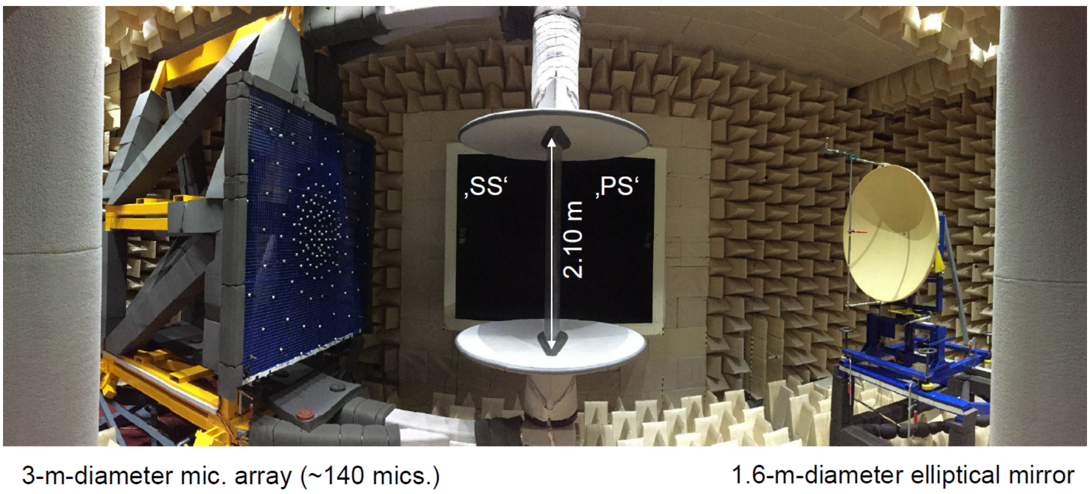

Figure 12: The NWB.

4 Results

In this chapter preliminary selected results are presented. These results present only a small part of the data base that was acquired.

4.1 Aerodynamic data

The lift and drag coefficients of the large NACA63018 model in clean configuration with serrations measured in the LTT and PLCT are compared in fig. 13. Overall the measurements in the

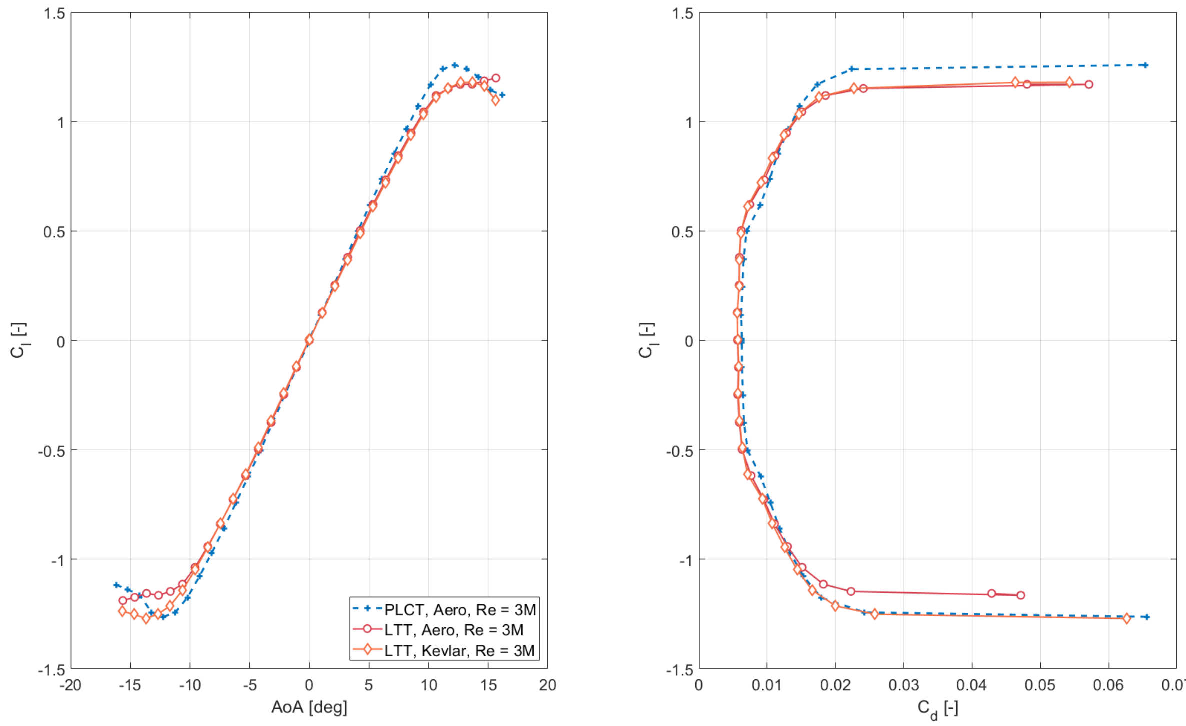

Figure 13: The lift vs. angel of attack and lift vs. drag polars of the NACA63018 in clean configuration.

two different wind tunnels show consistent results. Differences are very small. The drag measurement exhibits a laminar bucket with small values of the drag in the range $-0.5 > C_l < 0.5$ and again shows good agreement of the measurements in both tunnels. Maximum lift and stall characteristics are slightly different. This might be due the different aspect ratio in the two experiments. The slope of the lift vs. angle of attack is larger in the PLCT measurements. Further investigation of the pressure distributions on the aerofoil and a comparison of the wind tunnel corrections is needed to track down the origin of the difference. The measurement in the LTT was performed in acoustic and in aerodynamic configuration. The results of the facility are

consistent.
The polars of the aerofoil in tripped configuration are shown in fig. 14. Zigzag tape of 0.4

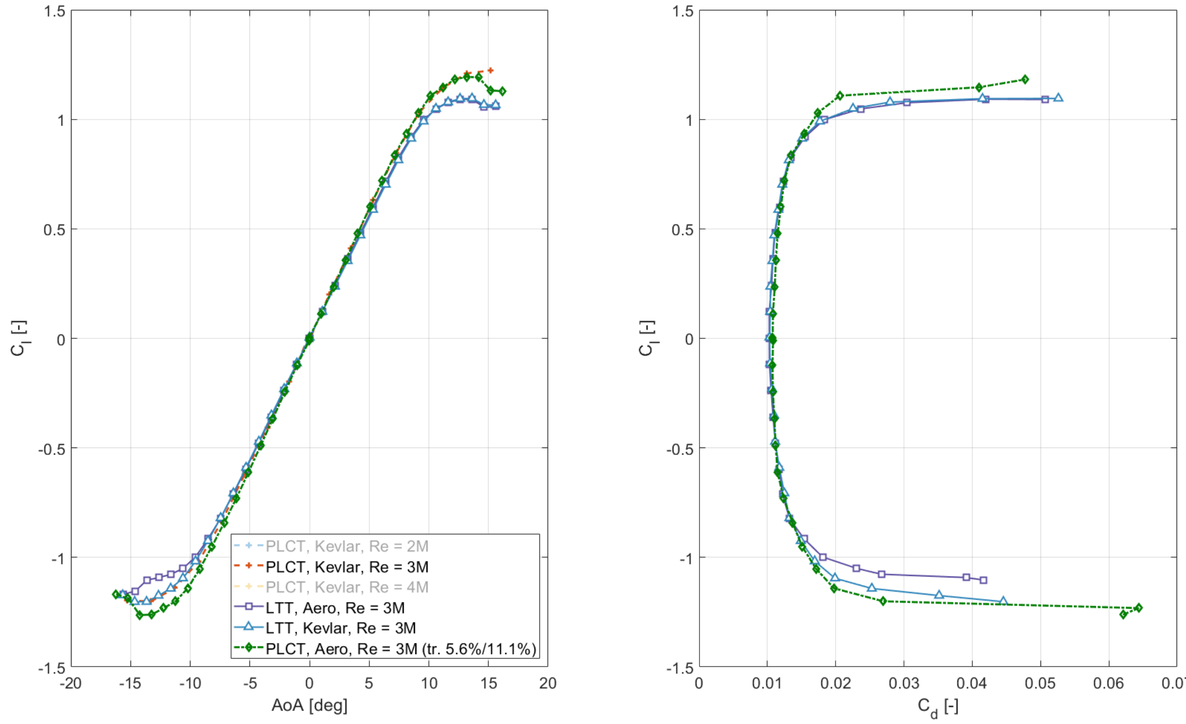

Figure 14: The lift vs. angel of attack and lift vs. drag polars of the NACA63018 in tripped configuration.

mm thickness, 12 mm width and an angle of 60 deg. was applied at the position x/c = 0.05 on pressure and suction side. We observe the same tendencies regarding the slope of the lift vs. angle of attack polar and differences at maximum lift as for the clean configuration. The increase in drag due to tripping the boundary layer is predicted in both facilities. Data of the aerodynamic and acoustic configuration of both tunnels is presented and both facilities show consistent results.

4.2 Acoustic data

In fig. 15 we compare the trailing edge noise spectra of the NACA63018 aerofoil at 0 deg. angle of attack in tripped configuration without serrations measured in the PLCT and in the AT. The spectra are scaled in order to account for the different conditions in the two facilities such as chord and span of the aerofoil model and distance of the trailing to the center of the microphone array as well as the different flow speeds during the measurements. The levels of of the spectra are scaled with the Mach number (flow speed) according to the power of 5, the inverse

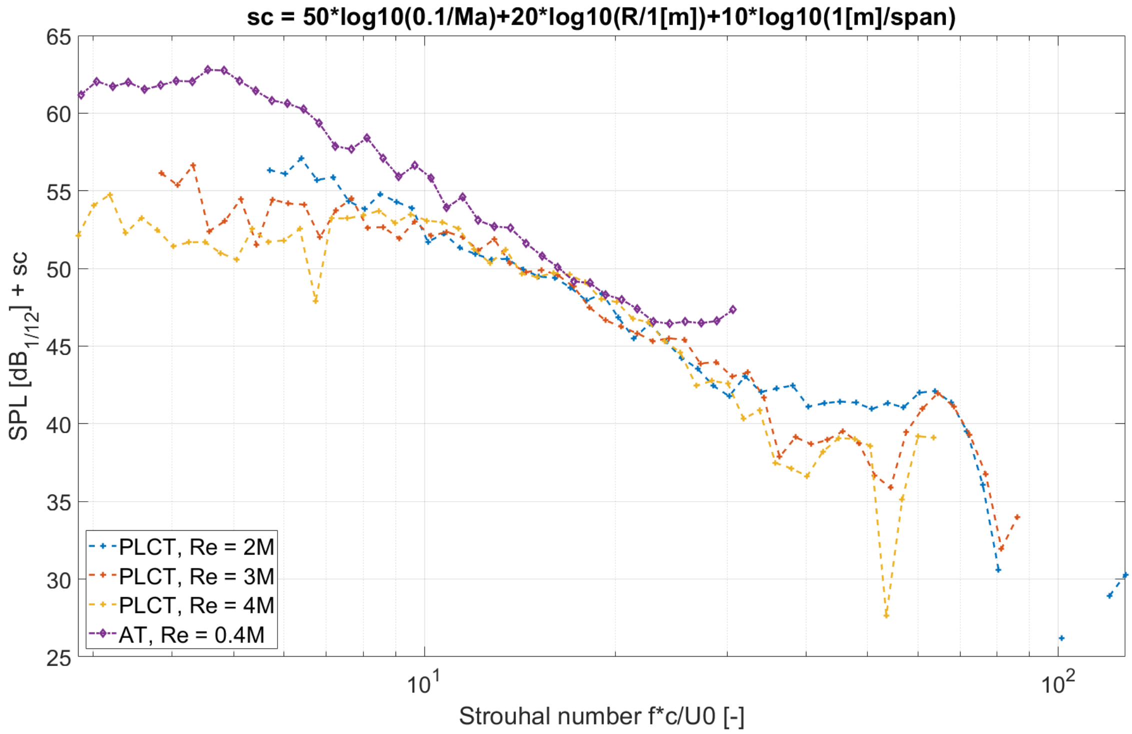

Figure 15: TE Noise spectra of the NACA63018 at 0 deg. angle of attack in tripped configuration without serrations.

of the distance with a power of 2 and the effective span (depending on the integration area of the beamforming map) with a power of 1. The Strouhal number is based on the chord length and the flow speed.

The data of the PLCT for different flow speeds collapses well with the proposed scaling. The scaled noise levels measured in the AT are slightly higher than the ones measured in the PLCT. This might be due to inaccuracies due to the Strouhal number scaling. The Strouhal number should be based on the boundary layer thickness instead of the chord length.

The results of the measurements with serrations performed in the PLCT and the AT are displayed in figs. 16 and 17. The AT measurements show that the iron shaped serrations (SI) give the largest noise reduction. The PLCT measurements confirm this result in the low frequency range. For higher frequencies the S0 serrations give a higher noise reduction. More data has to be analysed to draw conclusions. Trends with respect to angle of attack and Reynolds number have to be investigated.

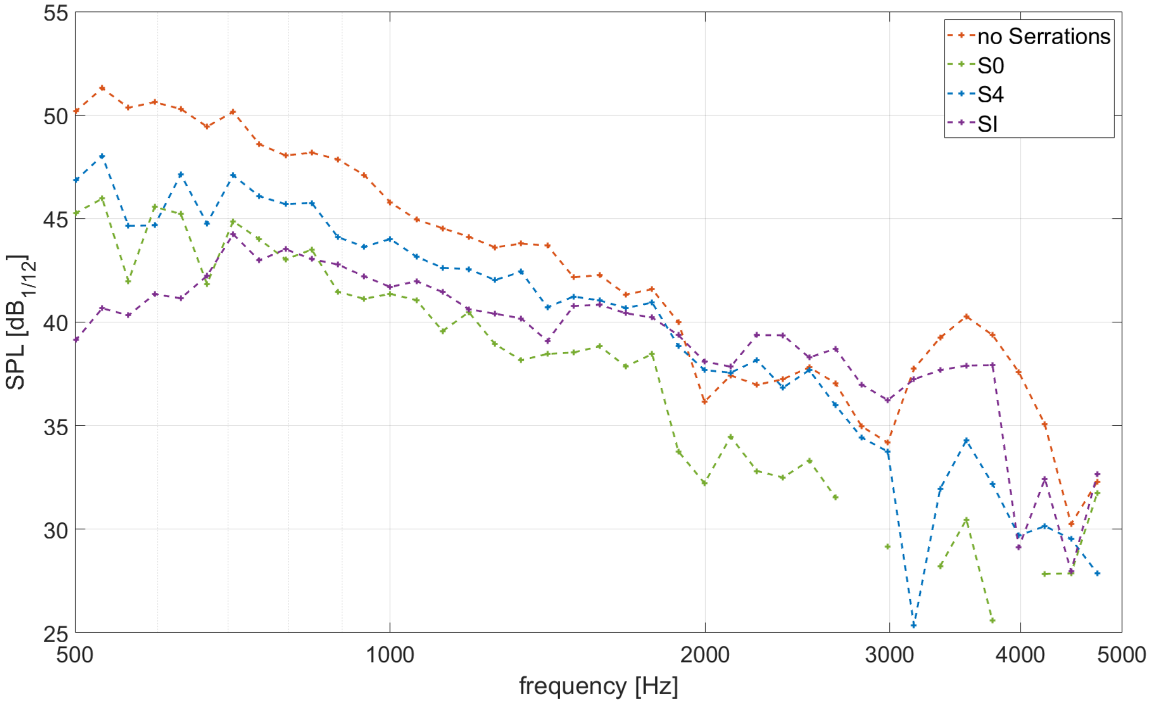

Figure 16: TE Noise spectra of the NACA63018 at o deg. angle of attack and Reynolds number 3 million for different serrations measured in PLCT.

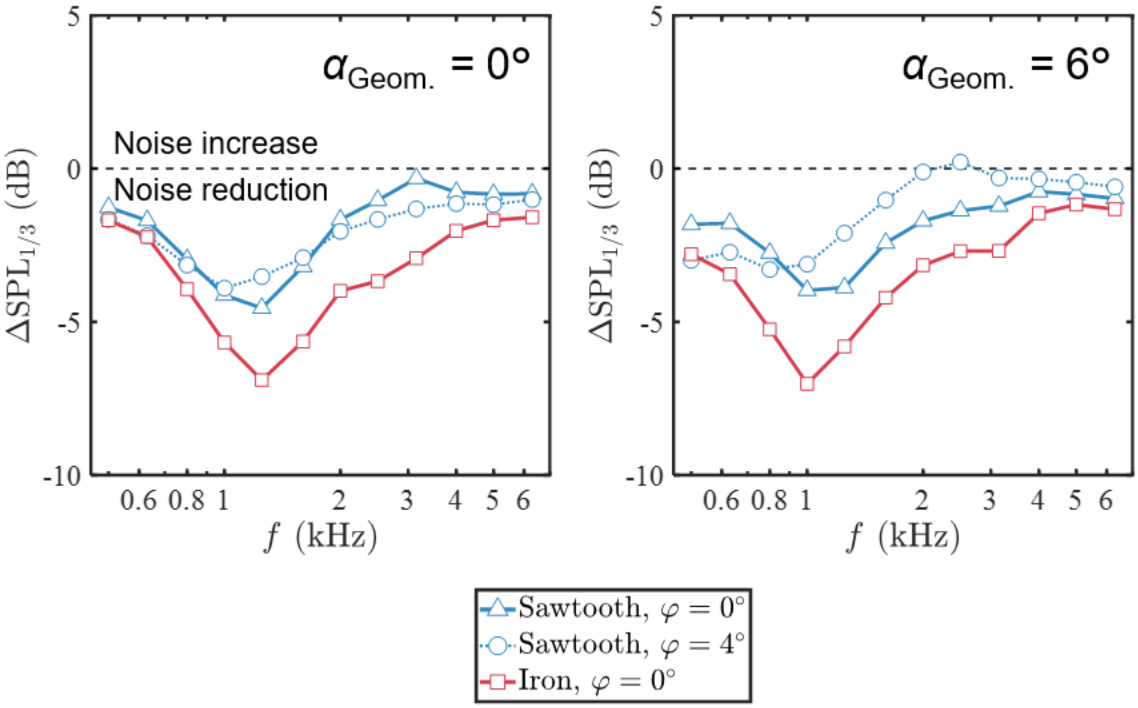

Figure 17: TE Noise reduction at Reynolds number 0.39 million with respect to the NACA63018 without serrations measured in the A tunnel.

5 Conclusions

A comparative test of two aerofoil models with trailing edge serrations was initiated to benchmark testing uncertainties in the leading aeroacoustic wind tunnel facilities in Europe and to provide a data base for model validation. 4 out of 6 measurement campaigns have been completed and the remaining 2 test campaigns will be finalised by mid 2021.
Preliminary analysis of the data showed a very good agreement of the aerodynamic data collected in different facilities with only minor differences. The acoustic measurements showed that the trailing edge serrations reduced the noise emitted by the aerofoil. A more detailed investigation is necessary to quantify the effects. The measurements in the different facilities agreed qualitatively.
The collaboration between 3 institutions has lead to results which could not be achieved by a single Institution on its own. A large data base was created. It can be used to better understand the noise reduction effects of trailing edge serrations. It is important to continue with an in depth data analysis and harvest the benefits of the work that has been conducted so far.

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