Experimental investigation of novel, low-noise turbine blade tip designs

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Introduction

The vortex that is generated at the tip of wind turbine blades is a significant source of flow-induced noise and as such is a major limitation to the expansion of wind power. In order to better understand the noise generation at the blade tip, an extensive wind tunnel study was performed on model blades with different tip geometries (for example flat or rounded tips). This was done both for the case of natural transition as well as for forced transition of the boundary layer. In a second step, additional experiments were performed on a set of novel blade tips, which were modified with either perforations, serrations or endplates. The aim of this project, which is a collaboration between researchers from Germany and Australia, is to empirically determine tip designs that lead to a notable noise reduction while maintaining the aerodynamic performance of an unmodified tip. In addition to acoustic microphone array measurements, hot-wire measurements were conducted to help analyze the effect of the modifications on the flow field around the blade tips.

The current paper presents an overview of the extensive experimental study and the resulting large dataset, using some examples to demonstrate first results.

Experimental Setup

Aeroacoustic Wind Tunnel

All experiments took place in the small aeroacoustic open jet wind tunnel at the Brandenburg University of Technology in Cottbus [1], using a nozzle with a rectangular exit area with a size of 0.23 m × 0.28 m. An acrylic glass side plate was attached to one side of the nozzle (see Figure 1), which allowed the mounting of different blade tips with different geometric angles of attack α. Measurements were conducted at flow speeds U between approximately 5 m/s and 51 m/s, leading to chord-based Reynolds numbers Re between 25,000 and 235,000 in steps of 25,000. Geometric angles of attack between -10° and 20° were adjusted.

Acoustic Measurements and Data Processing

The acoustic measurements were performed using a planar microphone array, which was positioned above the blade tips and outside of the flow. The array consists of 56 flush mounted microphones, however, for the present investigation, only 47 of the microphones were used. This was due to the fact that the remaining microphones were blocked from the blade tip by the acrylic side plate. In addition to the microphone array, six single microphones were used. Five of them were positioned along a vertical line at the side of the blade tip, while another one was located below the blade tip (see Figure 1). The results presented in this paper will focus on the results obtained with the microphone array only.

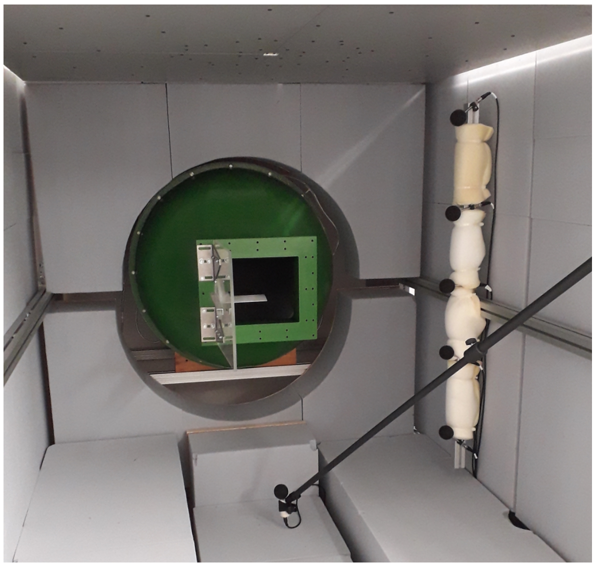

Figure 1: Experimental setup in the aeroacoustic wind tunnel.

All measurements were conducted with a sampling frequency of 51.2 kHz and a duration of 40 s. In post processing, which was done using the open-source code *Acoular* [2], the data were first transferred to the frequency domain using a fast Fourier transformation. This was done blockwise with 50 % overlapping, Hanning-windowed blocks. The block size was chosen depending on the examined cases: When narrowband spectral characteristics were investigated, for example for the cases with natural transition, it was set to a rather high value (for example 16,384 samples), while for the cases with forced transition (e.g. when the blades were tripped) only the broadband characteristics were of interest and each block contained 4,096 samples. The averaging of the resulting auto spectra and cross spectra of the array microphones yielded the cross spectral matrix, which was further processed using the CLEAN-SC beamforming algorithm [3]. This was done on a two-dimensional focus grid with a resolution of 0.01 m. From the resulting sound maps, sound pressure level spectra were obtained by integrating over sectors that contained distinct noise source regions, such as the tip of the blade as well as its leading edge or trailing edge (excluding the tip region).

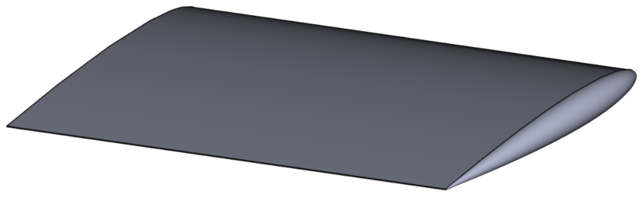

Figure 2: CAD drawing of a NACA0012 airfoil with rounded tip.

Constant Temperature Anemometry Measurements

In order to help understand the mechanisms responsible for the noise generation, hot-wire anemometry measurements were conducted for selected blade tips. They were done using a Dantec P54-type X-wire probe, which was oriented in such a way that the velocities both in the streamwise (x) direction as well as in the direction normal to the flow and normal to the span of the blades (the upwash component, z) were measured. The measurements were done in a plane downstream of the blade tips and normal to the flow. The probe was positioned using a three-dimensional traverse system. From the resulting data, the mean components in both directions as well as the turbulence intensity were calculated.

Blade Tip Designs

In total, three different investigations were conducted: The first one was aimed at understanding the noise generation of blades with either flat or rounded tips. For these experiments, both uncambered (NACA0012, NACA0015 and NACA0018) and cambered airfoils (NACA2412, NACA4412 and NACA6412) were used, which were manufactured from aluminum. A schematic of a NACA0012 airfoil with rounded tip is shown in Figure 2.

The second investigation focused on the effect of both serrated tips and flow-permeable tips of NACA0012 and NACA6412 airfoils on the resulting noise generation compared to the noise from the reference blades with flat or rounded tips. The serrations were defined regarding their amplitude and their wavelength using a sinusoidal function, the corresponding blade models were also manufactured from aluminum. The perforated tips, however, were 3D-printed from resin and mounted to an aluminum base wing (a schematic of one of the perforated tips is shown in Figure 3). They consisted of a tip with regular circular pores with different diameter and spacing. In total, eleven different serrated tips and nine different porous tips were used for the study.

The third investigation aimed at analyzing the aeroacoustic effect of endplates on NACA0012 and NACA4412 airfoils. Motivated by a past study on the positive effect of such endplates on the aerodynamics of an airfoil [4], a set of five different endplate designs was chosen from that study. This included circular plates, rectangular plates of different dimensions as well as triangular and trapezoidal plates. Endplates with thicknesses of 2 mm and 5 mm were manufactured from polyurethane.

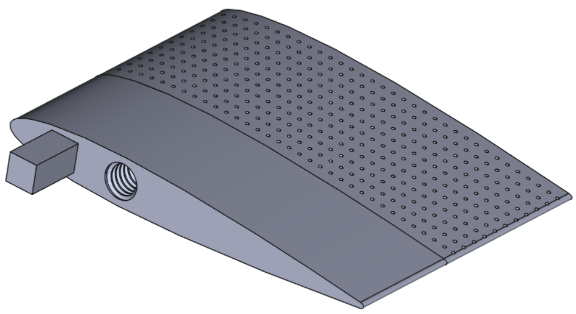

Figure 3: CAD drawing of one of the flow permeable blade tips.

In each case, the chord length s of the airfoil was 69 mm, while the span width b was 140 mm, resulting in an aspect ratio b/s of approximately 2. Each configuration was tested with both natural boundary layer transition (e.g. untripped) and forced boundary layer transition (where the blade was tripped with zig-zag trip tape applied at 10 % of the chord on both suction side and pressure side).

Experimental Results

Example 1: Comparison of Flat and Rounded Blade Tips

In a first step, the noise generated by blades with flat and rounded tips was analyzed. The full acoustic dataset from this investigation is openly available for the research community (see [5]).

As an example, Figure 4 shows third octave band sound pressure level spectra obtained for a NACA0012 airfoil, with flat and rounded tip at a geometric angle of attack of 10° and a Reynolds number of 150,000. Results for forced transition (tripped) as well as natural transition (untripped) of the boundary layer are shown. The spectra were obtained by integrating the sound maps over a sector that contained the whole airfoil (leading edge, trailing edge and tip) with the exception of the wall junction. Due to the relatively high angle of attack, the spectra obtained for the untripped airfoils are similar to those obtained for the tripped airfoils. It is visible that for both conditions the rounded tip leads to a notable noise reduction, especially for the tonal noise peak that can be seen at a third octave band center frequency of 10 kHz (for the tripped airfoil) and 8 kHz (for the untripped airfoil).

Figure 5 then shows sound maps obtained for the NACA0012 airfoils with flat and rounded tips at the third octave band that contains the tonal noise peak, as observed in Figure 4, confirming that the major noise source at this frequency is indeed the wing tip.

In addition, Figure 6 shows the turbulence intensity

$$Tu = \frac{\sqrt{\tilde{u}^2 + \tilde{w}^2}}{U}, \qquad (1)$$

measured in a plane normal to the flow, at a distance of 1 mm downstream from the trailing edge of the untripped blades. In Equation (1), $\tilde{u}$ and $\tilde{w}$ are the rms values

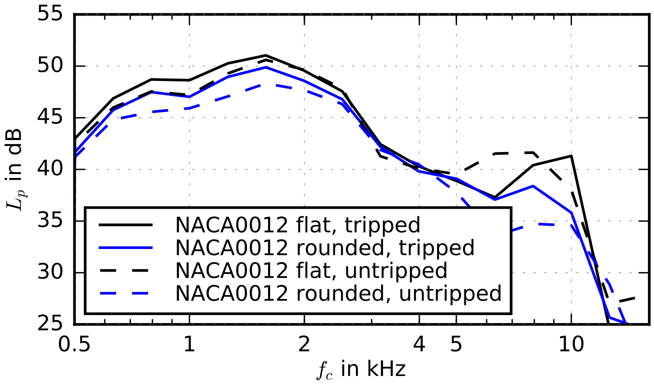

Figure 4: One-third octave band sound pressure level spectra obtained for NACA0012 blades with flat and rounded tips at an angle of attack of 10° and a Reynolds number of 150,000.

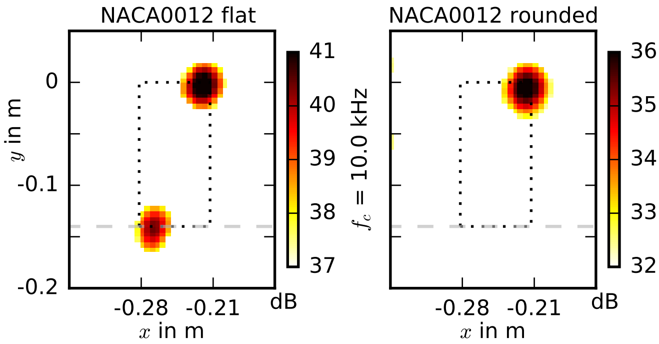

Figure 5: One-third octave band sound maps obtained for tripped blades with flat and rounded tips at an angle of attack of 10° and a Reynolds number of 150,000, using conventional delay-and-sum beamforming [6] (flow from left to right, dotted black line represents airfoil, dashed gray line represents side plate).

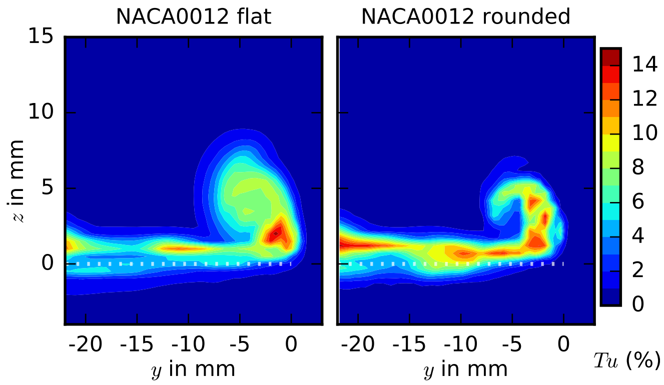

Figure 6: Turbulence intensity obtained in a downstream plane for untripped blades with flat and rounded tips at an angle of attack of 10° and a Reynolds number of 150,000 (dotted white line represents location of airfoil trailing edge).

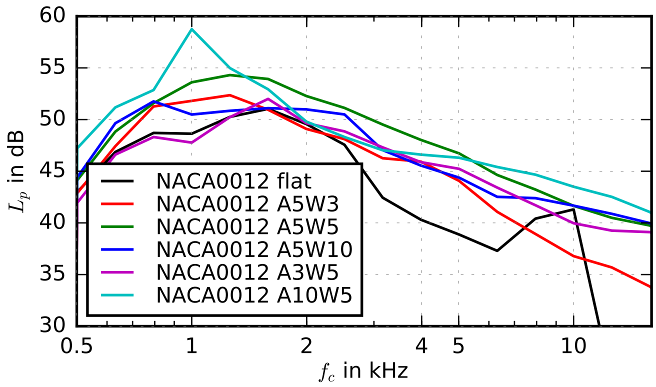

Figure 7: One-third octave band sound pressure level spectra obtained for tripped blades with serrated tips at an angle of attack of 10° and a Reynolds number of 150,000 (see Table 1 for details on the tip geometry).

of the velocity in x- and z-direction, respectively. Both plots show the tip vortex very clearly. Interestingly, it is visible that, although the rounded edge leads to a notable noise reduction (Figure 4), the turbulence intensity is not reduced, but rather slightly increased compared to the airfoil with flat tip.

Example 2: Blades with Serrated or Porous Tips

As a second example, Figure 7 shows sound pressure level spectra obtained for a NACA0012 airfoil with different serrated tips, while Figure 8 shows results for the same airfoil with porous tips. The corresponding tip configurations are described in Table 1 and Table 2, respectively[1]. Again, the full dataset obtained for the serrated tips and porous tips is openly available [7].

The results shown exemplarily for the serrated tips (Figure 7) reveal that in this case the serrations lead to an overall increase in noise compared to the flat tip. Still, it is visible that the spectra for the wings with serrated tips do not show the strong tonal peak due to the tip vortex, which can be seen for the airfoil with flat tip. This is most likely due to the fact that the serrations reduce the effective streamwise length of the tip, and hence no strong tip vortex forms. However, it is possible that a shedding of smaller vortices occurs at each serration.

The acoustic effect of flow permeable tips is then shown in Figure 8. It can be observed that all porous tips lead to a notable noise reduction at frequencies approximately below 3 kHz, which is in the order of 2 to 3 dB. However, at higher frequencies, nearly all of the porous tips lead to a strong noise increase. This additional noise generation increases with increasing diameter of the pores (see Figure 3 and Table 2). Based on a previous study on porous airfoils [8], this leads to the conclusion that the noise increase may be caused by a contribution of roughness noise.

Example 3: Blades with Endplates

Finally, Figure 9 shows the effect of different types of endplates on the reduction of the noise induced by the tip vortex. They had a rectangular, circular or trapezoidal shape and a thickness of 2 mm. Basically, it can be seen that all three endplates lead to a suppression of the tonal peak caused by the tip vortex. Again, accompanying hot-wire measurements were performed that confirmed this effect (not shown here for brevity). In

[1] Please note that the tables do not contain all configurations, but only those used in the present paper.

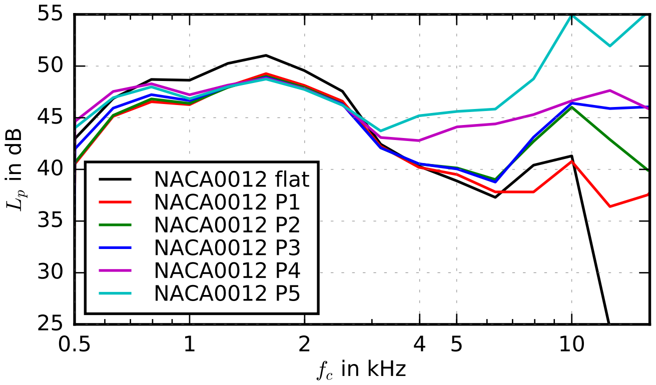

Figure 8: One-third octave band sound pressure level spectra obtained for tripped blades with porous tips at an angle of attack of 10° and a Reynolds number of 150,000 (see Table 2 for details on the tip geometry).

Table 1: Descriptions of serrated tips included in Figure 7

Tip	Amplitude (mm)	Wavelength (mm)	Number of chord-wise wavelengths
A5W3	5	23.3	3
A5W5	5	14	5
A5W10	5	7	10
A3W5	3	14	5
A10W5	10	14	5

addition, notable differences between the different endplates are visible in the sound pressure level spectra at frequencies below 1.6 kHz. A corresponding publication with more detailed results is in preparation.

Summary and Outlook

Noise resulting from the interaction of a tip vortex with a blade is a major contribution to the overall noise from wind turbines. A recent experimental study aims at the reduction of this noise source through different modifications of the blade tip. This includes rounded, serrated and porous tips as well as the addition of endplates. The experiments were conducted in an aeroacoustic wind tunnel and included microphone array measurements and hot-wire anemometry measurements. The present paper shows first results of the study, which reveal that several of the modification are indeed very effective for the reduction of flow-induced noise at the tip.
In a follow-up to the wind tunnel study presented here, detailed measurements were performed on the most promising configurations in a rotor test rig at the University of New South Wales in Australia. These measurements will provide information on the usability of the modifications when applied to a set of rotating blades.

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Table 2: Descriptions of porous tips included in Figure 8

Tip	Pore diameter, top (mm)	Pore diameter, side (mm)	Porosity (%)
P1	0.6	0.6	13.8
P2	1	0.6	27.2
P3	1	0.8	31.2
P4	1.6	1.6	40.4
P5	2	2	50.0

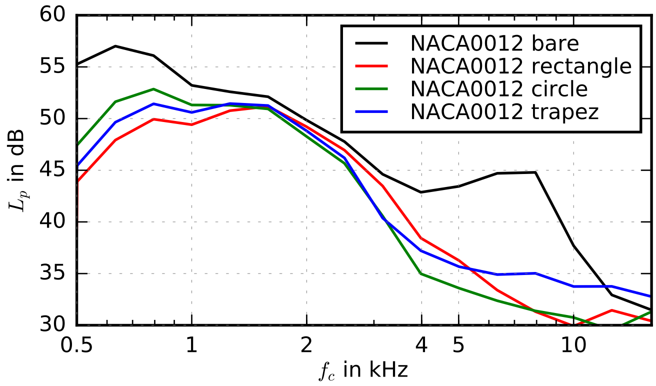

Figure 9: One-third octave band sound pressure level spectra obtained for tripped blades with different endplates at an angle of attack of 15° and a Reynolds number of 150,000.

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