Numerical Investigation on the Noise Generation of Iced Wind Turbine Airfoils

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This paper is based on the final thesis of Richard Hann "Aeroakustische Analyse vereister Profile einer Windenergieanlage" completed in the period September 2012 till February 2013 at the University of Stuttgart, Germany. The intention of the research was to investigate the influence of atmospheric icing on the noise emission of modern wind turbines. The results of the thesis were presented at the international wind energy conference WINTERWIND 2013 in Östersund, Sweden.

Introduction

The vast development of wind energy within the last decade has led to an increased awareness of the public to noise pollution. This has resulted in today's strict noise regulations and substantial scientific efforts to understand and decrease wind turbine noise. However, very little work has been done to take into account the special conditions in cold climate regions. This study takes a first approach to investigate the increased noise generation of iced airfoils and blades for wind turbines in cold climate using numerical simulation.

The main source of wind turbine noise is aerodynamic noise, which is caused by the interaction of the rotor blade surface with turbulent eddies [14]. These turbulences are either pre-existing in the incoming airflow due to natural atmospheric processes or generated in the boundary layer around the airfoil by viscous effects. The latter mechanism is defined as airfoil self-noise and is in general considered to be the overall dominating noise source for modern wind turbines [14]. In particular, two mechanisms can be identified that are relevant to aerodynamic noise in cold climate conditions. First, trailing-edge (TE) noise is induced by the interaction of turbulent eddies with the sharp trailing-edge, figure 1 [14]. This creates a strong broadband noise, which is the single most relevant noise source for regular (i.e. un-iced) wind turbines [12]. Second, if airflow detaches from the surface of the airfoil, it causes a separation bubble that subsequently generates vortexes, which are a potential noise source, figure 2 [14]. Separation noise is usually not relevant for modern wind turbines, since flow detachments only occur on a minor scale [7]. However, in cold climates, atmospheric icing can lead to the accretion of an ice horn on the leading-edge (LE) of the rotor blade [11]. The resulting ice geometries typically induce local flow separation, e.g. figure 3. On the one hand, this separation bubble will highly increase the turbulence in the boundary layer around the entire airfoil and thus enhancing trailing-edge noise. On the other hand, the flow detachment itself creates a vortex that also might create significant noise levels at the trailing-edge.

In order to investigate the influence of icing on the airfoil self-noise, both of these mechanisms (TE- and LE-noise) have to be considered. The goal of this research is to use numerical methods to analyze the relevance of the leading-edge separation noise and to compare it to the trailing-edge noise, for various icing conditions. Therefore two questions are to be answered: how much noise is generated by an iced leading-edge and how does it compare to the – thereby increased – trailing-edge noise?

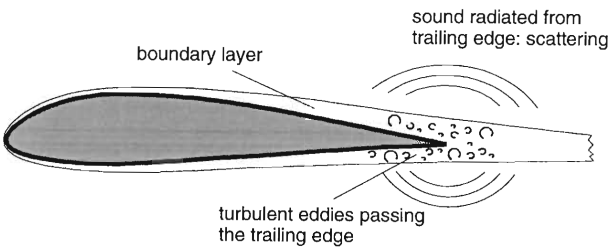

Figure 1: Principal mechanism of trailing-edge noise [14].

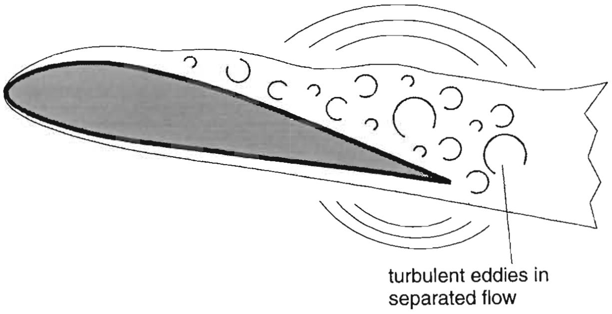

Figure 2: Principal mechanism of separation noise [14].

Methods

A general overview of the employed simulation chain is presented in figure 4. The input variables consist of a clean airfoil geometry, aerodynamic parameters and meteorological conditions. The result of the numeric simulations is a frequency spectrum of the expected noise levels.

For the creation of 2-d iced airfoil geometries, LEWICE 3.2.2 is being used [15]. LEWICE has been developed by the National Aeronautics and Space Administration (NASA) mainly for aircraft purposes, but has been successfully applied for wind turbine icing problems in the past. Three different meteorological icing conditions have been selected in order to determine the influence of different icing typologies (glaze, mixed, rime) on the noise generation, which are described in table 1 and figure 5.

The airflow around the iced airfoils is calculated with TAU, a computational fluid dynamics (CFD) code, developed by the German Aerospace Center (DLR) [3]. TAU uses a finite-volume method to solve the Reynolds-averaged Navier-Stokes (RANS) equations, considering compressible and viscous flow effects. In table 2 the most important geometrical and aerodynamic parameters are summarized. All investigated cases (iced and clean) did not show any instationary flow behavior in the CFD simulations, Therefore stationary flow conditions were assumed for the acoustic analysis.

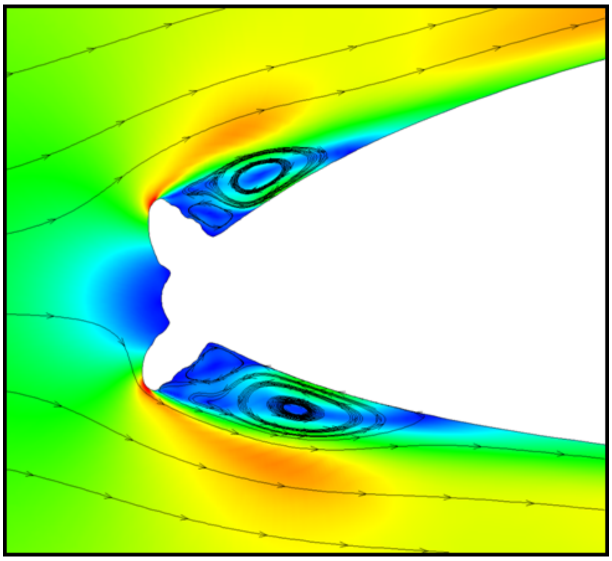

Figure 3: Flow separation on the leading-edge due to icing.

For the simulation of the noise generation two different computational aeroacoustic (CAA) approaches are used. PIANO is a modern aeroacoustic code which was developed by the DLR in order to investigate aircraft airframe noise [2]. PIANO utilizes statistical noise theory and is thus a very versatile tool, that can be used to simulate numerous noise generation mechanisms (e.g. noise emissions of high-lift systems, landing gear, jet engine turbine blades, combustion and airfoils), as well as far-field noise propagation [1]. A finite-differences method is used to solve the acoustic perturbation equations (APE) according to Ewert and Schröder [6]. To simulate the wave propagation in inviscid, unsteady flows, the following equations are evaluated [2]:

$$\frac{\partial p'}{\partial \tau} + a^2 \nabla \cdot \left(\rho\, u' + u\, \frac{p'}{a^2} \right) = a^2 \cdot q_c \qquad (1)$$

$$\frac{\partial u'}{\partial \tau} + \nabla (u \cdot u') + \nabla \cdot \left(\frac{p'}{\rho} \right) = q_m \qquad (2)$$

The momentum source q_m and the convective source q_c represent acoustic source terms that are induced by turbulent eddies [4]. While the convective part can be neglected, the momentum term (also referred to as Lamb vector) can be estimated using a fast random particle mesh (FRPM) method [5]. Therefore this stochastic approach creates a field of unsteady sound sources in a specified area from a steady CFD solution. The location of the noise source (FRPM patch) is chosen either at the leading-edge separation bubble or at the sharp trailing-edge. The FRPM patch generates instationary acoustic perturbations, which have identical time-averaged turbulent properties to the RANS simulation. With this approach, PIANO is suitable to simulate leading-edge separation noise and trailing-edge noise. It should be noted, that the involved calculations are very complex and thus the computational requirements are very high.

For this reason a second acoustic method is being used. RNOISE is an acoustic code specifically designed to estimate broadband wind turbine trailing-edge noise developed at the Institute of Aerodynamics and Gas Dynamics (IAG) at the University of Stuttgart [10]. It is based on the solution of a simplified theoretical model, that has been introduced by PARCHEN [13]:

$$P(k_1, k_3, \omega) = 4\rho^2 \cdot \left(\frac{k_1^2}{k_1^2 + k_3^2}\right) \cdot \int\limits_0^{+\infty} \Lambda_{t2}(y) \cdot \overline{u_2^2} \cdot \left(\frac{\partial U}{\partial y}(y)\right)^2 \cdot \Phi_{22}(k) \cdot \Phi_m \cdot (\omega - U_c(y) \cdot k_1) \cdot e^{-2|k|\,y} \,\mathrm{d}y \tag{3}$$

$$S(\omega) = \frac{L}{4\pi R^2} \cdot \int\limits_{-\infty}^{+\infty} \frac{\omega}{a \cdot k_1} \cdot P(k_1, k_3, \omega)|_{k_3=0} \,\mathrm{d}k_1 \tag{4}$$

Here, the wall pressure fluctuations in the boundary layer near the trailing-edge (eq. 3) are evaluated in order to approximate the far-field acoustic noise spectrum $S(\omega)$ (eq. 4) in the distance of R. The information about the turbulence at the trailing-edge are extracted from the same RANS solutions that are used for PIANO.

Mesh generation is realized with the commercial tool POINTWISE V17.0. For TAU a hybrid mesh is applied, with a structured boundary layer and an unstructured far-field. The number of points on the airfoil surface have been determined by grid convergence analysis. For clean airfoils 160 points are used on the upper and lower surface each. The boundary layer is discretized with 55 layers. Ice horns are resolved with approximately 200–300 points. PIANO requires a fully structured H-grid with a grid solution of $\Delta x_{\text{Acoustic}} = 2 \times 10^{-3}\,\text{m}$ in the acoustic domain in order to capture the far-field noise propagation. For the noise generation in the FRPM patch a very fine resolution of $\Delta x_{\text{FRPM}} = 1.5 \times 10^{-4}\,\text{m}$ is required.

	Glaze	Mixed	Rime
Icing time τ	30 min	30min	30 min
Temperature t_∞	-2 °C	-5 °C	-10 °C
Mean volume diameter MVD	20 μm	20 μm	20 μm
Liquid water content LWC	0.59 g/m³	0.53 g/m³	0.43 g/m³

Table 1: Meteorological parameters used for the characteristic ice geometries.

Airfoil	DU96
Chord c	0.7 m
Reynolds number Re	3.79×10^6
Mach number Ma	0.21
Angle of attack α	-0.74 °
Temperature T	268.15 °K

Table 2: Airfoil and aerodynamic parameters.

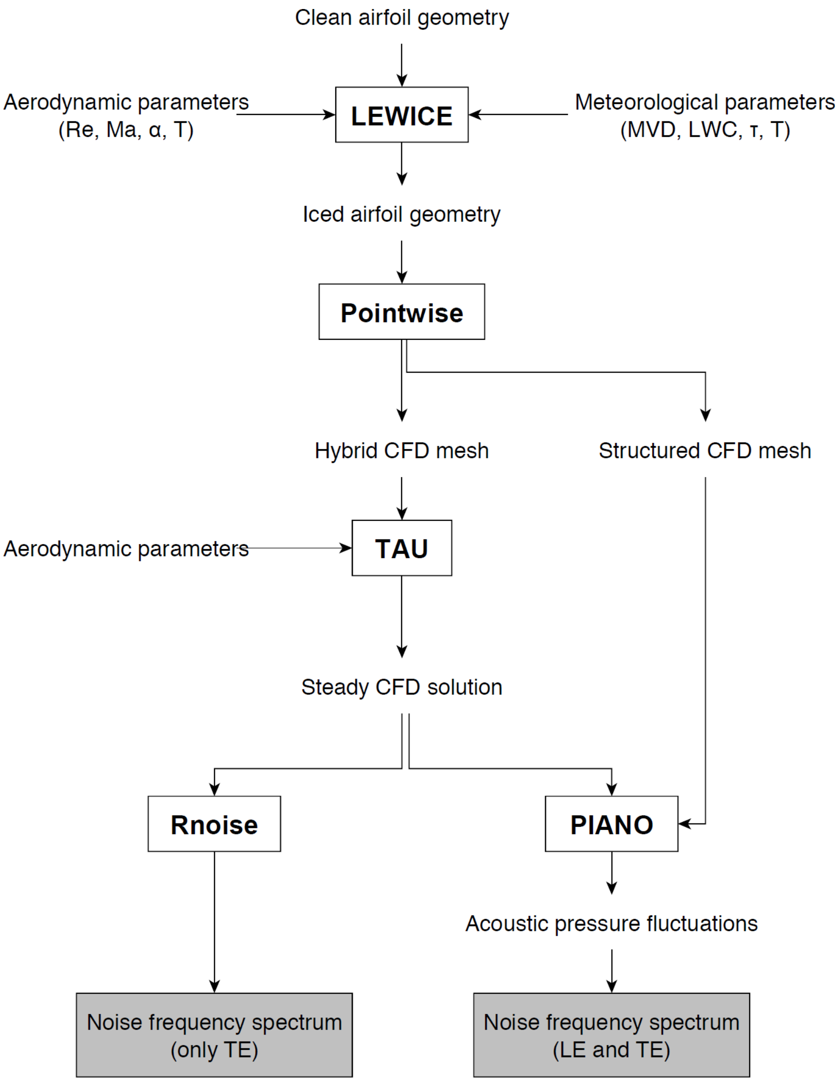

Figure 4: Flowchart of the simulation process chain.

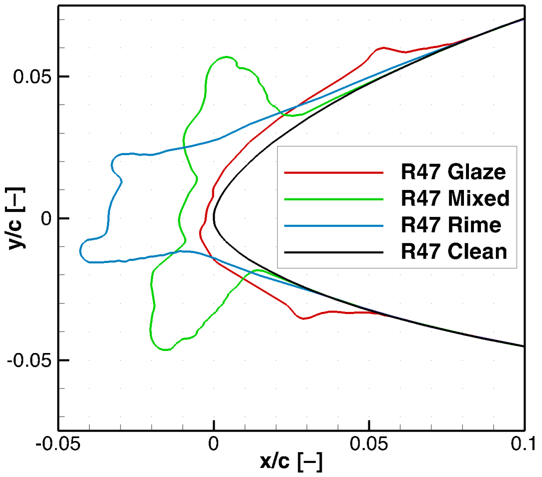

Figure 5: Comparison of the iced airfoil geometries generated by LEWICE.

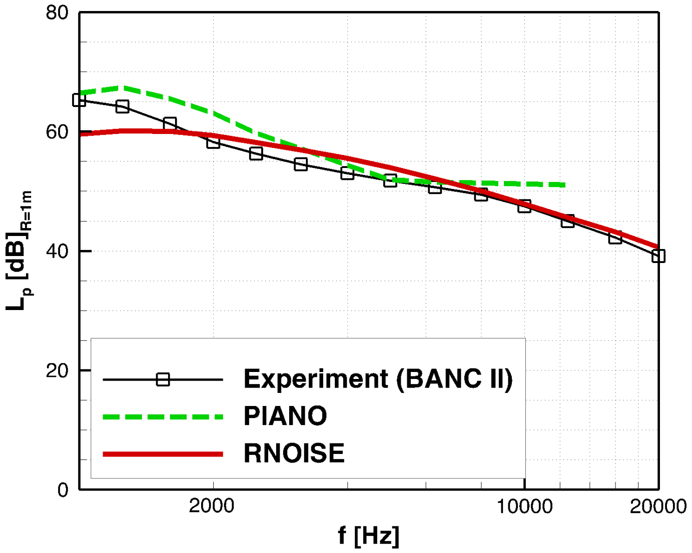

Figure 6: Validation results for PIANO and RNOISE for the BANC-II experimental data.

Validation

In order to ensure the quality of the simulation results, it is paramount to verify them with experimental data. Unfortunately at the present time, there were no experimental acoustic wind tunnel measurements available for iced airfoils. Therefore, the decision was made to thoroughly validate each step of the simulation chain (LEWICE, TAU, PIANO/RNOISE), with the intent to prevent significant error accumulation. In the scope of this paper, only the results of the acoustic validation of PIANO and RNOISE are presented. The numerical results are compared with experimental data of trailing-edge noise which were provided by the BANC-II workshop [9]. Here, the test case #5 for a DU96 (a commonly used wind turbine) airfoil was selected for the validation. The reference point for all noise levels is at 1 m distance in a 90 ° angle, above the the trailing-edge.

The validation results are presented in figure 6. Both simulation methods seem to be consistent with the experimental data. The RNOISE results show very good agreement at higher frequencies and a slight deviation below 2 kHz. A possible explanation might be, that in reality a small separation bubble can be found at the trailing-edge of the DU96 airfoil, which could not be reproduced in the CFD calculation with TAU. In most parts the PIANO results show a similar trend as the experimental data, with an offset of about 3 dB. Above 10 kHz a larger deviation can be detected. The maximum frequency to which PIANO can capture sound waves is determined by the grid resolution of the acoustic domain and the FRPM patch. The grid has been chosen to represent frequencies up to 12.5 kHz. In the vicinity of that limit, jamming can occur because the resolution is too coarse to fully capture small scale turbulent eddies.

In conclusion, both numerical approaches prove to have the capability to simulate trailing-edge noise with an acceptable accuracy. Nevertheless, it has to be stated, that there are small deviations from the experimental data. This implies that the numerical results have certain limitations and should not be trusted unconditionally. However, the goal of these investigations is to compare the noise emissions between clean and iced airfoils and not to find absolute noise levels. Therefore the given accuracy is assumed to be sufficient.

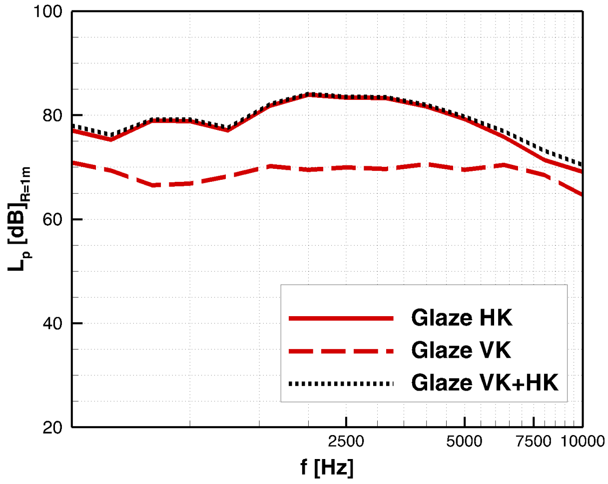

Figure 7: Comparison of LE and TE noise levels for glaze.

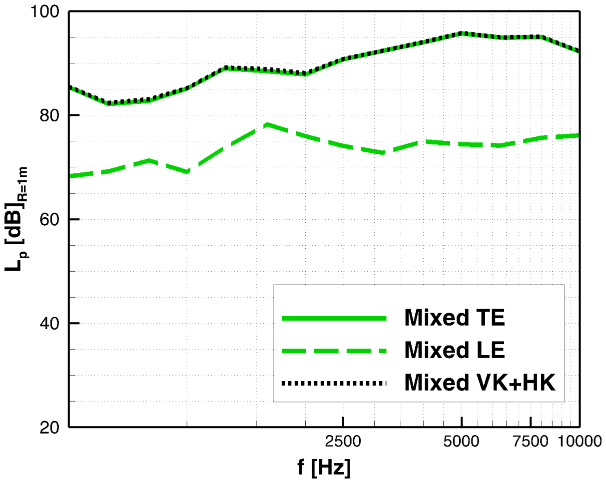

Figure 8: Comparison of LE and TE noise levels for mixed.

PIANO

PIANO is used to compare the broadband leading-edge separation noise with the trailing-edge noise for the three characteristic icing cases presented in figure 5. The simulation results of the leading-edge noise for the clean and rime configuration did not yield any significant information. Both these cases show a smooth leading-edge geometry, which results in low turbulence in that region. This means that the turbulent eddies in the boundary layer are very small and cannot be captured by the chosen PIANO grid resolution. Further investigations with a refined grid were not conducted, because the necessary computational costs would be extremely high. However, it is known that clean airfoils do not emit relevant leading-edge noise and the separation bubble for rime is relatively weak [14]. Therefore it is assumed that for clean airfoils and for rime icing leading-edge noise can be neglected.

The simulation results for glaze and mixed are presented in figure 7 and 8. In both cases a strong flow separation will occur at the leading-edge ice accretion, therefore increasing kinetic turbulent energy in the boundary layer. On the one hand, this means that the separation bubble itself will generate significant noise levels. On the other hand, the trailing-edge noise will be increased as well due to the increased overall turbulence. When compared, both icing cases show a similar behavior. The sound pressure levels at the trailing-edge are higher than at the leading-edge. Sound pressure levels L_p are measured in decibels and addition has to be done logarithmically. Therefore higher sound pressure level will always dominate over lower levels, here $L_{p,Total} = L_{p,LE} + L_{p,TE} \approx L_{p,TE}$. This means that the leading-edge noise can be neglected and that the trailing-edge noise is the only relevant noise source. In addition, it can be seen, that the noise levels for mixed are considerably higher than for glaze. The reason for this can be found in the intensity of the flow separation, which is stronger for mixed.

Rnoise

The PIANO results from above show, that trailing-edge noise seems to dominate in all cases over the leading-edge noise. Since only trailing-edge noise is relevant, the faster RNOISE approach can be applied. In order to get a broader perspective on the influence of icing on the noise emissions,

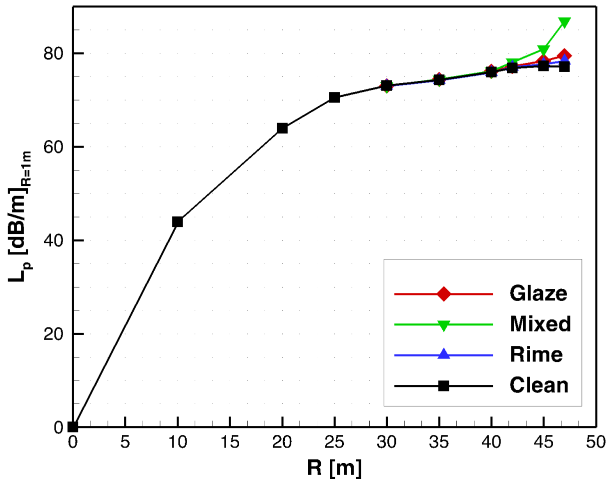

Figure 9: TE noise (RNOISE) for the rotor blade.

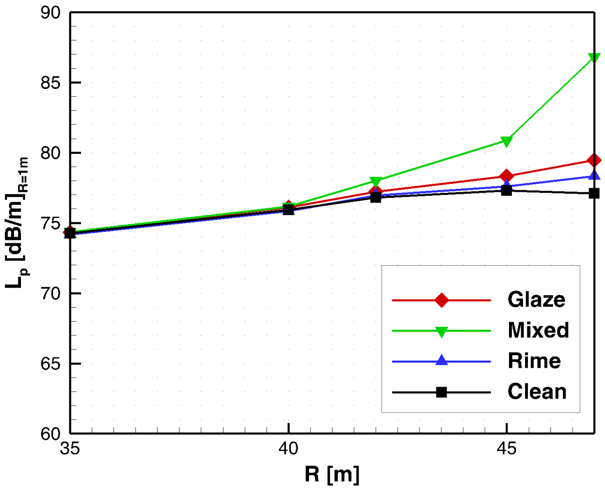

Figure 10: TE noise (RNOISE) for the blade tip.

an entire rotor blade is investigated for different icing conditions. For this a generic model blade of a 2.5 MW wind turbine with a rotor diameter of 100 m is used. Again, the three characteristic icing conditions from table 1 are considered. Figure 9 and 10 show the resulting noise levels for selected 2-d intersections. As usual for wind turbines, the noise emissions are the highest on the outer third of the rotor blade, which is due to the higher flow velocities in that region. Also, it can be observed, that icing only affects the noise emission of the outer part of the blade. The reason for this can be found in the size of the ice accretions. On the inner part of the blade, the resulting ice geometries are so small, that they do not significantly increase the turbulence in the boundary layer. On the outer blade, starting from a rotor radius of $R = 42\,\mathrm{m}$, strong effects of icing on the noise emissions can be detected. At this point it should be noted again, that these simulations are not quantitatively representable. For instance, only a comparatively small amount of sampling points are chosen and all 3-d effects are neglected. Also, the reference point for the 2-d noise levels is again 1 m from the trailing-edge. However, these results yield enough information to find some qualitative conclusions. It can be clearly observed, that the meteorological conditions have a significant impact on the intensity of noise increase. In case of mixed ice – where the strongest flow separation occurs – noise levels are increased up to 10 dB. Glaze seems to have a much lower influence on the noise levels. For rime, the resulting ice geometries are relatively smooth, which means that the increase in turbulence, and thus noise, is low.

Conclusion

First, it should be noted, that – as with every numerical approach – there are certain limits to the validity of the results, which are due to simplifications in modeling and simulation. Since there are no experimental aeroacoustic wind tunnel measurements for iced airfoils, it is not possible to verify the quantitative significance of the found numerical results. Overall, there are several aspects indicating that the increase in noise levels is rather underestimated in this work. For instance, the additional ice surface roughness has been neglected in all of these simulations. The ice surface roughness is likely to increase the turbulence in the boundary layer and thus increase leading- and trailing-edge noise [8]. In addition to this, the simulated ice geometries by LEWICE are relatively smooth and not as “rugged” as in reality. Also, the number of grid points for the discretization of the ice horn were restricted to keep computational requirements low. All these aspects may lead to less induced turbulence and hence a lower noise increase due to icing than in reality. In total, this means that all the numerical results lack quantitative certainty.

However, there is no evidence preventing to draw the conclusion of qualitative statements. The results yield a number of important information, that are valuable for further research and development. Most import of all, the numerical simulations with PIANO indicate, that trailing-edge noise is dominating over leading-edge separation noise, even for quite extreme ice formations. This means that for further research on the influence of icing on wind turbine noise only trailing-edge noise has to be considered and thus it is sufficient to use simplified and well established numerical tools.

Using RNOISE, it has been shown, that site-specific meteorological conditions might have a very distinct impact on the intensity of increased noise levels. Furthermore the results indicate, that ice accretions only influence the noise generation in the outer part of the rotor blade. This means, that it is sufficient to install anti- or de-icing systems in that area, in order to prevent increased noise levels. However, since de-icing systems generally allow the accretion of certain amounts of ice before their activation, further research should be done to assess their effectiveness to prevent noise.

Finally, the used simulation process chain proved, that it is possible to determine the impact of characteristic meteorological icing condition on the noise generation of a specific rotor blade. This overall approach could be used in the future in order to estimate the effect of increased noise due to icing in the planning process of new wind turbine projects.

Summary and Outlook

The research results clearly indicate that ice accretion will increase noise levels of wind turbines. Since no quantitative conclusions can be made, it seems advisable to include a minimal buffer of at least 10 dB when considering noise emissions from wind turbines in cold climate conditions. In order to verify and deepen these preliminary results, more research needs to be done. An important first step would be the generation of suitable experimental data for the validation of numerical models. Also, field measurements are required in order to assess the overall effect on the 3-d noise generation and to identify potential tonal noise sources.

In addition, there are a couple of numerical simplifications that could be reviewed in further investigations. Most of those simplifications were chosen merely to limit the computational costs. More refined geometries and the incorporation of 3-d effects can be adapted to this simulation chain with reasonable efforts. An aspect that needs deeper understanding and more intensive research is the influence of the additional surface roughness due to icing.

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