CAA/CFD based noise prediction for wind turbines affected by leading-edge erosion

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Introduction & Motivation

Leading-edge (LE) erosion can cause significant damage to wind turbine rotor blades, which may lead to environmental impacts including both material release into the environment and altered noise emissions from the turbine. The assumption of erosion damage in the preliminary work by Guembel [1] is based on descriptions from the literature, which are derived from field data. The resulting material loss is summarized as a function dependent on the blade length. For an average three-bladed onshore turbine in Germany, a maximum material loss of 139 kg over a 20-year lifespan is estimated. Together with that comes a simplified geometrical description of the damaged LE, which can be used for noise prediction. This description shows a radial distribution of the erosive damage related to the blade radius.

This paper combines the results from [1] with an efficient 2D CAA based noise prediction for wind turbines[2]. The complex damage is simplified by a forward step geometry and turbulent trailing-edge noise contributions of the turbine are summarized and extrapolated from 2D CFD/CAA computations.

Erosion process and extrapolation onto the blade

Leading edge erosion occurs as a result of repeated impact of particles at high velocities. These can be rain, ice, sand, dust and other particles. Environmental influences such as temperature, humidity, UV radiation, exposure to chemically active substances such as bird droppings, insects or even dissolved substances in the atmosphere also play a role. The surface of the rotor begins to roughen, cracks, pits and gouges appear and finally delamination occurs. This damage can onset after only 2-3 years in operation [3].

Due to the high peripheral speeds, the damage is most severe at the blade tip and decreases towards the hub. Along the chord length, the leading edge erosion spreads from the stagnation point towards the trailing edge. Sareen et al. [4] have precisely measured and classified various types of damage in extensive field data from onshore and offshore wind turbines. In [5] a weighting of the damages related to the rotor radius has been implemented. In [1] these data sets are now combined in order to estimate the erosive damage, the material loss and following from that the material entry into the environment for a standard turbine.

Erosion has so far been considered with a focus on wind turbine power output. Estimates of annual power losses range from a few percent to 25% [6]. The power loss below the rated speed is particularly high[7]. The change in the leading edge, additional roughness and formation of a step has a particular effect on the development of the boundary layer, the additional thickening of the boundary layer at the trailing edge and also on the transition position. In the case of an unaffected blade, the rotation effects stabilize the laminar boundary layer, whereas severe damage leads to a transition directly in the vicinity of the leading edge.

Due to the changed boundary layer development, it can be assumed that there must also be a significant influence on the trailing edge noise. This will be analyzed in this article using a 2D hybrid CFD/CAA Hifi method and fast extrapolation to the overall turbine.

Simulation method and settings

The simulation method is analogous to the procedure in [8]. The idea is that the rotor blade is represented with a few 2D sections instead of full 3D. For an operating point, the local flow conditions are determined using a blade element method, here QBLADE[9], and 2D RANS and 2D CAA simulations are performed with the DLR codes TAU and PIANO/FRPM. A total of 3 configurations are considered:

- FIX: natural transition, unaffected LE surface
- FUL: fully turbulent, unaffected LE surface
- ERO: fully turbulent, eroded LE surface

The transition position is based on a result from a very similar turbine at similar operation conditions [10]. Since no 3D CFD simulations were carried out as part of [1], but the rotation effect or cross flow is of decisive importance for the transition position, this was the most effective way. For the rotor blade, only the trailing edge noise is modeled in this work. Although the method can also take into account separation and leading edge noise, this is of secondary importance for the comparison between eroded and undamaged leading edge. Furthermore, an operating point was selected at which no detachments occur in the outer third of the rotor blade.

PIANO/FRPM is used to simulate the trailing edge noise for the 2D sections. The averaged turbulence statistics of the RANS are used to model temporally fluctuating acoustic sources with the stochastic source model FRPM [11] (Fast Random Particle Mesh Method).

The modeling of the trailing edge noise uses a vortex sound source in which the linearized Lamb vector (Eq. 1) is modeled. The index 0 denotes the magnitudes of the base flow, the index t those of the turbulence statistics.

ϵ_{ijk} is the Levi-Civita symbol. v^0 is the base flow vector from the RANS and v^t the vector of turbulent velocities modeled by FRPM. ω denotes the respective vorticity, also from the RANS and modeled from FRPM. The basic flow is taken into account for the sound propagation.

$$L_i' = -\epsilon_{ijk}\omega_j^0 v_k^t - \epsilon_{ijk}\omega_j^t v_k^0 \qquad (1)$$

The question arises as to how the eroded blade geometry can be taken into account in the CFD. On the one hand, it is conceivable to use the surface roughness. However, the DLR TAU code can only take into account roughness heights that are below the logarithmic boundary layer thickness. This is largely exceeded. Similarly, a highly resolved simulation of the eroded blade surface is ruled out, as this would considerably increase the numerical effort. Instead, the authors decided to model the maximum damage case according to the classification [4] in the form of a forward step. This straightforward modeling represents a strong simplification of the complex and random shape of real erosion phenomena at the leading edge.

In experimental investigations by Zhang et al. [12], it was shown that the TEN spectrum for strong eroded blades with many pits, gouges and a complete removal of the top layer up to 3-4 % chord at the leading edge is almost identical to the case with just the same delamination of the leading edge, without pits and gouges. This is an indication that the effect of the step dominates with sufficiently strong erosion. However, the step represents a very advanced erosion level. Previous stages, which presumably also have an influence on the trailing edge noise, are not taken into account here.

For the present work, the dimensions in chord direction and the step depth are determined using the linked data from [1]. This results in a fixed depth from [1] and a variable expansion on the pressure and suction side, which increases towards the blade tip. For reasons of availability and usability of the rotor blade geometries, the authors decided to use a generic case of the NREL 5MW turbine [13]. The considered operating point is rated wind speed at standard atmospheric condition, see Tab.1: The distribution and number of slices considered is carried out in accordance with the previous work. In [2] it was shown that around 10 slices lead to a convergent result for the TEN spectrum. The depth of the step, which was determined using field and literature data and extrapolated to the NREL5MW system, is 3.81 mm. The expansion on the suction side ($x_{st,ss}$) is 0.03 x/c and on the pressure side ($x_{st,ps}$) 0.039 x/c. Where c is the chord length and r is the rotor blade radius. Tab.2 shows the radial sections, profiles and step geometries. The CFD grids are created with the grid generator Pointwise. The distribution and number of grid points is based on the best-practice rules developed in [14]. The grids are parametrically structured so that different profiles are meshed in the same way. The number of grid points is 520,000 points. The area near the profile is meshed in a strictly structured manner with 80 points within the boundary layer and a $y^+ \leq 1$.

Table 1: Operation conditions NREL 5MW

Windspeed [m/s]	RPM [1/min]	Pitch [deg]
11.4	12.1	0°

Table 2: Slices, Positions and step geometry

c	% r	Airfoil	c [m]	$x_{st,ss}$ [m]	$x_{st,ps}$ [m]
0	55.3	DU21_a17	3.592	0.108	0.14
1	64.0	DU21_a17	3.256	0.098	0.127
2	70.0	Naca64_a17	3.01	0.09	0.117
3	77.2	Naca64_a17	2.764	0.083	0.108
4	83.7	Naca64_a17	2.518	0.076	0.098
5	89.0	Naca64_a17	2.313	0.069	0.09
6	93.0	Naca64_a17	2.086	0.063	0.081
7	95.7	Naca64_a17	1.753	0.053	0.068
8	97.7	Naca64_a17	1.419	0.043	0.055
9	98.9	Naca64_a17	1.19	0.036	0.046

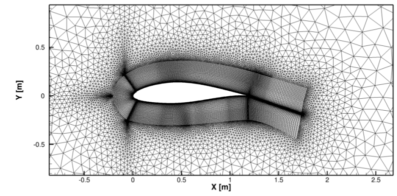

Figure 1: Coarse RANS mesh with step at the LE. Combination from structured near field and triangular farfield.

The CAA grids are structurally meshed with the DLR grid generator MegaCads. Since the PIANO code is dimensionless, all profiles are normalized with the chord length. The grid resolution can thus be kept constant and ensures sufficiently high frequency resolution for all cases.

Results and Discussion

For the resolution of the step, a mesh convergence study was carried out for the outermost section $c9$. The step height is greatest in the outer area relative to the profile chord. The grid resolution was varied parametrically in the structured area (see Fig.1) by doubling the grid points. The medium variant stands for the resolution that was selected without a step according to best practice. Fig.2 shows the grid points for the block at the step and the resolution of the 4 grid variants. This means that the number of grid points for the RANS grids varies between 1.7e5 (coarse) and 6e6 (finer). Within the grid variants, there is only a very small influence on the shape of the streamlines in the area of the step, but there is a clear effect on the distribution of the TKE. Fig.3 shows this. For the CAA simulation, however, the development of the boundary layer towards the trailing edge is more decisive, as the trailing edge noise is to be simulated here. In the source region, the mean velocities, TKE and turbulent length are interpolated to the FRPM patch. Fig.4 shows the influence of the grid resolution on the TKE in this area. Together with Fig.3, it can be seen that a convergent state occurs with regard to the TKE for the fine

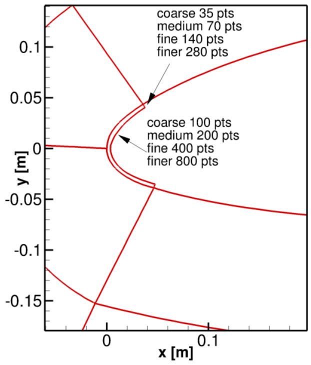

Figure 2: LE blocking. It shows the number of grid points within the step block. For the coarse mesh it is 35 pts in boundary layer direction times 100 pts

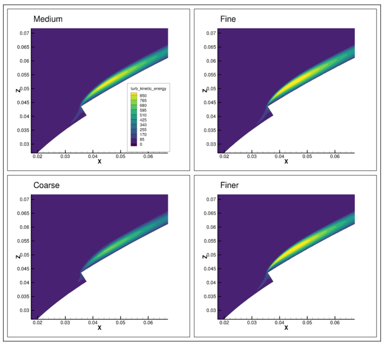

Figure 3: TKE distribution for different RANS meshes.

mesh. Thus, a RANS resolution twice as fine is selected for the eroded cases with the step as for the cases with an undamaged profile. As the step itself is very small compared to the acoustic wavelength, it is not resolved in the CAA grid itself. It can also be assumed that the base flow changes only marginally compared to the fully turbulent case without step, so that the RANS solution without step can be used for the sound propagation. The eroded CAA simulations thus use the background flow of the fully turbulent case without step, but the FRPM patch of the RANS with the step.

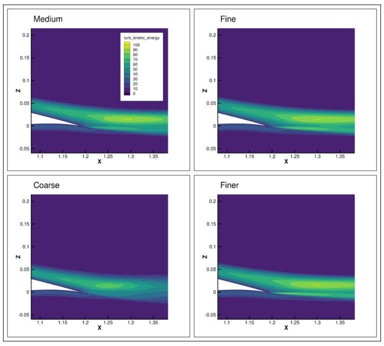

Figure 4: TKE distribution at the LE for different RANS meshes.

Single slice TEN spectra

The CAA results of the individual 2D TEN spectra are shown in Fig.5. The different sections take into account the local flow conditions and chord lengths. The spectra are normalized perpendicular to the flow below the trailing edge at a distance of 1m. If we first compare the results with natural transition (FIX) with fully turbulent boundary layer (FUL), two effects become apparent. The maxima of the spectra for FUL are higher and are shifted towards lower frequencies. Both effects are consistent with the increase in boundary layer thickness and the associated higher TKE levels in the trailing edge region, [15, 16]. The simulations with the eroded LE (ERO) are up to 6dB above the case with natural transition (FIX) from the SPL maxima for the cuts with outer area, where the step height is greater relative to the chord. If the step height is lower, the increase is also smaller. Furthermore, a shift of the maxima to lower frequencies can be observed, which increases with a higher relative step height. This was qualitatively confirmed in experimental investigations by Zhang et al. [12]. However, the Reynolds numbers were lower there. In [12] the explanation given, was the strong erosion, which was modeled as a step, leads to long-scale turbulence structures and a thicker boundary layer at the trailing edge. Santos et al. [17] also experimentally investigated the sound radiation and wall pressure fluctuations at the trailing edge of a NACA 0012 airfoil at low Reynolds numbers. Roughness elements on the LE were mapped with zigzag tapes of different heights. A shift towards lower frequencies was also observed here.

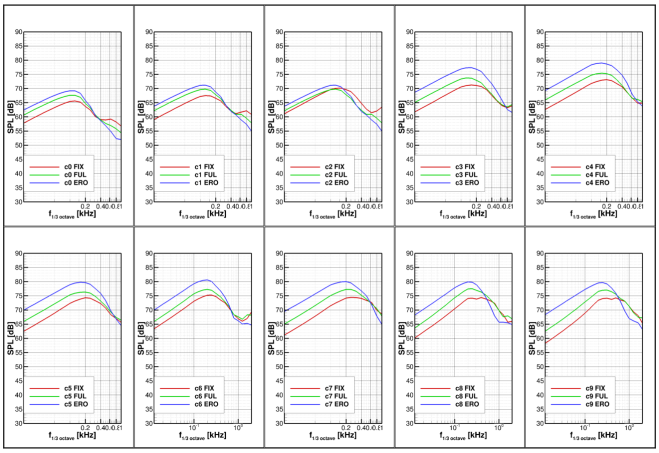

Figure 5: TEN spectra for 2D slices from Tab.2 normalized to 1m distance.

Single spectra at IEC Positions

The turbine prediction with the program TAP [2] enables the extrapolated output at a certain observer position. Here the isolated TEN spectra for the entire NREL 5MW at a position 100m downwind the turbine have been plotted in Fig.6. Again a clear increase between the maxima of the TEN spectra for natural transition FIX and full turbulent FUL, respective eroded blade ERO and a slight shift towards lower frequencies occurs. The differences between the surface conditions remain also for A-weighted SPL levels. Qualitative similar results were also obtained by Wang et al. [18] by using a zonal delay detached eddy simulation for the entire NREL 5MW plant. Actually the forward step over the entire outer rotor area is not a real case because the erosion dam-

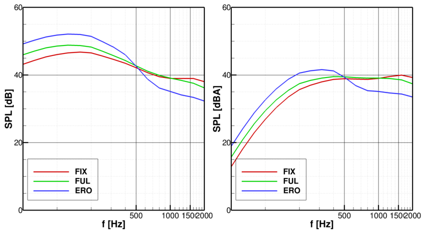

Figure 6: TEN spectra for NREL 5MW turbine at IEC position, 100m downwind at the ground. Right: A-weighted

age varies greatly over the rotor radius. This means that complete delamination is not to be expected over the entire outer rotor area. Rather, the further inwards you go, the more pitches and gouges there would be instead. However, it is conceivable that, for example, the case of complete delamination shown here, is largely applicable, if the main level of damage up to the most dominant sections, $c4$ - $c6$, see Fig.5, is delamination. In order to get an impression of how a strongly eroded surface without complete delamination affects the TEN spectra under realistic flow conditions, the result of a scale-resolving numerical simulation would be very helpful.

Conclusion & Outlook

The acoustic impact of erosion at wind turbine blades has been investigated with a very fast very fast hifi tool chain. In order to quantify the erosive damage on turbine blades after 15 years of operation an intensive literature study has been carried out in [1]. Following from that a simplified surface modeling was applied to capture the erosive damage. The results of the CFD/CAA tool chain were used to extrapolate the TEN spectra to a NREL 5MW rotor. A comparison of clean rotor blades, fully turbulent flow regime and eroded rotor blades has been carried out. Qualitatively good agreement with published experimental data for massively eroded surfaces and a plausible acoustic effect due to affected blade surface have been determined. We are looking forward to gain own experimental verification data possible from wind tunnel tests or from our test field in Krummendeich. Furthermore we are curious to use the 3D scan data from the field measurements in [1] for scale-resolving numerical simulations.

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References

[1] Gümbel, C.: Untersuchung des Ausmaßes von Vorderkantenerosion an Rotorblättern von Windkraftanlagen und die damit verbundenen Umweltauswirkungen. TU BS, 2024.

[2] Appel. C.: CAA based noise prediction for wind energy turbines. AIAA 2023-3739

[3] Verma, A. S. et al.: A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites, Wind Energy, vol. 24(11), 2021.

[4] Sareen, A., Sapre, C. A., Selig, M. S.: Effects of leading edge erosion on wind turbine blade performance. Wind Energy, vol. 17(10), 2014.

[5] Visbech, J. et al.: Introducing a data-driven approach to predict site-specific leading-edge erosion frommesoscale weather simulations, Wind Energy Sci., vol. 8(2), 2023.

[6] Mishnaevsky, L. et al.: Leading edge erosion of wind turbine blades: Understanding, prevention and protection, Renewable Energy, vol. 169, 2021.

[7] Im, H., Kim, B.: Numerical study on the effect of blade surface deterioration by erosion on the performance of a large wind turbine, JRSE, vol. 11(6), 2019.

[8] Appel, C., Fassmann, B., Lin, S.: CAA-basierte Schallvorhersage für Windkraftanlagen, DAGA 2020.

[9] Marten, D.: QBlade: A Modern Tool for the Aeroelastic Simulation of Wind Turbines. PhD thesis, TU Berlin, 2019.

[10] Imiela, M. et al.:MERWind - Multidisciplinary Design of Wind Turbines using High Fidelity Methods. DEWEK 2012.

[11] Ewert, R.: RPM - the fast Random Particle-Mesh method to realize unsteady turbulent sound sources and velocity fields for CAA applications, AIAA 2007-3506.

[12] Zhang, Y, Avallone, F., Watson, S.: Leading edge erosion detection for a wind turbine blade using far-field aerodynamic noise. Appl. Acoust., vol. 207(8345), 2023.

[13] Jonkman, J. et al.: Definition of a 5-MW Reference Wind Turbine for Offshore System Development. NREL/TP-500-38060, 2009

[14] Rautmann, C.: Numerical Simulation Concept for Low-Noise Wind Turbine Rotors, DLR FB 2017-35.

[15] Brooks, T. F., Hodgson, T. H.: Trailing edge noise prediction from measured surface pressures. JSV vol. 78(1), 1981.

[16] Herr, M.: Trainling-edge noise - reduction concepts an scaling laws. TU BS, 2013.

[17] Santos, F. L. et al.: Influence of Surface Roughness Geometry on Trailing Edge Wall Pressure Fluctuations and Noise, AIAA, 2021.

[18] Wang, H., Chen, B. Investigation on aerodynamic noise for leading edge erosion of wind turbine blade, J WIND ENG IND AEROD vol. 240, p. 105484, 2023.