Final report

General information

1. Project details

Project title	Leading Edge Roughness Categorisation (LERCat)
File no.	64021-2027
Name of the funding scheme	EUDP 2021-II
Project managing company / institution	Danish Technical University
CVR number (central business register)	30060946
Project partners	DTU, Vestas Wind Systems A/S (Vestas), Siemens Gamesa Renewable Energy A/S (SGRE), LM Wind Power (LM), Suzlon Energy Ltd. – Netherlands branch (Suzlon), PowerCurve Aps (PowerCurve)
Submission date	11 July 2025

2. Summary

Project summary:

The purpose of the project:

The LERCat project seeks to reduce the maintenance cost due to leading edge roughness (LER) on wind turbine blades by enabling the repair at the right time. Based on simulations and wind tunnel tests of LER topologies an open available categorisation scheme for the sectional aerodynamic and aeroacoustic performance losses was developed.

Results, conclusions and perspective:

The most important results:

- Developed a categorisation scheme linking blade inspection data with aerodynamic and aeroacoustic losses on wind turbine blade sections
- Established a database of LER topologies from mild erosion to very severe
- Developed a method to extract the LER topology from a scan without knowing the initial uneroded shape

- Developed a fully automated workflow which takes the extracted roughness topologies, wraps it around the leading edge of any aerofoil and creates a surface mesh, to be used for simulations or 3D printed
- Performed 2D and 3D simulations on aerofoils with realistic LER
- Established best practices for numerical simulation of LER
- Developed a method for testing realistic LER on wind tunnel models
- Performed noise measurements on a number of these LER configurations
- Performed measurements on the boundary layer properties with a boundary layer rake and surface microphones

As the scheme delivers a categorisation of the leading edge roughness with corresponding aerodynamic and acoustic performance losses it enables the estimation of the AEP losses for an entire wind turbine and allows the determination of the optimal time of repair based on a data-driven and objective workflow.

Initial investigations show that a one year offset from the optimal time of repair amounts to 2500 DKK/MW/year and a two-year offset amounts to 4000 DKK/MW/year. As the typical turbine sizes are above 4MW onshore and offshore beyond 12MW, a substantial amount can be gained.

Projektresumé:

Formålet med projektet:

LERCat-projektet søger at reducere vedligeholdelsesomkostningerne på grund af forkantruhed (LER) på vindmøllevinger ved at muliggøre reparation på det rigtige tidspunkt. Baseret på simuleringer og vindtunneltests af LER-topologier blev et åbent tilgængeligt kategoriseringsskema for sektionsvise aerodynamiske og aeroakustiske tab udviklet.

Resultater, konklusioner og perspektiv:

De vigtigste resultater:

- Udviklede et kategoriseringsskema, der forbinder vingeinspektionsdata med aerodynamiske og aeroakustiske tab på vindmøllevingesektioner
- Etablerede en database med LER-topologier fra mild erosion til meget alvorlig
- Udviklede en metode til at estimere LER-topologien fra en scanning uden at kende den oprindelige ikke-eroderede form
- Udviklede en fuldt automatiseret arbejdsgang, der tager de estimerede LER-topologier, folder dem rundt om forkanten på et vilkårligt vingeprofil og genererer et overfladenet, der kan bruges til simuleringer eller 3D-printes
- Udførte 2D- og 3D-simuleringer på vingeprofiler med realistisk LER
- Etablerede bedste praksis for numerisk simulering af LER
- Udviklede en metode til test af realistisk LER på vindtunnelmodeller
- Udførte støjmålinger på en række af disse LER-konfigurationer
- Karakteriserede grænselagene med en grænselagsrive og overflademikrofoner

Da skemaet leverer en kategorisering af forkantruheden med tilsvarende aerodynamiske og akustiske tab, muliggør det estimering af AEP-tabene for en hel vindmølle og tillader bestemmelse af det optimale tidspunkt af reparation baseret på en datadrevet og objektiv arbejdsgang.

Indledende undersøgelser viser, at en forskydning på et år fra det optimale reparationstidspunkt beløber sig til 2500 kr./MW/år, og en forskydning på to år beløber sig til 4000 kr./MW/år. Da de typiske turbinestørrelser er over 4 MW onshore og offshore over 12 MW, kan der opnås en betydelig gevinst.

3. Project objectives

The purpose of LERCat is to enable informed decisions on repair of leading edge roughness (LER) of wind turbine blades. Achieving this will result in an annual gain of 1 billion DKK for the combined turbine fleet of the project partners, Vestas, SiemensGamesa, LM Wind Power, Suzlon. The way to achieve this is by establishing an open, industry-wide standard for categorising LER on wind turbine blades and link it to the performance loss (both aerodynamic and aeroacoustic) of a turbine. By understanding the precise performance loss caused by the gradual degradation of the blades, it is possible to decide on the most cost-effective time to repair the blades over their 25-year service life from blade inspection data (performed at least once a year). This will shift the status-quo away from repairing blades at fixed intervals or subjective rules of thumb.

The turbine tip speeds are continuously growing in-line with the size of turbine rotors, whilst striving for greater production efficiency. This increases the impact energy of airborne particles and thus their erosive potential to such an extent, that LER is identified as a significant cost driver in wind energy. Although there is agreement that LER is a significant challenge, there is no agreement on how much a given level of LER affects the turbine performance. Large renewable energy providers like Ørsted see a “[...] lack of knowledge […] how to forecast [LER] impact on future sites”. Consequently, LER repair is often either done too early or too late, increasing maintenance cost unnecessarily (too early) or reducing energy production (too late). LERCat addresses this exact challenge, with DTU Wind and Energy Systems acting as an unbiased and neutral mediator in forming an industry-wide consensus on this matter.

A widely accepted and trusted categorisation would allow data-driven wind turbine maintenance, which diminishes the overall cost of green energy, as it enables informed and cost-effective maintenance decisions, i.e., repair at the right time.

To deliver a categorisation for widespread industry adoption, the project must achieve the following five objectives:

1) Create a digital twin of real in-field LER by mapping LER on full scale rotors

2) Establish an accurate, unbiased and open transfer function from real LER to losses in aerodynamic and aeroacoustic performance of aerofoil sections

3) Establish a common validation method (both aerodynamic and aeroacoustic) for testing LER in wind tunnels and computational approaches for specific aerofoil sections

4) Develop a common categorisation of LER to enable a prediction of AEP losses

5) Establish LERCat at the heart of maintenance decision making in the wind industry by open and transparent dissemination involving key stakeholders

4. Project implementation

In general, the project evolved satisfactory and there was always a good progress in the different work packages. Hence, most of the planned activities were carried out during the project.

As foreseen in the application the major risks encountered during the project were related to the numerical simulations and the wind tunnel tests.

The first wind tunnel model was delayed as the manufacturing was more complicated than first expected, as some of the subcomponents were more complicated to manufacturer. Since the model is made in aluminium it is necessary to coat it to measure the transition with infrared cameras. A proof-of-concept study with scaled models (1/4 size) had to be made before the right coating technique was found. The shift of the replaceable LE was also a concern as it should be possible to do relatively fast and without any larger steps between the LE-part and the main body. That also required some design iterations before a good method was found.

The initial design for testing the LER in the wind tunnel was not ideal and time had to be spent on finding an alternative method. After a few design iterations a new method was developed. The new method was still based on 3D prints, but as the first tests had shown the surface had to be smoother and the step between the replaceable LE and the aft part of the model had to be reduced to a minimum.

Due to the extra time needed to find an applicable method for testing the LER, the number of acoustic tests had to be reduced. However, acoustic tests were still performed on a variety of LER topologies, so it is still possible to develop a model for the increased noise from an aerofoil with LER.

LM also investigated the method for testing LER and succeeded in finding a good method. They performed an important parameter study on the effect of distributed roughness (i.e. sandpaper like roughness) at the bottom of the cavity and the shape of the edge of the cavity.

Studying leading edge roughness and erosion on aerofoils using high-fidelity CFD (computational fluid dynamics) has not been done previously. The only existing comparable studies originate from the aviation industry and investigated the impact of icing on aerofoil performance. However, whilst also larger-scale, ice accumulates on the surface, whereas erosion grows into the clean surface, which acts very differently on the flow. Developing a robust method for generating high-resolution surface grids from roughness maps required more time as expected, as it had to be developed from scratch. The same applies to the method generating the computational domain. The high-resolution required over the leading edge meant that a new mesh topology had to be developed, which had to be tested and adjusted several times, as some CFD models exhibited some unknown sensitivity to it. Finally, the computation expense of the 3D simulations meant that only a limited number of simulations could be performed, due to time and resource constraints, especially as DTU Wind's own high-performance computing facility, the only one available throughout the project, has reached its end of life and has become unstable, requiring restarting simulations several times.

An essential activity in the project was to obtain data of LER from real wind turbine blades, as it was important to base the categorisation scheme on real LER topologies and not just modelled LER. The collection of LER samples was very successful as all OEMs in the project was able to find blades with a variety of LER severities.

At the outset the idea was to make an automated method for extracting the LER topologies from the blade scans, however that turned out to be difficult to achieve so the method still requires some user input to give useable results and therefore it is a little time consuming. However, the developed method works, and it was possible to extract the LER topologies needed for the numerical simulations and wind tunnel tests.

Due to the challenges with the numerical simulations and the wind tunnel tests it was decided to start the work on the categorisation scheme before these results were available. The initial work on the categorisation was then based on data from the partners and the open literature. The initial work on the categorisation scheme gave valuable insights into the correlations (or lack of correlations) between the aerodynamic performance and the LER topologies. As the wind tunnel measurements and numerical simulations gradually became available, they were included in the analysis. Generally, they were in-line with the initial findings but was important in expanding the size of the dataset.

Through the meetings with the Sounding Board valuable feedback was received, that was instrumental in developing the categorisation scheme.

The partners are also very active in the IEA Task 46 Wind Turbine Erosion and the LERCat project also received useful feedback from these meetings. The participation in the IEA Task 46 phase 2 is also used to further develop the categorisation scheme.

Despite the problems with the lower number of simulations and lower number of wind tunnel tests on realistic LER topologies it was still possible to fulfil the main objectives of the project. Especially it was possible to develop a solid categorisation scheme where the performed simulations and wind tunnel tests contributed to increase the number of LER topologies included. Furthermore, very valuable knowledge was obtained in relation to simulating and testing LER that can be used in future projects and in the ongoing IEA Task 46 project.

5. Project results

As mentioned earlier the project must achieve the following five objectives to deliver a categorisation for widespread industry adoption:

1) Create a digital twin of real in-field LER by mapping LER on full scale rotors (WP2)

2) Establish an accurate, unbiased and open transfer function from real LER to losses in aerodynamic and aeroacoustic performance of aerofoil sections (WP5)

3) Establish a common validation method (both aerodynamic and aeroacoustic) for testing LER in wind tunnels and computational approaches for specific aerofoil sections (WP4 and WP3, respectively)

4) Develop a common categorisation of LER to enable a prediction of AEP losses (WP5)

5) Establish LERCat at the heart of maintenance decision making in the wind industry by open and transparent dissemination involving key stakeholders (WP6)

In general, the objectives were obtained with only minor shortcomings as described in the following sections. The sections describe each work package (WP) of the project, leaving out WP1 as it is the project management WP. In the list of objectives, the WP that links into the particular objective is given in the parentheses.

5.1 WP2:

A very important task of the project was to get many realistic LER samples ranging from mild to very severe roughness, so the data set for the categorisation scheme would be as comprehensive as possible.

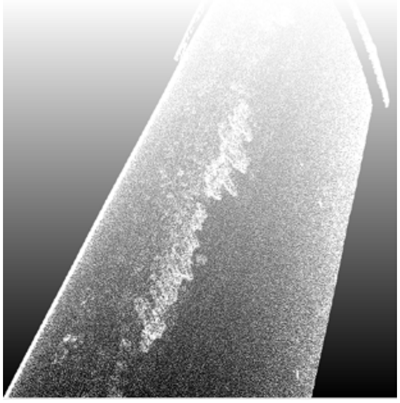
All the OEMS in the project identified blades (both on the ground and up-tower) with useable LER, resulting in a total length of damages in the order of 8-10 m.

Once the LER has been identified it needs to be converted to a LER topology useable for wind tunnel testing or numerical simulations.

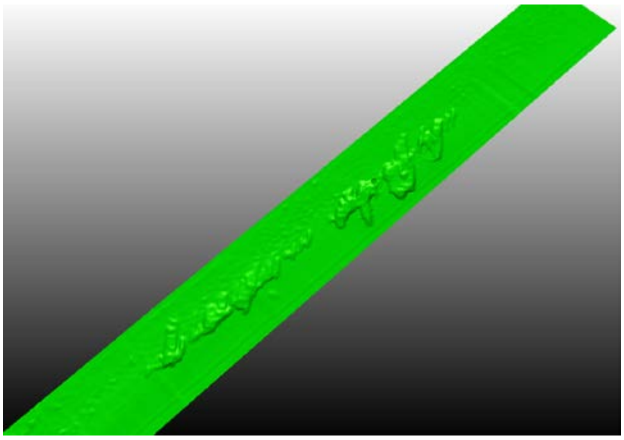
1: Wind turbine blade with LER

2: Mould for silicone imprint on the blade

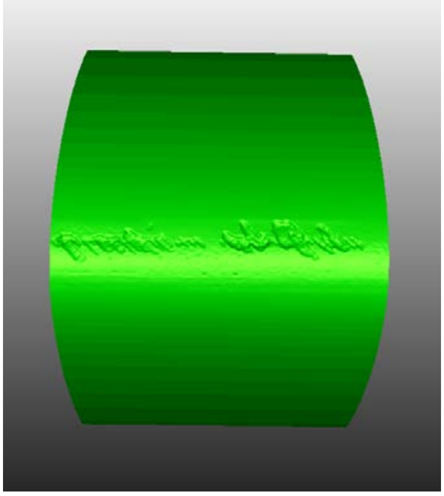
3: Plaster casting of the LER



4: Point cloud from the scanning of the casting



5: Unfolded LER patch



6: LER patch wrapped around the FFA-W3-211 aerofoil.

Figure 1: Workflow for extracting the LER patches from a wind turbine blade.

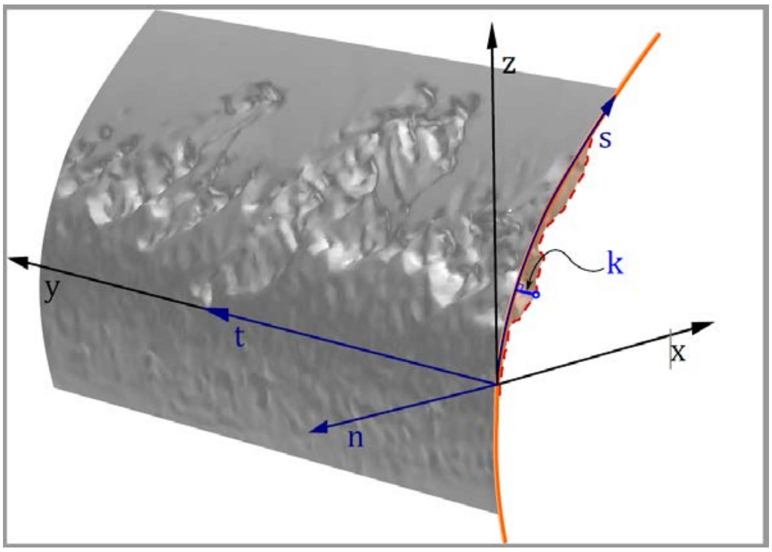


Figure 2: Example of estimated reference aerofoil shape (orange line) and LER topology. [1]

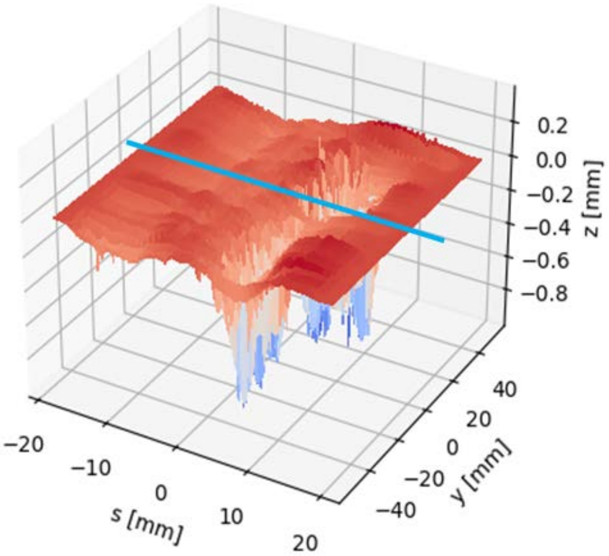


Figure 3: 3D roughness patch

The method is described in more details in [1] and [2]. [3] gives a guideline for making a silicone imprint and plaster casting of the LER.

Figure 1 shows the workflow for obtaining a realistic leading edge roughness topology applicable for CFD simulations and/or wind tunnel testing.

At first an imprint is made from a damaged blade, then a plaster cast is made from the imprint, and this casting is 3D scanned. Based on the scan, the roughness topology is extracted, and the pattern is unfolded, so it is possible to apply the pattern on any other aerofoil by wrapping it around the LE.

After the first round of imprints, it was found that it was as good and easy to make the scans directly on the blade, so that was done for the remaining part of the obtained LER samples.

The main issue when extracting the LER topology is that the reference aerofoil is not known, both due to missing information on the actual aerofoil and because there will inevitably be differences between the nominal shape and the manufactured blade. Hence a method to estimate the un-eroded LE had to be developed. The reference aerofoil is based on a convex hull approach. This method is described in more details in [1]. The method proved difficult to fully automate, due to various irregular variations of the un-eroded blade geometry in addition to the expected spanwise twist and thickness variations. Hence, the input parameters describing the reference aerofoil requires quite some manual fine tuning. Figure 2 shows an example of a scanned LE with LER and the estimated reference aerofoil.

The multiresolution analysis based on the discreet wavelet transformation as proposed by [4] was used for two purposes in this work: the statistical analysis of a roughness patch on different scales and localized removal of digitization noise when preparing a patch for CFD computations.

The multiresolution analysis decomposes the features of a roughness patch into bandpass-filtered patches containing only information related to a certain range of scales, Figure 3 and Figure 4. In this way surface roughness parameters such as the R_a can be analyzed on a spectral level and not only as an overall value for the patch, Figure 5.

The removal of spurious noise from the digitized roughness sample was crucial to obtain numerical convergence of the CFD computations with meshed roughness. The application of the method was described in detail in [1].

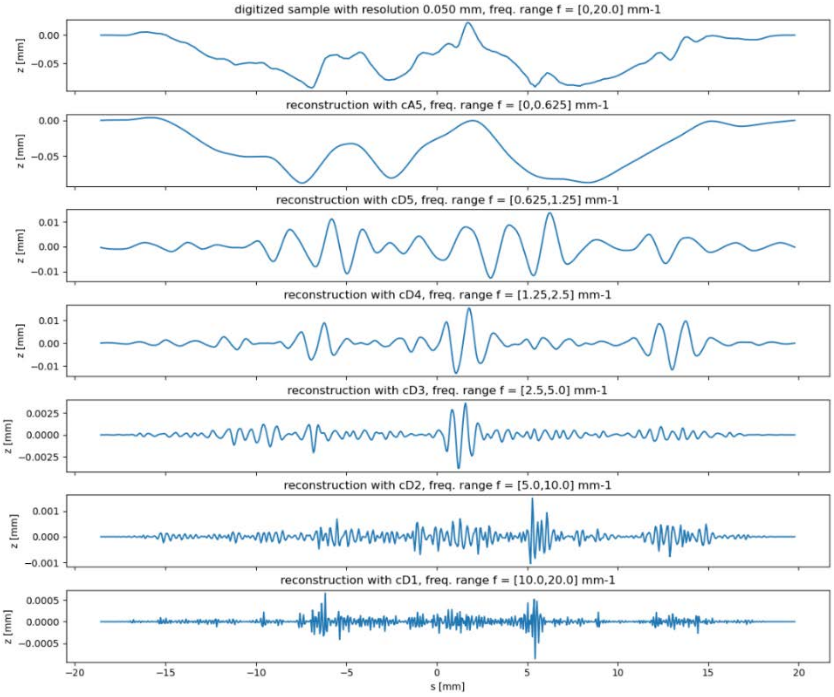


Figure 4: Approximation and details of a 2D roughness element selected from the 3D sample

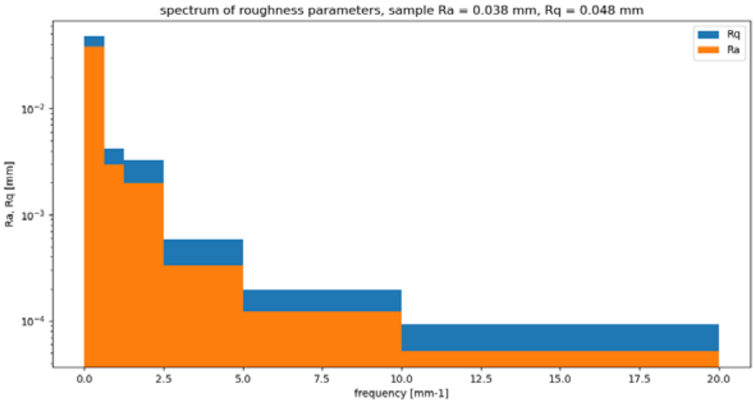


Figure 5: Spectrum of the R_a parameter of the 2D roughness element

5.2 WP3:

The goals of WP3 were to create a digital twin of real-world leading-edge roughness and erosion. Indeed, a fully automatised workflow, scripted in Python, has been created as shown in Figure 6, which takes the extracted roughness maps from WP2, post-processes them, wraps them around the leading edge of any aerofoil profile provided and creates a surface mesh, which can either be used in simulations or 3D printed for experimental assessment. This is the first workflow of its kind, even outside the area of wind energy. A detailed description of the workflow has been published in an open access journal [1], and some of the newly developed methods are available through DTU Wind's open-source geometry manipulation tool, PGLW [5]. The AeroMesher, the tool orchestrating the surface mesh generation, is closed source and hosted on DTU Wind's gitlab server. It is already used within other research and commercial projects and hence will be supported going forward.

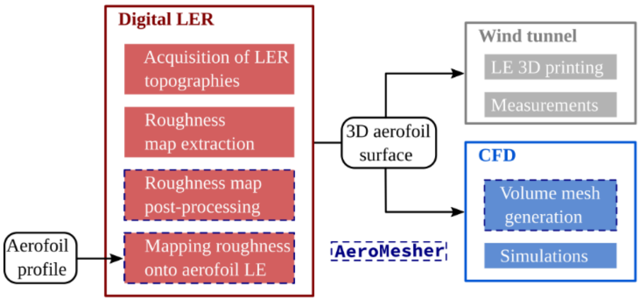


Figure 6: Digital LER creation and aerodynamic assessment workflow implemented within the LERCat project

Figure 7 shows the rendered leading edge surfaces representative of measured mild and severe erosion created using the newly developed workflow, that were aerodynamically assessed in both, Computation Fluid Dynamics (CFD) and DTU Wind's wind tunnel.

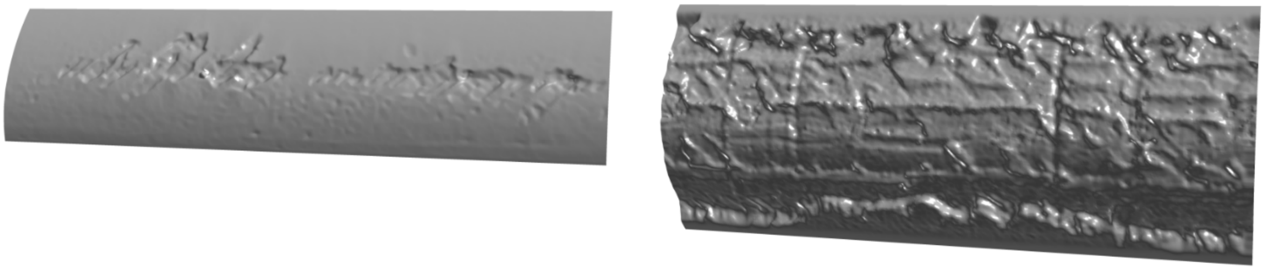


Figure 7: Rendering of the surface mesh for mild and severe erosion roughness maps wrapped the leading edge of an aerofoil

To accurately capture the effects of the damages on the flow field, the surface resolution over the erosion is relatively high with 100 microns in both directions. It is also this area of elevated resolution that required the development of a new meshing technique to enable them being simulated using CFD. The different components of the automated mesh generation are shown in Figure 8. It combines a number of DTU Wind's in-house meshing tools (HypGrid) that are controlled through Python interfaces, with PGLW and a new fractal mesh topology, which allows reducing the grid resolution away from the surface, making these simulations at all possible. As mentioned, the mesh generator is already used in other projects that require high-fidelity flow simulations, as needed in aeroacoustics.

Together with the great number of 2D CFD simulations of different idealised types of leading edge damage performed during the project, and published in a conference article [6], the 3D simulations allowed exploring a vast number of numerical sensitivities in the well-established CFD flow models used within industry and academia, establishing best practices for modelers. These were and are shared with stakeholders through strong engagement in the IEA task 46, more specifically by submitting simulation results of aerofoils with erosion and roughness to benchmarking exercises, presenting LERCat results to task members and conducting another aerodynamic benchmark using roughness topographies, CFD and wind tunnel results from the project. Results from this benchmark are expected to be presented at the international scientific conference TORQUE 2026.

To verify the high-fidelity simulations performed at DTU Wind and to demonstrate that industry can perform similar investigations, PowerCurve used the commercial CFD tool STAR-CCM+, using standard models only, to simulate the flow over several eroded leading edges. A workflow was developed that takes the surface mesh generated by AeroMesher in the form of a STL shell and generates an unstructured volume mesh using STAR-CCM+ internal meshing tools. The runs were then performed using commercial cloud computing resources. There were slight differences in the performance predicted by PowerCurve's simulations with respect to those performed by DTU, which was mostly related to the friction drag being underpredicted. Comparing with DTU's simulations helped identifying the reason for this mismatch; it stems from a sub-model in STAR-CCM+, that excessively limits the production of kinetic energy around the aerofoil leading edge, which hinders the development of turbulence in the boundary layer. Different to other commercial software, the limiter in STAR-CCM+ cannot be changed to the one used in EllipSys, DTU's tool. Nevertheless, overall the agreement between the two CFD codes was very favourable, also showing that the performance degradation originates from the same flow mechanism. PowerCurve also simulated additional erosion patterns not simulated by DTU extending the database for the LER categorization. A detailed comparison will be part of a future journal article.

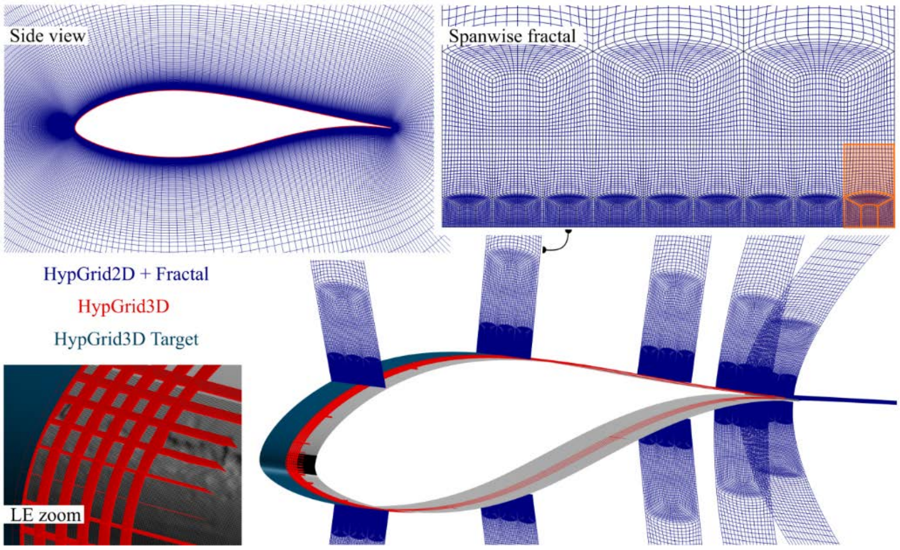


Figure 8: Colour-coded components of the 3D O-type structured volume mesh with uniformly high resolution around the leading edge

Another aim of the project was to relate erosion severity with certain flow mechanisms and link those back to aerofoil performance. Here high-fidelity 3D CFD is a valuable tool, as it accurately resolves even small-scale perturbations and provides data everywhere inside the flow domain, allowing detailed analysis of the flow fields. Figure 9 and Figure 10 compares the measured (from WP4) and computed span-averaged lift and drag coefficients for the two aerofoils mostly studied during the project with erosion.

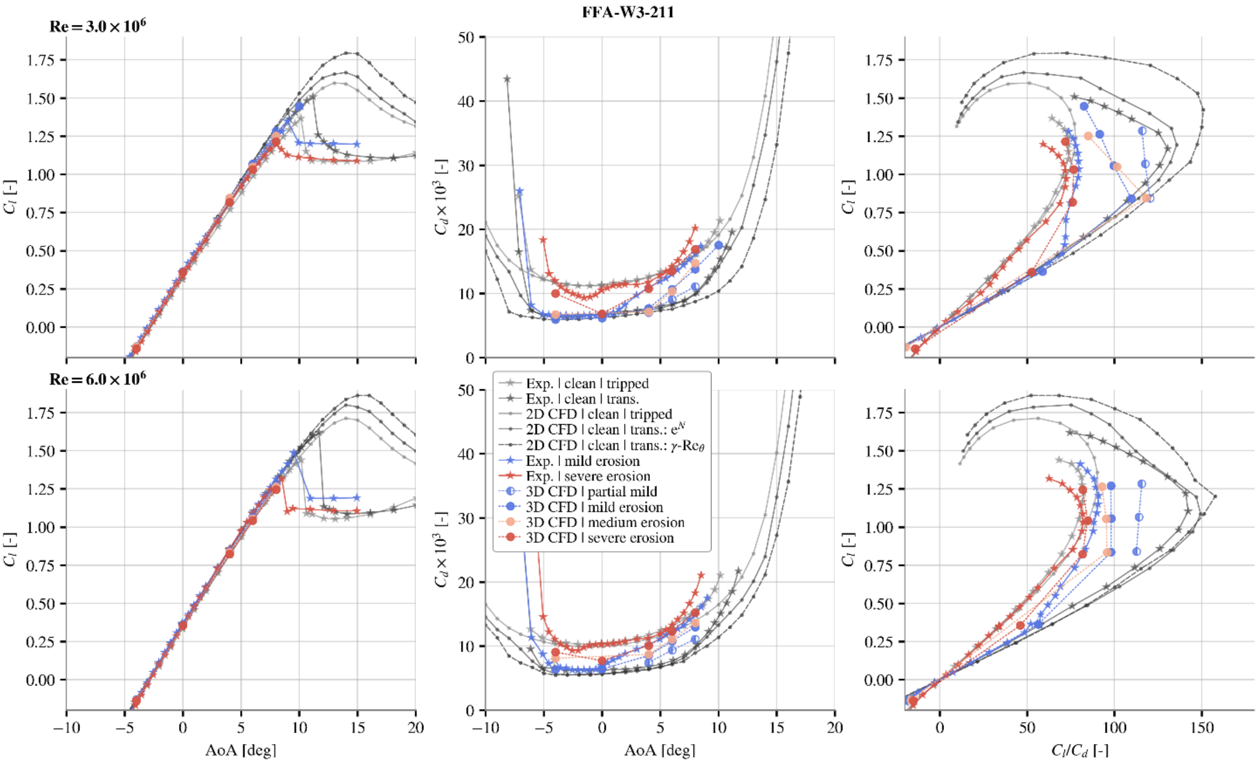


Figure 9: Lift-drag polars for the FFA-W3-211 at Reynolds numbers of 3 (upper row) and 6 million (lower row).

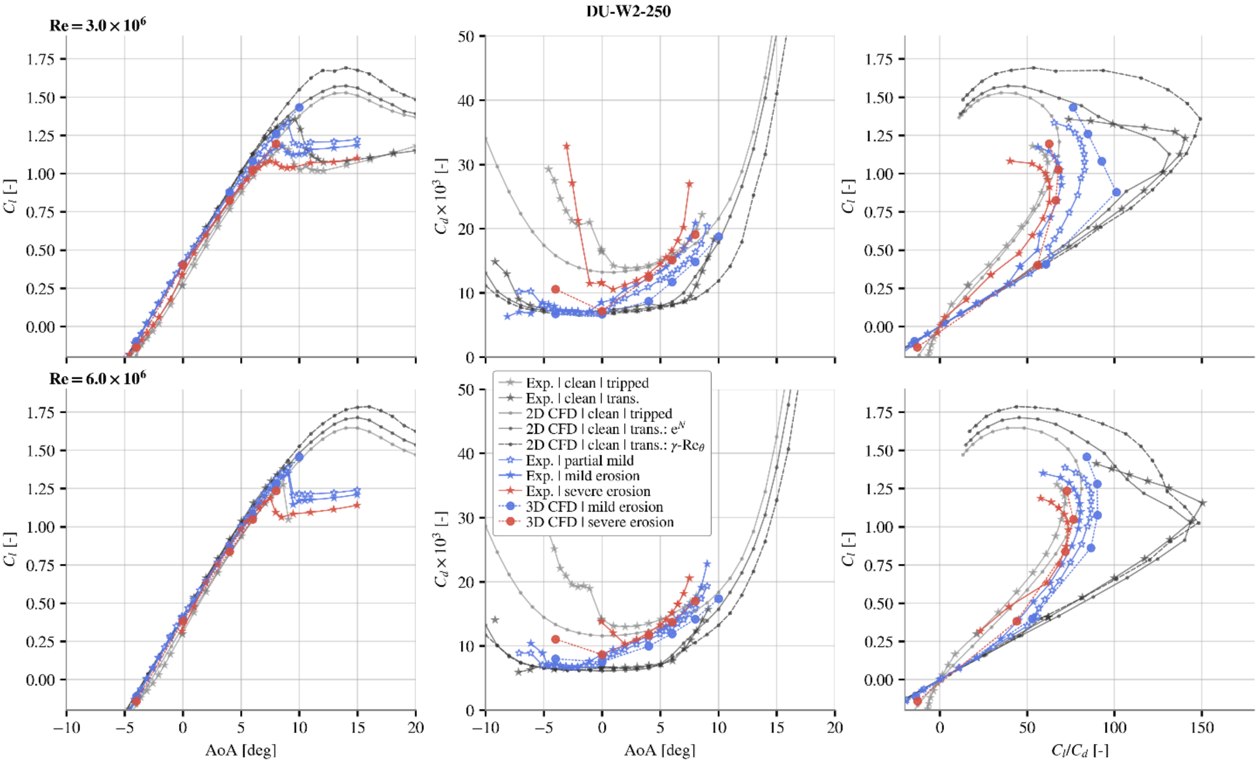


Figure 10: Lift-drag polars for the DU91-W2-250 at Reynolds numbers of 3 (upper row) and 6 million (lower row).

Overall, measurements and CFD agree reasonably well, especially the non-eroded cases, however despite the greatest efforts the representation of the erosion is not identical between both, as the 3D prints have some additional roughness originating from the printing process itself and also the attachment of the prints to the wind tunnel model in a smooth manner has been difficult. In the CFD simulations none of these features are present, hence especially when the change in the aerofoil performance originates from the erosion triggering premature erosion, as seen with mild erosion, CFD predicts higher performance, as transition is prematurely triggered only at higher angles-of-attack. Nevertheless, as mentioned above, having detailed flow and surface information, the CFD simulations served to clearly identify the performance loss mechanisms associated with different severity levels of erosion, as also discussed in detail as part of a conference paper [7]. Mild erosion mostly acts as a suction side transition trigger with limited impact on stall, whereas severe erosion, on top of triggering transition, additionally increases pressure drag significantly especially approaching stall. Whilst the computational setup was not appropriate to evaluate stall, the large drag increase towards stall and numerical instability clearly indicated that stall occurs prematurely with severe erosion. This overlaps with the measurements.

Figure 11: Example of a wind tunnel model with a replaceable LE.

5.3 WP4:

The wind tunnel measurements are made in the Poul la Cour tunnel (PLCT) at the DTU Risø campus and at the wind tunnel at LM. Both are closed-return tunnels with a maximum speed of 105m/s. In LM's tunnel the models are mounted horizontal with a span of 1.35m and the hight of the test section is 2.70m, in PLCT the models are mounted vertically with a span of 2m and a width of the test section of 3m. Hence the tunnels are comparable in sizes and wind speeds. In both tunnels the lift is based on wall pressures, as there is no pressure orifices in the 3D printed LE parts with the LER. A wake rake measures the drag.

The measurements in LM's wind tunnel are made with an existing model of the DU00-W-212 aerofoil. The model has a replaceable LE part with a length of 2% chord and a chord of 0.9m.

For the measurements in PLCT three new models were manufactured. A NACA63-618 (18% relative thickness), an FFA-W3-211 (21% relative thickness) and a DU91-W2-250 (25% relative thickness). All aerofoils have a replaceable LE (see Figure 11) and a chord of 0.9m. Figure 12 shows an outline of the aerofoils tested in PLCT.

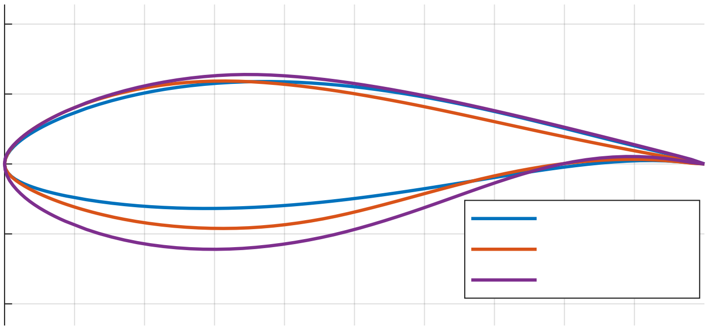


Figure 12: The three aerofoils manufactured for the PLCT.

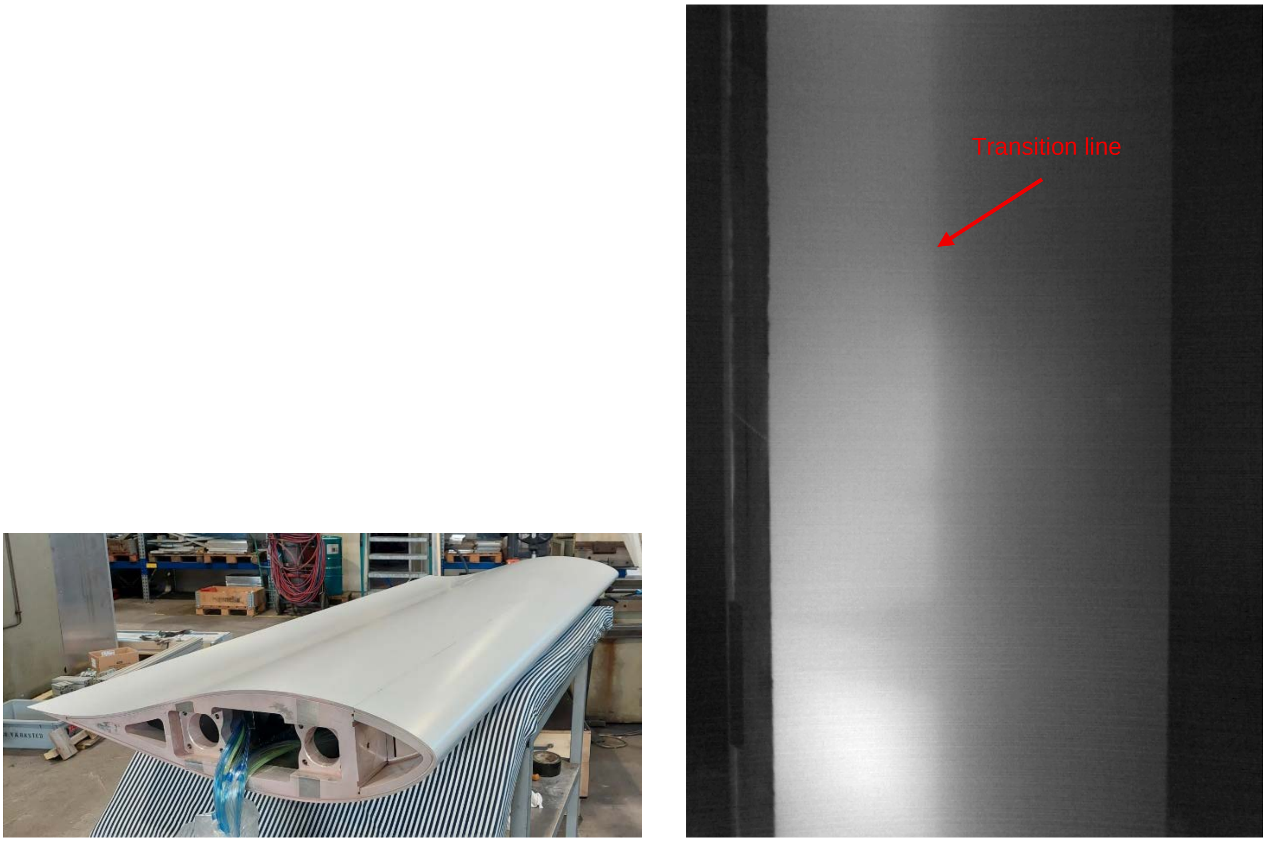


Figure 13: Left: The FFA-W3-211 after coating. Right: example of an IR picture where transition is visible (Re=3E6, AoA=8.5 deg., pressure side, LER-2).

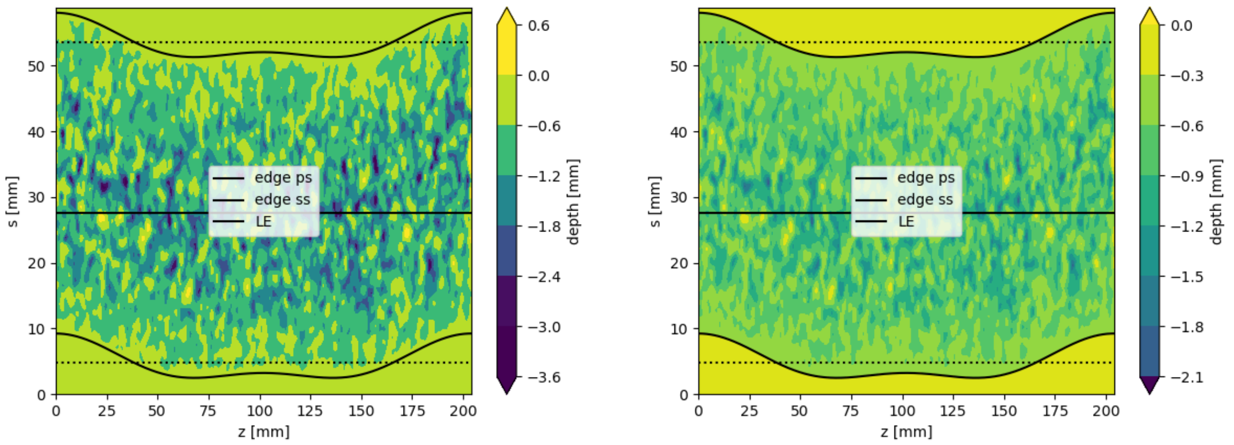
Figure 14: LER-2 mounted on the DU91-W2-250 in PLCT.

Figure 15: LE1 mounted on the DU00-W-212 in LM's wind tunnel.

The FFA-W3-211 model was coated so it was possible to measure the transition location with infrared cameras. An example a IR-picture is shown in Figure 13 for the pressures side with a Reynolds number of 3E6 and the LER-2 mounted (see Figure 14). The angle of attack is 8.5 deg., and it is seen that the transition line is relatively far downstream. This is because the stagnation point is downstream of the LER, so the first part of the flow is still laminar. However, the chordwise position is probably more forward than for the clean case, as the LER is heavily affecting the flow on the suction side.

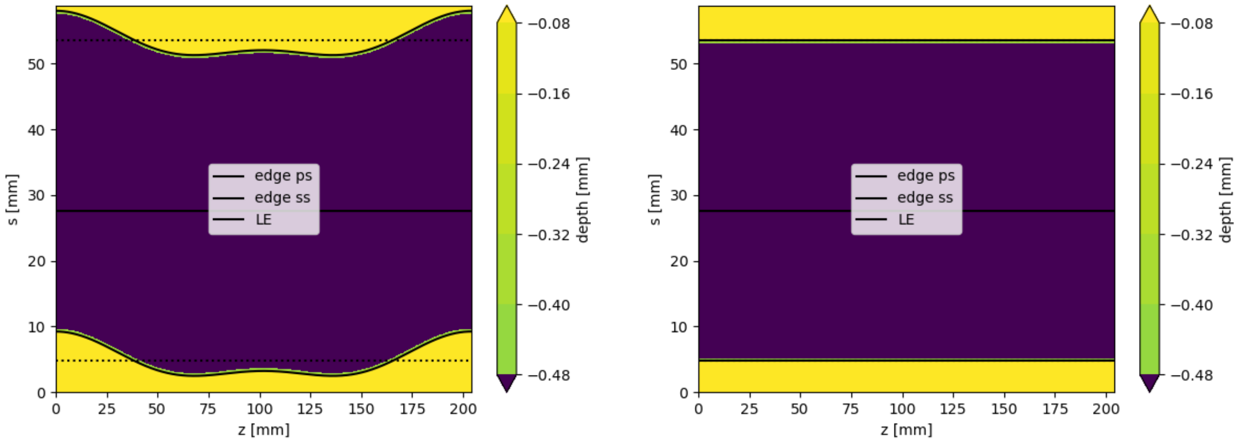
A part of the test program at LM was a parameter study on the shape of the edge of the damage cavity and the roughness inside the cavity. The four different LER topologies shown in Figure 16 were tested and the results are seen in Figure 17. The measurements show that the roughness inside the cavity has a large effect on the performance of the aerofoil, i.e. if there is no distributed roughness in the cavity (LE3 and LE4) the performance is almost identical to the performance with clan surface and no cavity. The shape of the edge has almost no effect on the performance as seen by comparing the results for LE3 and LE4 in Figure 17.

Figure 15 shows the model with LE1.



LE1: Wavy edge, severe distributed roughness in damage.

LE2: Wavy edge, mild distributed roughness in damage.



LE3: Wavy edge, no distributed roughness in damage.

LE4: Straight edge, no distributed roughness in damage.

Figure 16: Example of the LER topologies used for the parameter study.

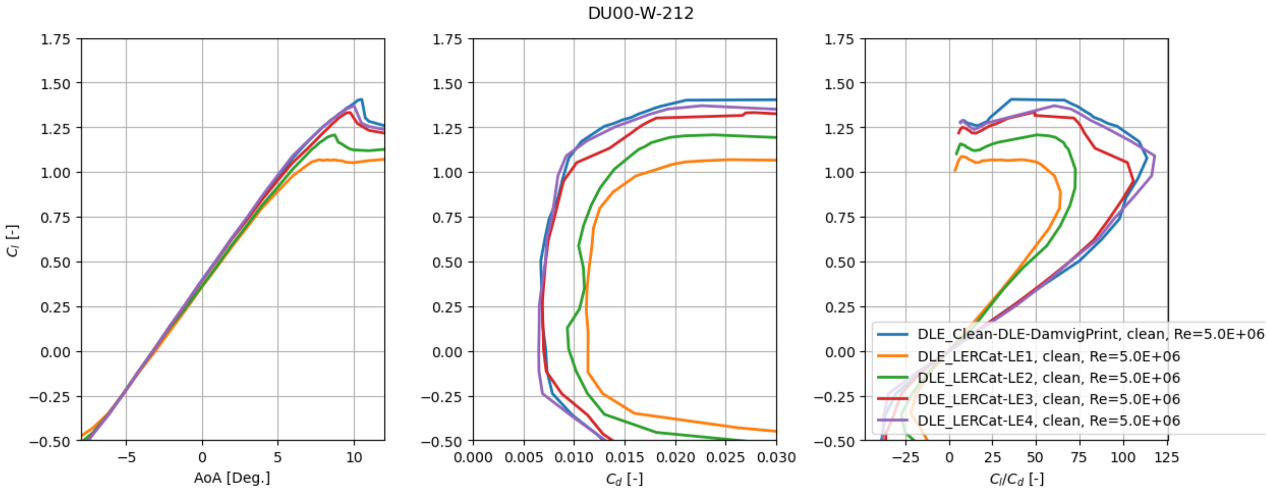


Figure 17: Measurements from LM's wind tunnel with the LER topologies shown in Figure 16.

After a useable method for testing real LER topologies were established, three different LER topologies were tested. A mild LER topology (LER-1, see left of Figure 7) and a heavy LER topology (LER-2, see right of Figure 7) and a modified version of the LER-1, where half of the damage was filled (LER-1 half filled).

Figure 18 shows the measurements together with measurements with 0.4mm thick zigzag-tape at 5% chord on the suction side and 10% chord on the pressure side. It is seen that the performance degradation flows the severity of the LER topology, and it also show that the zigzag-tape results has the largest increase in drag as long as the flow is attached. However, the decrease in maximum lift is highest for the heavy erosion (LER2). The zigzag tape configuration is the standard method for simulating LER in the PLCT, so the measurements show that this configuration, except for the maximum lift is applicable and in fact gives conservative estimates for the drag.

It is also interesting to note that the results for the two cases of the mild erosion almost goes back to the clean performance at negative angles of attack. This is because the damage is on the suction side, so at negative angles of attack the flow is accelerated around the LE which reduces the effect of the LER.

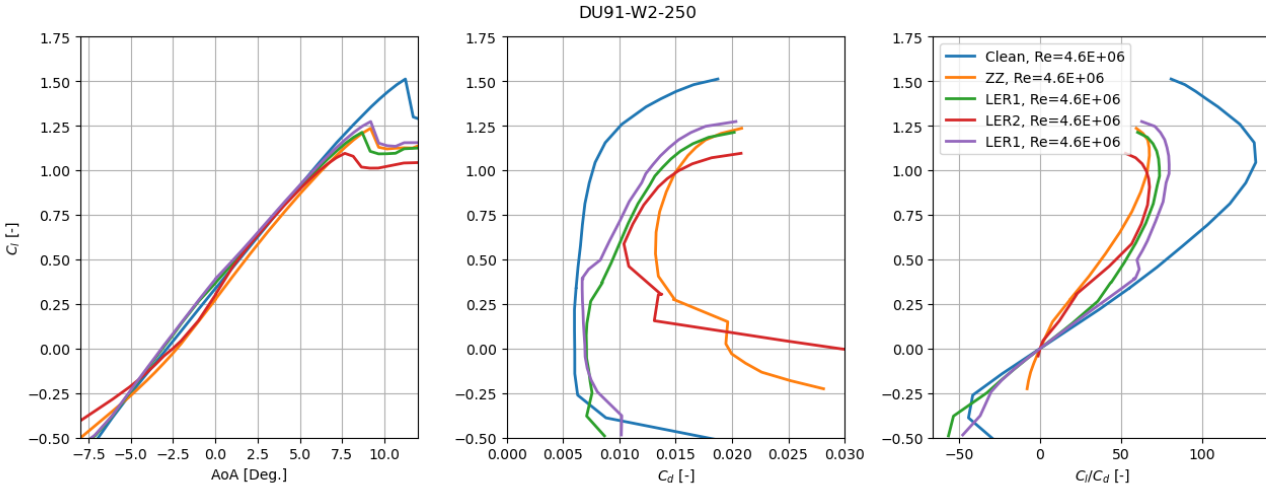


Figure 18: Measurements from PLCT with different LER topologies.

5.3.1 Boundary layer measurements with a total pressure rake

The effect of surface roughness on the aerodynamic and acoustic performance of an aerofoil is closely related to its influence on the boundary layer flow of the aerofoil. The measurement of boundary layer flow profiles is therefore a crucial instrument to study these effects. The most accurate technique to measure boundary layer flow id with a traversing hot wire anemometer. However, this method is very time consuming and difficult to implement in a wind tunnel. A much faster method to measure boundary layer profiles is with a total pressure rake on the aerofoil surface, Figure 19.

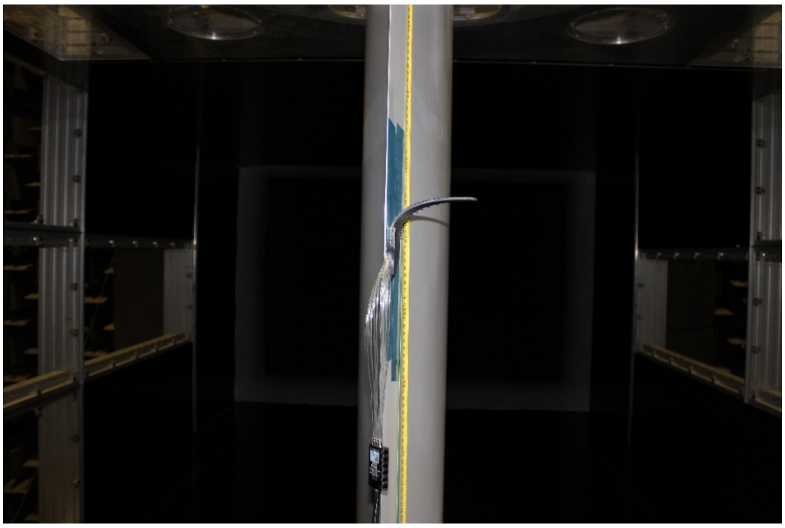


Figure 19: Total pressure rake mounted in the wind tunnel

The measurements with a total pressure rake need correction due to wall proximity and shear effects [8]. The measured and corrected velocity profiles on the FFA-W3-211 aerofoil were compared to CFD RANS computations, Figure 20.

Overall, the measurements and computations matched well. Hence, we could confirm that the roughness characterisation through CFD RANS is a valid method.

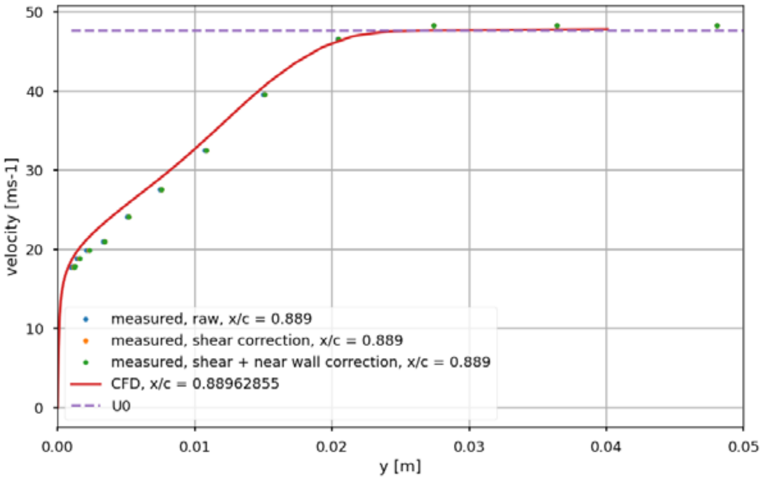


Figure 20: Measured and computed boundary layer profile for the FFA-W3-211 aerofoil at angle of attack of 3 degrees and flow speed 50 m/s.

5.3.2 Surface Microphones:

Aeroacoustic measurements were conducted in the PLCT during the project to assess the acoustic emission of various leading edge roughness conditions. Two types of measurements were made; far field noise at a distance of 2.3m from the aerofoil using a microphone array, and surface microphones mounted on the aerofoil

Leading edge roughness adds energy to the aerofoil boundary layer, creating a thicker boundary layer with bigger vortices. Since the boundary layer spectrum is the main cause of aerofoil trailing edge noise, it is expected that leading edge roughness increase the overall noise emission. It is however poorly understood in which part of the acoustic spectrum the increase occurs, and by how much.

The surface microphone tests presented were done on the FFA-W3-211 aerofoil, and 4 surface microphones were mounted in three different chord-wise locations, as seen in Figure 21.

The measurements are done with two different leading edge roughness conditions and are measured in the aero (hard wall) test section. The comparison is done at Reynolds number 4.5E6 and an angle of attack of 8 deg.

Figure 21: Locations of the surface microphones on the suction side of the FFA-W3-211 aerofoil.

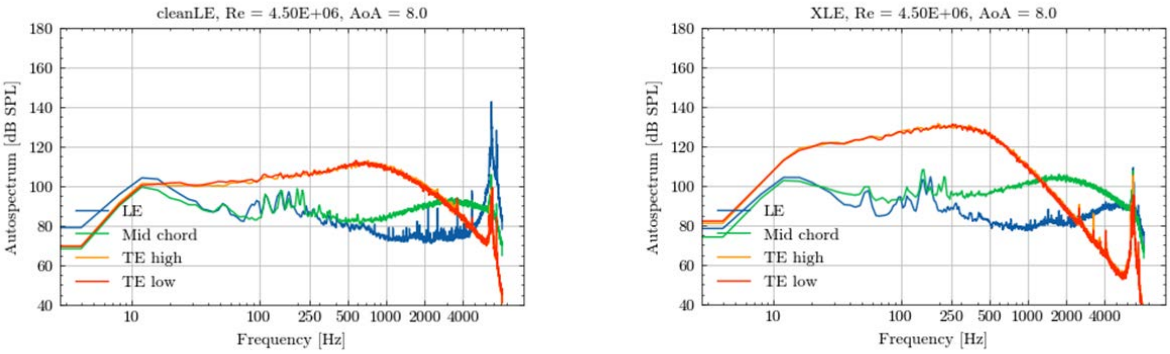


Figure 22: Spectra from the surface microphones on the suction side of the FFA-W3-211 aerofoil at Re=4.5E6, AoA=8deg. Left: clean LE. Right: LER-1 (first version).

Figure 22 shows the obtained spectra. On the left it is the clean leading edge, and, on the right, it is the LER-1 roughness topology (the mild erosion). Starting near the leading edge (LE), little change is observed in the surface spectra. This is expected since the microphone is placed before the expected transition point and thus in the laminar boundary layer. Moving to mid chord, a large increase in high-frequency content is observed from 250Hz-4000Hz. A broad band hump is seen moving its peak from 4000Hz at 95dB to 1800Hz at 105dB. This increase could be due to the transition point between the two conditions. The mid chord surface microphone might be in the laminar boundary layer in the clean condition, but with the added leading edge roughness, the transition point is moved towards the leading edge and the mid chord surface microphone is now in the turbulent boundary layer. Consulting pictures taken with an infrared camera (that detects transition points), see Figure 23, it is evident that the observed behaviour is not related to laminar vs turbulent boundary layers, as the mid chord microphone is already in the turbulent boundary layer in the clean configuration, but in fact due to the increase leading edge roughness.

A similar observation can be made with the surface microphone positioned near the trailing edge. The broad band hump in the clean condition is centred around 800 Hz with a peak value of 116dB. For the LER-1 configuration this peak move towards 250Hz with a value of 130dB.

Similar observations can be made for an angle of attack of 10 degrees.

Overall, it is evident that the acoustic surface spectrum changes significantly when leading edge roughness is added. The spectrum is moved to lower frequencies, and the level is increased.

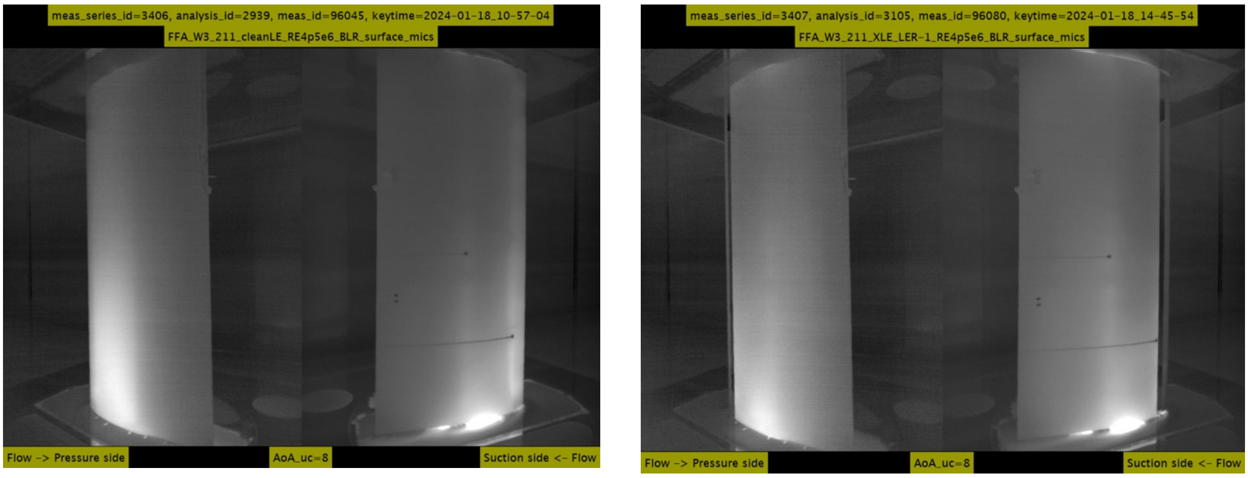


Figure 23: Infrared pictures from the FFA-W3-211 aerofoil at Re=4.5E6, AoA=8deg. Left: clean LE. Right: LER-1 (first version).

5.4 WP5:

Due to the delay in the numerical simulations and wind tunnel measurements an initial literature survey has been conducted about existing LE erosion classification systems from an aerodynamic point of view. This highlighted the diversity between different sources but also highlighted that most of the data available are based on wind tunnel tests. This observation inspired the idea of comparing those data to extrapolate general trends which could help in establishing a robust classification system based on evidence from wind tunnel tests. Table 1 illustrates the heterogeneity in the available wind tunnel tests being different in terms of facility, aerofoil shapes, test condition (i.e. Reynolds number) and technique to model erosion in the wind tunnel. Despite this, some consistent trends emerged between the main aerofoil performance parameters (i.e. lift coefficient Cl, drag coefficient Cd and aerodynamic efficiency L/D), which are illustrated in Figure 24. More details of the initial analysis is found in [9].

Table 1: Wind tunnel measurements on LER

Source	**Airfoil**	**t/c [%]**	**Wind tunnel facility**	**LE erosion modelling technique**	**Data Reynolds number [million]**										
					1	**1.2**	**1.5**	**1.75**	**2**	**2.2**	**3**	**4**	**4.5**	**5**	**6**
Vestas	Proprietary shapes	18, 24	LWK Stuttgart	Printed pattern		x		x	x	x	x			x	
	NACA63$_3$-418	18	PLC DTU	Printed pattern							x			x	
Sandia	NACA 63$_3$-418 S814	18, 24	LSWT Texas A&M	Sandpaper with different grit levels			x		x		x	x			
IRPwind	NACA 63$_3$-418	18	LSLT TUDelft	Sandpaper with different grit levels	x				x		x				
DTU	NACA 63$_3$-418	18	PLC DTU	Sandpaper with different grit levels							x			x	x
	NACA 63$_3$-418	18	LWK Stuttgart	Sandpaper with different grit levels							x				
	NACA63$_3$-618 FFA-w3-211 DU91-w2-250	18, 21, 25	PLC DTU	Sandpaper and 3D printed patterns							x		x		x
LM	DU00-w-212 Proprietary shape	18, 21.2	LM	3D printed pattern							x				x
UIUC	DU96-w-180	18	UIUC	Pits and gouges add-ons	x		x		x						

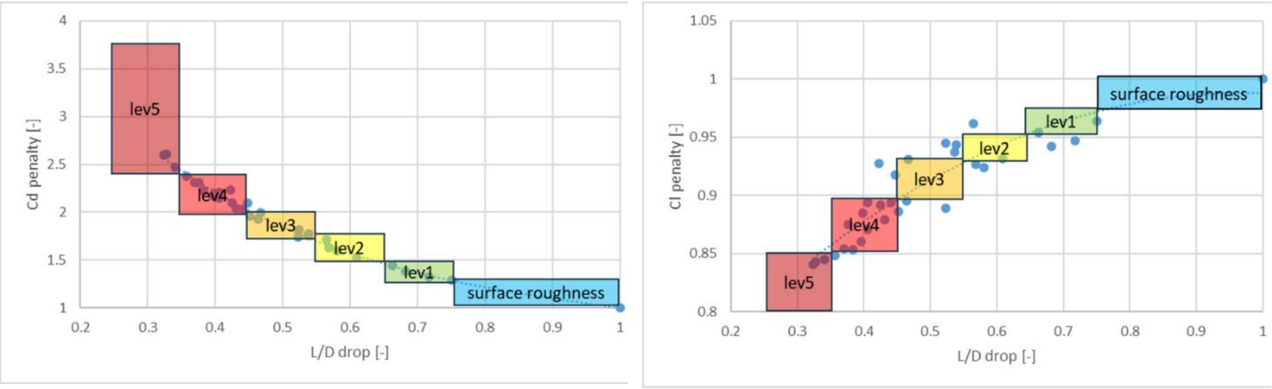
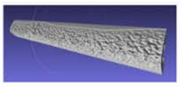


Figure 24: Analyses of the data in Table 1.

As more and more results from the wind tunnel tests and numerical simulations became available the data from the open literature was supplemented with those and the first version of the LERCat categorisation scheme is developed, see Table 2

Table 2: LERCat categorisation scheme version 1.

Picture	LER Category	Label	Tagging	Clmax/Clmax, clean [-]	(Cl/Cd)/(Cl/Cd)clean [-]	Cd/Cd, clean [-]	Cl/Cl, clean [-]	Δ OA SPL [dB
	A	Minor localised damage / roughness	Top coat Scratch Flaking Discrete	0.975+/-0.025	0.864 +0.121 (-0.182)	1.141 +0.266 (-0.127)	0.986 +0.013 (-0.027)	1.2 +1.8 (-0.9
	B	Discrete erosion	Topcoat Pinholes Peeling Discrete	0.925+/-0.025	0.683 +0.126 (-0.150)	1.405 +0.333 (-0.194)	0.959 +0.020 (-0.033)	3.0 +2.2 (-1.3
	C	Continuous mild erosion	Topcoat Erosion Continuous	0.875+/-0.025	0.588 +0.107 (-0.118)	1.598 +0.332 (-0.215)	0.940 +0.022 (-0.033)	4.3 +2.2 (-1.5
	D	Continuous severe erosion	Laminate Erosion Continuous	0.825+/-0.025	0.541 +0.085 (-0.096)	1.716 +0.303 (-0.200)	0.928 +0.020 (-0.030)	5.1 +2.0 (-1.4
	E	Very severe damage, incl. through-going holes	Structure Through Erosion Hole Continuous	0.775+/-0.025	0.518 +0.065 (-0.083)	1.780 +0.276 (-0.170)	0.922 +0.017 (-0.027)	5.5 +1.9 (-1.1

Based on the categorisation scheme it is possible to estimate the energy production loss for a given turbine with a given distribution of LER, by following the workflow outlined in Figure 25. The box with the question marks in the dashed red box is the categorisation scheme as developed in LERCat and with version 1 shown in Table 2.

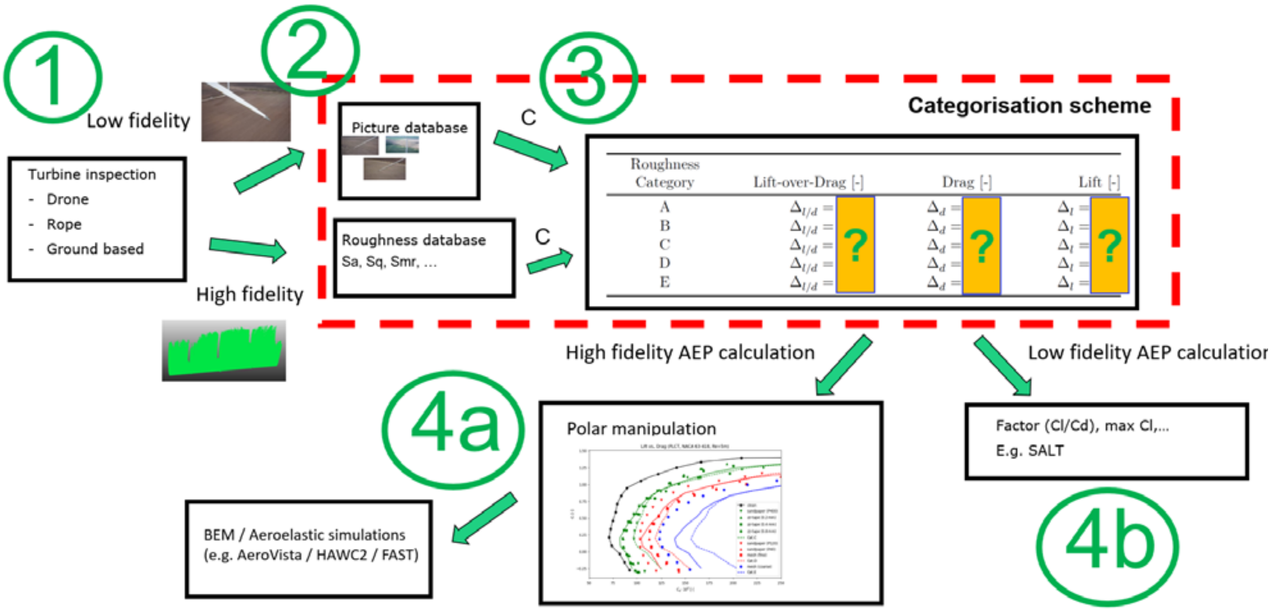


Figure 25: LERCat workflow.

The tasks needed to complete the workflow in Figure 25 are:

1. Map the condition of the blade leading edge using photos (low fidelity) or scans (high fidelity) from blade inspections
2. Analyse the photos and tag each damage within the photo with for example a box surrounding its extent
3. For each tagged damage, assign the following metadata:
   a. a corresponding category (A to E)
   b. spanwise extent
   c. radial position (distance from hub centre to centre of damage)
4. Use all of the metadata from step 3 to estimate the energy loss. This can be done in two ways:
   a. Higher fidelity/lower uncertainty. If the details about the blade geometry and the aerodynamic data are already known, a detailed simulation model like the Blade Element Momentum (BEM) method can be used together with degraded aerodynamic input data, the so-called polars that are lift, drag and moment as a function of angle of attack. The polars can be degraded guided by the LERcat scheme in Table 2. This BEM-based method can compute the power of the turbine and thereby the loss in power and energy can be determined.
   b. Lower fidelity/higher uncertainty. If the details about the blade geometry and the aerodynamic data are not known, simplified methods exist to determine the power and energy loss. In these models overall information about the rotor diameter, rated power, wind climate and the distribution of the aerodynamic penalty categories along the blades are required and the energy loss is determined based on this.

The details of the derivation of the LERCat categorisation scheme are given in [10].

5.5 Commercial results and target group:

The developed categorisation scheme from WP5 is the single most important commercial outcome of the LERCat project. As the developed categorisation scheme is open and intended to be an industry standard it cannot directly be turned into a saleable product. However, as the scheme delivers a categorisation of the leading-edge roughness with corresponding aerodynamic and acoustic performance losses it enables the target group (i.e. OEMs, turbine owners and independent service providers) to estimate the AEP losses for the entire wind turbine and allow them to determine the optimal time of repair based on a data-driven and objective workflow. This optimum depends on their individual cost models for lost production and repair costs and their overall inspection/repair schedules.

The initial investigations made for the application, which is still valid, shows that a one year offset from the optimal time of repair is in the order of 2500 DKK/MW/year and a two-year offset is in the order of 4000 DKK/MW/year. As the typical turbine sizes are above 4MW onshore and offshore beyond 12MW, it is a substantial amount that can be gained by using the scheme.

5.6 WP6:

A linkedIn page was established [11] to have a channel for presenting news and to gain visibility of the project.

The project has been presented at several conferences and in a number of journals:

- Papers
  - Forsting AM, Olsen AS, Sørensen NN, Bak C. The impact of leading edge damage and repair on sectional aerodynamic performance. 2023. Paper presented at 2023 AIAA SciTech Forum, National Harbor, Maryland, United States.
  - Forsting AM, Olsen AS, Sørensen NN, Bak C. The impact of leading edge damage and repair on sectional aerodynamic performance. In Proceedings of AIAA SCITECH 2023 Forum. Aerospace Research Central (ARC). 2023. 0968 doi: 10.2514/6.2023-0968
  - Meyer Forsting A, Olsen AS, Sørensen NN, Fischer A, Markussen CM, Bak C. An aerodynamic digital twin of real-world leading edge erosion: Acquisition, Generation and 3D CFD. In The Science of Making Torque from Wind (TORQUE 2024): Aerodynamics, aeroleasticity, and aeroacustics. IOP Publishing. 2024. 02021. (Journal of Physics: Conference Series; No. 2, Vol. 2767). doi: 10.1088/1742-6596/2767/2/022021
  - Meyer Forsting AR, Olsen AS, Gaunaa M, Bak C, Sørensen NN, Madsen J et al. A spectral model generalising the surface perturbations from leading edge erosion and its application in CFD. In Turbine Technology; Artificial Intelligence, Control and Monitoring. IOP Publishing. 2022. 032036. (Journal of Physics: Conference Series; No. 3, Vol. 2265). doi: 10.1088/1742-6596/2265/3/032036
  - Meyer Forsting, A., Dicholkar, A., Sørensen, N. N., Olsen, A. S. (2025). High-resolution 3D CFD simulations of wind turbine aerofoils with 3D scanned leading edge roughness. In Proceedings of AIAA Aviation 2025, Las Vegas, Nevada, United States (in print).
  - Lylloff O, Fischer A, Olsen AS. Aeroacoustic investigation of leading edge erosion in a wind tunnel. In Bertagnolio FRJ, editor, 11th Edition of the International Conferences on Wind Turbine Noise: Conference Proceedings. DTU Wind and Energy Systems. 2025

- Conference contributions
  - Bak, C., Olsen, A. S., Forsting, A. M., An approach to detect the aerodynamic degradation due to erosion, 1 Feb 2022, 3rd International Symposium on Leading Edge Erosion of Wind Turbine Blades, Risø, Denmark
  - Bak, C., Olsen, A. S., Forsting, A. M., Setting a new standard - Why an aerodynamic industry standard is necessary for blades damage inspection, 26 Oct 2022, Blades Europe 2022, Conference, Hamburg, Germany
  - Olsen, AS et al, How does LER on real blades look like?, 4th International Symposium on Leading Edge Erosion of Wind Turbine Blades, 2023, Risø, Denmark

- Forsting, AM et al, The impact of leading edge damage and repair on sectional aerodynamic performance, 4th International Symposium on Leading Edge Erosion of Wind Turbine Blades, 2023, Risø, Denmark
- Olsen, AS et al, Wind tunnel tests of real LE Roughness, 5th International Symposium on Leading Edge Erosion of Wind Turbine Blades, 2024, Risø, Denmark
- Forsting, AM et al, An aerodynamic digital twin of real-world leading edge erosion, 5th International Symposium on Leading Edge Erosion of Wind Turbine Blades, 2024, Risø, Denmark
- Meyer Forsting, A., Olsen AS, Bak C. Estimating production losses from blade leading edge roughness and erosion. 7th Wind Farm Operators Forum, 2024, Sopot, Poland.
- A Meyer Forsting, AS Olsen, S Ildvedsen, NN Sørensen, C Bak, J Beckerlee, A Fischer. Challenges in wind tunnel measurements and CFD simulations of LER effects at high Reynolds numbers, Sandia Blade Workshop, 2024, Albuquerque, New Mexico, United States.
- Olsen, AS, Bak C, Categorising the Power Production Loss From Leading Edge Roughness – The LERCat Project, Panel discussion 28 Nov 2024, Wind Energy Denmark 2024 Conference, Odense, Denmark
- Olsen, AS et al, Continued wind tunnel testing of real LE roughness, 6th International Symposium on Leading Edge Erosion of Wind Turbine Blades, 2025, Risø, Denmark
- Forsting, AM et al, The aerodynamically critical roughness height of LER, 6th International Symposium on Leading Edge Erosion of Wind Turbine Blades, 2025, Risø, Denmark
- Olsen, AS et al, Wind tunnel testing of realistic leading edge roughness, Poster at WindEurope 2025 Conference, Copenhagen 8-10 April 2025.
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- Olsen, AS, Forsting, AM, Bak, C, Munoz, A, Madsen, J, Hansen, R, Wind Tunnel Tests of Leading Edge Roughness for an Aerodynamic Categorisation Scheme. Wind Energy Science Conference (WESC) 2025, Nantes, France, 24-27 June 2025.
- Grasso, F, Leading edge erosion classification based on wind tunnel tests. Wind Energy Science Conference (WESC) 2025, Nantes, France, 24-27 June 2025.

6. Utilisation of project results

The main product from the project is a categorisation scheme for aerodynamic and acoustic losses due to leading edge roughness (LER). Based on numerous wind tunnel tests and calculations using Computational Fluid Dynamics (CFD) it has been possible to generalise the aerodynamic losses for sections along the blade and in this way provide a detailed picture of how the aerodynamic and aeroacoustic behaviour degrades based on blade inspection photos.

The high-resolution LER topographies extracted from real-world blades are hosted on DTU Data, DTU’s data repository, and openly available. It is the only dataset of its kind, covers most of the common damage types seen on blades and is hence expected to be of great interest to the entire wind energy industry and academia. The LERCat dataset could be expanded by evaluating some of the yet unused topographies and applied to different aerofoils to assess their LER sensitivity or used to design, new, more erosion resistant aerofoils. The latter is of special interest to consultancies and OEMs, as it would give their designs a competitive advantage. The topographies may also be of interest beyond the wind energy industry, since the aerodynamic effects of surface roughness are equally important in fields such as aviation, shipping, and industrial flows. The need from these industries has created an especially active area of research that tries to link surface roughness statistics to high-fidelity flow predictions, which is increasingly incorporating machine learning techniques. Here the topographies might also be of great value and help establish some general statistics for different LER severities.

Yet, it is not just the data, but also the methods developed for acquiring and extracting the topographies that are easily transferable to other measurements of complex topographies with high-resolution 3D laser scanners, that cannot just be used in erosion studies but also for instance in icing or soiling investigations. All methods developed to generate the digital twin have been documented and codes are hosted on DTU Wind's GitLab repository. The codes will be supported as they are already used within other projects. The developed workflows are automatised and robust, thus it is reasonably simple to apply to any of the other, not yet evaluated roughness topographies and can easily be run by third parties.

A comprehensive set of data from the CFD simulations and wind tunnel measurements with the different LER topographies are also openly available from DTU Data. These can be used to benchmark results obtained with other numerical tools and from other wind tunnels. Indeed, a benchmark study on a subset of the LER measurements is already underway as part of the IEA task 46, Erosion of Wind Turbine Blades. It is expected to be used in many future benchmarks, industrial and academic publications. Publishing all data openly also ensures full transparency, giving the chance to third parties to verify our conclusions and provide feedback.

Another important outcome of the project is that to predict the production loss from LER at an individual turbine level requires extremely detailed information as to where along the blade the damage is found and how much of the blade it covers. Even though there are not many aerodynamic categorization schemes, the one published by the IEA task 46 and some of those used already by OEMs, assume that the damage severity peaks towards the tip and quickly diminishes moving inboard, however looking at inspection data, mostly taken from drones, this was mostly not the case; the manifestation of LER on an individual turbine level is highly stochastic, the assumed damage patterns are only valid over a fleet of turbines, i.e. as within a farm. Hence the categorization scheme developed within LERCat is meant to be used only at a sectional level, only in combination with the detailed information of the location of damages along the blade is the production loss of the entire turbine computed. Here it also needs to be stressed that damages can vary strongly between blades on the same wind turbine. This also opens up opportunities for inspection companies and downstream inspection data processing service providers, as they can target their inspection technology at providing the highly detailed damage information. Indeed PowerCurve, through collaboration with various drone inspection companies, has that type of data already available, and utilises it in the AeroVista tool. Furthermore, it was found that the losses from LER can be highly blade design/aerofoil dependent, so the accuracy of the loss prediction also depends on having an accurate aerodynamic representation of the turbine. PowerCurve have access to 3D blade geometry models, which are integrated within AeroVista, as do OEMs, so they should be able to provide enhanced lower-uncertainty results and services to their customers.

As the overall business model for the categorisation scheme is to use it for planning the repair of the blade at the right time the categorisation scheme can be used by OEMs, turbine owners and independent service providers. As mentioned earlier the categorisation scheme is not a commercial product, but the value of the scheme lies in the derived effects it has when used, e.g. in better planning of blade repairs. The OEMs are expected to include the categorisation scheme in the service agreements they offer and independent service providers, such as PowerCurve, will benefit from the systematic and transparent development of the scheme in their AEP loss assessments. The developed categorisation scheme will be the first open, widely accepted LER categorisation and thus has no direct competitors. However, most OEMs, owners and independent service providers have some form of categorisation scheme. However, these are mostly based on avoiding structural damages to the blade and mostly do not consider the performance losses they might incur. Generally, these in-house categorisations lack credibility, as they are not impartial and depend on the party defining them, where the LERCat categorisation scheme has been endorsed by all participating parties. To firmly establish the categorisation within the industry, it will, additionally to the aerodynamic benchmark, be introduced to the participants of the IEA Task 46 Phase II by demonstrating how it can be used to make consistent LER-related AEP loss estimates.

Leading edge protection (LEP) systems are applied increasingly to blades during manufacturing and is also applied as retrofits to already operating turbines. This of course comes with an installation cost and most often these solutions affect the turbines' energy production, just as LER does, since the solution cannot be fully integrated into the blade surface. The developed categorisation scheme is a useful tool in predicting the tipping point where the cost associated with the loss in production due to the LER is higher than the installation cost of a LEP solution and the costs associated with the production loss with the LEP. Whilst LEP is marked as providing full lifetime protection, it is still likely to show some forms of erosion during the usual 25 years of operation to which the categorisation scheme will apply.

Concluding, LER repairs will be necessary in the foreseeable future, showing the need for a LER categorisation for many years to come to assess losses on new and old wind turbines.

7. Project conclusion and perspective

The key outcome of the LERCat project is the categorisation scheme that links blade inspection data with aerodynamic and aeroacoustics losses on wind turbine blade sections (see Table 2). The scheme enables OEMs, turbine owners and independent service providers to estimate the losses in Annual Energy Production (AEP) caused by leading edge roughness (LER) for a wind turbine and allow them to determine the optimal time of repair based on a data-driven and objective workflow. The developed categorisation scheme is open and intended to be an industry standard.

To formulate the LER categorisation multiple images and laser surface scans from turbine blades were collected and analysed. Based on the developed method to extract the detailed LER topologies from a scan without knowing the initial uneroded shape a database of LER topologies from mild to severe erosion was established. A fully automated workflow which takes the extracted roughness topologies, wraps it around the leading edge of any aerofoil and creates a surface mesh, thus the collected LER topographies could be evaluated aerodynamically using numerical simulations and wind tunnel tests. The established best practices for numerical simulations and wind tunnel test of aerofoils with LER was used to create a dataset of aerodynamic and aeroacoustics performance of aerofoils with different severities of LER (from mild to heavy LER). This dataset together with data from the open literature formed the basis for deriving the sectional performance loses outlined in the categorisation scheme.

To firmly establish the categorisation within the industry, it will be introduced to the participants of the Sounding Board and of the IEA Task 46 Phase II by demonstrating how it can be used to make consistent LER-related AEP loss estimates. Furthermore, the OEMs are expected to include the categorisation scheme in the service agreements they offer and independent service providers, such as PowerCurve, will benefit from the systematic and transparent development of the scheme in their AEP loss assessments.

It is the intention to further strengthen the categorisation scheme if more data, both simulations and wind tunnel tests, becomes available in the future, e.g. for some of the yet unused topologies.

The LERCat dataset can be applied to different aerofoils to assess their LER sensitivity or used to design, new, more erosion resistant aerofoils. The latter is of special interest to consultancies and OEMs, as it would give their designs a competitive advantage.

Most importantly, since the categorisation scheme is openly available and closes the link between observed LER (images/scans collected at least once a year) and performance losses it can serve as a universal tool for deciding on the most cost-effective time of blade repair, allowing optimally balancing losses and maintenance costs. This will shift the status-quo away from repairing blades at fixed intervals or subjective rules of thumb.

Achieving this will result in an annual gain of 1 billion DKK for the combined turbine fleet of the project partners. However, as not all topologies and only a limited number of aerofoils have been tested, the LERCat categorization scheme is expected to evolve as more data becomes available, which should also enable reducing the uncertainty that remains within the current scheme.

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