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# High-resolution 3D CFD simulations of aerofoils with 3D scanned leading edge roughness

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Wind turbine blades operate under harsh environmental conditions throughout their lifetime—easily exceeding 20 years—especially exposing the blade leading edge (LE) to damage (e.g., from rain, hail, sand, sea spray) and contamination (e.g., insects, pollen, ice) with severe implications regarding aerodynamic performance [1, 2, 3, 4]. Together with icing, LE erosion and roughness (LER) creates the aerodynamically most detrimental topographic surface imperfections. Therefore, in the industry, aerodynamic performance losses related to LER are anticipated, though their exact extent is challenging to accurately determine because of insufficient high-resolution LER data from full-scale, in-service blades [1, 5, 6, 7]. Modern wind turbine aerofoils operate at Reynolds numbers between 5 to 20 million, which requires a spatial surface resolution of at least 50-100 $\mu$m to capture aerodynamically relevant surface features [5, 8], which can only be provided by high-resolution 3D optical, laser or computed tomography (CT) scanners, making it difficult to obtain such data from full-scale blades.

Within the Leading Edge Roughness Categorisation (LERCat) project[1], headed by DTU Wind, castings and laser scans of in-service or decommissioned blades exhibiting LER of varying severity were performed. A workflow was established that extracts roughness topographies from those high-resolution 3D scans and applies them digitally to any other aerofoil surface that can subsequently be assessed aerodynamically using 3D CFD or wind tunnels [9]. As shown by Stebbins *et al.* [10, 11] for LE icing, RANS accurately captures even complex flow features around and within complex LE surface topographies, especially at lower angles-of-attack, as also demonstrated by Bons *et al.* [12] for a patch of resolved gas turbine blade roughness. Due to the computational cost of resolving LER—in the order of 100 $\mu$m surface resolution is required at relevant Reynolds numbers—existing CFD investigations of wind turbine LER rely on simulating 2D slices [6, 13, 4, 7] or reducing the complexity of the erosion [14].

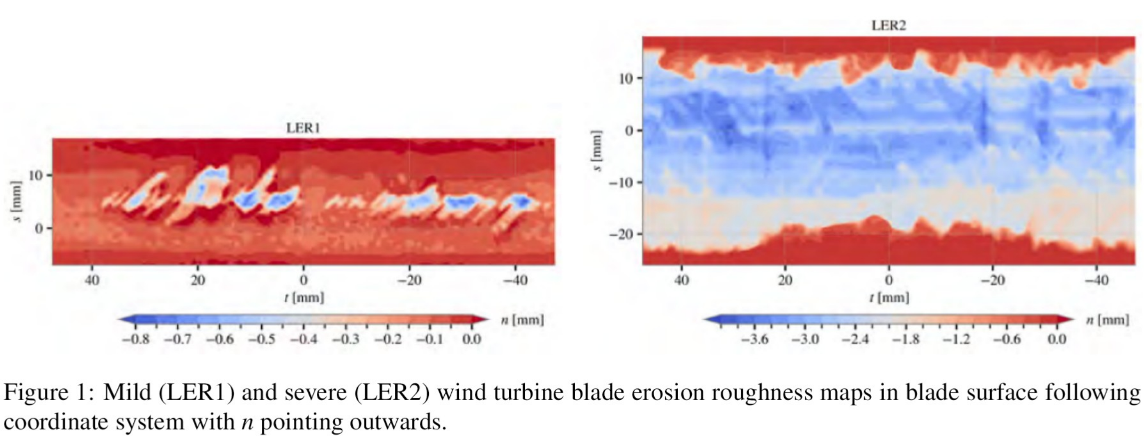


Figure 1: Mild (LER1) and severe (LER2) wind turbine blade erosion roughness maps in blade surface following coordinate system with $n$ pointing outwards.

[1]Sponsored by the Danish Energy Council; Partners: DTU Wind, Vestas Wind Systems A/S, Siemens Gamesa Renewable Energy A/S, LM Wind Power A/S, Suzlon Energy Nederlands Branch, PowerCurve ApS

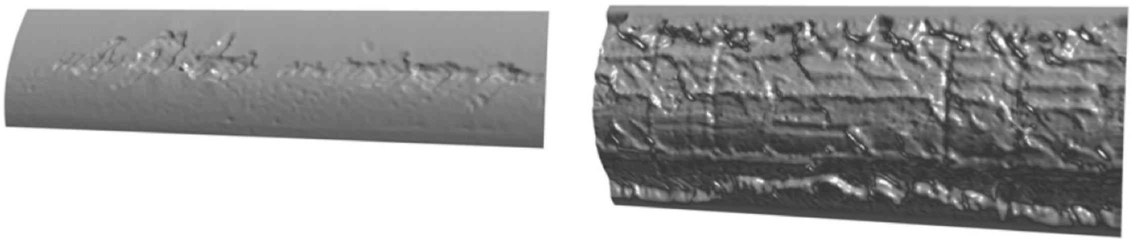

Figure 2: Rendering of the surface meshes for mild (LER1) and severe (LER2) wind turbine blade erosion.

Here, two distinct roughness topographies recently extracted from high-resolution 3D scans ($10 - 100$ $\mu$m point-to-point distance) of LER are applied to the FFA21-W3-211 aerofoil [15]—a commonly used 21% relative thickness wind turbine profile—with 900mm chord and aerodynamically evaluated using 3D RANS CFD. The roughness maps of both topographies, which are representative of mild and severe erosion seen on blades, are shown in Figure 1, with their corresponding LE surfaces shown in Figure 2. One topography exhibits a sparse distribution of damages of limited depth (max. $\approx 0.8$ mm) that lie towards the suction side, whereas the other exhibits spanwise-uniform deep erosion (max. $\approx 4$ mm) creating sharp forward facing steps and overhangs. The complex flow features developing over those LEs are resolved by keeping the chord- and spanwise resolution below 110 $\mu$m around the roughness features. Simulations are performed with DTU's in-house solver EllipSys3D and STAR-CCM+ at Reynolds numbers between 3 and 6 million.

The focus lies in attributing departures from clean aerofoil performance changes in terms of integral measures to LER induced alterations at the boundary layer level over a wide angle-of-attack range. Whether certain LER features triggers premature transition is evaluated by running the simulations with the $\gamma$-$Re_{\theta t}$ transition model. A visualisation of the complex vortical structures developing over the severe erosion is given in Figure 3, exhibiting strong three-dimensionality and some laminar flow (blue) within the cavity and, surprisingly, even beyond the forward-facing step. Furthermore 2D chordwise slices are extracted from the 3D aerofoil with LER and simulated to quantify the error from using 2D representations of 3D LER for evaluating roughness related aerodynamic performance loss.

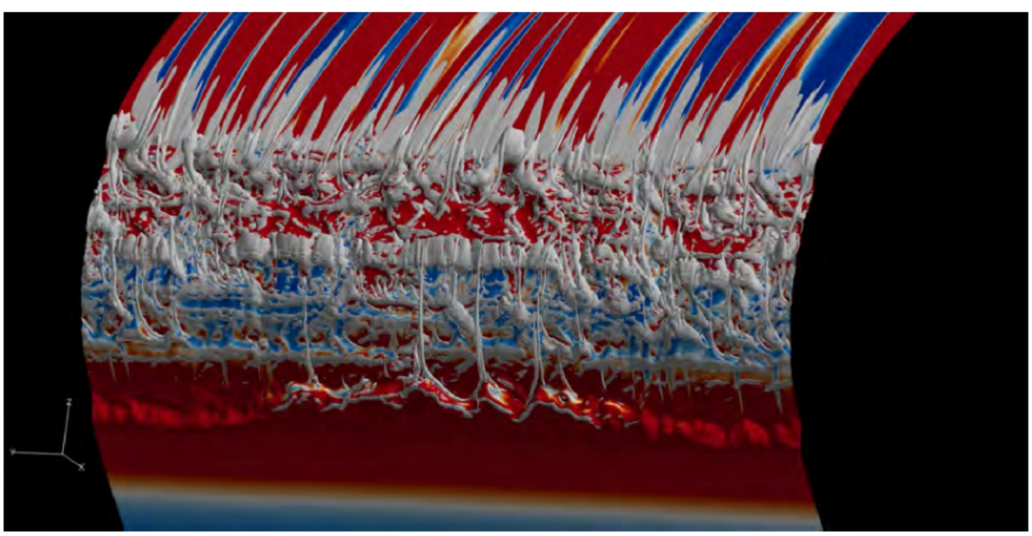

Figure 3: Vortical structures developing over LER2 (iso-surfaces of Q-criterion) at an angle-of-attack of 6° and Reynolds number of 3 million. Surface colouring indicates laminar (blue) and turbulent flow (red).

**Closing Remarks** In 2D CFD simulations the incoming flow only sees the extracted slice, thus reacting more strongly to the local geometry features of the roughness patch than for the 3D section. In the 3D section, the geometry features of the LER patch causes the flow to deviate from its 2D nature seen in clean aerofoil sections and instead impart 3D characteristics to the flow. The 3D nature of the flow owing to the LER patch geometry in the neighbourhood of the extracted slice can suppress the boundary layer transition. In contrast the 3D-unaware 2D CFD simulations predicts an earlier transition where the 3D simulation does not.

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