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AERODYNAMIC EROSION MODELING ON TURBINE BLADES

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RATIONALE
ERODED ROUGH WIND TURBINE BLADE

- The influence of surface roughness in the form of erosion or contamination is of great practical importance for the wind industry.

- The **tip part of the blade**, due to the higher speeds, contributes to majority of the torque production, however the higher speeds also results in higher droplet impact velocity and the erosion rate at this part of the blade.
  - Eroded or contaminated blades may result in sub-optimal performance of the rotor and significant loss in **annual energy production (AEP).**
  - Detailed **understanding of the impact on aerodynamic performance** due to the eroded and rough leading edge (LE) is required to optimise the repair and operation, and accurate modelling tools are therefore essential.

INTRODUCTION
COMPUTATIONAL MODELLING OF ERODED BLADES – TWO PART STUDY

Erosion is modelled on blade section level and the corresponding loss in AEP through a standard BEM code

- First part:
  - Development and calibration of transport equation based boundary layer transition model for surfaces with distributed roughness
  - Focused on **modelling the textural differences (0.1 - 0.2mm)** at the leading edge due to blade erosion or contamination
- Second part:
  - Aerodynamic performance of scanned eroded wind turbine blade sections using RANS CFD
  - Focused on **modelling the actual shape change (10 - 20mm)** at the blade leading edge due to erosion

PART 1:
CFD TRANSITION MODEL FOR SURFACES WITH DISTRIBUTED ROUGHNESS

FLOW TRANSITION PREDICTION FOR ROUGH SURFACES
INTRODUCTION

- Boundary layer transition process is an extremely complicated process that has been studied extensively for almost a century
- Langtry-Menter's local correlation based transition model (SSTLM) has shown promising results for clean surfaces at moderate Reynolds numbers (~3million)
- In 2012, Dassler, Kozulovic and Fiala[1] originally proposed the idea of introducing an additional transport equation coupled to SSTLM for triggering transition for rough surfaces
  - This approach uses an additional field variable to be a transported downstream to generate a region of influence due to the prescribed roughness, thus the underlying transition model is triggered accounting for the effect of surface roughness.
  - Later in 2017, Langel et al[2] firstly reported its implementation with it performance using the OVERFLOW-2 solver

1. *Patrick Dassler, Dragan Kozulovic, and Andreas Fiala. "An approach for modelling the roughness-induced boundary layer transition using transport equations." In: Europ. Congress on Comp. Methods in Appl. Sciences and Engineering, ECCOMAS. 2012.*
2. *Christopher M Langel et al. A Transport Equation Approach to Modeling the Influence of Surface Roughness on Boundary Layer Transition. Tech. rep. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2017*

FLOW TRANSITION PREDICTION WITH ROUGH SURFACES

FORMULATION

- Essentially, a new equation for Re_θ accounting roughness is defined based on the, local roughness amplification quantity (Ar).

$$Re_{\theta,rough} = Re_\theta + \frac{1}{3}u^+\left(\frac{Ar}{c_{r1}}\right)^3 - \frac{1}{2}\left(\frac{Ar}{c_{r1}}\right)^2$$

- Which is used to lower the triggering $Re_{\theta t}$ within the production term of its transport equation:

$$\tilde{P}_{\theta t} = c_{\theta t}\frac{\rho}{t}\left[(Re_{\theta t} - \tilde{R}e_{\theta t})(1 - F_{\theta t}) - bF_{Ar}\right]$$

- The transport equation for Ar is defined similar to those of the underlying transition model

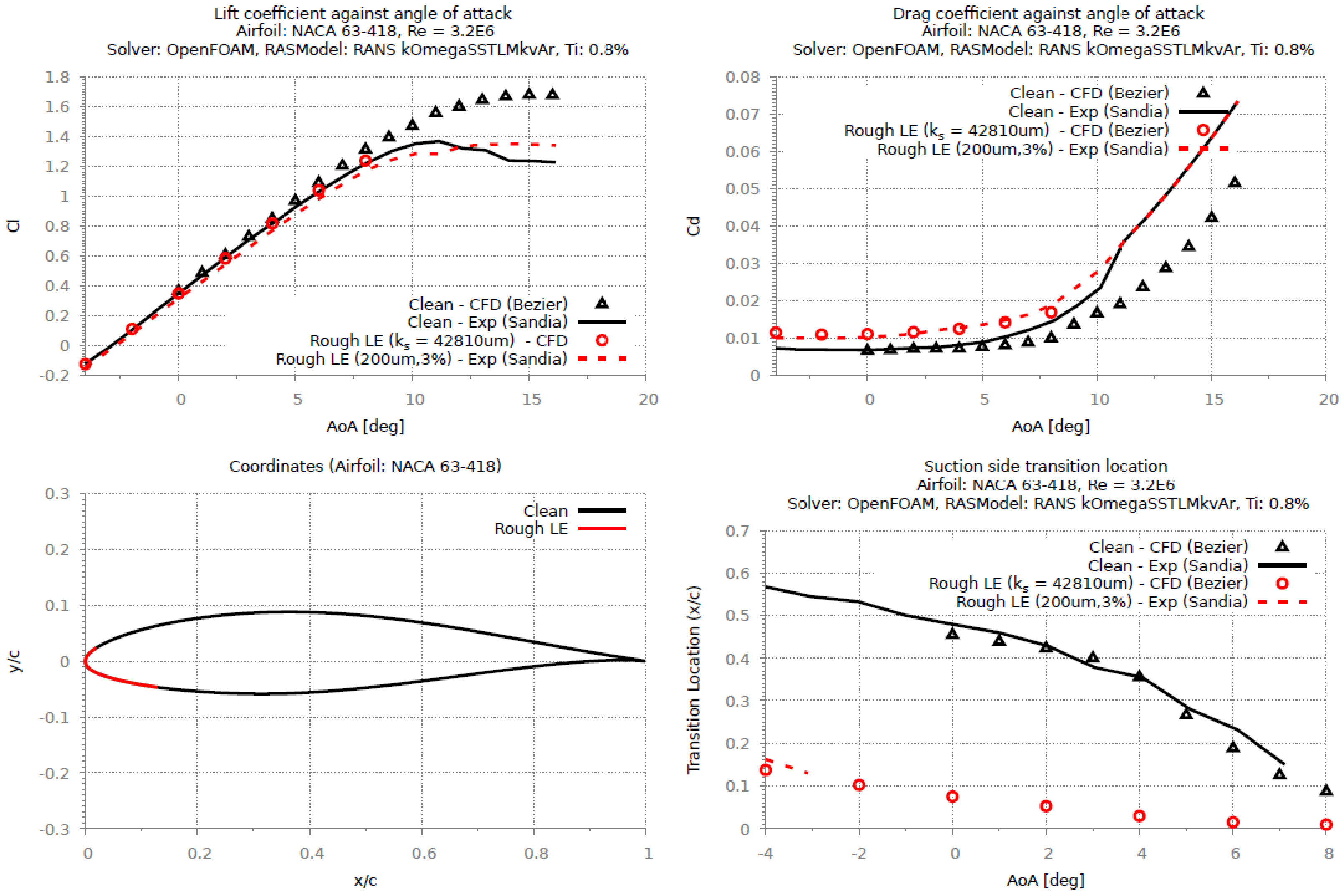
$$\frac{\partial(\rho Ar)}{\partial t} + \frac{\partial(\rho U_j Ar)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\sigma_{ar}(\mu + \mu_t)\frac{\partial Ar}{\partial x_j}\right]$$

- The distribution of Ar is prescribed at the boundary condition of the rough walls section based on an equivalent sand grain roughness height (ks)

$$Ar|_{wall} = c_{r1}k^+ \text{ with } k^+ = \sqrt{\frac{\tau_w}{\rho}}\frac{k_s}{\nu}$$

<- measurable quantity

RESULTS
LEADING EDGE ROUGHNESS = 200UM



Despite only calibrating the ks values to match the measured transition locations, the results show very good agreement between the modelled and the experimented drag force, especially for the large roughness heights of 140um and 200um

All modelled results showed notable differences (10%) with the measured lift forces, where the relative reduction in lift was captured well, while the absolute values were over-predicted.

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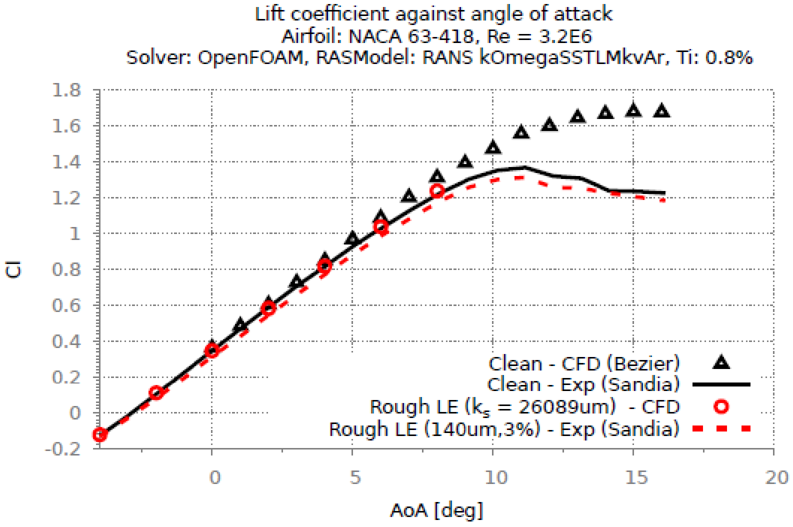
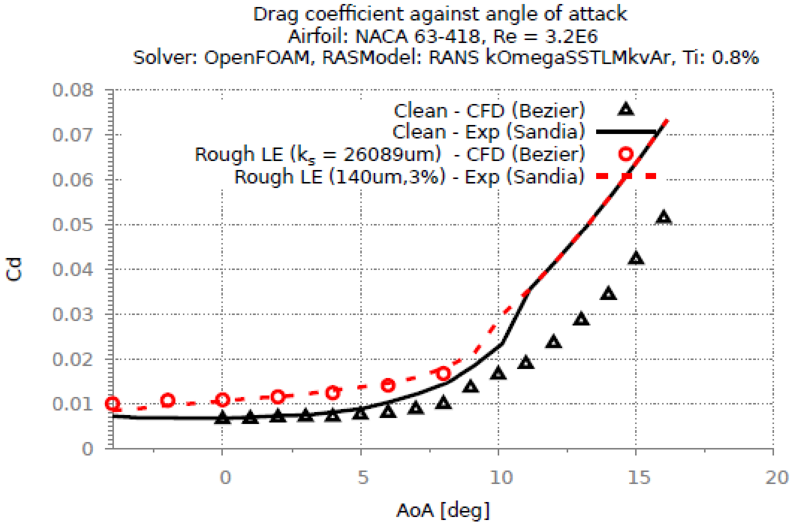
RESULTS

LEADING EDGE ROUGHNESS = 140UM





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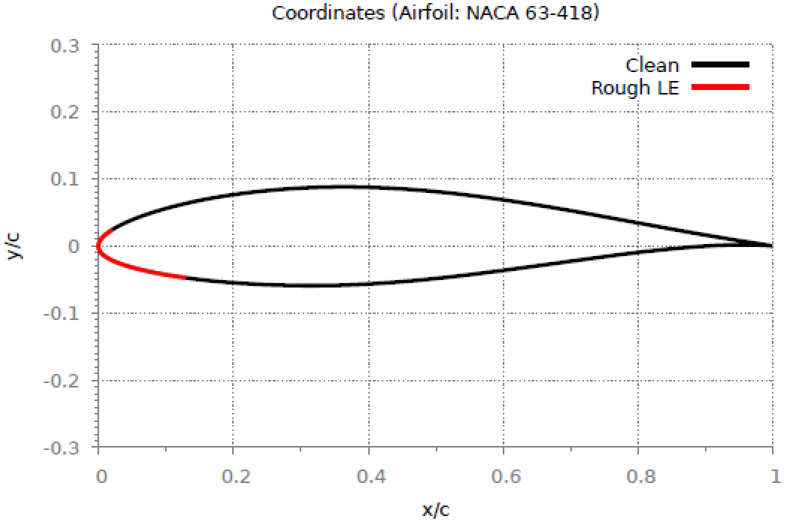

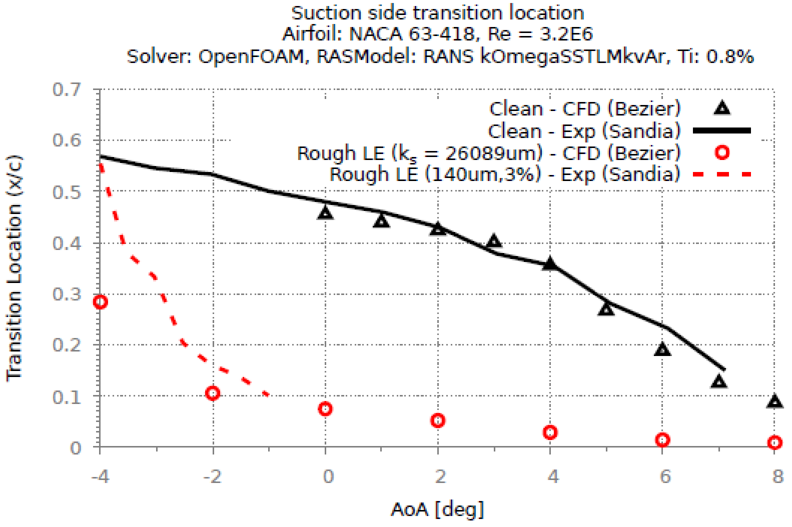

All modelled results showed notable differences (10%) with the measured lift forces, where the relative reduction in lift was captured well, while the absolute values were over-predicted.

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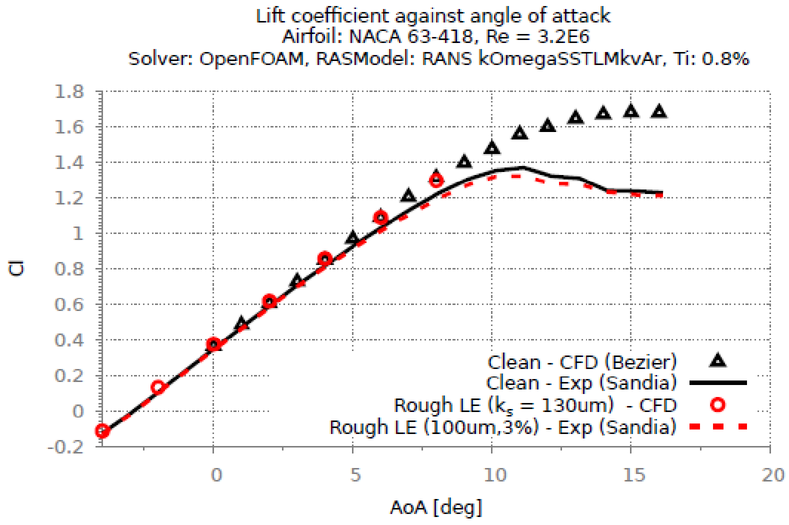
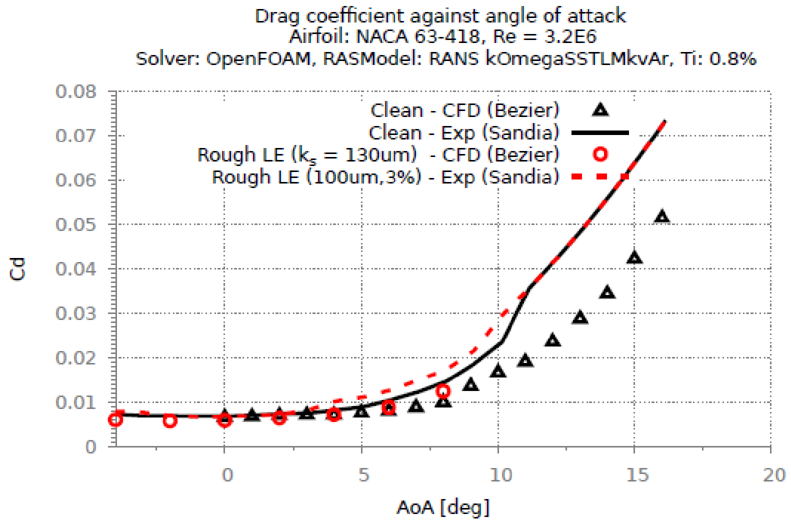
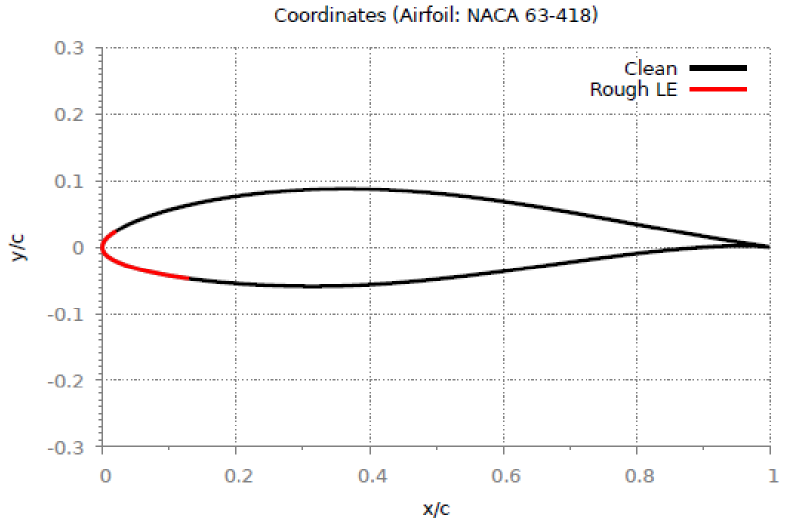
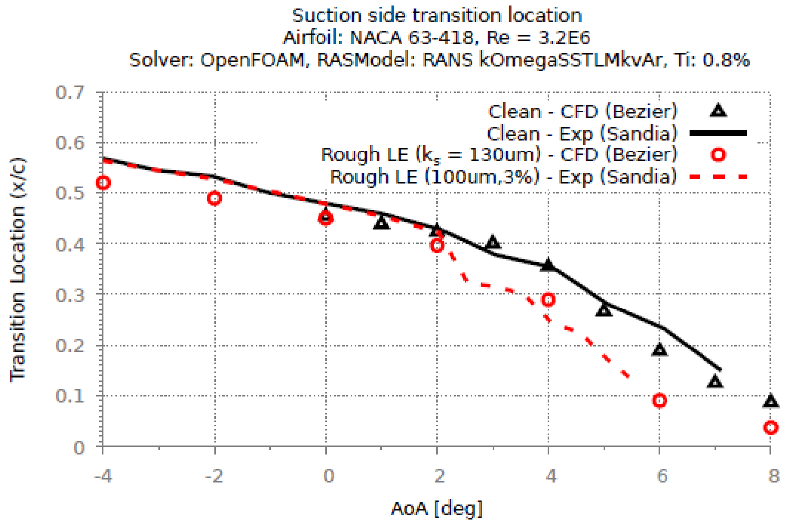
RESULTS

LEADING EDGE ROUGHNESS = 100UM









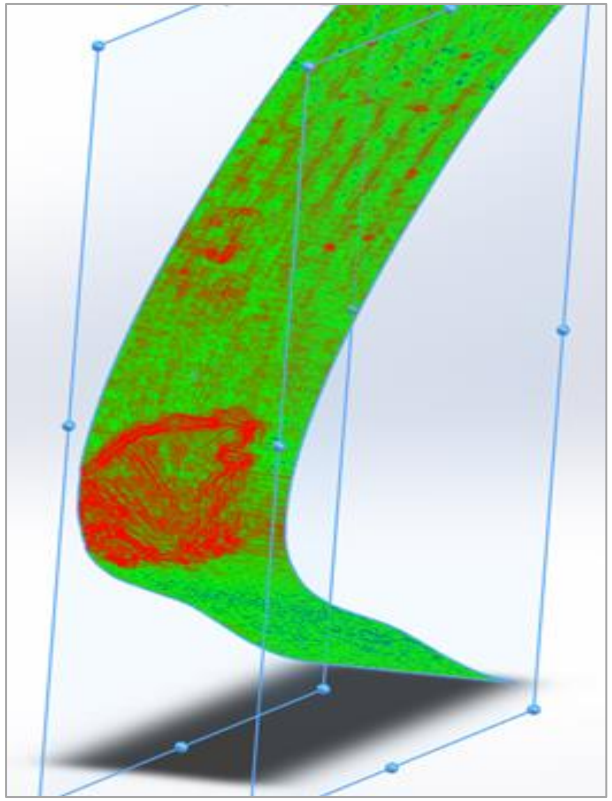
For the roughness height of 100um, the calibrated results showed reasonable agreement with the measured transition location. However, the corresponding results on the drag forces were under-predicted in comparison with the measured values.

PART 2:
AERODYNAMIC PERFORMANCE OF SCANNED ERODED WIND TURBINE BLADE SECTIONS USING RANS CFD

3D SCAN OF DAMAGED BLADE

NON-CONTACT LED SCANNING

- The generated 3D point cloud was preprocessed to remove holes, imperfections and noise.
- The “watertight” mesh model was transformed into a CAD format, *.IGS or *.STP, for CFD simulations.

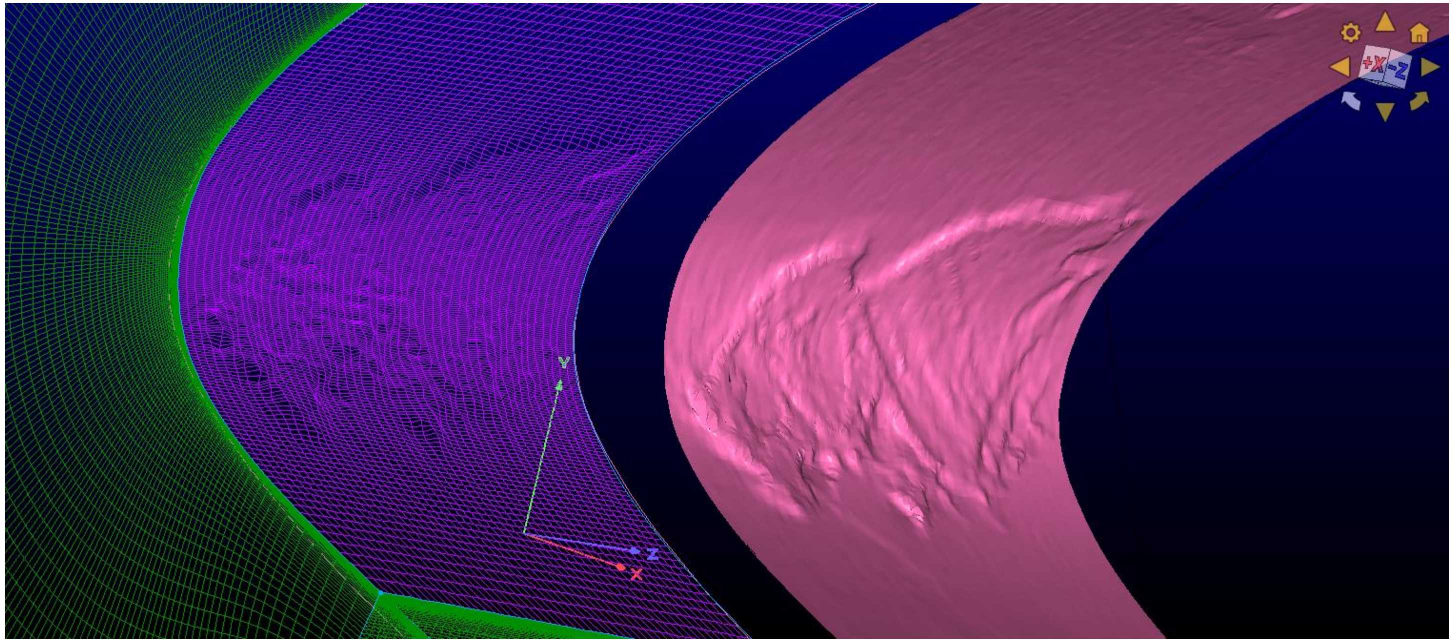


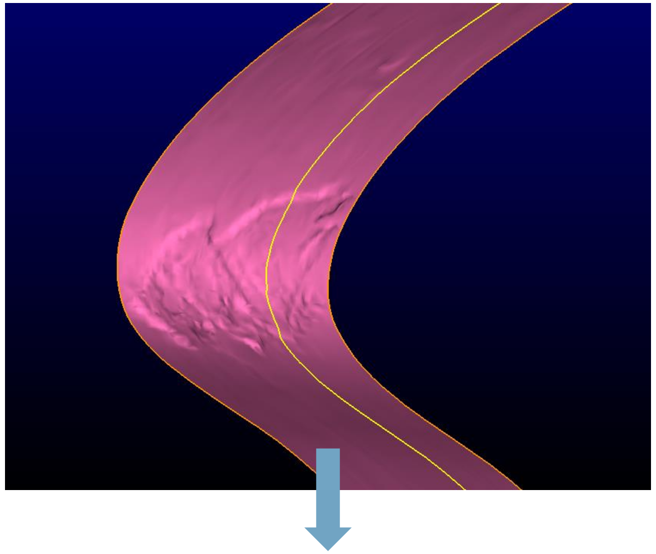
Source: H.J. VAN DER MIJLE MEIJER (TNO)

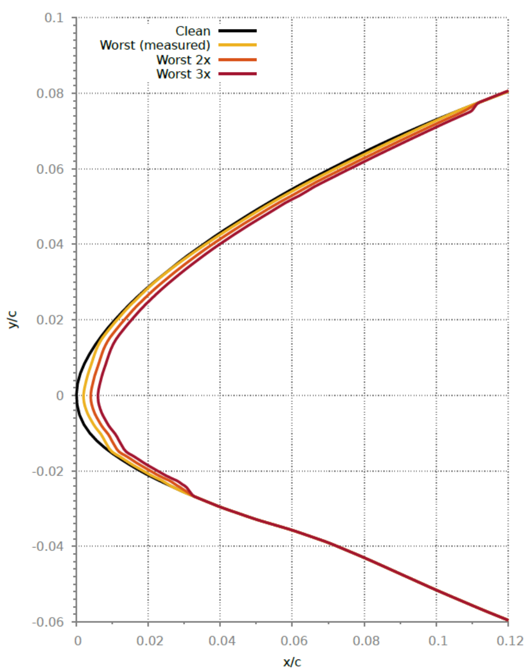
CFD MODELLING

3D SCAN OF DAMAGED BLADE TO CFD

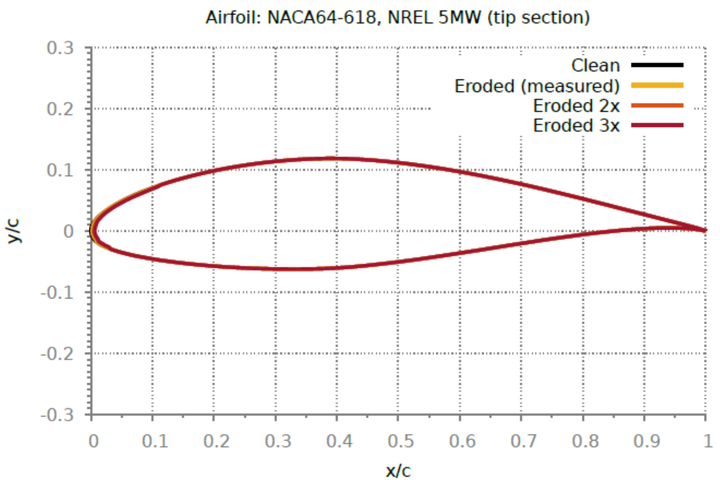
- Sensitivity study using 2D CFD
- Aero performance using 3D CFD

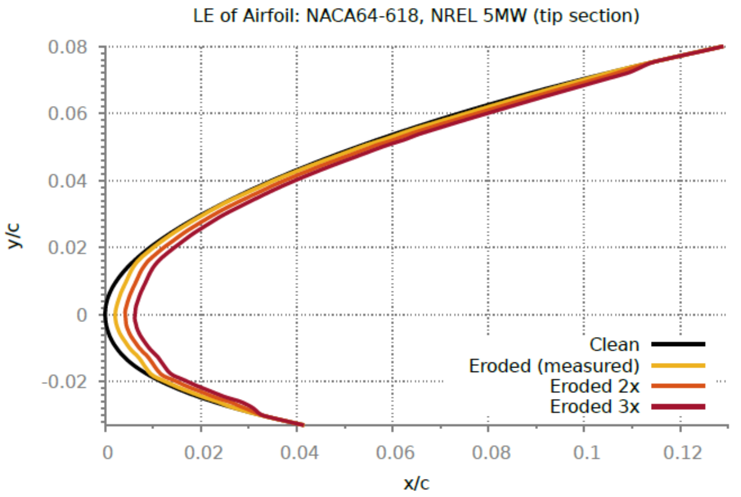


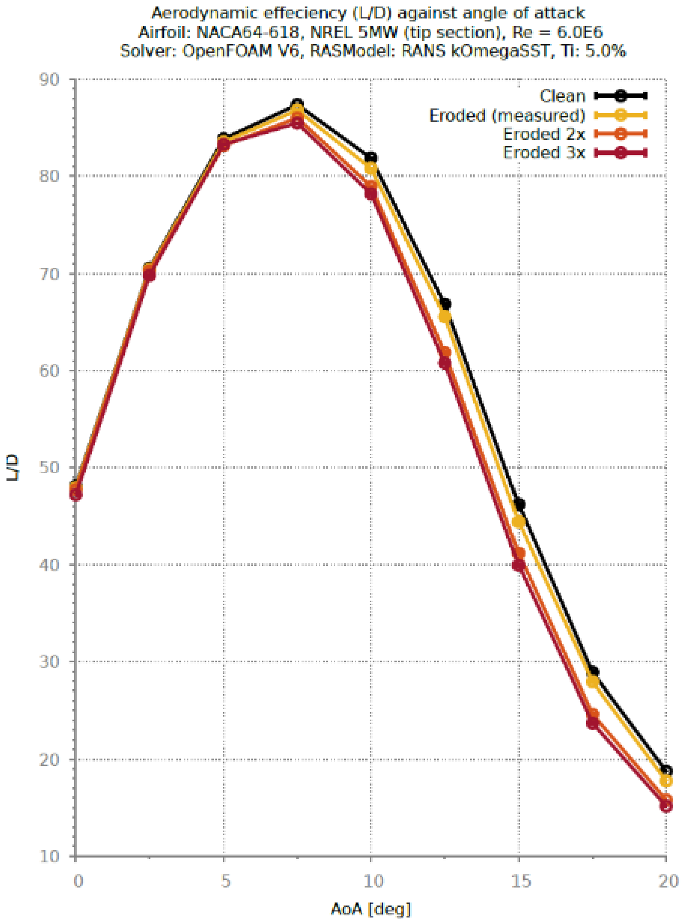


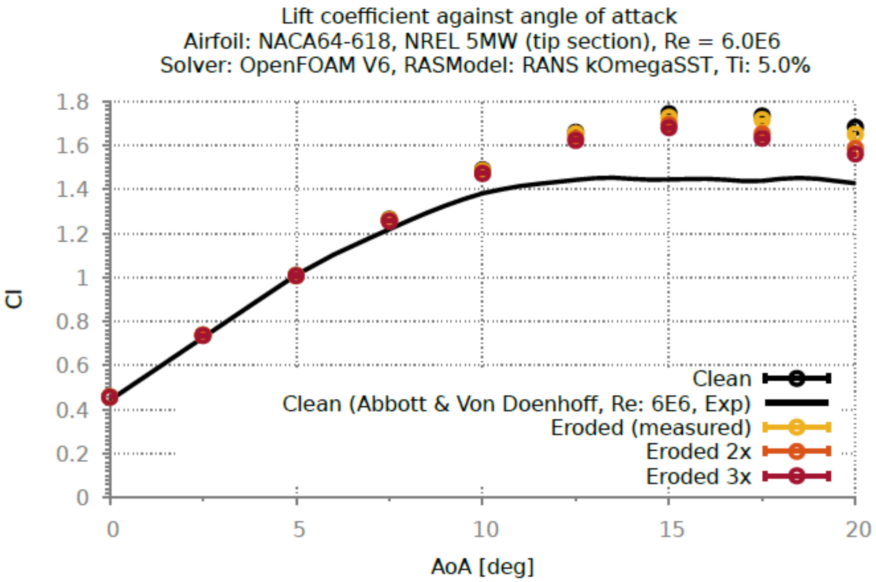


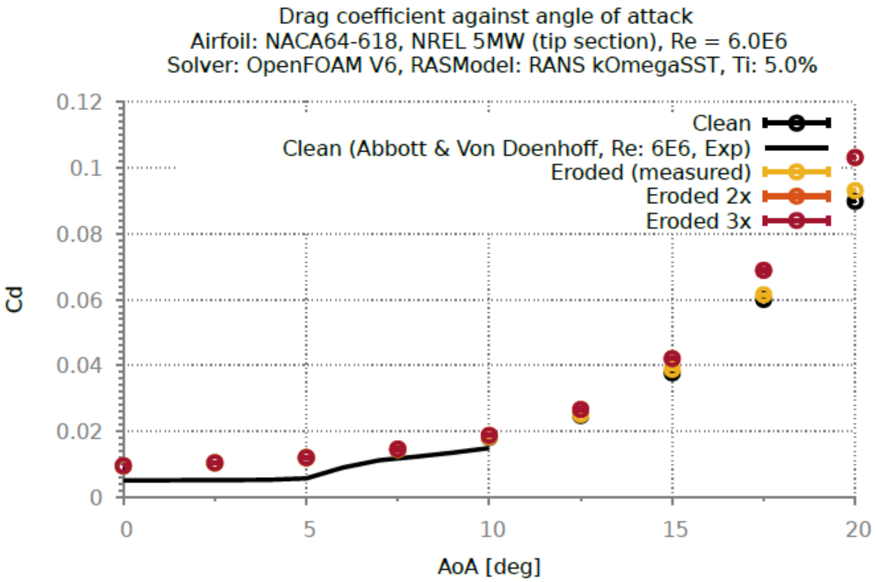
NACA64-618 (NREL 5MW TIP SECTION)
FORCED TRANSITION (SST)



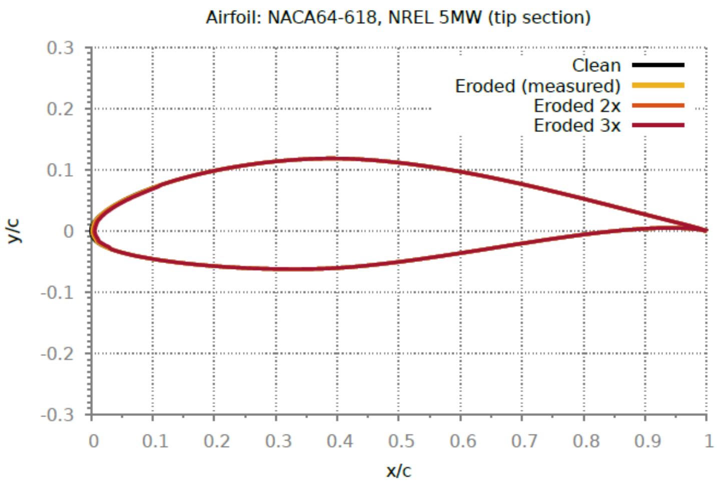


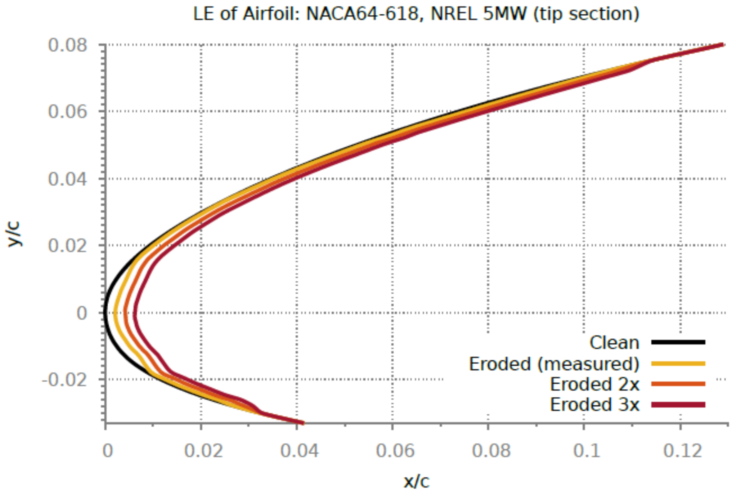


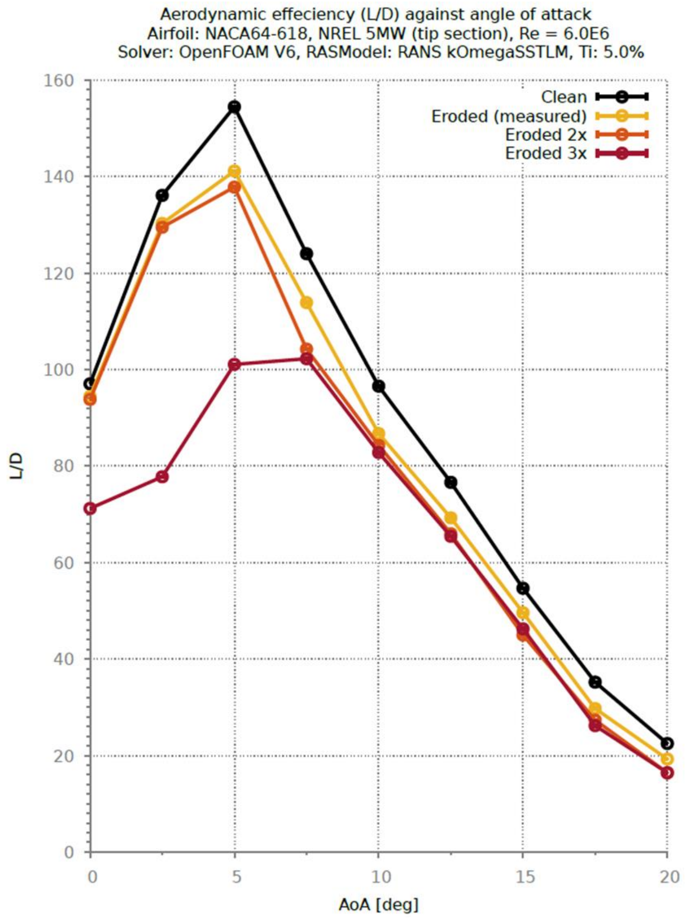


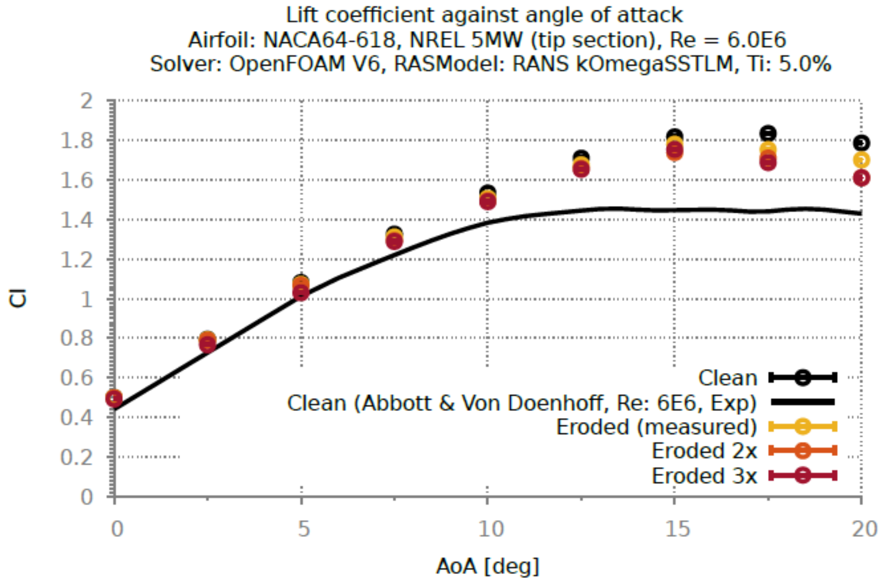


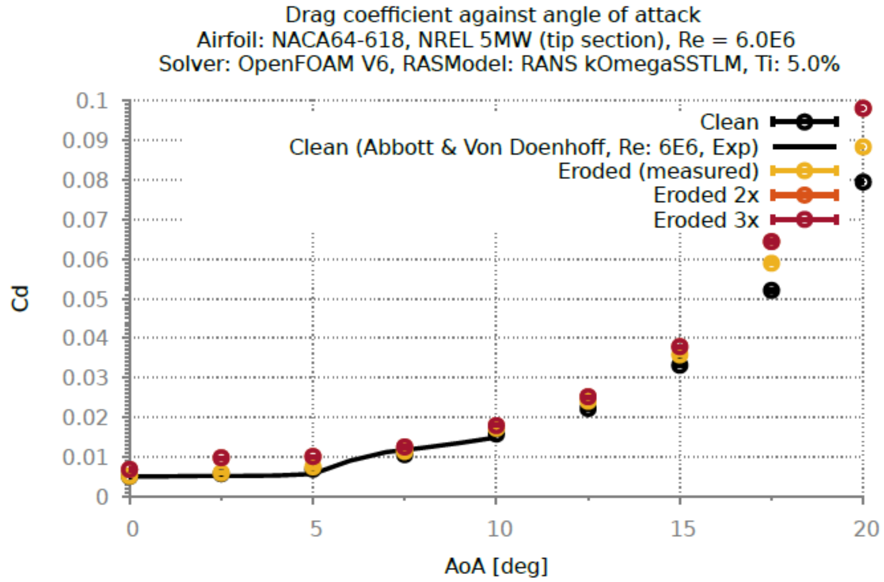
NACA64-618 (NREL 5MW TIP SECTION)
FREE TRANSITION (SSTLM)











RELATIVE CHANGE IN AEP

USING BEM CONSIDERING CHANGE IN POLAR DATA AT THE TIP

- Comparison of the AEP - erosion up to 15% from tip.

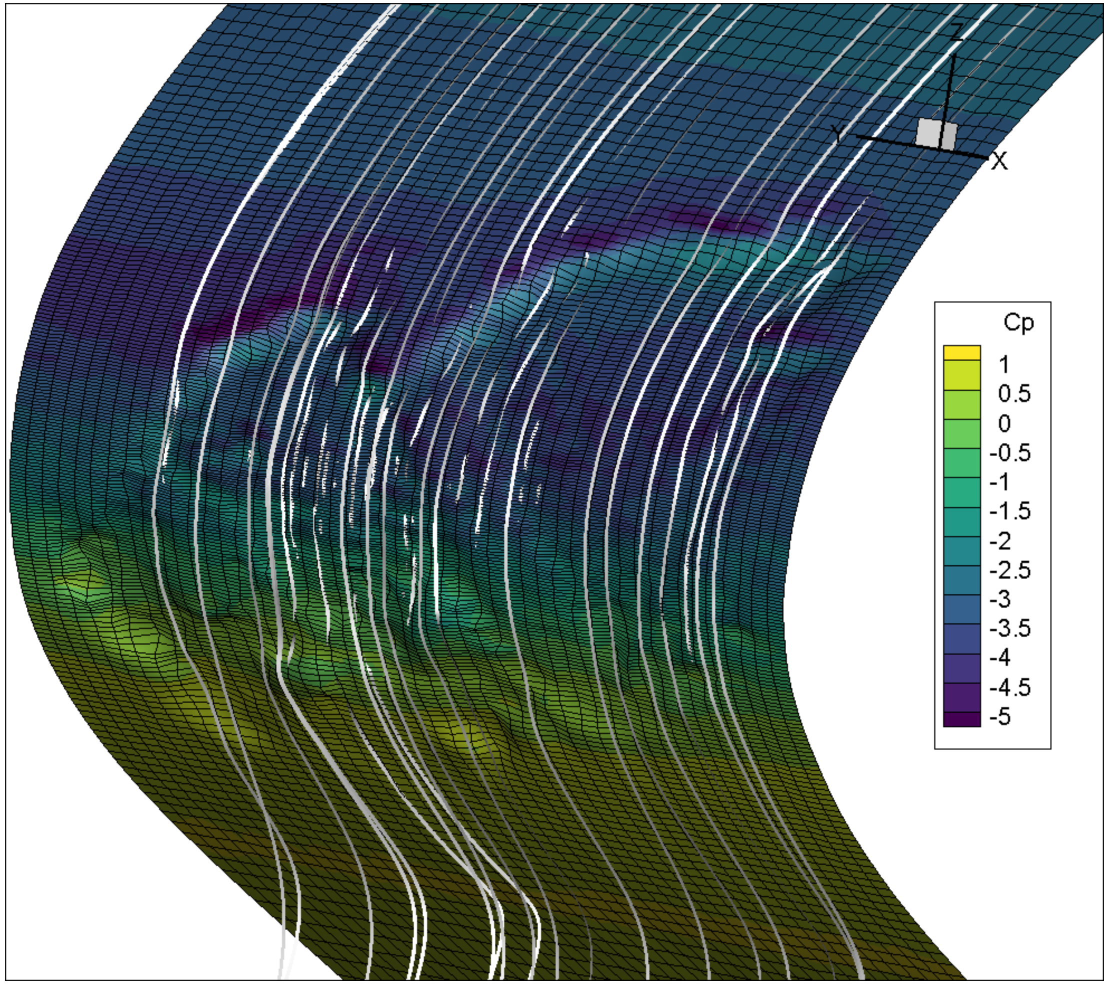
	Relative to Clean (SST)	Relative to Clean (SST LM)
Clean	0	0
Eroded (measured)	-0.01%	-0.06%
Eroded 2x	-0.02%	-0.02%
Eroded 3x	-0.11%	-0.77%

- Relative change in AEP of NREL5MW rotor considering different degree of LE shape erosion for different span extents from tip

Relative change in AEP (Relative to SSTLM Clean)	Span extent from tip [%]		
	30	20	10
Eroded (measured)	-0.11%	-0.09%	-0.05%
Eroded 2x	-0.12%	-0.10%	-0.06%
Eroded 3x	-0.86%	-0.71%	-0.38%

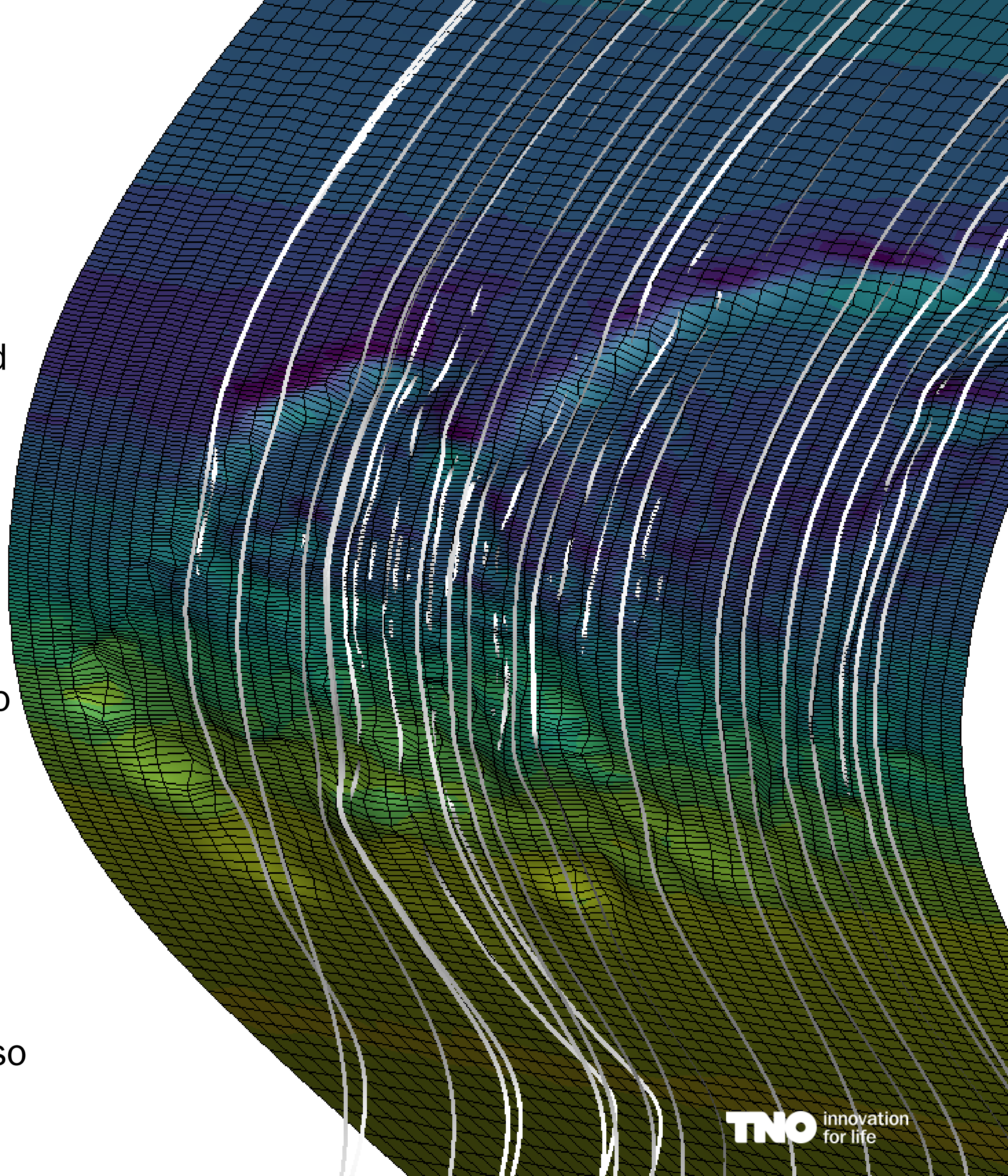
- Under fully turbulent conditions, such as tripping the boundary layer, desensitises the eroded LE. This shows the least influential effect on aero performances, thus resulting in negligible difference to AEP
- Under transitional flow conditions results show much larger aerodynamic impact. Up to 50% reduction in aerodynamic efficiency is realised, which contribute to **0.86-1.24%** reduction in AEP.

CFD results of the eroded section at AoA = 10deg



CONCLUSION

- **Shape change due to erosion**
  - We see significant damage at the tip section
  - Reduction in AEP of in the range of 0.86-1.24% is realised when the LE shape is eroded by >0.8% of the chord
- **Modelling transition for rough surfaces with additional transport equation**
  - Very good agreement with the measurement for leading-edge roughness heights in the order of 140-200um.
  - For smaller roughness height of 100um, the model fails to accurately predict the measured drag forces.
- **Further work:**
  - Incorporate both parts of the study to investigate shape change with the effect of exposed fibres
  - Effects of erosion at high Reynolds numbers
  - Validate calibrated transition model for rough surfaces also with thicker sections



PUBLICATION
WIND ENERGY SCIENCE

- Please see our publication for more discussion and details on the results

Vimalakanthan, K., van der Mijle Meijer, H., Bakhmet, I., and Schepers, G.: CFD modeling of actual eroded wind turbine blade, Wind Energ. Sci. Discuss. [preprint], https://doi.org/10.5194/wes-2022-65, in review, 2022.

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Topsector Energy

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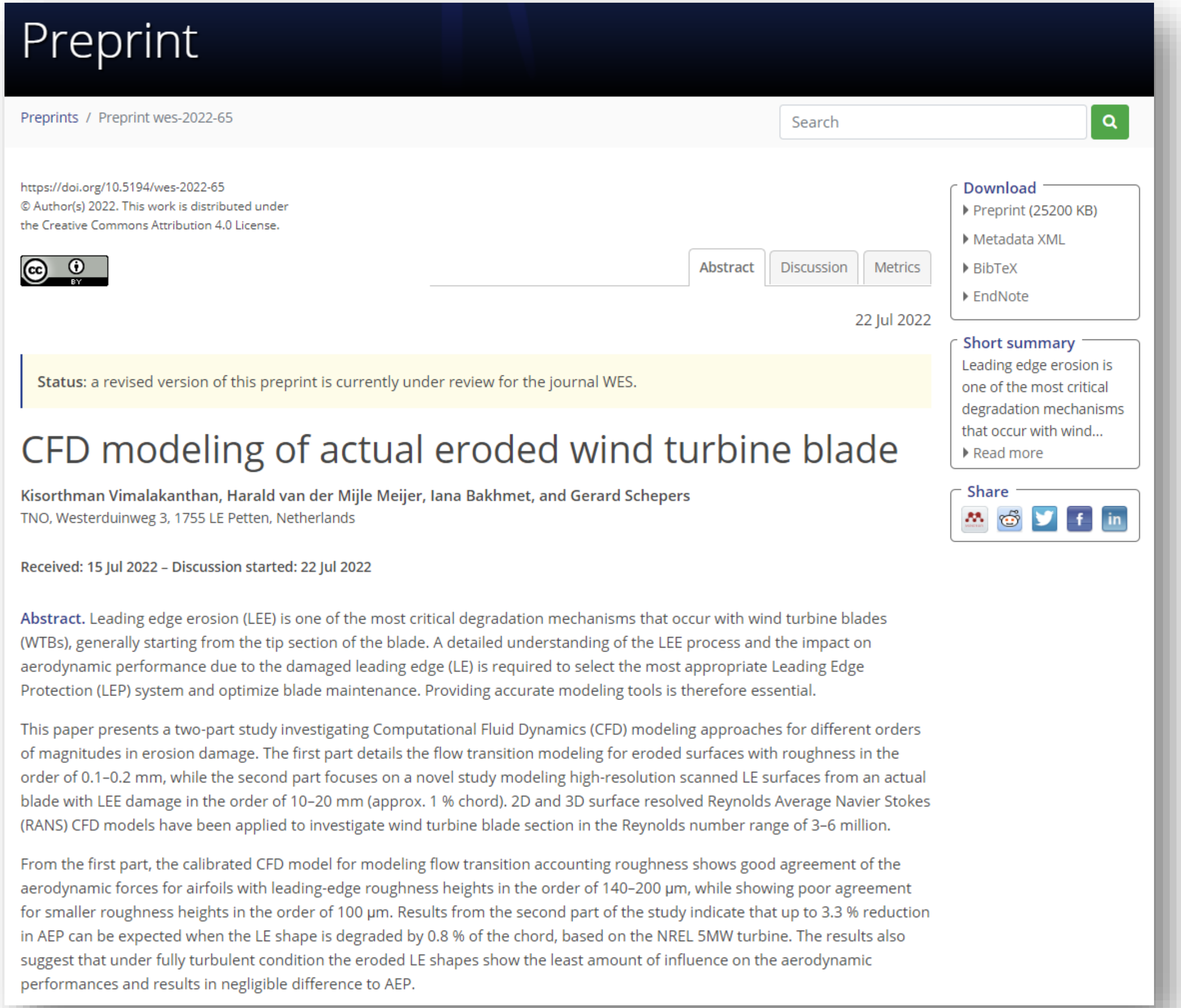
Sandia National Laboratories


Preprint

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https://doi.org/10.5194/wes-2022-65

Abstract | Discussion | Metrics

22 Jul 2022

Status: a revised version of this preprint is currently under review for the journal WES.

CFD modeling of actual eroded wind turbine blade

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Received: 15 Jul 2022 – Discussion started: 22 Jul 2022

Abstract. Leading edge erosion (LEE) is one of the most critical degradation mechanisms that occur with wind turbine blades (WTBs), generally starting from the tip section of the blade. A detailed understanding of the LEE process and the impact on aerodynamic performance due to the damaged leading edge (LE) is required to select the most appropriate Leading Edge Protection (LEP) system and optimize blade maintenance. Providing accurate modeling tools is therefore essential.

This paper presents a two-part study investigating Computational Fluid Dynamics (CFD) modeling approaches for different orders of magnitudes in erosion damage. The first part details the flow transition modeling for eroded surfaces with roughness in the order of 0.1–0.2 mm, while the second part focuses on a novel study modeling high-resolution scanned LE surfaces from an actual blade with LEE damage in the order of 10–20 mm (approx. 1 % chord). 2D and 3D surface resolved Reynolds Average Navier Stokes (RANS) CFD models have been applied to investigate wind turbine blade section in the Reynolds number range of 3–6 million.

From the first part, the calibrated CFD model for modeling flow transition accounting roughness shows good agreement of the aerodynamic forces for airfoils with leading-edge roughness heights in the order of 140–200 μm, while showing poor agreement for smaller roughness heights in the order of 100 μm. Results from the second part of the study indicate that up to 3.3 % reduction in AEP can be expected when the LE shape is degraded by 0.8 % of the chord, based on the NREL 5MW turbine. The results also suggest that under fully turbulent condition the eroded LE shapes show the least amount of influence on the aerodynamic performances and results in negligible difference to AEP.

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Short summary
Leading edge erosion is one of the most critical degradation mechanisms that occur with wind...
- Read more

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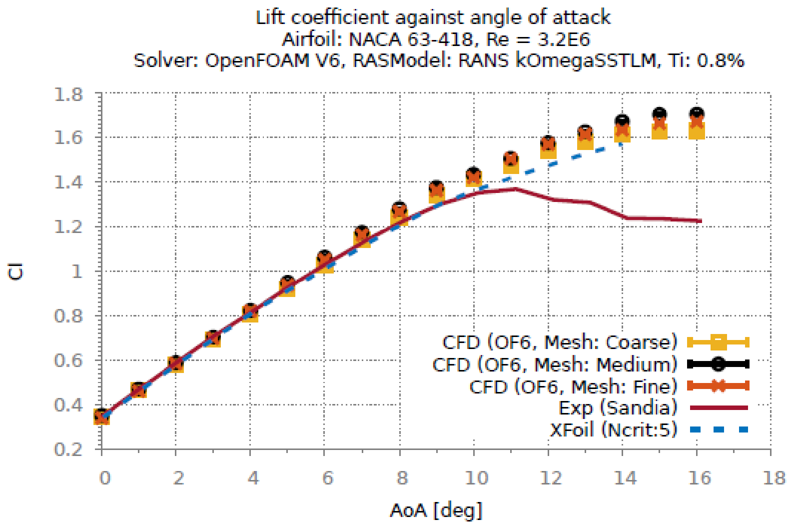
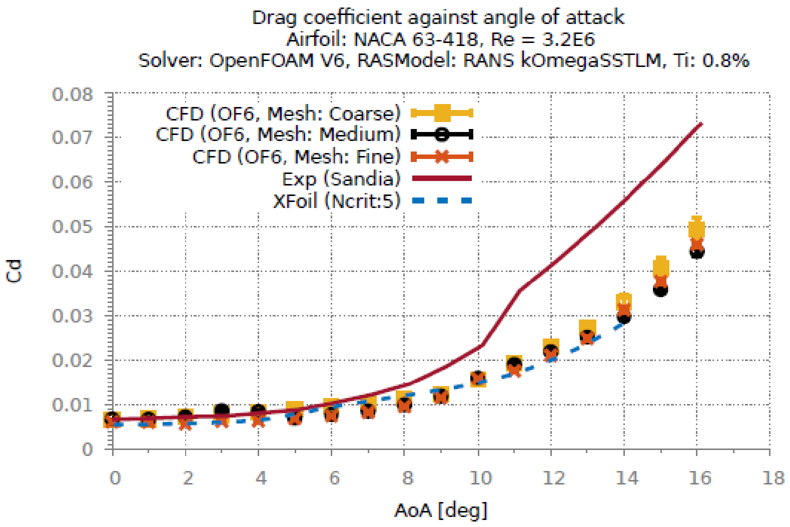
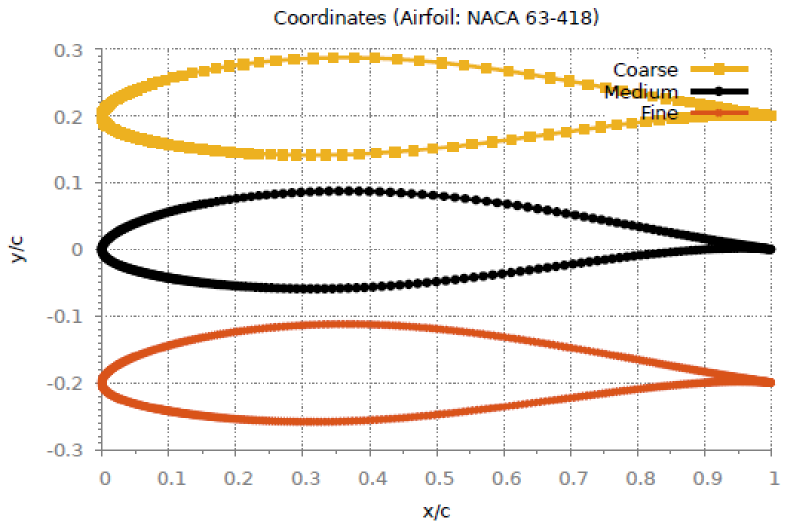
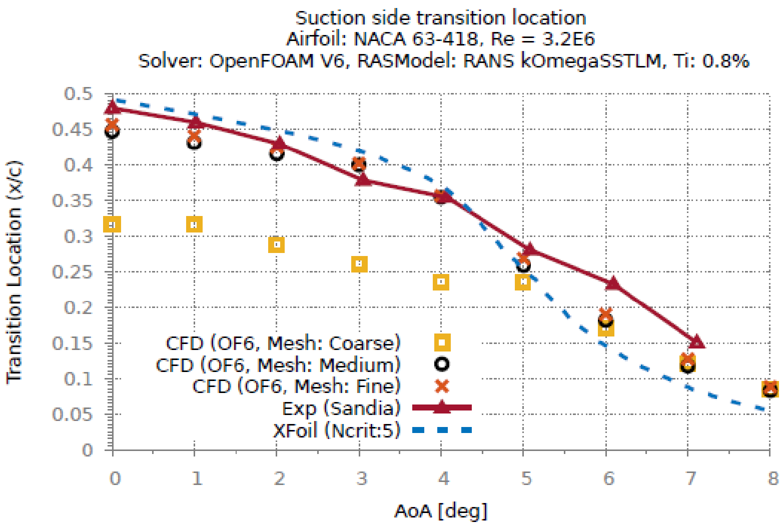
GRID CONVERGENCE

NUMBER OF POINTS





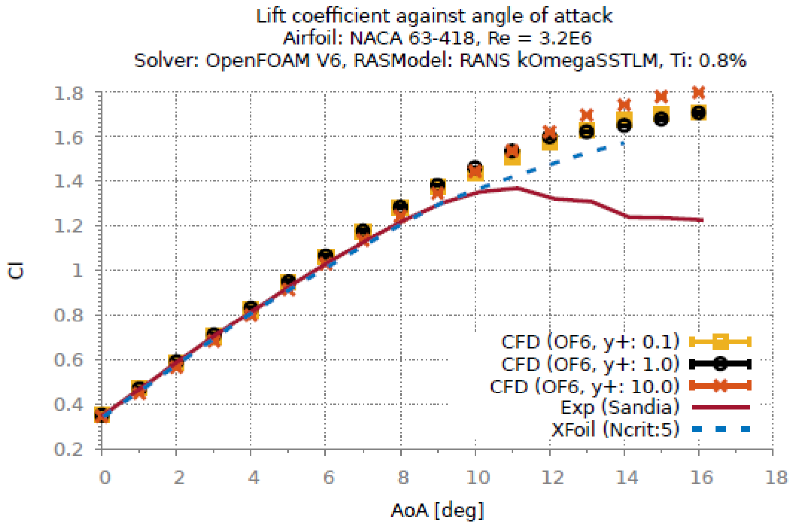


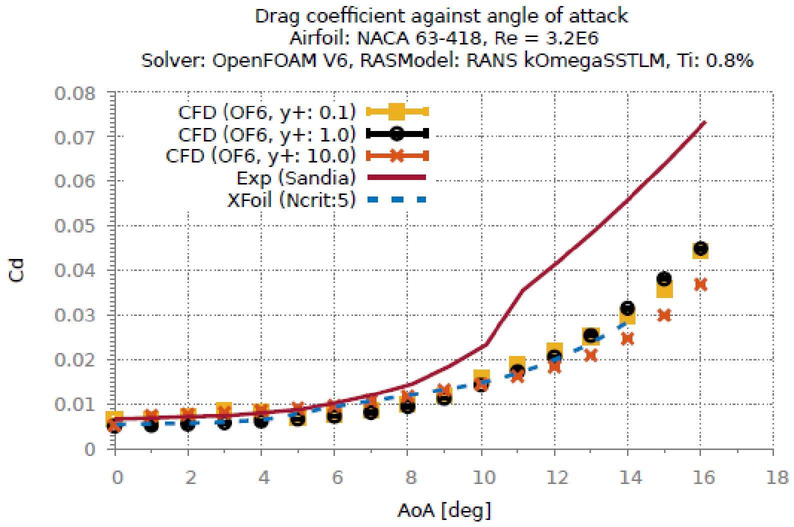


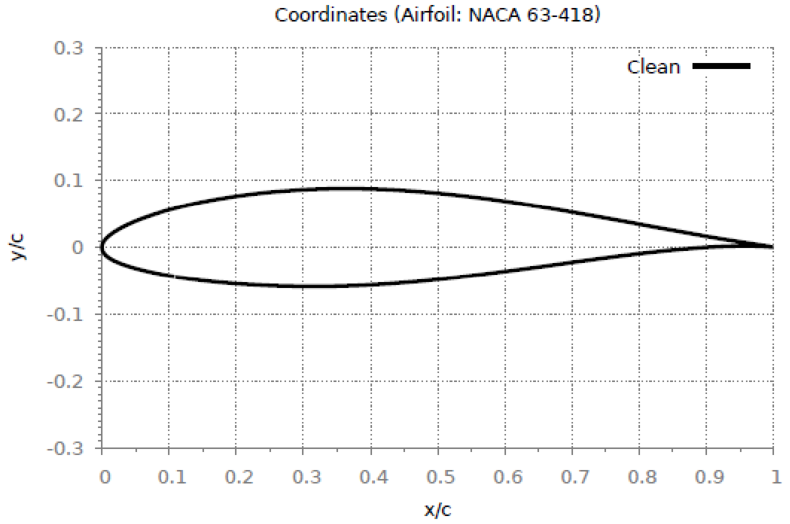
The results from the grid refinement study showed that a minimum of 350points (Mesh: Medium) are required to resolve the airfoil section to achieve a grid-independent solution.

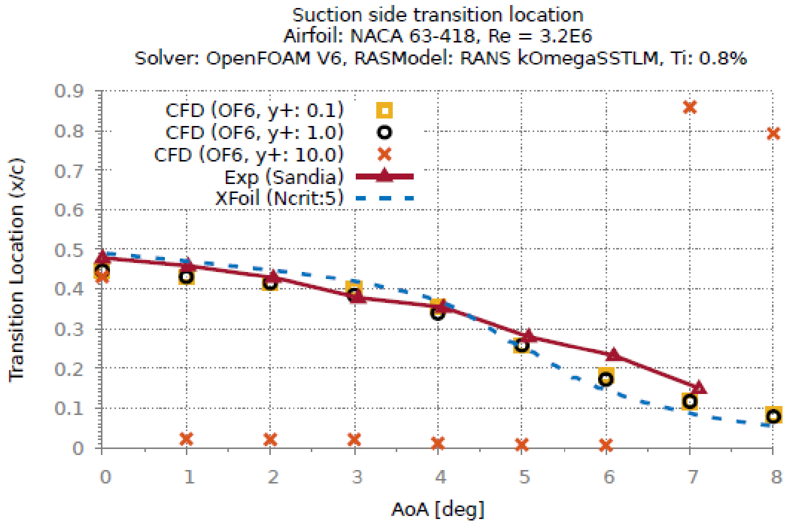
GRID CONVERGENCE

Y+









The study assessing different initial grid heights normal to the wall has revealed that a minimum y+ value of 1 is required to achieve physical transitional results.