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TNO report

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CFD transition model for rough surfaces

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Summary

An investigation to develop and implement a transport equation based boundary layer transition model for rough surfaces was successfully completed. This implementation was carried out for the open-source CFD code OpenFOAM, which was then calibrated using an experimental study. Numerous verification and validations studies were performed to establish realistic results for predicting roughness induced flow transition for wind turbine application.

Based on this study, it is clear that the newly developed CFD model, calibrated with the measured transition locations shows good agreement of the aerodynamic forces for airfoils with leading-edge roughness heights in the order of 140-200um. Despite matching the location of the transition point, the results indicate that for a smaller roughness height of 100um, the model fails to accurately predict the measured forces. Due to a limited number of measurement data used for calibration of this model, further tuning with validation study using another independent measurement is recommended, especially for modelling the effect of roughness density.

Contents

List of tables and figures

Tables

Figures

1 Introduction

The influence of surface roughness in the form of erosion or contamination is of great practical importance for many flow application and particular interest for the wind industry. This form of blade degradation process is known to accelerate the boundary layer transition to result in substantial loss of the blade's aerodynamic performance [1].

Boundary layer transition process is an extremely complicated process that has been studied extensively for almost a century. During this phenomenon the flow characteristics are changed from a streamlined laminar flow to a chaotic turbulent flow. Modelling flow transition for wind turbine blades has previously shown promising results for validating computational models [2]. Accurate prediction tools for simulating various roughness distribution and its influence on boundary layer transition are therefore fundamental for efficient design optimisation and implementation of wind power systems.

The objective of this work was to develop and calibrate the roughness amplification model for the open source flow solver OpenFOAM [3]. This model was originally envisaged by Dassler, Kozulovic and Fiala [4, 5] in 2010, and recently in 2017 Langel et al from Sandia National Laboratory has published a detailed thesis [6] on this model implementation into the flow solver OVERFLOW-2. Langel et al work was used as the basis for this development and calibration of the roughness amplification model for OpenFOAM.

This model implementation allows for 2D and 3D boundary layer transitional CFD simulations including the effect of surface roughness. This is achieved via an additional transport equation for modelling roughness on to a pre-existing transition model. 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.

Firstly, this report will outline the results from validating the underlying transition model within the OpenFOAM solver applied to clean surfaces. For verification purposes, the results are also compared against the panel code XFOIL. Then after the implementation of the transport equation based roughness model and its calibration study for airfoil sections with rough leading edge are presented accordingly.

1.1 Simulation setup - OpenFOAM

The so-called steady-state incompressible simpleFoam solver was used for all OpenFOAM simulations. The name comes from the fact that SimpleFoam uses the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm of Patankar and Spalding to enforce the pressure/velocity coupling. It is a steady-state solver for incompressible turbulent flows. It can be used with a variety of turbulence models which are available in OpenFOAM. The momentum equations are solved using the 2nd order bounded Gauss linearUpwind scheme. The turbulence closure relations are solved using the bounded Gauss limitedLinear numerical scheme that limits towards 1st order upwind in regions of rapidly changing gradient, while other parts of the domain are resolved using 2nd order linear scheme to achieve greater numerical stability.

Following OpenFOAM solvers were used for solving the corresponding equations describing the system.

- The momentum, k, omega, ReTheta, gamma and Ar equations:

  The smoothSolver is used with a symmetric GaussSeidel smoother.

- The pressure equation:

  The GAMG (Geometric-algebraic multi-grid) solver was used for pressure equation. GAMG solver also requires a smoother for its operation, thus once again GaussSeidel smoother was used with GAMG to ensure a faster convergence. The size of the initial coarse mesh is specified through in the nCellsInCoarsestLevel entry, which was specified to be 1000 based on 24cpu computations. The agglomeration of cells is performed by the selected FaceAreaPair method.

Numerical convergence was assessed based on the RMS residual for all equations < 1E-7 for all simulations with a steady hysteresis on the lift and drag forces (Figure 1).

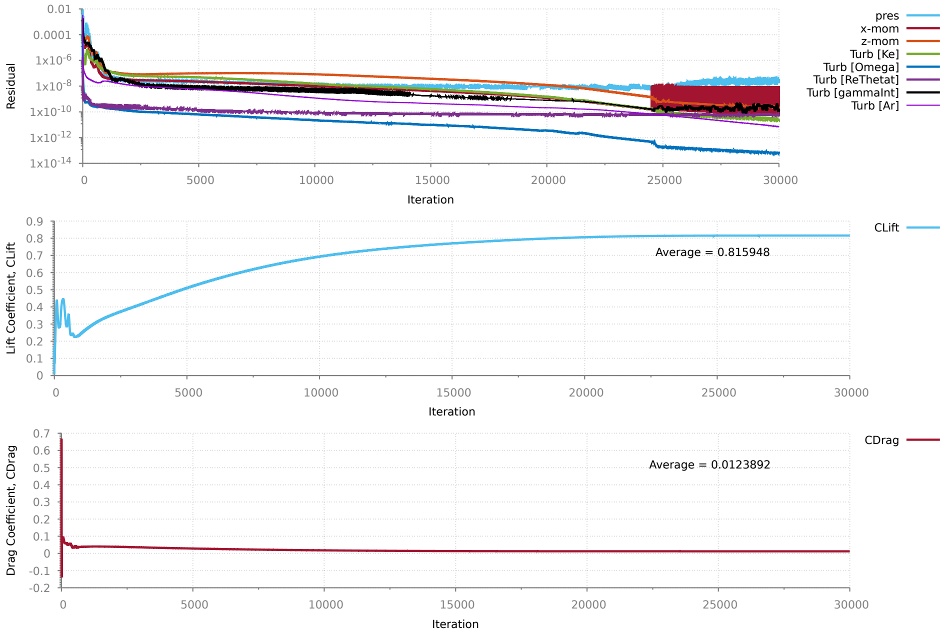

Figure 1: Computed residuals for NACA 63-418 with rough leading edge with 200um roughness height at AoA=4°

2 Flow transition prediction on clean surfaces - Validation/Verification study

The roughness amplification model uses the Langtry-Menter's local correlation based transition model (SSTLM) [7, 8] as the underlying model to trigger boundary layer transition, while the fully turbulent parts of the domain are resolved with Menter's k-Omega SST model [9]. In order to establish performance of the underlying transition model, two test cases were studied to verify and validate with experimental measurements.

The first test case was conducted using the EROCOFTAC T3A experiments studying a flat plate geometry [10], which has become a renowned benchmark case for validating computational transition models. The simulated boundary conditions are presented in Figure 2. Due to the inherent decay of turbulence with RANS modelling, a slightly higher turbulence intensity (3.7%) compared to the experimented 3% was prescribed at the inlet to match the value measured at the start of the flat plate. Based on the results (Figure 3) the underlying transition model (SSTLM) accurately predicts the decay of measured turbulence intensity, however the transition point is predicted earlier than measured.

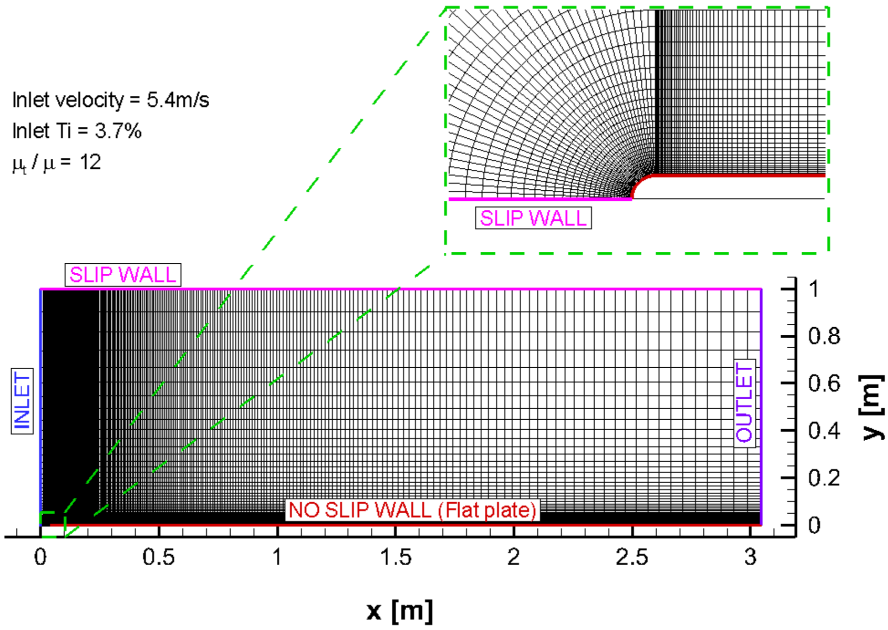

Figure 2: Turbulence kinetic energy and Wall shear stress along clean flat plate

The second test case was conducted using Sandia's experimental study (LEES-Dataset) [11] using NACA 63-418 airfoil at three different Reynolds numbers (Re= 2.4E6, 3.2E6 and 4.0E6). RANS 2D CFD simulations were performed with a domain extent of 90 chords was used to model the far-field (Figure 4).The results from the grid refinement study (Figure 5) showed that a minimum of 350points (Mesh: Medium) are required to resolve the airfoil section to achieve a grid independent solution. Similarly, a study assessing different initial grid height normal to the wall (Figure 6) has reviled that a minimum y+ value of 1 is required to achieve physical transitional results. The transition location was evaluated based on the rapid increase in intermittency variable (gamma), as detailed in [2].

In the initial stages of this investigation the original NACA 63-418 airfoil geometry

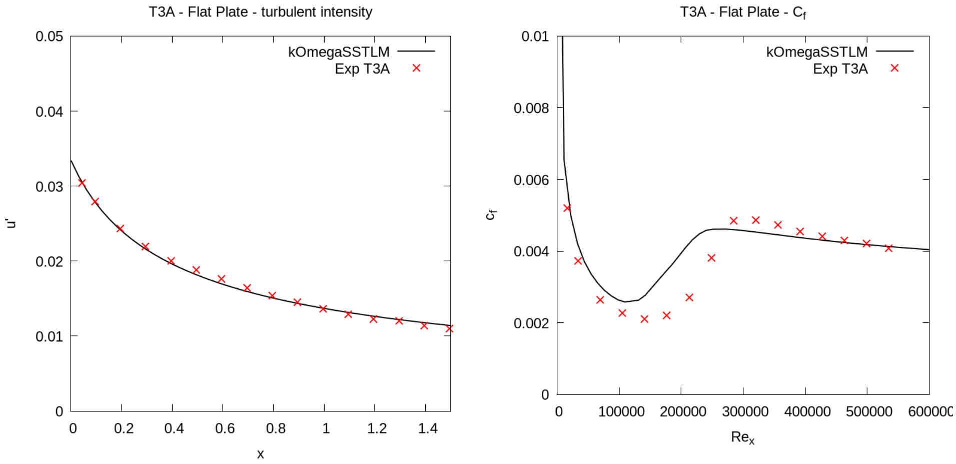

Figure 3: Turbulence kinetic energy and Wall shear stress along clean flat plate

from Abbott & von Doenhoff[12] was used to verify numerical accuracy as also used for validation study by Wilcox [13]. However, there has been a slight uncertainty was experienced with the exact geometry used in experiment. Different publications using the this experimental dataset(LEES-Dataset) for validating their numerical models have considered slightly different geometries, such as using the original geometry [13] defined by Abbot & von Doenhoff [12], while others have considered the geometric definition using a Bezier curve [14].

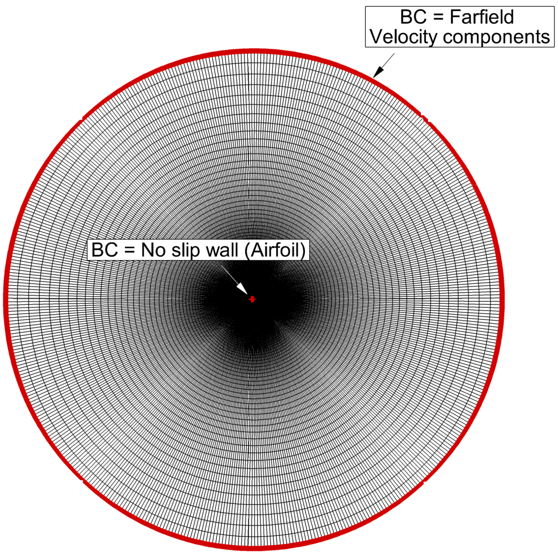

Figure 4: O-grid with 90chord domain extent showing the Full Hex grid with boundary conditions

The reason which plead for the Bezier geometry is that, in there publication [14] Langel et al has provided the control points to be able to regenerate the potential experimental geometry in a continuous fashion for numerical simulations. This Bezier curve is consistent with the interpolated model coordinates provided by Ehrmann in his thesis [15], where he has described the experimental model coordinates being interpolated directly from Abbott & von Doenhoff's geometry. The experimental pressure taps locations from the Sandia's LEES-Dataset [11] is also consistent with the Bezier curve.

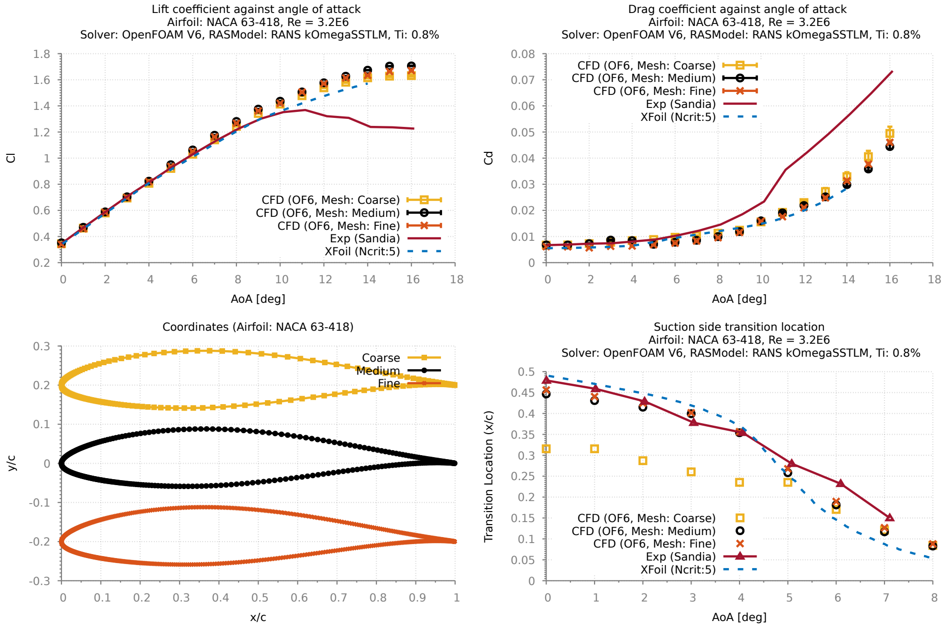

Figure 5: Comparing results for different grid densities

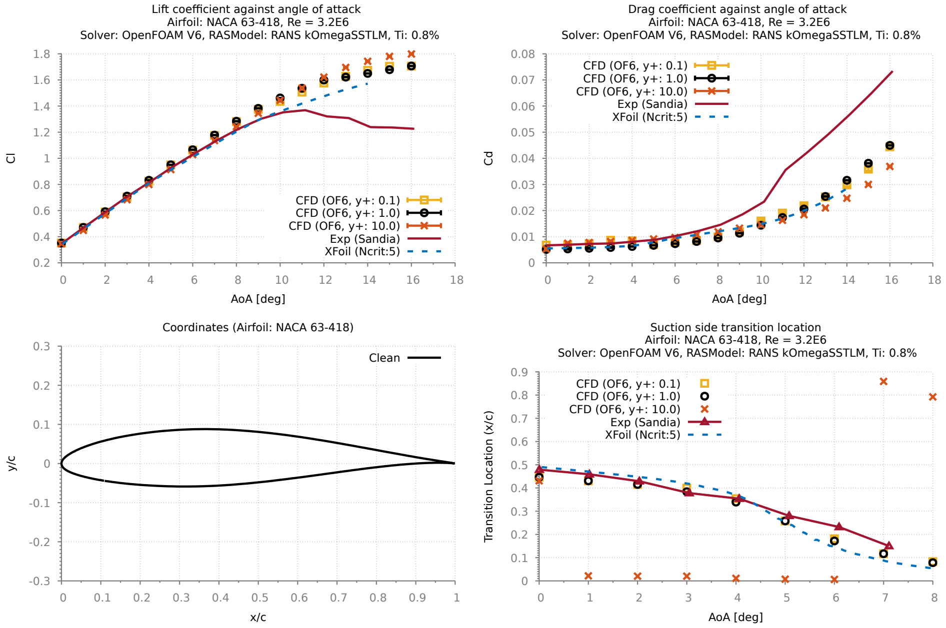

Figure 6: Comparing results for different y+ values

Despite having very small differences between the geometries, results comparing the numerical simulations of both geometries (Figure 7) has revealed that better validation is achieved using Abbot & von Doenhoff's original geometry, while the computed lift coefficients are slightly over predicted with the Bezier geometry. Comparing the surface pressure distribution has shown that XFOIL and CFD results slightly under-predict the measured pressure values, irrespective of the geometry. It is noted that despite showing negligible differences between the computed pressure distributions for both geometries, for three different Reynolds numbers (Figure 7-10) the validation results with Abbot & von Doenhoff's original geometry shows good agreement between the calculated and measured lift curve slope.

Nevertheless, the findings from both of the aforementioned test cases, it is clear that the intended underlying SSTLM model is able to capture transition locations that agree well with the measurements, particularly for the Sandia experiment [11] using the Abbot & von Doenhoff's original or the Langel et al Bazier form of the NACA 63-418 geometry. However, to be consistent with the original experimental work as reported in [15] (best measurement of the as-tested model) the Bezier geometry was chosen for calibrating the roughness amplification model.

It is also noted that this study was conducted using the SSTLM model originally implemented by Menter without the modification proposed by Langel et al. In order to reduce sensitivity to free stream turbulence values Langel et al [6] has adopted the recommendation from Khayatzadeh et al [16] to use a different transition onset equation. This was accomplished by increasing the constant from 2.193 to 3.29 in the onset equation. However, the results from this verification study clearly shows good agreement with the measured transition locations without this modification, thus the value of 2.193 originally implemented by Menter was used throughout this work.

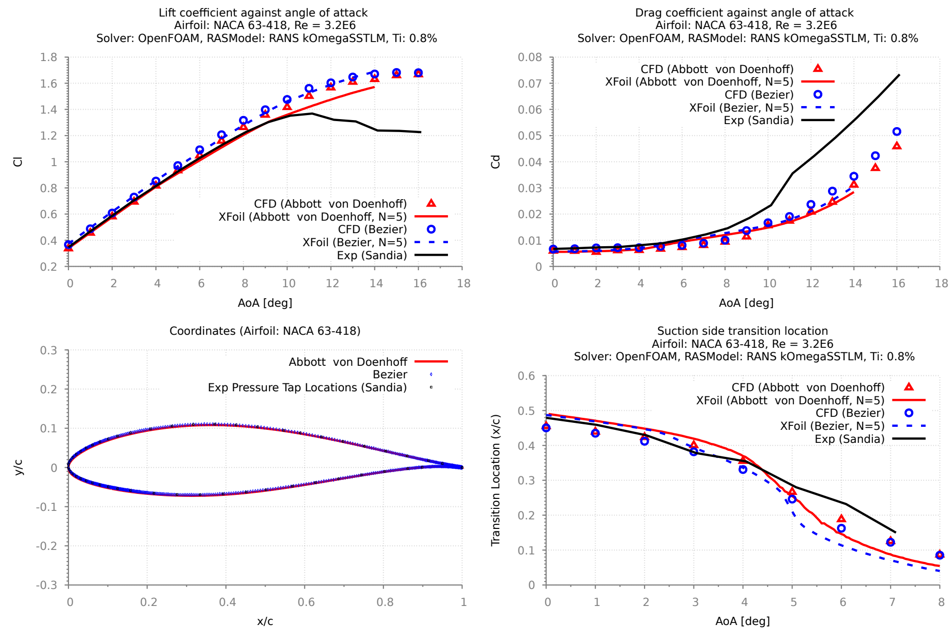

Figure 7: Comparing results for different NACA 63-418 geometries used to validate Sandia experiments

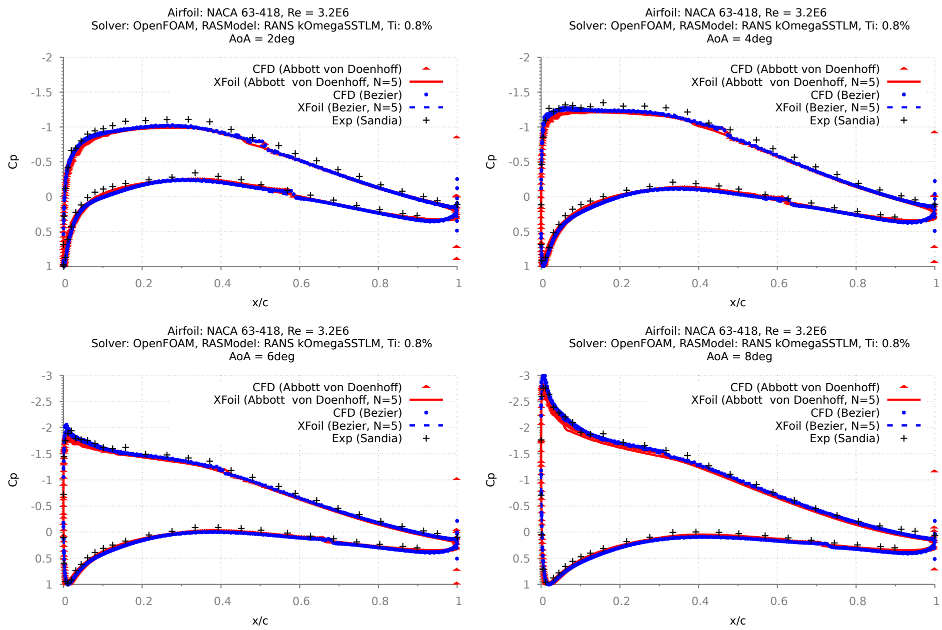

Figure 8: Comparing surface pressure distribution for different NACA 63-418 geometries used to validate Sandia experiments

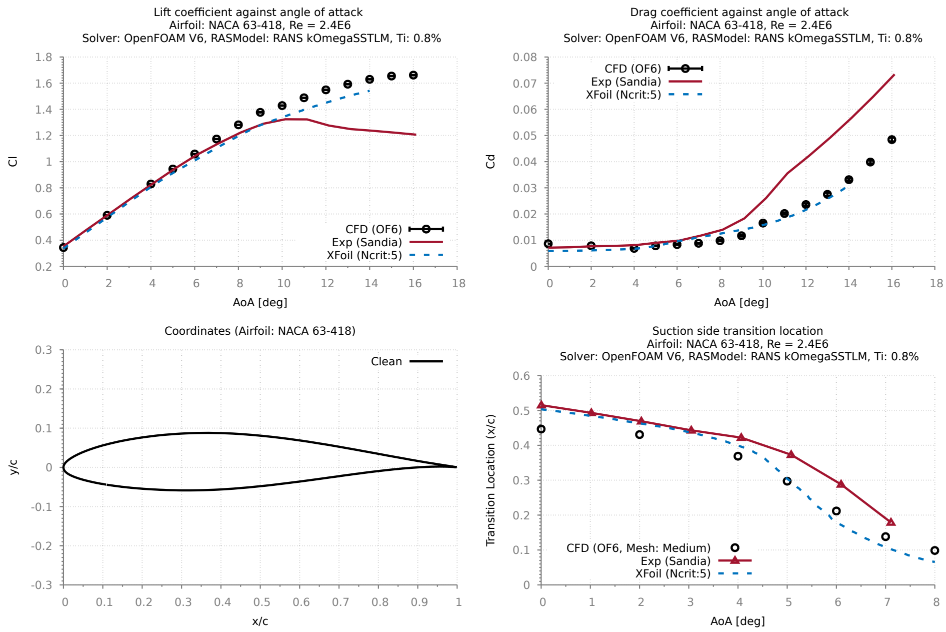

Figure 9: Validation results at Re= 2.4E6 using the Abbott & von Doenhoff's NACA 63-418

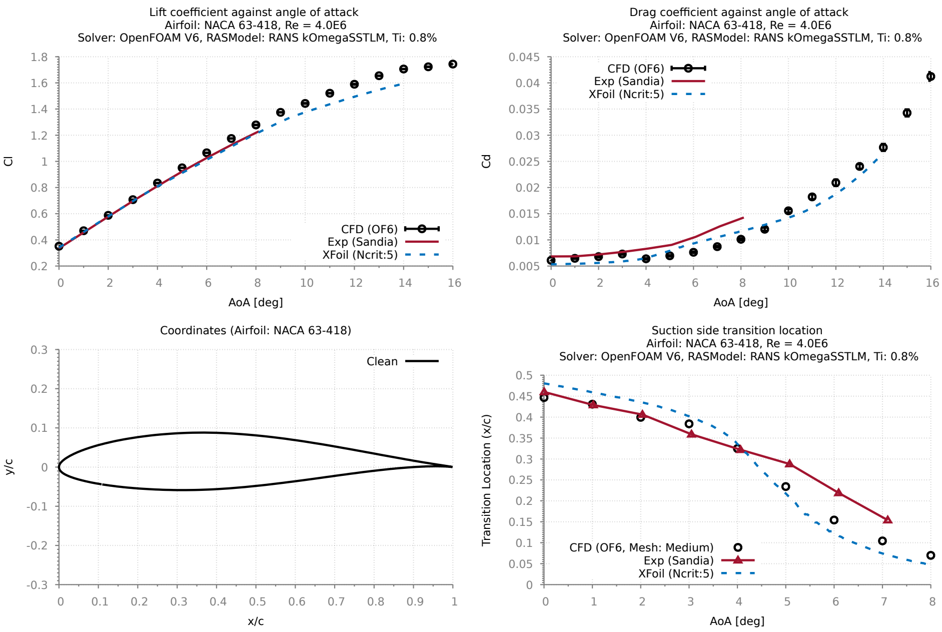

Figure 10: Validation results at Re= 4.0E6 using the Abbott & von Doenhoff's NACA 63-418

3 Flow transition prediction with rough surfaces - Verification and calibration

The detail derivation of the model description for flow transition on rough surfaces is well documented by Langel et al [6]. Essentially, a new equation for Re_θ accounting roughness is defined based on the, local roughness amplification quantity (Ar).

$$Re_{\theta,rough} = Re_\theta + \frac{1}{3}u^+ \left(\frac{Ar}{c_{r1}}\right)^3 - \frac{1}{2}\left(\frac{Ar}{c_{r1}}\right)^2 \tag{3.1}$$

Where u^+ is the logarithmic function for mean velocity profile, c_{r1} is the model constant 8.0.

With the additional Ar variable, one can choose to increase the local momentum thickness Reynolds number using the Eqn 3.1 or reduce the correlated critical value by similar amount. Similar to Langel et al's implementation latter is considered by lowering the local correlation variable $\tilde{R}e_{\theta t}$ within the production term of its transport equation (Eqn 3.2).

$$\tilde{P}_{\theta t} = c_{\theta t}\frac{\rho}{t}\left[(Re_{\theta t} - \tilde{R}e_{\theta t})(1 - F_{\theta t}) - bF_{Ar}\right] \tag{3.2}$$

This implementation using the F_{Ar} function serves to reduce the $\tilde{R}e_{\theta t}$ values downstream of the rough boundary, where elevated Ar values are expected. With lower $\tilde{R}e_{\theta t}$, the Re_θ values required to trigger turbulence intermittency production is achieved easier, thus triggering transition with smaller disturbances. This approach allows onset transition to take place within the rough boundary itself, depending on the roughness height.

The transport equation for Ar is defined similar to those of the underlying transition model, with a model constant $\sigma_{ar} = 10.0$:

$$\frac{\partial(\rho Ar)}{\partial t} + \frac{\partial(\rho U_j Ar)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\sigma_{ar}(\mu + \mu_t)\frac{\partial Ar}{\partial x_j}\right] \tag{3.3}$$

The distribution of Ar is prescribed at the boundary condition of the rough walls based on an equivalent sand grain roughness height (k_s) following:

$$Ar|_{wall} = c_{r1}k^+ \text{ with } k^+ = \sqrt{\frac{\tau_w}{\rho}}\frac{k_s}{\nu} \tag{3.4}$$

The secondary cubic function (Eqn 3.5) with model constants c_{r2} and c_{r3}, 0.0005 and 2.0 respectively are used at the lower Ar values to maintain small values for hydraulically smooth walls, where it has no effect on the transition model. A linear function is switched at $C_{Ar} = \sqrt{c_{r3}/3c_{r2}}$ to matches the slope of the cubic function in order to prevent unphysical overshoots at high levels of Ar.

$$F_{Ar} = \begin{Bmatrix} c_{r2}\cdot(Ar)^3 & : Ar < C_{Ar} \\ c_{r3}\cdot(Ar - C_{Ar}) + c_{r2}C_{Ar}^3 & : Ar \geq C_{Ar} \end{Bmatrix} \tag{3.5}$$

A blending function is also introduced to limit the process of reducing the production term of $\tilde{Re}_{\theta t}$ when its value nears the prescribed minimum:

$$b = \left[\frac{1}{2} sin\left(\frac{\pi}{155}\tilde{Re}_{\theta t} - \frac{97\pi}{155}\right) + \frac{1}{2}\right]^2 \tag{3.6}$$

Although the Ar quantity allows for early transition triggering due to roughness, the effects on a fully turbulent boundary layer and the lowering of turbulent dissipation rate (ω) is also required to be adjusted in order to establish accurate calculation of the wall shear stresses. The following update is used for ω boundary condition at the wall:

$$\omega|_{rough\ wall} = \frac{\mu_\tau^2 S_r}{\nu} \text{ with } \mu_\tau = \sqrt{\frac{\tau_w}{\rho_w}} \text{ at wall} \tag{3.7}$$

where S_r is based on the non dimensional sand grain roughness height (k^+):

$$S_r = \begin{Bmatrix} (50/k^+)^2 & \text{if } k^+ \leq 25 \\ 100/k^+ & \text{if } k^+ > 25 \end{Bmatrix} \tag{3.8}$$

3.1 Verification study (T3A)

Similar to the study conducted to verify the underlying SSTLM model, the T3A test case was used again to test the working of the implemented roughness amplification model (SSTLMkvAr) with its effect on modelling distributed roughness on the entire flat plate. The results from this study (Figure 11) clearly shows the forward movement of the transition location with increasing roughness parameter (k_s). It is also evident from the results, that the effect of roughness not only triggers early transition but as intended, it is transported downstream to accounts for larger wall shear stresses.

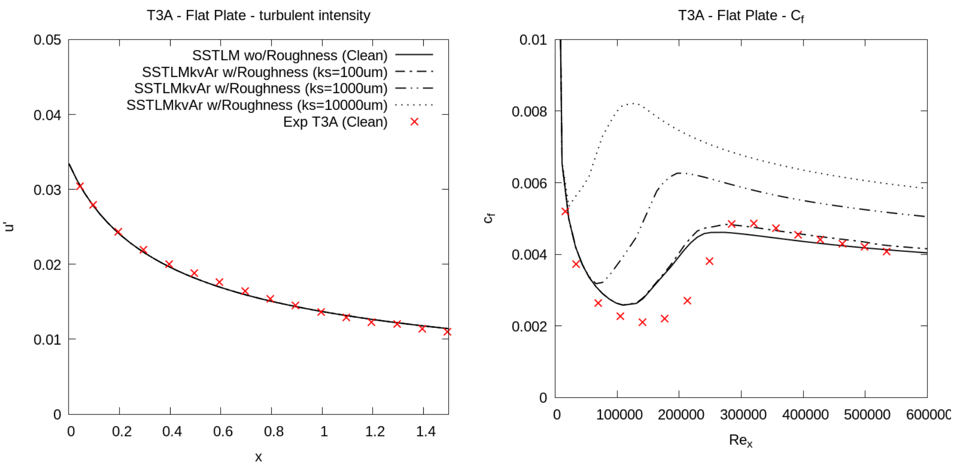

Figure 11: Turbulence kinetic energy and Wall shear stress along clean and rough flat plate

4 Calibration

Ehrmann's experimental work [15] documents the findings from testing various distributed roughness on the NACA 63-418 airfoil at three different Reynolds numbers (Re= 2.4E6, 3.2E6 and 4.0E6), the data from this work is published in the LEES dataset [11]. Using the measured transition locations from this dataset, the newly implemented SSTLMkvAr model was calibrated for its sand grain roughness height (k_s). This calibration was performed for three different roughness heights: 100, 140 and 200um, at a constant roughness density of 3%. Furthermore, the calibration of three different densities (3, 9 and 15%) was performed using the data for the roughness height of 100um. For both parameters, the calibration was performed at the flow Reynolds number of 3.2E6.

The calibration study was conducted by using a cost function that minimises the errors between the calculated and measured transition locations across the whole experimented range of angles of attacks (-4 to 6°). As a result the following equation was established for k_s as a function of roughness height (R_h) and density (R_D).

$$k_s = \left[1.49783 \times 10^9 \sqrt{9.29170684919976 \times 10^{24} R_h - 9.24939916631901 \times 10^{26}} - 2950.72\right] \times \left[-0.768462 + 5.46075 \times 10^{17} \times \sqrt{3.16961301221313 \times 10^{32} \times R_D + 9.79025531790832 \times 10^{31}}\right] \tag{4.1}$$

Despite only calibrating the k_s values to match the measured transition locations, the results show a very good agreement between the modelled and the experimented drag forces, especially for the large roughness heights of 140um and 200um (Figure 12 and 13). All modelled results showed notable differences (10%) with the measured lift forces, where the relative reduction in lift due to the rough leading edge was captured well, while the absolute values were over-predicted.

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. Due to the lack of experimental data, it was only possible to study the effect of roughness density at the height of 100um. The results from this study (Figure 14 - 16) clearly shows that the calibrated CFD model is able to calculate the forward movement of the transition point with increasing roughness density, while the corresponding effect on the drag forces is poorly predicted. These results indicate that the calibrated CFD model fails to predict the measured aerodynamic forces for small LE roughnesses (100um).

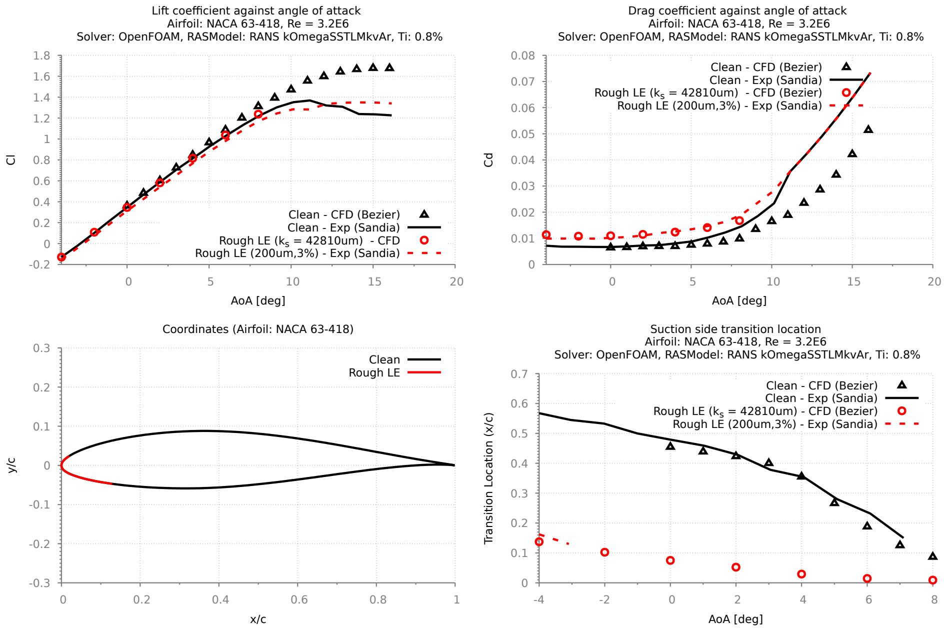

Figure 12: Calibration results at Re= 3.2E6 for NACA 63-418 with LE roughness height of 200um and 3% density

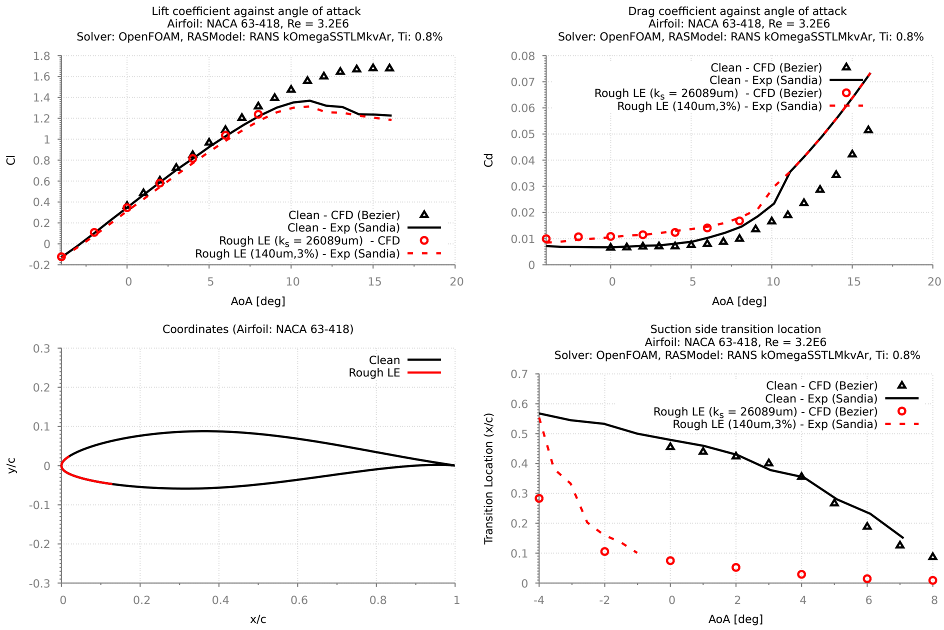

Figure 13: Calibration results at Re= 3.2E6 for NACA 63-418 with LE roughness height of 140um and 3% density

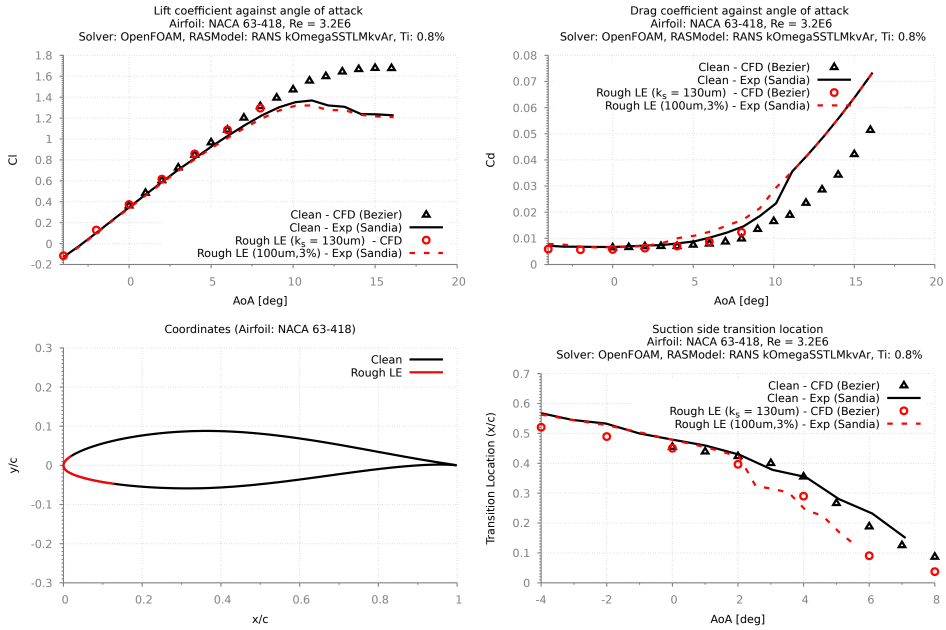

Figure 14: Calibration results at Re= 3.2E6 for NACA 63-418 with LE roughness height of 100um and 3% density

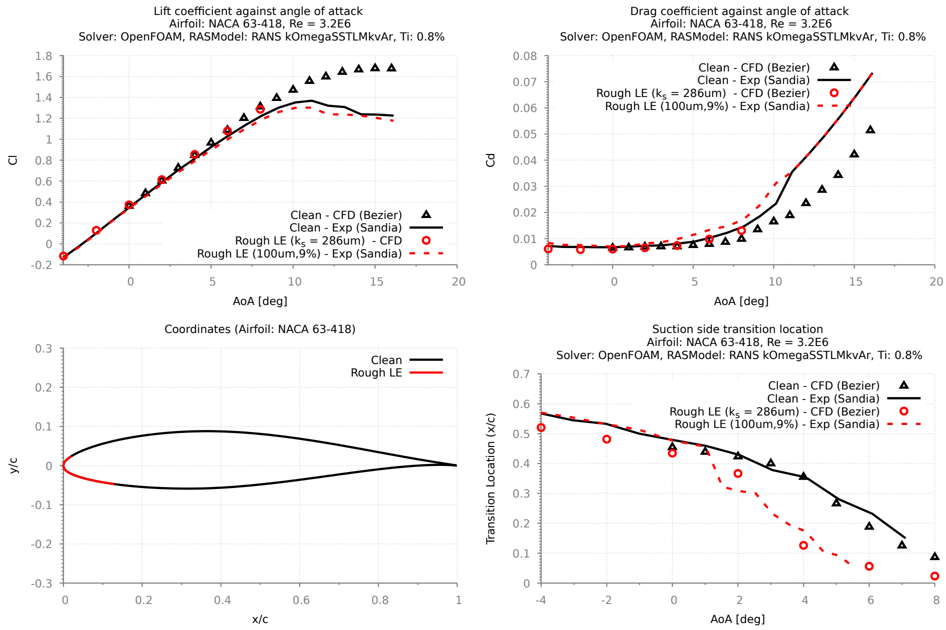

Figure 15: Calibration results at Re= 3.2E6 for NACA 63-418 with LE roughness height of 100um and 9% density

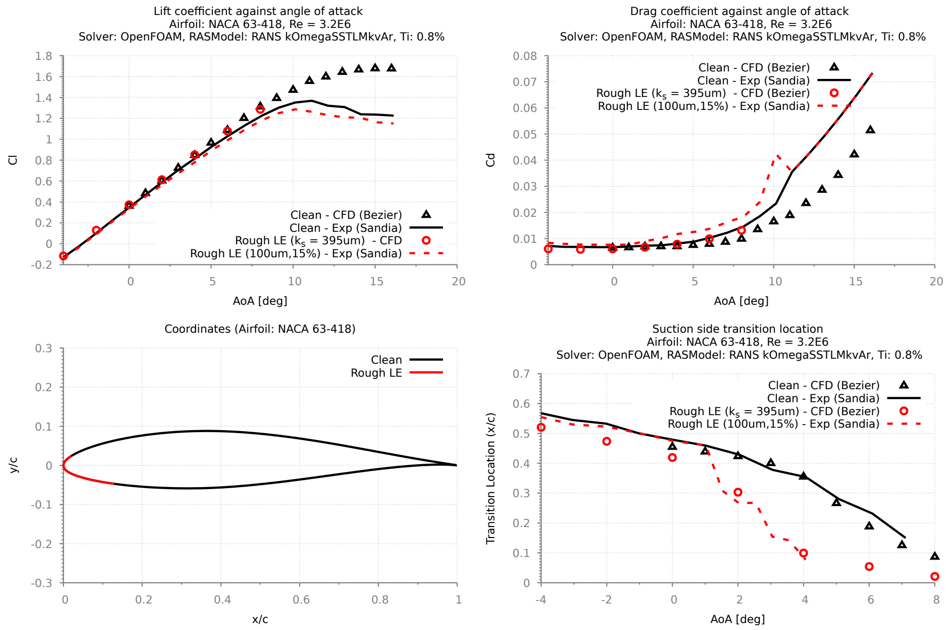

Figure 16: Calibration results at Re= 3.2E6 for NACA 63-418 with LE roughness height of 100um and 15% density

5 Conclusions

An investigation to develop and implement a transport equation based boundary layer transition model for rough surfaces was successfully completed. This implementation was carried out for the open-source CFD code OpenFOAM, which was then calibrated using an experimental study. Numerous verification and validations studies were performed to establish realistic results for predicting roughness induced flow transition for wind turbine application.

Based on this study, it is clear that the newly developed CFD model, calibrated with the measured transition locations shows good agreement of the aerodynamic forces for airfoils with leading-edge roughness heights in the order of 140-200um. Despite matching the location of the transition point, the results indicate that for a smaller roughness height of 100um, the model fails to accurately predict the measured forces. Due to a limited number of measurement data used for calibration of this model, further tuning with validation study using another independent measurement is recommended, especially for modelling the effect of roughness density.