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Detached Eddy Simulation Model for the DU-91-W2-250 Airfoil

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Abstract. This paper presents aerodynamic investigations of the DU-91-W2-250 airfoil at Reynolds number of $3 \cdot 10^6$ employing 2D Reynolds-averaged Navier–Stokes (RANS) solver and 3D detached eddy simulation (DES) technique. RANS simulations are performed in the angle of attack range between -20° and $+20^\circ$ whereas DES results are given only for the angle of attack of 7.08° .

Measurements have been done at the LM Wind Power Low Speed Wind Tunnel. The lift and drag are obtained from airfoil pressure and wake rake respectively.

The obtained numerical results, lift and drag coefficients as well as static pressure distributions are in a good agreement with the experimental results in the linear part of the lift coefficient curve. The Transition SST turbulence model gives much more appropriate results in comparison with the $k-\omega$ SST model, especially for the drag at low angles of attack. The DES approach allows to obtain 3D flow characteristics near the S-shaped airfoil tail.

1. Introduction

In multi-megawatt horizontal-axis wind turbines thick profiles ($\geq 25\%$) are used at inboard and mid-span regions. Thick airfoils provide higher stiffness of blades and lower weight reducing costs and fatigue loads. The following aerodynamic requirements are desirable at midspan: low roughness sensitivity, moderate to high lift and high lift-to-drag ratio. A DU 91-W2-250 airfoil with a maximum thickness of 25% thickness is developed at the Delft University of Technology. Small upper surface thickness of the DU 91-W2-250 reduces roughness sensitivity. In order to achieve sufficient lift an S-shaped aft-loading tail is used. Timmer and van Rooij [1] investigated aerodynamic performance of a series of DU airfoils in a wind tunnel and using a modified version of XFOIL. Aerodynamic performance of the DU91-W2-250 profile can be significantly increased by using vortex generators [2]. Rooij and Timmer [3] examined the effect of roughness on the performance of a few airfoils dedicated for large wind turbines. These authors concluded that the DU 91-W2-250 profile is one of the special purpose airfoils that has the lowest roughness sensitivity and the best overall performance. Lift and drag coefficients and pressure coefficients for the DU 91-W2-250 airfoil were computed using XFOIL and RFOIL programs at a Reynolds number of $1 \cdot 10^6$ [4].

Nowadays computational methods in fluid dynamics have become a popular tool in the design of aircraft and wind turbines airfoils. Raciti Castelli et al. [5] investigated capabilities of two turbulence



models, the Spalart-Allmaras and the γ - θ Transitional, to study the laminar to turbulent transition on the DU91-W2-250 airfoil. 2D CFD simulations of these authors showed that the transitional turbulence model much better predicted the drag coefficients than assuming a fully turbulent flow. The k - ω SST turbulence model and transition model with the empirical function for determining the turbulence intermittency were used by Bertagnolio et al. [6] to simulate the flow around the wind turbine airfoil DU 91-W2-250 at a Reynolds number of $1 \cdot 10^6$. Bangga et al. [7] simulated flow over the DU 91-W2-250 airfoil at high Reynolds numbers employing the eddy-viscosity Menter Shear-Stress-Transport turbulence model with a modified turbulent viscosity formulation. This modification was done in order to simulate the presence of turbulators on the airfoil surface. Bak et al. [8] presented in their report airfoil characteristics of the FFA-W3 airfoil series, also used in large wind turbines, at large Reynolds number between $6 \cdot 10^6$ and $12 \cdot 10^6$. 2D CFD calculations of these airfoils were performed using two turbulence models: the k - ω SST model and the transition γ - Re_θ model. Drag and lift coefficients of the DU 91-W2-250 airfoil at $Re=5 \cdot 10^5$ were measured in a wind tunnel and simulated employing OpenFOAM and XFOIL by Donisi et al. [9]. In these investigations, the results of lift coefficients obtained using the Spalart-Allmaras and k - ω SST turbulence models are in good agreement with the experiment whereas the calculated drag coefficients are overestimated in comparison with the experimental data. RANS simulations of the DU 91-W2-250 airfoil together with a leading edge slat were performed by Schramm et al. [10].

Reynolds-averaged Navier-Stokes (RANS) solvers are sufficient for flows without significant effects of separation but for high angles of attack where the boundary layers separate [11-14]. For such flows Large-Eddy Simulation (LES) techniques may be needed. Unfortunately, the computational cost in LES approach is very high [15]. Therefore, in recent years, hybrid RANS-LES techniques have been developed. One of such strategies is detached-eddy simulation (DES) model developed by Spalart et al. [16] to be used for separated flows at high Reynolds numbers. Kotapati-Apparao et al. [17] used the DES approach with the Spalart-Allmaras turbulence model for analysis of flow around the A-airfoil at an angle of attack corresponding to the maximum lift and at a Reynolds number of $2 \cdot 10^6$.

The purpose of the paper is to study the capability of the DES model with the Transition SST turbulence model to analyse the flow over the DU91-W2-250 airfoil. These investigations also compare results of the DES technique with the two-dimensional RANS approach employing two often used turbulence models: the SST k - ω by Menter [18] and the Transition SST by Menter et al [19].

2. Flow configuration

The investigated blade section has the DU-91-W2-250 airfoil with a constant chord. The Reynolds number for the freestream velocity $U_\infty=51$ m/s is equal to $3 \cdot 10^6$ and the Mach number is 0.15. Based on the experiment, the critical angles of attack are -10.16° and 9.62° . In order to examine the computing method, it has been decided to investigate aerodynamic forces for a range of angles of attack between -20° and 20° using a 2D RANS solver with two turbulence models and for one angle of attack of 7.08° using the DES approach. In the literature there are many studies of airfoils at very high angles of attack (often between 25 and 60 deg) [20, 21]. Therefore, the validation of the hybrid RANS/LES approach for more realistic angles of attack is justified. The shape of the DU-91-W2-250 airfoil is presented in Fig. 1.

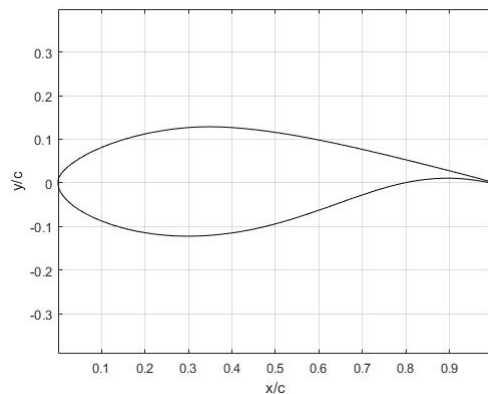


Figure 1. DU-91-W2-250 airfoil.

3. Experimental data

The LM Low Speed Wind Tunnel (LSWT) is of a closed loop type. The fan is 1MW and can deliver up to 105 m/s in the 2.7m x 1.35m x 7m (HxWxL) test section. The test section has a turbulence intensity of less than 0.05%. Measurements are averaged over a period of 50 seconds at a recorded sample rate of 5 Hz.

The measurements were done in May 2015 on a 900mm chord DU-91-W2-250 airfoil model. The model is made with carbon fiber with a trailing edge thickness of 1.5 mm. It is fitted with 62 pressure taps in order to measure the airfoil pressures. Lift and drag are calculated from the airfoil pressure except in the drag bucket where the drag is calculated from the momentum deficit measured behind the airfoil using a traversing wake rake. The data has been corrected using widely used standard wall corrections [22].

4. Numerical methods

4.1. The numerical simulation set-up

All numerical results presented in this paper are obtained using ANSYS Fluent CFD software. The compressible Navier-Stokes equations are discretized using a finite volume method.

A 2D structural C-mesh was used for all RANS simulations presented in this paper. The distance from the airfoil surfaces to the pressure far field region is equal to 20 airfoil chords in each direction. According to Dighe [23], such a distance is sufficient to the boundary condition pressure far field does not affect the wall bounded flow near the airfoil surfaces. The number of mesh cells on the airfoil surface is 400. The grid stretching ratio in the normal direction to the airfoil surfaces is fixed at 1.1. A mesh resolution study (mesh sensitivity test) was performed for two different values of the mesh cells on the airfoil: $N=300$ and $N=400$. Table 1 presents lift and drag coefficients for the angle of attack of -0.04° obtained for the Transition SST turbulence model and for two values of mesh cell numbers on the airfoil surfaces. As it can be observed from the table, the results both for C_L and C_D , are only slightly better for the higher value of N . Therefore, further increase in the number of mesh cells on the airfoil surfaces does not significantly affect the results of aerodynamic loads but the computational effort drastically increases.

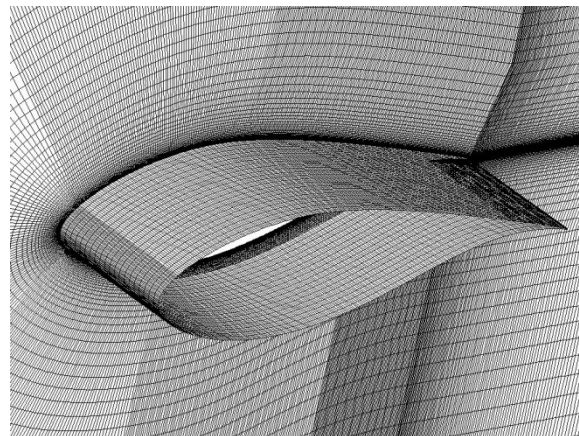
Table 1. Mesh sensitivity test

	Experiment	Transition SST $N=300$	Transition SST $N=400$
C_L	0.39	0.395524	0,397915
C_D	0.0072	0.007978	0.007867

The 3D computational domain, extruding from the 2D grid, extends 0.3 chord lengths in the spanwise direction (z -direction). According to Zhang et al. [24] who investigated the NACA 23012 airfoil under large Reynolds number values, in order to properly represent the chaotic characteristics of turbulence in the wake flow, the spanwise dimension should be equal to 30% of the chord length. The number of mesh points in spanwise direction is 20. For high number of mesh cells in the spanwise direction the computational time would increase significantly therefore the mesh sensitivity analysis was not performed. The final 3D computing grid consists of 4 271 393 cells. The computational mesh is performed to satisfy the following criteria [25]:

- Chordwise: $\Delta x^+ \leq 900$
- Wall-normal: $\Delta y^+ \leq 0.6$
- Spanwise: $\Delta z^+ \leq 800$

Figure 2 presents the final computational grid around the DU-91-W2-250 airfoil.

**Figure 2.** Computational grid.

4.2. Turbulence modelling

The Transition SST and the $k-\omega$ SST turbulence models are used for the RANS simulations of the DU-91-W2-250 airfoil. The shear stress transport (SST) $k-\omega$ turbulence model is a popular two-equation viscosity model developed by Menter [18]. This model uses the $k-\omega$ formulation in the inner part of the boundary layer and the $k-\epsilon$ formulation in the freestream. Many authors use this model as a Low-Re turbulence model [12]. The four-equation SST Transition turbulence model (also known as the $\gamma-Re_\theta$ turbulence model) is based on the two-equation SST $k-\omega$ turbulence model. In addition to the SST $k-\omega$ model, the transition model makes use two additional transport equations for the intermittency and the transition onset criteria. The Transition model gives more physical results in comparison to full turbulence models such as e.g. the RNG $k-\epsilon$ model [13].

Because of the Reynolds number ($3 \cdot 10^6$) aerodynamic forces cannot be predicted by large eddy simulation (LES) model. In order to avoid the high resolution requirements of LES model for high Reynolds number flows, hybrid RANS/LES models such as for example the detached eddy simulation

(DES) are developed. The idea of the DES approach is to simulate the near-wall regions using the unsteady RANS turbulence model, whereas the regions away from the near-wall are computed using LES approach. ANSYS Fluent offers different turbulence models for the detached eddy simulation approach. One of them is the Transition SST turbulence model. More information about these techniques can be found in ANSYS documentation, Inc. Release 17.1.

5. Results

Results of 2D RANS simulations are presented as drag and lift coefficients as function of the angle of attack as well as static pressure distributions at a few angles of attack. Results of the DES model are given only for one angle of attack of 7.08° . They are presented as drag and lift coefficients as well as using iso-surfaces of vorticity.

Figures 3 and 4 present respectively drag and lift coefficients versus angle of attack for 2D RANS simulations employing two turbulence models: the $k-\omega$ SST and the Transition SST. The obtained numerical results are compared with the experimental results from the LM Low Speed Wind Tunnel for the Reynolds number of $3 \cdot 10^6$. For the linear part of the lift curve, the numerical results are in a good agreement with the experiment up to the critical angles of attack of approx. $+9.6^\circ$ and -10.1° . For high angles of attack the drag coefficients predicted by both used turbulence models are underestimated in comparison with the experiment. As it can be observed from Figures 3 and 4, the results obtained using the Transition SST turbulence model are consistent with the experiment and are much better than those computed by the full turbulence model $k-\omega$ SST.

The obtained numerical results are compared with the results by Bangga et al. [7] (Fig. 5). The numerical data taken from literature were obtained using the $k-\omega$ SST turbulence model. It is shown in Fig. 5 that the ratio C_L/C_D computed using the Transition SST turbulence model is in good agreement with the experimental results. The results obtained by the authors of this paper using the $k-\omega$ SST model are comparable with these obtained by Bangga et al. [7] but they are too far from the experimental data.

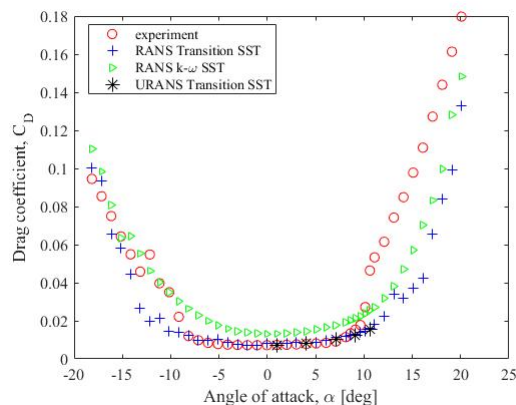


Figure 3. Drag coefficients vs. angle of attack.

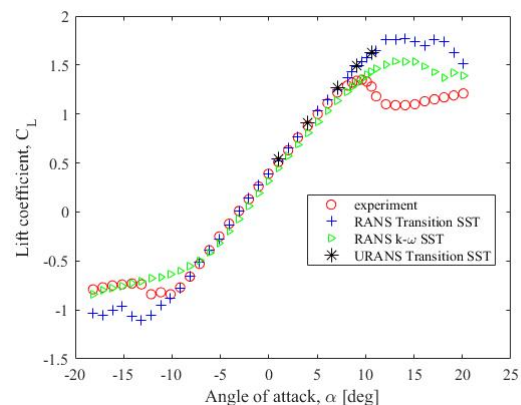


Figure 4. Lift coefficients vs. angle of attack.

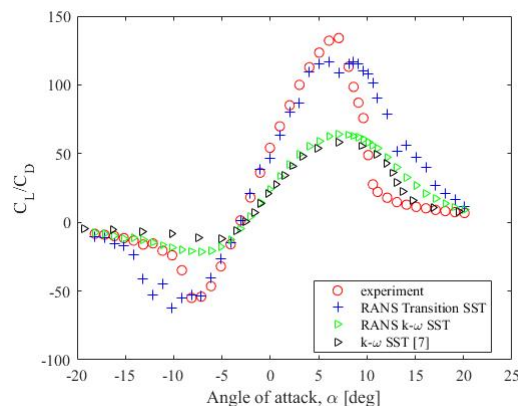


Figure 5. Lift to drag coefficient ratio.

The results of static pressure distributions for four angles of attack are presented in Figure 6. Deficiencies of the $k-\omega$ SST turbulence model are observed mainly at negative angles of attack. The results of the Transition SST model are more physical in comparison with the $k-\omega$ SST turbulence model.

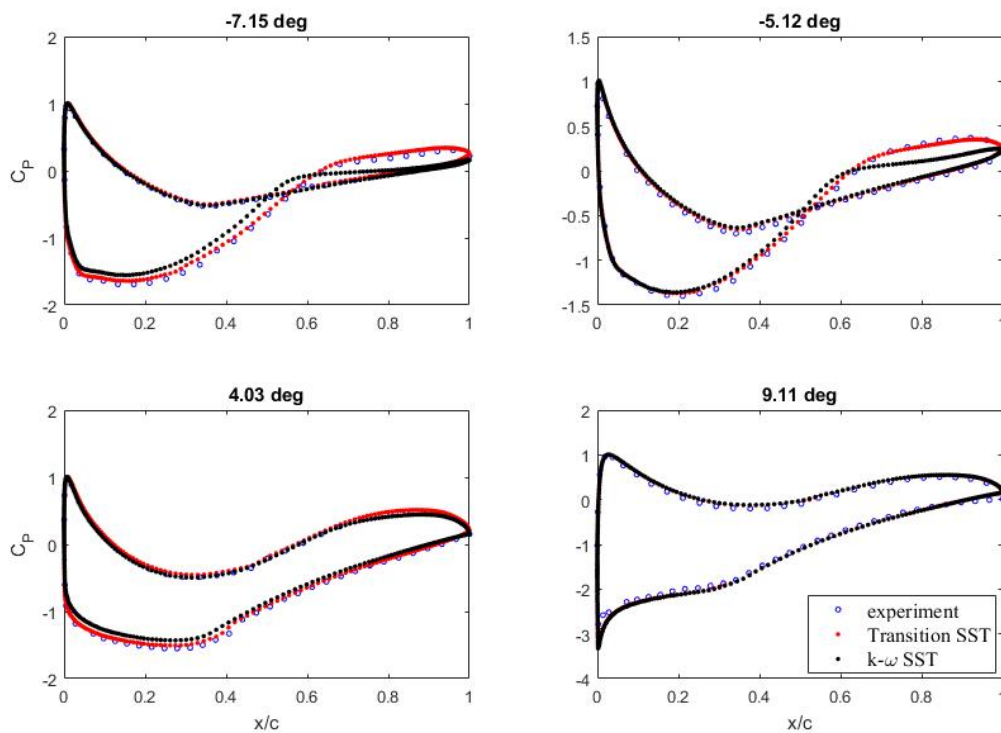


Figure 6. Pressure coefficients for 2D RANS simulations.

Computational effort required for the detached eddy simulation approach is very high. Therefore, in this paper the results of flow parameters around the airfoil are given only for the angle of attack of 7.08° which corresponds to the design angle of attack. Figure 7 presents the comparison of static pressure distributions for 2D RANS simulations and for DES technique. Basically, the results of all

used methods are very similar. Small differences between the C_p characteristics are visible for the DES curve on the upper side of the airfoil at x/c location of approx. 0.37 and on the pressure side at x/c of approx. 0.5. The first location is associated with the laminar to turbulent transition. During the experiment the location of transition on the suction side was measured. For the angle of attack of 7° the ratio x/c was 0.35. This value is very similar to that obtained with CFD. Figure 8 presents a contour map of a wall shear stress distribution. This figure shows that the distribution of wall shear stress is not uniform at the pressure side of the airfoil at the location x/c of 0.5. Figure 9 presents iso-surfaces of vorticity magnitude coloured by velocity magnitude. Small vortex structures in the S-shaped airfoil tail can be observed from this figure. Table 2 presents values of lift and drag coefficients at the design angle of attack. The drag coefficient predicted by the DES model is the closest to the experimental results. Lift coefficients calculated by all used approaches, with the exception of the $k-\omega$ SST turbulence models, are slightly overestimated in comparison with the experiment. C_p -curves presented in Fig. 6 indicate slightly overestimated results on the suction side of the airfoil. Moreover, analysing the iso-surfaces of vorticity (Fig. 9) a small laminar bubble is also seen on the suction side of the airfoil at the location of x/c of approx. 0.033.

Table 2. Lift and drag coefficients

	Experiment	RANS Transition SST	RANS $k-\omega$ SST	URANS 2D Transition SST	DES
C_L	1.22	1,251681	1,132829	1,272351	1,291751
C_D	0.009079	0,011481	0,017736	0,010338	0,010064

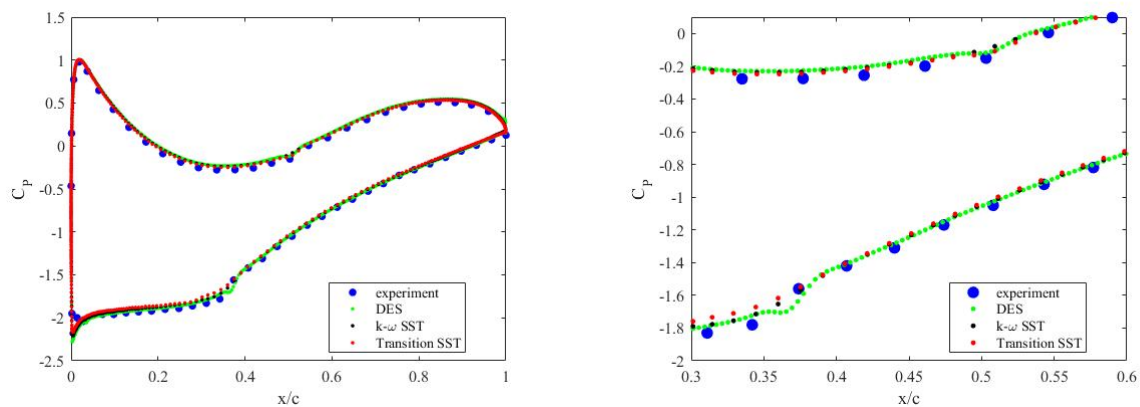


Figure 7. Static pressure distribution at the angle of attack 7.07° . The comparison between 2D RANS and DES

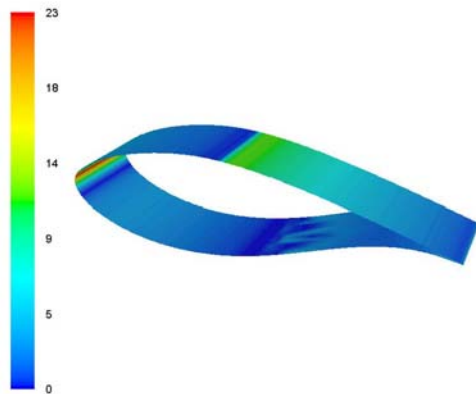


Figure 8. Wall shear stress in pascal.

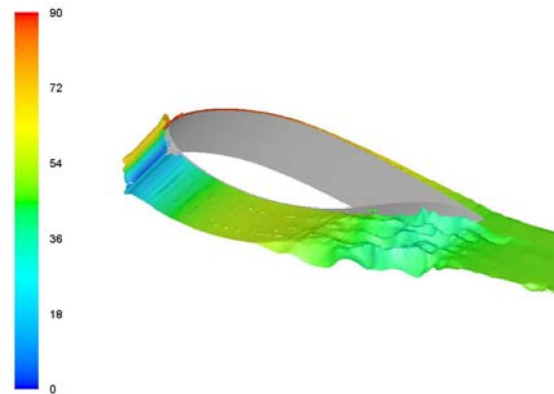


Figure 9. Iso-surface of vorticity magnitude coloured by velocity magnitude.

6. Conclusions

The main objective of this research is the analysis of flow past a 25% thickness airfoil DU 91-W2-250. In this investigation two RANS turbulence models, $k-\omega$ SST and Transition SST, and DES approach were used. The obtained numerical results allow to present the following general conclusions:

- The minimum values of the drag coefficient obtained by the $k-\omega$ SST turbulence model is even two times larger in comparison with the Transition SST and experimental results.
- The $k-\omega$ SST turbulence model fails at high negative angles of attack.
- Lift and drag coefficients as well as static pressure coefficients calculated by the Transition SST model agree with the experiment in the linear part of the C_L curve.
- No used turbulence model gives appropriate values of critical angles of attack presented by wind tunnel measurements.
- The Transition SST turbulence model is able to predict an appropriate location of the laminar to turbulent transition.
- At the design angle of attack of 7° the DES technique allows to see three-dimensional flow structure on the pressure side of the airfoil.

Acknowledgments

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