Validation of the SST-HL turbulence model for separated flows and flows around airfoils

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Abstract. Testing of the modification of the SST turbulence model (SST-HL) developed for improvement of prediction of flow around airfoils was carried out for different flows. Although the SST-HL model is slightly worse than the original SST model for turbulent separated flows the agreement of the SST-HL model with the experimental data is quite satisfactory. For flow around airfoils the SST-HL demonstrates superiority over the SST model for separated flow regimes near stall conditions.

1. Introduction
The accurate prediction of airfoil characteristics in regimes near stall where flow is separated and maximal lift coefficient is achieved is an important task for aviation and wind power, as well as for turbomachinery flows. For prediction of these flows the Reynolds Averaged Navier-Stokes (RANS) approach in combination with different semi-empirical turbulence models is widely used in engineering practise. However, it is observed that the maximum lift coefficient and corresponding angle of attack are systematically overpredicted by these models which however, can predict separated flow properly, for example k-ω SST model [1]. The disagreement (error can be about 40% [2]) is caused by a delay of turbulent boundary layer separation under adverse pressure gradient condition. Since the separation position is controlled by the turbulence model, special tuning of the models for such flows is required. Such modification of the SST model SST High Lift (SST-HL) was suggested in [3] for improvement of prediction of airfoil characteristics near stall conditions. This modification consists in replacing the a1 constant of the SST model with the function $A_{HL}$ which accelerates the separation on the airfoils and does not destroy model calibration for simple wall-bounded and free-shear flows. However the SST-HL model was tested only for a few cases: prediction of the flat plate boundary layer [4] and flow around an A-Airfoil [5].

Thus the aim of present study is the wider testing of this model for two types of flows. The first type is separated flow over a backward-facing step and flow in an axisymmetric diffuser. The second one is flow around different airfoils in a wide range of angles of attack including the stall regime.

2. Separated flows
Two cases with separation were considered. An experimental investigation of the first case, an incompressible flow downstream of a Backward-Facing Step (BFS), was carried out by Vogel and Eaton [6]. The Reynolds number based on the maximum inlet velocity and the step height $H$ is equal to $Re = 2.8 \cdot 10^4$. The inlet boundary is placed $3.8H$ upstream, and the outlet boundary is located...
approximately $40H$ downstream from the step. In order to reproduce the experimental inflow conditions in the simulations, a precursor computation of the flow in the plane channel was carried out, and the inflow conditions were extracted from this computation at the cross-section where the experimental boundary layer displacement thickness was matched.

The second test case, CS0 diffuser by Driver [7], presents an example of shallow separation from a smooth wall. The test case geometry consists of an axisymmetric diffuser caused by adverse pressure gradient with an internally mounted cylinder along the centreline. The Reynolds number based on the maximal inlet velocity and the inner cylinder diameter $D$ is equal to $2.8 \times 10^5$.

Figure 1 shows schematics of the flows and the skin friction coefficient distribution for the considered cases. One can see that the SST-HL model predicts separation slightly worse than the SST model. Nevertheless the agreement of the SST-HL model with the experimental data can be assessed as quite satisfactory.

![Schematics of the flows and skin friction coefficient distribution for BFS and CS0 diffuser](image)

**Figure 1** Schematics of the considered flows (upper row) and comparison of computational skin friction coefficient with the experimental data for the backward-facing step and CS0 diffuser (lower row).

### 3. Flow around airfoils

**Problem definition**

Five aerodynamic airfoils with different shapes and thicknesses (from 13% to 30%) are considered. Experimental investigations [8]-[12] were carried out in low turbulence rectangular wind tunnels ($Tu < 1\%$) at relatively high Reynolds numbers ($Re > 10^6$) based on airfoil chord and freestream velocity (Table 1). The measurement procedure was identical for all the considered experiments. The static pressure was measured in the vicinity of the mid-span section of the wing and sectional pressure distribution was numerically integrated to obtain the lift coefficient. The airfoil shapes and more detailed information about experiments are shown in the Table 1. For all the airfoils except DU-97-W-300 the boundary layer was «tripped» with the use of a short «rough» tape placed at the leading edge. Thus it is assumed that flow around these airfoils is fully turbulent and in case of the «clean» DU-97-300 airfoil model the laminar turbulent transition should be taken into account in computations. Since the experimental Mach number did not exceed 0.15, incompressible flow was considered in all cases.

It should be noted that the use of a three dimensional rectangular wind tunnel for the computational domain is required in order to capture complex flow structures (so called mushroom cells) on the suction side of the wing surface for angles of attack near stall (see for example [5], [13], [14]) and the blockage effect of upper and lower wind tunnel walls [2]. For covering different flow regimes the computations...
were carried out for angles of attack up to 15°. Steady Reynolds Averaged Navier-Stokes equations were solved in combination with the SST and SST-HL models. For the DU-97-W-300 airfoil the additional intermittency equation \([15]\) was solved together with the \(k\) and \(\omega\) equations for both model in order to predict free laminar-turbulent transition (\(\gamma\)-SST and \(\gamma\)-SST-HL models) on the wing surface. For each wing the lift coefficient was computed by integrating pressure over the airfoil in the experimental measurement section.

### Table 1: Considered airfoils and parameters of wind tunnel and flow in the experiments

| Airfoil     | Thickness | Surface | Wind Tunnel Height | Wing Aspect Ratio | Re/10^6 |
|------------|-----------|---------|--------------------|------------------|---------|
| S805       | 13.50%    | Tripped | 3.60\(C\)          | 2.50\(C\)        | 1.00    |
| S825       | 17.10%    | Tripped | 5.00\(C\)          | 2.00\(C\)        | 2.00    |
| S809       | 21.00%    | Tripped | 3.00\(C\)          | 2.00\(C\)        | 2.00    |
| S814       | 24.00%    | Tripped | 2.76\(C\)          | 1.92\(C\)        | 1.50    |
| DU-97-W-300| 30.00%    | Clean   | 3.00\(C\)          | 2.00\(C\)        | 3.00    |

**Computational domain and boundary conditions**

The height of the computational wind tunnel and the wing aspect ratio corresponds to the experimental parameters shown in Table 1 (Figure 2). Inlet and outlet boundaries were located 10\(C\) upstream of the leading edge and downstream of the trailing edge airfoil respectively. A constant velocity was specified at the inlet section of the computational domain. The inlet turbulent kinetic energy matched the experimental turbulence intensity and the specific dissipation rate is specified as \(\omega = 10 \cdot U_\infty / C\) \([16]\) (where \(U_\infty\) and \(C\) is the freestream velocity and airfoil chord respectively). No-slip conditions were used on the wing surface and constant pressure was specified on the outlet. In the present study the effect of the boundary layer of the wind tunnel walls is not taken into account. Thus symmetry boundary conditions were specified on the wind tunnel upper, lower and side walls for imitation of the slip-walls.

![Figure 2](image)

**Figure 2.** Computational domain and boundary conditions

**Computational mesh**

In order to facilitate mesh generation for the computations of the airfoil in the wind tunnel at different angles of attack, the following approach was used. The airfoil was placed into a sub-domain of circular shape, which can be rotated to adjust the angle of attack. In this “rotating” sub-domain and in the “static” sub-domain covering the remaining part of the wind tunnel, structured meshes are generated, with a relatively small “buffer zone” near the interface (inside the rotating sub-domain), in which an unstructured hexahedral mesh is used. This static/rotating interface (purple color on Figure 2) consists of 360 cells which leads to a fully conformal mesh interface in case of “discrete” rotation (changing the angle of attack) by 1 degree. The position of the axis of the rotating sub-domain coincides with the position of axis of rotation of the airfoil in the experiments. The meshes were refined normal to the wall in order to resolve the viscous sublayer (\(\Delta y_1 < 1\)). The grid features about 400 points along the airfoil, 81 points in spanwise direction and total mesh size of about 6 million cells. All the meshes are built with the use of ANSYS ICEM CFD software and provide grid converged solutions.
4. Results and discussions

Flow structure
The flow topology for near stall conditions is complex, depends on the airfoil shape and flow regimes. However we can distinguish three scenarios for all the considered cases (Figure 3). For the first scenario (S825 and S814 airfoils) one mushroom cell is formed on the suction side of the wing surface at some angles of attack. Increase of the angle of attack increases the size of the mushroom cell and the lift coefficient decreases. For the second scenario (DU-97-W-300) the model predicts two mushrooms when the lift coefficient starts to decrease. Finally the last scenario shows the most complex evolution of the flow (S805, S809). At a particular angle of attack one mushroom cell appears on the suction side of the airfoil and the lift coefficient starts to decrease. However for higher angles of attack one mushroom cell transforms into two mushroom cells which leads to an increase of the lift coefficient.

| Scenario | Description |
|----------|-------------|
| 1        | (An example for the S825 airfoil) |
| 2        | (An example for the DU-97-W-300 airfoil) |
| 3        | (An example for the S809 airfoil) |

**Figure 3.** Flow scenarios for considered airfoils visualised by sectional lift coefficient and streamlines on the suction side of the wing (perspective view). For each flow topology the following colors are used: red - two dimensional flow, blue - three dimensional flow with one mushroom cell, green - three dimensional flow with two mushroom cells.
Comparison results with the experimental data

The SST-HL model predicts the complex flow structure on the suction side of the considered wings while the SST model predicts two dimensional flow up to $\alpha = 14^\circ$ for almost all of the cases. The earlier appearance of three dimensionality for the SST-HL model than for the SST model has a great impact on the lift coefficient value for angles of attack near stall (Figure 4). One can see that the SST-HL model significantly improves prediction of the airfoil characteristics in comparison with the original SST model. In particular the SST-HL model captures “waviness” of the lift coefficient for the S809 airfoil for $\alpha = 9^\circ$-$15^\circ$. However for DU-97-W-300 airfoil the SST-HL model still significantly overpredicts the experimental lift coefficient in stall for $\alpha = 13^\circ$-$15^\circ$. The reasons for such disagreement are unclear, but the most likely of them is the different flow topologies on the suction side of the wing for these flow regimes in the experiment and computations.

![Figure 4](image_url)

Figure 4. Comparison of experimental and computational sectional lift coefficient for different airfoils in a wide range of angles of attack. The measurement section is the same for the computational setup and experiment.

5. Conclusions

The present study presents detailed tests of the SST-HL model for separated flows and flows around airfoils in wide range of angles of attacks covering wall-bounded separated regimes in stall. For separated flow over backward-facing step and flow in an axisymmetric diffuser the SST-HL model demonstrates satisfactory agreement with the experimental data and with the SST model. In case of flows around airfoils the SST-HL model predicts earlier appearance of the three dimensional structures than the SST model which leads to significant improvement in prediction of the lift coefficient for separated flow regimes. For these regimes the computational lift coefficient is in good agreement with the experimental data. However the SST-HL model still significantly overpredicts the lift coefficient for the DU-97-W-300 airfoil in stall. The most likely reason for such disagreement is the different flow topologies on the suction side of the wing in the experiment and in computations.
Acknowledgements
The results of the present work were obtained using computational resources of Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (http://www.spbstu.ru).

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