TRANSITION MODELING FOR HYPERSONIC AIR INTAKE FLOWS IN SCRAMJET APPLICATIONS

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Abstract. The transition modeling for scramjet intake computations is analyzed using three-dimensional high-resolution simulations. A mesh-adaptive Reynolds-averaged Navier-Stokes solver is used with the Shear Stress Transport (SST) turbulence model. The transition is modeled using the $\gamma$-$Re_\theta$ model proposed by Langtry/Menter [13, 14]. It is extended with an in-house correlation for onset and length of transition [11]. Computations with the SST transition model are compared to computations with the SST model (no transition model). A comparison to experimental results at $M_\infty = 7$ test condition shows the advantages of using the proposed transition model.

1 Introduction

The intake of a supersonic combustion ramjet (scramjet) mostly consists of one or more exterior compression ramps followed by an interior part. Oblique shock waves generated by the ramps and the cowl lip are performing the compression of the incoming flow. Since the flow field of a scramjet intake highly depends on the boundary layer, the laminar-to-turbulent transition is crucial to characterize the state of the boundary layer.

A fully three-dimensional intake has been designed at the German Aerospace Center (DLR) in Cologne. Two test campaigns using a V-shaped lip (2012 [9]) and a straight lip (2013) were performed. Since experimental measurements are very costly and difficult to perform, numerical computations are necessary to analyze and understand the flow phenomena. Thus, a numerical analysis in cooperation with the German Aerospace Center Cologne is performed. First results for the V-shaped lip using the SST model for wind tunnel conditions and flight conditions were presented in [6].

Within this paper multi-level computations for the V-shaped lip are analyzed using the Shear Stress Transport turbulence model (SST) as well as the $\gamma$-$Re_\theta$ model proposed...
by Langtry/Menter [13, 14] extended with an in-house correlation for onset and length of transition (SST transition) [11]. The numerical results are compared to experimental data, showing the advantages of the SST transition model. In addition, in cooperation with the second experimental test campaign (2013), mesh-adaptive computations for the straight lip are performed for both models (SST and SST transition). Computations with fixed transition point are currently performed. For the straight lip, a comparison to experimental data will follow as soon as the experimental data are published.

2 Experimental Settings

The geometry of the considered scramjet intake is shown in Figure 1. The front part of the cowl is movable and two different shaped lips are available: a V-shaped lip and a straight lip. The configuration was tested at the Hypersonic Windtunnel H2K at the German Aerospace Center in Cologne. The surface pressure in the intake was measured by a total of 55 Kulite pressure probes [9]. During the experiments, the following condition is used: $M_\infty = 7.0$, $Re_\infty = 2.6 \times 10^6/m$, $T_{0,\infty} = 64.8$ K and $T_{wall} = 300$ K. These values are used as inflow conditions in the simulations. The computations are performed for lip position $x_{lip} = 330$ mm (V-shaped lip) and $x_{lip} = 400$ mm (straight lip).

3 Numerical Method

3.1 Solver Quadflow

Quadflow has been developed over a period of more than one decade within the Collaborative Research Center SFB 401 “Flow Modulation and Fluid Structure Interaction at Airplane Wings” and the Research Training Group GRK 5 “Transport Processes in Hypersonic Flow” at RWTH Aachen University. It has been validated extensively against different test cases [2, 3, 17, 10].

To simulate turbulent flow, the SST model is applied. The transition is modeled using the $\gamma$-$Re_\theta$ model proposed by Langtry/Menter [13, 14] extended with an in-house correlation for onset and length of transition (SST model with two additional equations for modeling transition). A detailed description of the model and the implementation is given in [11].
Quadflow is parallized using MPI and space-filling curves [4, 5]. The computations are performed using 60 processors of the Bull cluster of RWTH Aachen University.

3.2 Multi-Level Computations

To prepare the mesh-adaptive computations and to gain experience with the new scram-jet intake, we perform multi-level computations using uniformly refined grids. The multi-level computations start on the refinement level \( L = 1 \) until a residual of \( 10^{-4} \). Then, this intermediate solution is used to initialize the next refinement level until the final level \( L = 4 \) is reached. Since, the computation starts with a good initial solution on the higher refinement level, less computationally costly iterations are necessary. Compared to computations starting on fully refined grids, the computational effort is reduced. All computations for the V-shaped lip are multi-level computations. The final, uniformly refined grid at refinement level \( L = 4 \) consists of 13,516,800 cells. The minimum wall distance is \( 1 \times 10^{-6} \) m which corresponds to a \( y^+ < 1 \). Due to the computational effort no grid convergence study using a level \( L = 5 \) grid (108,134,400 cells) is performed. More information can be found in [6].

3.3 Mesh-Adaptive Computations

An additional gain in CPU time can be reached through truly mesh-adaptive computations, since the grid size of the adapted grids is less than the grid size of uniformly refined grids. Previously, the mesh-adaptive approach was successfully applied to several 2D configurations and to a different three-dimensional scramjet intake showing that the CPU time is reduced to one third for the 3D computations [7, 8]. For the straight lip, first results of mesh-adaptive computations are shown.

Typically, a mesh-adaptive simulation starts on a very coarse grid (e.g., 15,000 cells in 3D). After a certain residual (here: \( \epsilon = 5 \times 10^{-3} \)) is reached, the adaptation procedure is applied. It is based on a multiscale decomposition of the flow data with coarse scale data and details describing the update between data of two successive refinement levels. All cells with details \( d_l \) higher than the specified threshold value (here: \( \epsilon_{thres} = 4 \times 10^{-2} \)) are split into eight cells. The simulation continues on the new, adapted grid. This adaptation procedure is repeated several times (e.g., 6 times with 6 adaptation levels). After the last adaptation, the simulation continues until convergence is reached on the final grid. The final grid has a very fine grid resolution in areas where interesting flow features, such as boundary layers, relaminarization and shock waves occur, and a coarse grid resolution everywhere else. In comparison to non-adaptive grids, the resolution of adaptive grids close to the wall is high, without the whole domain being refined. A detailed description of the adaptation procedure can be found in [15] and its embedding into the solver in [16].

All computations for the straight lip are mesh-adaptive computations. The software GridPro [1] is used to generate a uniformly distributed grid, which is transformed by Gnagg into a multiblock-structured data format. Gnagg is an in-house grid generator.
providing in each block a grid mapping that implicitly defines the grid hierarchy of the multiscale analysis by uniformly refining the parameter space [12]. To achieve an initial refinement towards the walls on level \( L = 1 \), stretching functions are applied within Gnagg. This initial refinement is not required by the adaptation procedure but it reduces the necessary number of adaptation levels needed to resolve correctly the strong gradients close to the wall.

The initial grid on refinement level \( L = 1 \) consists of 15,840 cells and is shown in Figure 2 (left). For the computations, six adaptation levels are used. Currently, only results on level \( L = 5 \) (SST model) and on level \( L = 4 \) (SST transition model) are available. The adapted grid at refinement level \( L = 4 \) consists of approximately 5 million cells and is presented in Figure 2 (right). The minimum wall distance of the \( L = 4 \) grid is \( 3 \times 10^{-5} \) m. Hence, an improvement of the accuracy of the results at level \( L = 5 \) and \( L = 6 \) is expected.

4 Results

First of all, the general flow features for the V-shaped lip are discussed. Next, the SST model and the SST transition model are compared to experimental data for the V-shaped lip. Afterwards, preliminary results of the mesh-adaptive computations for both models are shown and discussed. Since the leading edge shock hits the upper wall close to the lip for both considered geometries, the general flow features of the computations are similar.

4.1 V-shaped lip

General flow features

To illustrate the three-dimensionality of the flow, Figure 3 presents the normalized wall heat flux in terms of the Stanton number at the wall. The Mach number at different cross sections is also shown. The heat load at the exterior portion of the intake is moderate, except for the leading edges of the ramp and the lower side wall. As the flow moves inside the intake, more shock waves are generated by deflection and impinge on the surface,
creating several areas of intense heating. The Mach number plots show the strong interaction of the leading edge shock wave and the side wall shock wave. Both shock waves are of approximately the same strength due to similar deflection angles. In the last cross section, a third shock wave, generated by the V-shaped cowl, appears and intensifies the interaction. Thus the flow is highly three-dimensional.

Comparison of the transition modeling

Figure 4 shows the Mach number contour for the SST model and the SST transition model. For both computations, the flow is compressed by the leading edge shock (1). At the lower intake wall, a turbulent boundary layer develops and thickens (3) due to side wall effects and the impinging cowl shock. For the SST model, the boundary layer is fully turbulent in the computation due to the chosen turbulence model. This is done because no information about the location of the laminar-to-turbulent transition is known from the experiments. Since the SST transition model computes the laminar-to-turbulent transition, the boundary layer starts laminar. For the SST transition model, the flow separates at $x \approx 0.25$ m and a large separation bubble (11) occurs at lower intake wall. The flow reattaches (12) at $x \approx 0.45$ m. For the SST model, the flow does not separate in this region. For both models, outside the boundary layer (2) the flow is not disturbed by the side wall compression. Due to the chosen off-design lip-position, the leading edge shock hits the upper intake wall and interacts there with the lip shock and the boundary layer. The shock-shock-interactions and shock-boundary-layer-interactions (4) result in an oblique shock from the upper intake wall (5). Due to separation bubble (11), predicted by the SST transition model, the shock angle (4) differs slightly from the shock angle
predicted by the SST model. Close to the lip, where the shock interacts with the boundary layer, the recirculation zone is predicted smaller by the SST transition model. The shock (5) impinges on the thick boundary layer at the lower wall and is reflected. Due to the expansion, the boundary layer thickness decreases (6). At the complete upper intake wall the flow is separated (7).

To analyse the flow further, the distributions of the pressure coefficient:

$$c_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty u_\infty^2},$$

and the Stanton number:

$$St = \frac{q_w}{\rho_\infty |u_\infty| c_p(T_{0,\infty} - T_w)},$$

are shown for both intake walls in Figure 5.

All flow features described above can be identified here as well. Due to the adverse pressure gradient that can be clearly seen in the pressure coefficient, the boundary layer at the lower intake wall (3) thickens. At the lower intake wall, the first pressure rise is caused by the cowl shock (5) hitting the wall. At the kink between the movable and fixed part ($x = 550$ mm) of the cowl, an oblique shock (9) occurs and causes the rise of the pressure coefficient at the upper intake wall. At the second pressure rise at the lower intake wall shock (9) interacts with the flow at the lower intake wall and is reflected (8). The cowl shock (5) is reflected as well (8). After the interface to the combustor ($x = 650$ mm),
the intake divergences slightly and at the upper intake wall, the interaction of the shock reflection and the expansion (10) can be seen.

For the pressure coefficient, the experimental data are shown as well. At the bottom wall, both models show an overall good agreement to the experimental data and only slight differences can be seen here. Nevertheless, the heat transfer differs significantly. For the SST transition model, the boundary layer is laminar and separates at $x \approx 0.25$ mm. Whereas, for the SST model, the boundary layer is fully turbulent and, hence, stays attached to the surface. Here, the heat transfer is higher. For the SST transition model, at $x \approx 0.45$ m the reattachment shock can be seen in the increase of the Stanton number. The peak heating corresponding to shock (6) is higher for the SST transition model, since the boundary layer is thinner in this region. At the top wall, the advantages of the SST transition model can be clearly seen. Whereas the SST model is not able to predict the first pressure peak, the SST transition model follows the experimental data closely. The peak heating predicted by the SST model is smaller than the peak heating predicted by the SST transition model. Both computations do not resolve all pressure peaks correctly. This can be improved using computations on the next refinement level $L = 5$. Due to the limited computational resources, this was not done here.

Although both models predict a similar pressure coefficient distribution at the bottom wall, the heat transfer shows large differences due to the state of the boundary layer. In contrast to the SST transition model, at the top wall, the SST model is not able to predict the first pressure peak. The peak heat transfer predicted by the SST model is only 60% of the heat transfer predicted by the SST transition model. This shows, the importance of a correct prediction of the laminar-to-turbulent transition especially for the heat transfer at the walls.

Figure 5: Pressure coefficient (left) and Stanton number (right) at the walls in the symmetry plane.
4.2 Straight lip

Adaptive Procedure

The adaptive procedure is illustrated for an adaptive computation with 5 refinement levels. The SST model is used for this computation. The number of grid cells at the different refinement levels are shown in Table 1. The adaptive grid at $L = 4$ only contains 50% of the cells of the uniformly refined grid. At $L = 5$ the difference between the grid size of the adaptive grid and the uniformly refined grid is even higher. Here, the adaptive grids contain only 15% of the cells of the uniformly refined grid at $L = 5$. The large difference in grid size reflects the differences in memory consumption and CPU time.

<table>
<thead>
<tr>
<th>refinement level</th>
<th>$L=1$</th>
<th>$L=2$</th>
<th>$L=3$</th>
<th>$L=4$</th>
<th>$L=5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>adaptive grid</td>
<td>15,840</td>
<td>125,320</td>
<td>921,759</td>
<td>4,628,049</td>
<td>9,868,613</td>
</tr>
<tr>
<td>uniformly refined grid</td>
<td>15,840</td>
<td>126,720</td>
<td>1,013,760</td>
<td>8,110,080</td>
<td>64,880,640</td>
</tr>
</tbody>
</table>

*Table 1: Evolution of cell numbers during the adaptive procedure.*

Figure 6 shows the grid and the Mach number distribution at the symmetry plane for different stages of the adaptive computation. During the first and the second adaptation, most cells are refined. The following adaptations only refine the cells near the shock waves and in the boundary layers as well as the separation areas. To prove grid convergence.
for adaptive computations, the solution on one refinement level is compared to the solution on the next refinement level. This is shown for the pressure coefficient and the Stanton number distribution along the symmetry plane at the lower intake wall in Figure 7. Whereas the differences between \( L = 1 \) and \( L = 2 \) are large, the differences between \( L = 4 \) and \( L = 5 \) are comparably small. Due to the significant differences between \( L = 4 \) and \( L = 5 \), the solution at \( L = 4 \) is not grid converged as can be expected because of the first wall distance \( y_{wall} = 3 \times 10^{-5} \) at \( L = 4 \).

**Comparison of the transition modeling**

Similar to the computations using the V-shaped lip, along the lower intake wall, the boundary layer thickens (3) faster for the SST model than for the SST transition model. The separation bubble at the lower intake wall (11) only occurs for the SST transition model due to the laminar boundary layer. After the reattachment (12), the boundary layer is thinner and stays attached. For the SST model, the boundary layer separates at region (6), where the shock (5) impinges. This does not occur for the V-shaped lip. In contrast to the computations using the V-shaped lip, at the upper wall, the flow is only separated in a small region close to the lip (4). For both computations of the straight lip, at the rest of the upper wall, the flow is attached (7).
5 Conclusions

Multi-level computations and mesh-adaptive computations of three-dimensional scramjet intake are analyzed. The simulations show that due to off-design condition with respect to the cowl position, the leading edge shock wave impinges on the underside of the
cowl. Due to similar compression angles on ramp and side walls, the interior flow remains largely homogeneous. Investigations of the transition model show the importance of a correct prediction of the laminar-to-turbulent transition. Especially when no experimental information of the transition point is available, transition models like the $\gamma$-Re$_\theta$ model proposed by Langtry/Menter are a good approach for computations. A comparison to experimental data for the pressure coefficient shows a better agreement for the SST transition model than for the SST model (no transition model). In addition, first results for mesh-adaptive computations using both models are presented. The comparison to experiments will follow as soon as the experimental data are analyzed and published.

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REFERENCES


