Deliverable D3.2-36

[Excerpt relating to Periodic 2D Hills test case]

“Assessment of the RSM, URANS and hybrid models with respect to the different roadmaps including the industrial application challenges”

August 2012
# Table of Contents

1  Summary of excerpt.................................................................................................................. 3
2  Review of the stepping stones .............................................................................................. 3
3  ST01: 2D periodic hill (TUD) .............................................................................................. 3
   3.1  Test case description ....................................................................................................... 3
   3.1.1 Test case description ................................................................................................... 3
   3.1.2 Results and discussion ............................................................................................... 6
   3.1.3 Conclusions .................................................................................................................. 9
1 Summary of excerpt

This is an excerpt from the ATAAC project deliverable D3.2-36, whereby only the results relating to the Periodic 2D Hills test case are shown.

3 Review of the stepping stones

3.1 ST01: 2D periodic hill (TUD)

3.1.1 Test case description

The flow over a series (in a periodic sense) of smoothly contoured symmetric hills (Figure 3.1.1) has numerous interesting features: streamwise periodicity, separation from a continuous curved surface, reattachment, flow relaxation in the post-reattachment region, alternating adverse (flow deceleration) and favourable (flow acceleration) pressure gradient effects (globally along the flow but even across the same streamwise location - e.g. at the lee-ward side, Figure 3.1.1 right), streamline curvature effects, wall proximity effects, Reynolds-stress anisotropy, etc. The flow configurations characterized by Reynolds numbers based on the hill height and mean velocity at the hill crest of $\text{Re}_H=10600$ and $\text{Re}_H=37000$ were in focus of the computational activities in the framework of the ATAAC project.

Reference database

Detailed reference databases were made available by three highly-resolved Large-eddy Simulations (LES) - Mellen et al. (2000, LES-FMR), Temmerman and Leschziner (2001, LES-TL) (both result sets are analyzed in details in Froehlich et al., 2005) and Breuer (2005, LES-B). This configuration served as the test case of two ERCOFAC SIG15 Workshops (Jakirlic et al., 2002; Manceau, 2003). Different RANS models ranging from simple 1-equation models (e.g. Spalart-Allmaras) via the 2-equation linear and non-linear eddy-viscosity-based model schemes up to differential second-moment closure models were applied. A very extensive analysis of the model performances is provided by Leschziner (2002). The present report is drawn upon this document to some extent. According to Leschziner the computational data exhibit high quality and
reliability level. Accuracy and resolution checks were performed by analysing the spectra and two-point correlations at different location in the flow field, ratio of the representative grid spacing to the Kolmogorov scale, the contribution of the SGS (subgrid-scale) transport, etc. Recently, the above-mentioned computational database was enriched by a complementary experimental investigation performed by Rapp and Manhart (2007, EXP-RM; see also Rapp, 2008, Breuer et al., 2009 and Rapp and Manhart, 2011). In addition, the same flow geometry at two higher Reynolds numbers (Re = 19000 and 37000) was also measured. The higher flow Reynolds number represents also the ATAAC test case.

Contributors and turbulence models applied

Following ten groups contributed to the collaborative computation of this test case: CHA (Chalmers University Gothenburg), FOI (Swedish Defence Research Agency), ICL (Imperial College London), NTS (New Technologies and Services, St. Petersburg), TUD (Technical University Berlin), TUD (Technische Universität Darmstadt), UniMAN (University of Manchester), IMFT (Institut de Mécanique des Fluides de Toulouse), NUM (NUMECA - Numerical Mechanics Application International, Brussels) and ANS (ANSYS Germany). Four groups of cross-plotted results (corresponding to both Reynolds numbers respectively) are presented in accordance with the model formulations employed:

I. RANS, Eddy-viscosity model (EVM) group: 1-eq. model due to Spalart-Allmaras (SA), two-equation models (k-ε and k-ω SST) and 4-equation ERM-based models (ERM - Elliptic Relaxation Method), Figures 3.1.6 (see also SST results in Figures 3.1.7-right and 3.1.8-lower)

II. RANS, Reynolds stress models (RSM): Differential (DRSM) and Explicit Algebraic (EARM) model variants; Figures 3.1.7-3.1.8

III. DES (Detached-Eddy Simulation) related models: DES, Delayed DES (DDES) and Improved Delayed DES (iDDES), both in conjunction with SA and k-ω SST. Also the DES method denoted as kDES based on a 1-equation model solving the transport equation for the kinetic energy of turbulence (applied by FOI); Figures 3.1.9-3.1.10

IV. Unsteady simulations by PANS-k-ε (CHA; a seamless, so-called Partially-Averaged Navier-Stokes method in conjunction with a low Reynolds number k-ε model), SAS-SST (SAS: Scale-Adaptive Simulation; this is the original version developed and applied by ANSYS), SAS-DRSM (TUD; SAS methodology in conjunction with a differential low Reynolds number second-moment closure model), and two further seamless Hybrid RANS/LES models – one based on 0-Eq. RANS model (FOI denoted by HYB0; also a HYB0 modification accounting for the energy back-scatter – denoted by HYB0M – was tested) and another on the ERM-like phi-f model (UniMan; the results of the RANS calculations using the same model are displayed within the first group); Figures 3.1.11-3.1.12.

Mandatory mesh consisting of N_x,N_y,N_z=160x160x60 grid cells was designed by an appropriate coarsening of the 13 M cells fine grid made available by Breuer (2005), Figure 3.1.2. This grid was appropriate to be applied for computing the flows at both Reynolds numbers considered (Figure 3.1.2 illustrates the distribution of the non-dimensional distance y^+ of the wall-next numerical node along the lower wall extracted from the velocity fields obtained by the SAS-DRSM model; accordingly the grid is sufficiently fine also for the higher Reynolds number case; the NTS group refined further this grid for the Re = 37000 case consisting finally of 180 grid cells in the normal direction). The grid exhibits a fairly high level of orthogonality. It should be noted that not all computational groups used the proposed grid, see model and grid details in the tables specifying the participating groups in one of the previous reports, e.g. Deliverable D3.1-18.
Moreover, the ICL group applied the three-2dhill-segment geometry by specifying the LES data at the inlet and zero-gradient conditions at the outlet, Figure 3.1.4. The motivation for such an application was the elimination of a possibly negative influence of the streamwise periodicity on the model performances, because the errors in the solution in the inner flow domain can be fed back through the inlet plane, thus amplifying the departure of the “real” model solution, Leschziner (2002).

**Overall flow features**

Let us mention the basic features of the turbulent flow separation pertinent to the presently considered configuration before starting with the result presentation and corresponding discussion. Their qualitative behaviour is similar in both Reynolds number cases. The flow over a symmetric 2D hill is characterized by a nominally two-dimensional separation pattern and is steady in mean. However, the highly-unsteady shear layer that “separates” the main stream (through-flow) from the recirculation is dominated by the organized, large-scale coherent structures, influencing to a large extent the overall flow behaviour. It should be recalled that the conventional, time-averaged RANS methods, almost independent of the modelling level, unlike in some flows separated from the sharp-edged surfaces (with fixed separation point; e.g., backward-facing step geometries), perform fairly poor in the flows separated from continuous surfaces (it is also valid for flows...
separated from fences and ribs). The latter flow configurations exhibit a number of features typically associated with an unsteady flow separation (highly intermittent separation and reattachment regions). Here, the separation point oscillates over a larger portion of the wall. These oscillations are conveyed into the separated shear layer, whose spreading is much more intensive. Likewise, the mean dividing streamline is much more complex (stronger curvature and more intensive turbulence production). All these features can be neither qualitatively nor quantitatively reproduced by a RANS model. The outcome is a fairly poor reproduction of turbulence field (too low turbulence activity in the separated shear layer) and accordingly the mean velocity field having a much longer recirculation zone as a consequence.

3.1.2 Results and discussion

The present result presentation includes the friction factor development (indicating both separation and reattachments points) at the lower wall and the profiles of mean axial velocity, turbulent kinetic energy and streamwise and shear stress components at only one streamwise location (due to sake of brevity; see Deliverable D3.1-18 for more results): \( x/H = 2.0 \). The flow at this representative location is characterized as follows:

- \( x/H = 2.0 \) – this location crosses the recirculation zone and the curved detached shear layer featured by intensive mixing and an additional turbulence production due to the (local) streamline-curvature-induced strain rate (stabilizing curvature). Keeping in mind that this shear layer impinges at the reattachment region (shear layer – wall interaction: strong modification of the fluctuating pressure field causing intensive turbulent energy redistribution among stress components and consequently strong modulation of the Reynolds stress anisotropy) followed by the flow bifurcation it becomes clear how important is its correct capturing.

All these features should be correctly represented by a turbulence model. It should be recalled that the computational activity within the ATAAC project is primarily directed towards the employment of the turbulence models on the second-moment closure level (algebraic and differential Reynolds stress models).

The performances of the models will be discussed in parallel with respect to both Reynolds numbers. The profiles of all quantities exhibit qualitatively very similar shape in the Reynolds number range considered. Accordingly, the results analysis can be conducted jointly for both Reynolds numbers. The model performances concerning the Reynolds number dependence on the flow development differ primarily with respect to the turbulence enhancement in the separated shear layer and the consequent separation bubble shortening.

EVM RANS models

In spite of the latter objective, a reasonable number of contributions using different eddy-viscosity models were submitted. As the results obtained are comparable to those pertinent to the Reynolds stress models a selection of them will be displayed (Figures 3.1.7-right and 3.1.8-lower) and discussed without performing an in-depth analysis. The results obtained confirmed the findings of both SIG15 workshops discussed by Leschziner (2002):

- The basic flow topology was returned by all EVM models applied. However, apart of the overall velocity profile evolution obtained by the “simplest” linear k-\( \varepsilon \) model due to Launder and Sharma (employed by the ICL group), all other results agree poorly with the reference database.
- The k-\( \varepsilon \) SST model (employed by the NTS Group) predicts the separation region being too large compared to the reference database. Similar result was obtained by the 1-equation SA model. The turbulence level in the separated shear layer (\( x/H = 2 \)) is by far too low. It is well-known that the turbulence level in the separated shear layer controls the size of the recirculation zone. For example, a higher level of the shear stress implies an enhancement of the fluid entrainment into the shear layer - higher momentum transport - and consequently a shorter recirculation bubble. Contrary to that, a lower
turbulence level is consistent with a longer separation zone. Presently, the shear stress level is very low having an excessive separation as a consequence, the fact being in line with the previous statement. On the other hand, the linear EVM models (the Launder and Sharma model and two UniMAN models based on the Elliptic-relaxation Method) – employed in conjunction with the dissipation rate as the scale-supplying variable - predict much shorter recirculation zones despite the turbulence level being comparably low with the one obtained by the k-ω SST and SA models.

- Correct capturing of the wall-proximity effects is one of the important prerequisite for the successful computation of the present case. Accordingly, two ERM-based models were employed by the UniMAN group. These models account, to a certain extent, for the near-wall anisotropy through the inclusion of the normal-to-wall stress component into definition of the turbulent viscosity damping by approaching the solid wall. It led to a very good prediction of the reattachment length (despite delayed separation), see friction factor development obtained by the UniMAN-EVM-PhiBar model (dotted line in Figure 3.1.6-upper). Unfortunately, all other results do not indicate any important improvement compared to the basic models. It should be recalled that the ERM EVM models reduces to the standard linear k-ω model apart from the near-wall region. The specification of both EVM-ERM models version could be found in Billard et al. (2010).

RSM RANS models
The Reynolds stress models are inherently capable of capturing the majority of the time-averaged flow features and associated turbulence phenomena: streamline curvature effects, alternating deceleration and acceleration characterized by enhanced irrotational straining, pressure-scrambling process and Reynolds stress anisotropy. The 2-D hill case belongs to the category of the flows influenced locally by the streamline curvature, which in fact implies additional effects on the kinetic energy production rate through an extra strain rate \( (U^2/R)n_\sigma \), where \( U \) stands for the velocity component tangentially directed to the streamline - \( U_t \), \( n_\sigma = R \, dt/d\sigma \) denotes direction normal to \( t \) and \( R \) is the radius of the streamline curvature. The global effect in the present case is the attenuation of the turbulence production in accordance with the mean flow angular momentum increase with curvature radius (stabilizing curvature). Contrary to the EVM models being beyond the reach of these effects, the RSM models accounts correctly for the turbulence level reduction. However, it led presently to a further weakening of the already low turbulence level (Figure 3.1.8) and to a very long recirculation zone (see friction coefficient evolution and corresponding reattachment points in Figure 3.1.7). This is in particular the case when the differential Reynolds stress models coupled with the \( \varepsilon \)-equation. Better overall agreement (turbulence level enhancement) was obtained by RSM models solving the \( \omega \)-equation for the length-scale determination. This is especially the case when employing the Explicit Algebraic Reynolds Stress Models (note the FOI results). On the other hand, the same models (e.g., FOI-EARSM-HWJ and FOI-DRSM) show less sensitivity to the Reynolds number increase concerning the recirculation zone shortening. Even opposite outcome – longer recirculation zone – was obtained.

Important improvement was obtained after introducing the SAS term into the JH DRSM model (being already used in the framework of SAS-DRSM model; this term has the same functional dependency as the original formulation by Menter et al. – proposed in conjunction with the k-ω SST model – the appropriately transformed model coefficients were slightly adjusted to the background RSM model). Let us recall that the introduction of the SAS-term in the instability sensitive second-moment closure version – unsteady flow simulation (denoted by SAS-DRSM, see next section) – contributed strongly to the turbulence enhancement (originating from the resolved motion) in the region around the separation point. The positive production of the \( \omega \)- i.e. \( \varepsilon \)-variable affected by the SAS term led to the modelled turbulence suppression allowing development of the resolved motion. In a pure RANS model applied in the steady computational mode an opposite action is necessary: the scale-supplying variable has to be appropriately reduced leading consequently to the increase of the (modelled) turbulence. Accordingly, the same SAS-term was introduced into the \( \omega_\alpha \)-equation but with the negative sign. The evaluation of the term has shown that it was active only in the separation region, Figure 3.1.5. The inclusion of this term led to appropriate increase of the turbulence level.
activity in the region aligned with the mean dividing streamline resulting in the improved capturing of the velocity field and recirculation zone shortening (see Figures 3.1.7 and 3.1.8).

Figure 3.1.5: Magnitude of the “negative” \( P_{\text{SAS}} \) term in the 2D hill flow field introduced into the JH RSM model

It should also be noted that the application of all RANS models resulted in the steady solution. The so-called “temporal under-relaxation” was applied sometimes to strengthen the diagonal dominance of the coefficient matrix, implying that actually unsteady computations were performed. However, such an unsteady calculation ended up, as expected, in a steady solution.

Unsteady flow simulations: DES-, Seamless hybrid RANS/LES (PANS, HYB0 and HRLV2F) and SAS-related models

Here, different, LES-related unsteady simulations using appropriate models were performed. The simulations were performed employing four DES-relevant schemes (DES, Delayed DES – DDES, Improved DDES – IDDES and kDES, S.-H. Peng), three seamless hybrid RANS/LES / instability-sensitive Unsteady RANS model formulations - the PANS-k-\( \varepsilon \) formulation of Ma et al. (2010; CHA), a hybrid method based on an appropriate length scale switch enabling smooth transition between the RANS and LES sub-regions (S.-H. Peng, 2005, denoted by HYB0 relying on a 0-eq., mixing-length-type model), a hybrid model based on the \( v_2f \)-type model (Uribe et al., 2010; denoted by HRLV2F) - and two novel instability-sensitive URANS models, denoted by SAS-SST (original SAS-based k-\( \omega \) SST model proposed by Menter et al., 2010, ANS) and SAS-DRSM, of Maduta and Jakirlic (2010, TUD). The common feature of all these models is an appropriate modification of the scale-determining equation providing a dissipation rate level which suppresses the turbulence intensity towards the subgrid (i.e. sub-scale/subfilter) level in the regions where large coherent structures with a broader spectrum dominate the flow, allowing in such a way evolution of structural features of the associated turbulence. Whereas an appropriate dissipation level enhancement in the PANS method is achieved by reducing selectively (e.g. in the separated shear layer region) the destruction term in the model dissipation equation (i.e. its coefficient; the standard value \( C_{\varepsilon} = 1:92 \), prevailing in the near-wall region, decreases towards the value around 1.4 in the separated shear layer of the periodic 2D hill flow), an additional production term was introduced into the \( \omega \) equation in the SAS framework. This term is modelled in terms of the von Karman length scale comprising the second derivative of the velocity field, which is capable of capturing the vortex size variability, Menter et al. (2003, 2010). Whereas FOI employed the basic DES-SA model formulation, the NTS employed DDES and IDDES in conjunction with both k-\( \omega \) SST and SA models using mandatory grid and TUB performed three simulations by the IDDES-SA model combination, but varying the grid size, grid structure (grid refined appropriately towards the walls and equidistant grid) and temporal resolution. Apart of the results obtained by the TUB-IDDES-SA3, employing more than 20 times coarser time step compared to the TUB-IDDES-SA1 and TUB-IDDES-SA2 simulations – leading to a higher turbulence level, all other results (apart of some slight differences) agree very well with the reference database in all characteristic regions of the flow. The SAS-SST and SAS-DRSM models exhibit high level of agreement with respect to all analyzed flow features (evolution of mean flow and turbulence quantities, friction factor development, size and shape of the recirculation zone) for both
Reynolds numbers. The results obtained by the kDES model as well as two seamless hybrid schemes – HYB0 and HRLV2F – show important improvement compared to the background turbulence models they are based upon. However, some further refinement of the kDES and HYB0 schemes is necessary in order to get consistently good agreement in the entire flow domain. It is especially related to the specific intensification of the turbulence production in the region corresponding to the flow re-acceleration – not shown here. On the other hand the mean velocity field exhibits high level agreement with the reference results indicating that the afore-mentioned departure could also be an outcome of the evaluating (averaging) procedure. These circumstances should be clarified.

3.1.3 Conclusions

It can be concluded without going into great details that the correct capturing of the present 2d-hill flow configuration is beyond the reach of the conventional, inherently steady RANS closures, almost independent of the modelling level. Some models perform better with respect to the global development of the mean velocity profile (e.g. the EARSM model coupled with Menter’s ω-equation – also, the turbulence level obtained by this model at some positions agrees reasonably with the reference data; however, it is highly nonsatisfying that the “best RANS velocity field” is obtained by a model with a poorest physical background – a linear k-ε model of Launder and Sharma). All other RANS results exhibit very poor agreement: skin friction development, shape, form and size of the separation bubble, profile shapes of turbulent quantities - qualitatively and quantitatively, including also their behaviour in the immediate wall vicinity, etc. Work on the possible improvement should include term-by-term modelling of the turbulent interactions (stress redistribution, turbulent diffusion, stress dissipation,...) in the budgets of the corresponding transport equations (governing the Reynolds stress components but also the scale-determining variables).

The inclusion of the negative SAS term – promoting the turbulence activity enhancement in the separated shear layer – fulfilled the expectations: the resulting mean flow variables (mean velocities and Reynolds stress components) displayed a very good agreement with respect to the reattachment length, profile shapes of both velocity and turbulence intensities – e.g. velocity overshoot due to acceleration on the hill crest, turbulence level in the separated shear layer - in the entire flow domain. Obviously that the structure of the model was “correct enough”, the only weakness was inappropriate dissipation level. The inclusion of this term led also to a significant improvement in the flow in a 3D diffuser (stepping stone ST04). The effect of the negative SAS term was also checked in some “stable” flows, like e.g. in a channel flow and in a mixing layer. Here, there were no differences between the results obtained with the RANS-RSM-P_{SAS} and RANS-RSM models.

On the other hand, the results of the unsteady flow simulations, almost independently of the method used, follow closely the reference data in all characteristic flow regions: separation region, recirculation zone, reattachment, recovery region, windward hill region characterized by high re-acceleration of the flow and near-wall regions.
Figure 3.1.6: $Re_H=10600$, Eddy-viscosity model group – cross-plot comparison of the friction factor development (upper) and axial velocity, turbulent kinetic energy and shear stress profiles at the location $x/H=2.0$

Figure 3.1.7: Friction factor development obtained by the Reynolds stress (and SST) model group - $Re_H=10600$ (left) and $Re_H=37000$ (right)
Figure 3.1.8: Reynolds stress (and SST) model group – cross-plot comparison of axial velocity, turbulent kinetic energy, streamwise and shear stress profiles at the location x/H=2.0; ReH=10600 (upper raw), ReH=37000 (lower raw)

Figure 3.1.9: Friction factor development obtained by the DES-related model group - ReH=10600 (left) and ReH=37000 (right)
Figure 3.1.10: DES-related model group – cross-plot comparison of axial velocity, turbulent kinetic energy, streamwise and shear stress profiles at the location $x/H=2.0$; $Re_H=10600$ (upper raw), $Re_H=37000$ (lower raw).

Figure 3.1.11: Friction factor development obtained by the Seamless hybrid RANS/LES (PANS, HYB0 and HRLV2F) and SAS-related model group - $Re_H=10600$ (left) and $Re_H=37000$ (right).
Figure 3.1.12: Seamless hybrid RANS/LES- (PANS, HYB0 and HRLV2F) and SAS-related model group – cross-plot comparison of axial velocity, turbulent kinetic energy, streamwise and shear stress profiles at the location $x/H=2.0; \text{Re}_H=10600$ (upper raw), $\text{Re}_H=37000$ (lower raw).