

Improved RANS Computations of Flow over the 25°-Slant-Angle Ahmed Body

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ABSTRACT

The present work is concerned with the Steady RANS (*Reynolds-Averaged Navier-Stokes*) computations of inherently unsteady separating flow configurations. The focus is on the flow past the well-known Ahmed body ([Ahmed et al., 1984](#)), the rear slant angle of which corresponds to 25°. Unlike all (near-wall) RANS models, independent of modelling level, predicting a massive flow detachment occupying the entire slanted region, the present RANS model reproduces correctly the mean flow topology characterized by a thin separation bubble reattaching already at the slanted surface. It is achieved by intensifying appropriately the turbulence activity at the region of boundary layer separation by introducing an correspondingly formulated sink term (P_{AU}) into the relevant scale-supplying equation. The latter negative production term is modelled in terms of the second derivative of the mean velocity field (ΔU), as proposed originally by [Rotta \(1972\)](#). The underlying turbulence model, the present work is primarily focussed on, represents a differential near-wall Reynoldsstress model (RSM), but the effects of the additional source term is also checked in conjunction with the widely used $k-\omega$ -SST eddy-viscosity model. The numerical robustness of the RSM model formulation is enhanced by appropriately weighting the explicit treatment of the divergence of the Reynolds stress tensor in the momentum equation with its implicit treatment by utilizing the Boussinesq correlation; only a small portion of the implicit part – up to 20% - is needed to substantially stabilize the computation. The predictive capabilities of the extended RSM version, along with the performance of its baseline version, are in addition illustrated by computing some generic test cases subjected to separation from continuous and sharp-edged surfaces.

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INTRODUCTION

The Ahmed body ([Ahmed et al., 1984](#)) is certainly one of the most frequently computed benchmarks for studying car aerodynamics. The analysis of the aerodynamic behavior of such a simplified car model relates primarily to the flow separation at the rear slant and the subsequent wake region. Two most interesting Ahmed body configurations are those characterized by the slant angles 25° and 35° degrees. Both configurations served as test cases at the occasion of two computational workshops organized by the ERCOFTAC-SIG15 interest group on refined turbulence modelling ([Jakirlic et al., 2002](#), and [Manceau et al., 2003](#)). The main difference between these two cases is that the flow detaches and reattaches at the slanted surface for the lower slant angle value, while for the 35°-slant-angle the flow detaches and forms a fairly large single recirculation region at the entire slanted surface, turning into a wake region behind the body, [Figures 1](#).

Whereas the underlying mean flow structure of the 35-slantangle case can be correctly returned by applying turbulence models in the (steady or conventional unsteady) RANS (Reynolds-Averaged Navier Stokes) framework, the RANS computations of the 25°-slant-angle configuration result in a completely wrong flow topology, resembling

actually that pertinent to the 35-slant-angle case (see e.g., [Guilmineau et al., 2008, 2016](#)). The reason for such an incorrect outcome lies primarily in an inadequately low turbulence activity within the separated shear layer, implying a low intensity momentum exchange between the main stream and separated region, resulting typically in a correspondingly longer recirculation zone. This is the expected consequence of the physical rationale of the RANS method, which is, as such, not capable of capturing the large-scale eddy structures with a broader spectrum and the bulk flow unsteadiness – as encountered in the flows involving separation; see e.g. [Wang et al. \(2003\)](#), [Fröhlich et al. \(2005\)](#), [Leschziner \(2006\)](#) and [Jakirlic and Maduta \(2015\)](#) for reference. Correct capturing of the spectral dynamics, typical for the separated shear layer region, is possible only by applying an LES (Large-Eddy Simulation; see e.g., [Krajnovic and Davidson, 2005](#)) or relevant eddy-resolving model schemes such as DDES (Delayed Detached Eddy-Simulations; see e.g., [Ashton and Revell, 2015](#)) and PANS (Partially-Averaged Navier-Stokes; see e.g. [Mirzaei et al., 2015](#)). However, it implies an unsteady, time-accurate flow simulation in conjunction with an appropriately fine grid resolution, which is not easily affordable in the case of industrially-oriented computational activities. However, from the point of view of a practical application, it would be highly beneficial if a correctly predicted time-averaged turbulence field and consequently the mean

velocity field can be achieved within the Steady RANS framework. Statistical turbulence models employed within the RANS framework are still the preferred choice for computations of the largest majority of industrially relevant flow configurations. In the present paper a correspondingly upgraded turbulence model is presented which makes it possible to obtain correct results of the 25-slant-angle case even when applying a steady RANS method.

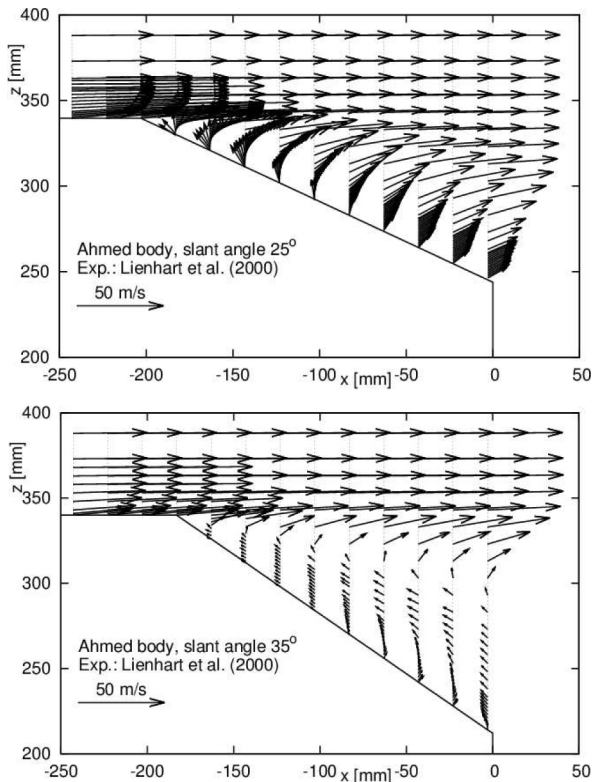


Figure 1. Ahmed body: mean velocity vector plots obtained experimentally for both characteristic slant angles 25° (upper) and 35° (lower)

Presently, we revisited the Rotta's two-point correlation equation, concentrating in particular on an additional production term containing mean velocity gradients. If the term in question is evaluated in its original exact form around the separation point (this is actually the point where improvement concerning the turbulence level enhancement is needed), it represents a sink term (negative production) in the lengthscale-supplying equation. The sink term magnitude increases within the narrow region around the point of separation and, consequently, within the separated shear layer due to the increased curvature of the velocity profile. This action is much more pronounced in the flows separating from continuous curved surfaces, but also from fences and ribs, compared to separated flows in suddenly expanded pipes and channels (resembling the backward-facing step configurations). The outcome is an appropriate reduction of the dissipation rate level relative to the kinetic energy of turbulence. It implies finally an enhanced turbulence activity resulting in an intensified momentum transport between the separated shear

layer and its surrounding. Consequently, appropriate shortening of the recirculation zone takes place. Following closely the Rotta's proposal, further improvement is achieved concerning a somewhat simplified structure of this additional term and its region of influence.

Even though computer power has increased, the eddyviscosity RANS models are still the most widely used model group for the flow applications of engineering relevance. This is mostly due to a high numerical robustness compared to the Reynolds-stress models (RSM). Accordingly, a relevant algorithmic modification concerning the enhanced numerical stability of Reynolds-stress models is proposed. By introducing a small 'fraction' of the Reynolds-stress tensor defined via the linear Boussinesq relationship into the momentum equation, and by adequately modifying the explicit treatment of the Reynolds stress divergence, the model becomes highly applicable for computational setups utilizing coarse and awkward meshes as well as poor initial flow fields; it furthermore enables stable use of higher-order numerical schemes.

Prior to the Ahmed body computations the feasibility of the presently proposed physical and numerical upgrades of the Reynolds stress model is demonstrated by computing some relevant separated flow configurations, including the backwardfacing step flow, the flow over a 2D fence as well as the flow over a periodic arrangement of smoothly contoured 2D hills. In addition the Ahmed body case is computed using the wellknown $k-\omega$ -SST eddy-viscosity model (Menter, 1994) extended by the negative ω -production term P_{AU} .

COMPUTATIONAL MODEL

The time-averaged continuity ($\partial U/\partial x_i = 0$) and momentum equations governing a three-dimensional incompressible flow read:

$$\frac{\partial}{\partial x_j} (U_i U_j) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i u_j} \right) \quad (1)$$

The key to enhancing the stability concerning the coupling of the velocity (U_i) and Reynolds-stress ($\overline{u_i u_j}$) fields is an appropriately blended Reynolds stress tensor entering the divergence operator on the right-hand-side of the momentum equation (Eq. 1). A similar practice has been proposed by Basara and Jakirlic (2003), where the velocity-stress coupling has been in its entirety accomplished by applying the turbulence viscosity concept with the kinetic energy of turbulence k and its dissipation rate ε originating from the background Reynolds stress model ($\nu_i \propto k^2 \varepsilon$). Instead, the presently applied procedure combines appropriately the Reynolds stress tensor originating from the differential RSM model and Boussinesq correlation. Such a "hybridized" Reynolds stress tensor reads:

$$\overline{u_i u_j} = 0.8 \overline{u_i u_j}_{\text{RSM}} + 0.2 \overline{u_i u_j}_{\text{Boussinesq}} \quad (2)$$

Here, the Reynolds-stress tensor $\overline{u_i u_j}$ RSM is obtained by directly solving the Reynolds stress transport equations and the tensor $\overline{u_i u_j}$ Boussinesq follows from the Boussinesq relationship pertinent to a linear eddy-viscosity model.

$$\overline{u_i u_j} \text{ Boussinesq} = -v_t \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij} \quad (3)$$

The turbulent viscosity v_t is modeled in terms of the Reynolds stress anisotropy parameter A , the specific turbulence dissipation rate $\omega = \varepsilon / k$ and the turbulent kinetic energy k (computed directly from the Reynolds stress tensor: $k = 0.5 \overline{u_i u_i}$); the viscosity effects are introduced via the Kolmogorov length scale $\eta_k = (v^3 / (k\omega))^{1/4}$; see [Jakirlic and Maduta \(2015\)](#). It should be mentioned, that the blending factor value can vary depending on underlying Reynolds-stress models. In general, it has been found that a portion larger than (20-25)% originating from the Boussinesq relation is not necessary. More important is the fact that this weighting procedure only marginally affects the quality of the Reynolds stress components prediction in terms of possible weakening of the Reynolds-stress anisotropy and its influence on the mean velocity field, see [Figures 2](#).

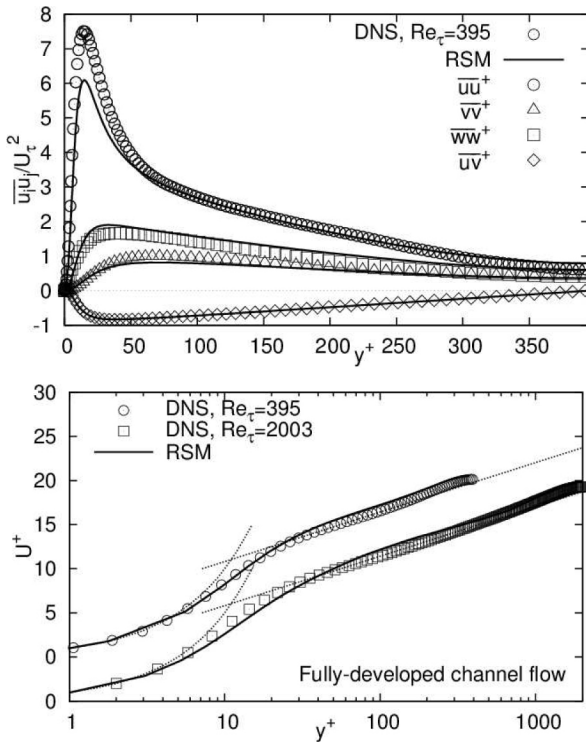


Figure 2. Reynolds stress component and mean velocity profiles in a fully-developed channel flow at $Re_m = 13750$ ($Re_\tau = 395$) and $Re_m = 86000$ ($Re_\tau = 2003$)

The negative production term, denoted by P_{AU} throughout the work, acting towards the turbulence activity intensification in separated shear layers can be straightforwardly added to the right hand side of the scale-supplying equation of a Reynolds stress model of interest. Presently, the Reynolds-stress model based on the so-called homogeneous dissipation ($\varepsilon^h = \varepsilon - 0.5 \partial(v \partial k / \partial x_j) / \partial x_j$) described in [Jakirlic and Maduta \(2015\)](#) is used. The final form of the transport equation for the specific dissipation rate $\omega^h (= \varepsilon^h / k)$ reads:

$$\begin{aligned} \frac{D\omega^h}{Dt} = & -C_{\omega,1} \overline{u_i u_j} \frac{\partial U_i}{\partial x_j} \frac{\omega^h}{k} - C_{\omega,2} \omega^h \omega^h \\ & + \frac{\partial}{\partial x_k} \left[\left(\frac{1}{2} v + \frac{v_t}{\sigma_\omega} \right) \frac{\partial \omega^h}{\partial x_k} \right] \\ & + \frac{2}{k} \left(C_{cr,1} \frac{1}{2} v + C_{cr,2} \frac{v_t}{\sigma_\omega} \right) \frac{\partial \omega^h}{\partial x_k} \frac{\partial k}{\partial x_k} \\ & + 2v \frac{v_t}{k} \frac{\partial^2 U_i}{\partial x_j \partial x_l} \frac{\partial^2 U_i}{\partial x_j \partial x_l} + S_l - P_{AU} \end{aligned} \quad (4)$$

with the sink term P_{AU} modelled in terms of the intensity of the second derivative of the mean velocity field (cf. [Rotta, 1972](#)):

$$P_{AU} = f \left(\left| \frac{\partial^2 U_i}{\partial x_j^2} \right| \sqrt{k} \right) \quad (5)$$

Furthermore a generalized sensitivity parameter

$$B = L_S \left[\left| \frac{\partial^2 U_i}{\partial x_j^2} \right| / \left| \frac{\partial U_k}{\partial x_l} + \frac{\partial U_l}{\partial x_k} \right| \right] \quad (6)$$

is introduced, switching off the additional production term for $B < 5$, which would mean that the velocity profile curvature is not strongly pronounced compared to its gradient. $L_S (= k^{1/2} / \omega^h)$ represents the turbulent length scale. This formulation is adopted from the SAS (Scale-adaptive Simulation) methodology ($B \sim L_S / L_{vk}$; with the von Karman length scale L_{vk} , representing the ratio of the first to the second derivative of the velocity field), [Menter and Egorov \(2010\)](#); see also [Jakirlic and Maduta \(2015\)](#). The sink term P_{AU} is active only in the narrow area at the separation region and early portion of the separated shear layer development. In the remainder of the flow domain its effect vanishes.

In the case a CFD (Computational Fluid Dynamics) code using turbulence models which are based on a transport equation for ε or any other length scale determining equation than $\omega (= k^{-1} \varepsilon)$, the previously introduced negative production term can be easily converted by applying derivation rules. This reads for instance for an ε -based transport equation:

$$\frac{D\varepsilon^h}{Dt} - P_{AU}k = \frac{D(\omega^h k)}{Dt} - P_{AU}k = \frac{D\omega^h}{Dt} k + \frac{Dk}{Dt} \omega^h - P_{AU}k \quad (5)$$

By explicitly computing $\omega^h = \varepsilon^h/k$ before solving the ε^h transport equation, derivatives of ω^h can be directly included into the source terms without transforming them into complex combinations of k and ε^h derivatives, as it would be the case with some parts of the P_{AU} term. The relevant length-scale determining equation (Equations 4 or 5) is solved in conjunction with the following model equation governing the dynamics of the Reynolds stress tensor (written in symbolic notation):

$$\frac{D\overline{u_i u_j}}{Dt} = \frac{\partial}{\partial x_k} \left[\left(\frac{1}{2} \nu + \frac{\nu_t}{\sigma_{\overline{u_i u_j}}} \right) \frac{\partial \overline{u_i u_j}}{\partial x_k} \right] + P_{ij} - \varepsilon_{ij}^h + \Phi_{ij} \quad (6)$$

Interested readers are referred to [Jakirlic and Maduta \(2015\)](#) for the complete model specification.

The wall boundary condition for ω^h based on the linear behavior of the Taylor microscale λ (see [Jakirlic et al., 2010](#) and [Jakirlic and Maduta, 2015](#)) expressed asymptotically in terms of the wall distance can be sometimes too stiff. As a remedy, λ can be transformed to a proper boundary condition for ε^h defined as function of the wall distance and k , offering more flexibility. For instance, the ε^h -based model is presently used for the Ahmed body computations.

All simulations dealing with the boundary layer separation have been performed by using the scale-supplying equation including the so-called length-scale correction term S_ν , Eq. (4). This is introduced aiming at avoiding the mean streamline back-bending at the reattachment point; this anomalous behavior is related to the Reynolds stress model group in general. Interested readers are referred to [Hanjalic and Jakirlic \(1998\)](#) and [Jakirlic and Maduta \(2015\)](#) for more details as well as for the model term specification.

Numerical Method

The original Reynolds-stress model formulation (RSM) and its modified version (RSM- P_{AU}) are implemented into the open source toolbox OpenFOAM® (www.openfoam.com), utilizing a cell-center-based finite volume method on an unstructured numerical grid and employing the solution procedure based on the well-known SIMPLE method for coupling the pressure and velocity fields. All simulations are performed by using the 2nd order accurate Central-Differencing Scheme (CDS) for the diffusion transport in the entire computational model. The convective term in the momentum equation is discretized by a blended upwind-CDS scheme implemented in a deferred correction manner with up to 95% CDS. The upwind differencing scheme was applied for the convective transport discretization in equations governing the turbulent quantities.

RESULTS AND DISCUSSION

Selected results illustrating the predictive performances of the present models (denoted by RSM- P_{AU} throughout the work; the denotation RSM is used for the baseline model) in computing flow configurations featured by boundary layer separation are shown in

Figures 3–20: separation from smoothly contoured hills (detailed reference databases were made available by highly-resolved Large Eddy Simulations by [Froehlich et al., 2005](#) and [Breuer, 2005](#)), flow past a wall-mounted fence followed by a highly-curved separated shear layer reattaching at a longer distance (experimental data were provided by [Larsen et al., 1999](#)), backward facing step flow (experiment by [Jovic and Driver, 1995](#); DNS by [Le et al., 1997](#)) and finally the flow past the 25°-slant-angle Ahmed body (experimental reference by [Lienhart and Becker, 2003](#)).

Figures 3 and 4 illustrate the pressure contours and associated streamline pattern as well as the profile development of kinetic energy of turbulence, Reynolds shear stress and axial velocity components in the flow over a periodical arrangement of two-dimensional hills (with hill height H) at a hill-height-based Reynolds number $Re_H = 10600$.

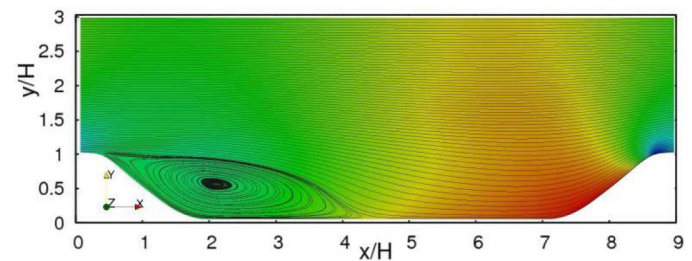


Figure 3. Pressure contours and mean streamlines in the 2D hill flow at $Re_H = 10600$ obtained by the RSM- P_{AU} model

The 2D solution domain length (9d) corresponds to the distance spanning two consecutive hill crests, Fig. 3. The upper flat channel wall is positioned at $3.03 H$; the Reynolds number corresponds to the channel height is 21518. The computational campaign has been performed by applying three different grid resolutions containing of 320x320 (grid1), 160x160 (grid 2) and 80x100 (grid 3) cells. In all cases, the grid cells are squeezed towards the walls, providing a dimensionless distance of the wall-next computational node corresponding to $y^+ \leq 0.8$. The mean flow and turbulence results displayed in Figures 3 are virtually independent of the grid resolution. The basic, non-modified RSM results in a remarkably low level of the turbulent shear stress component and the kinetic energy of turbulence and consequently in a too large recirculation zone with reattachment point (RP) positioned at $(x/H)_{RP} = 6.3$ (we recall the LES results by [Breuer et al.](#) corresponding to $(x/H)_{RP} = 4.69$). It should be recalled that the lower turbulence intensity pertinent to the separated shear layer region is not the outcome of this specific model only; it is typical of all RANS models independent of modelling level; see e.g. the results of two ERCOFTAC workshops on refined turbulence modelling, [Jakirlic et al. \(2002\)](#) and [Manceau \(2003\)](#). The inclusion of the P_{AU} term causes appropriate increase of the turbulence activity in the region aligned with the mean dividing streamline resulting in the significantly improved prediction of the velocity field and associated recirculation zone shortening down to $(x/H)_{RP} = 4.6$, agreeing well with the reference LES solution.