Mitteilung

Fachgruppe: Turbulenz und Transition

Modification of the SSG/LRR-ω Model for Separated Shear Flows Using Boundary-Layer Sensors

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One paradigm for transport-equation-based statistical turbulence modeling in computational fluid dynamics (CFD) is the restriction to local flow quantities. All terms in the turbulence model equations should depend only on the local solution of mean-flow gradients and turbulence quantities (as well as their gradients). The paradigm of locality is applied not only to RANS turbulence modeling, but also to hybrid RANS/LES modeling (in particular for the design of blending functions to switch from the attached-boundary-layer-flow RANS region to the outer LES region).
An extension of the paradigm was initially proposed in [5]. For the unstructured CFD solver TAU, an additional data structure was developed which provides, for each surface point, the field points on a wall-normal line. Another data structure allows to map, for each surface point, the values of surface quantities to all field points on this wall-normal line. This enables the evaluation of the boundary layer thickness δ_{99}, integral boundary layer parameters such as displacement thickness δ^*, momentum thickness θ and the shape factor $H_{12}=\delta^*/\theta$, and pressure gradient parameters in the inner scaling $\Delta p_s^+=\nu/(\rho u_\tau^3)(dP/ds)$ and in Rotta-Clauser scaling $\beta_{RC}=\delta^*/(\rho u_\tau^2)(dP/ds)$. Here, u_τ denotes the friction velocity and ν is the kinematic viscosity.
The boundary layer quantities can be used to define blending functions for boundary layers, which remedy shortcomings of existing blending functions [5]. Such blending functions have a value of one inside the boundary layer and decay to zero in the outer flow. There are wide-spread blending functions based on the paradigm of locality, e.g., the function F_1 used in the SST model and the function f_d used in the SA model. However, the boundary layer thickness predicted by f_d was found to be too small in turbulent boundary-layer flows in a strong adverse pressure gradient [5]. Moreover, the functions F_1 and f_d often yield unwanted behaviour near stagnation points and for the wake flow regions downstream of stagnation points and upstream-located parts of multi-element airfoils and wings.
The modification of RANS turbulence models for separated shear layer is another application of such boundary layer sensors, which is presented in this work. As described in [1], ''one of the fundamental dilemmas in turbulence modeling'' is that ''model constants are not physical constants''. The constant α_ω of the production term of the ω-equation used in the SSG/LRR-ω model controls the growth rate of shear layers. The value used in the outer layer is 0.44, which is suitable for attached boundary layers. However, a lower value of 0.30 is more suitable for free-shear slows like the mixing layer. (An alternative view for an RSM was given by Eisfeld in [9], who found that the Reynolds stress anisotropy a_{12} changes from a value around 0.15 in attached boundary layers to 0.165 in mixing layers, which can be accounted for by a flow-specific adjustment of the pressure-strain correlation model). In the present work, a sensor function is proposed which allows to change the value of α_ω between attached boundary layers and free shear layers (see Fig. 1 (left)). The modification yields a significant improvement for the reattachment of the flow over the NASA wall-mounted hump [8] (see Fig. 1 (middle)).
Another flow phenomenon for which the SSG/LRR-ω model was found to require modification is wake flow in a significant APG. Two versions to modify the dissipation rate locally in the wake subjected to APG are used. The first modification is the so-called $S_{\omega 4}$ term by Probst & Radespiel, based on previous works by Hanjalic & Leschziner. The second modification is extending an APG modification for turbulent boundary-layer flows based on the half-power law [6]. Both modifications increase the dissipation in the wake at APG [7], hence reduce the Reynolds stresses and increase the model tendency for flow reversal in the wake, i.e. to predict a region of negative values of the centerline velocity U_{CL} (see figure 1 (right)). The use of the

modification for wake flow in an APG also requires a sensor to identify the wake flow region and to characterise the strength of the pressure gradient in the free shear flow.

Besides the presentation of modifications for separated shear flows and reattachment, the potential of boundary layer sensors for the improvement of RANS turbulence models is outlined. The boundary layer sensors also allow to identify different sub-regions of attached boundary layers. RANS models are based on a generalized law of the wall [4], which does not account for Reynolds number effects. Re-effects have been observed for zero-pressure gradient boundary layer flows, e.g., the beginning of the log law in the mean velocity is near $y^+=2.6(\delta^+)^{1/2}$ [2], where δ^+ is the Reynolds number based on the friction velocity. The influence on the predictive accuracy for zero-pressure gradients has not been studied. However, Re-effects were found to be important in adverse pressure gradients [3,6].

The boundary layer sensors are also useful for the assessment of the reliability of aerodynamic predictions. The prediction of the separation point using present RANS models is known to be not fully reliable. As a remedy, empirical criteria to characterise the state of the boundary layer are useful. This could be threshold values for the shape factor (H_{12}>2.5-2.6) and for the pressure gradient β_{RC}, above which the reliability of RANS models decreases due to not yet understood effects of strong adverse pressure gradients. Such threshold values could also be trained from large databases (and refined for special airfoil geometries and flow conditions).

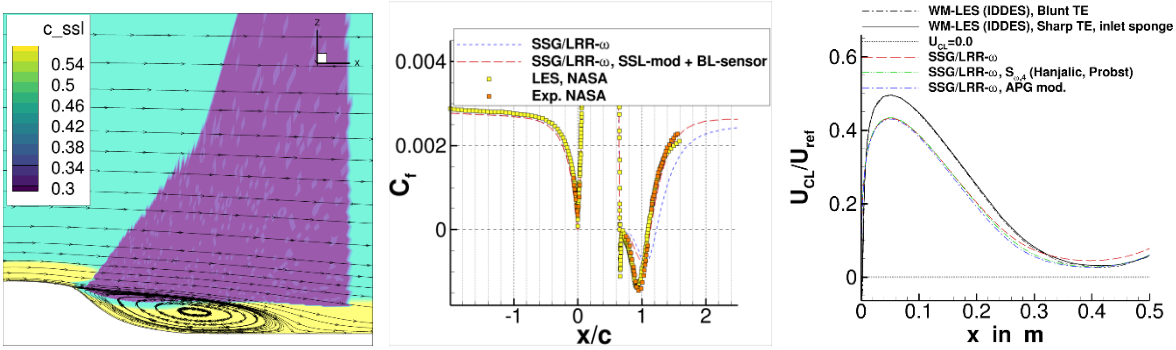

Figure 1: Flow-adapted adjustment of the coefficient α_ω (denoted by c_ssl in the legend) of the SSG/LRR-ω model in the separated shear layer (SSL) (left). Prediction for skin-friction coefficient and flow reattachment for the NASA hump flow (middle). Turbulent wake flow at adverse pressure gradient using two modifications of the SSG/LRR-ω model in the wake for the improved prediction of the tendency for flow reversal of the centerline velocity U_{CL} (right) compared to the reference LES [7].

Finally, the flow sensors for attached flow and separation are well suited to be used for turbulence model augmentation terms obtained by machine-learning methods, e.g., the field-inversion/ machine learning (FI/ML) and the gene-expression programming (GEP) approach.

Acknowledgement: This work was funded by the DLR internal project ADaMant and by DFG under the project ''Complex Wake Flows'' (grant no. KN 888/3-2).

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