Mitteilung

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Validation and Analysis of the Reynolds-Stress Model SSG/LRR-ω for Wall-Bounded Flows with Mean-Streamline Curvature

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The present work is dedicated to validation and analysis of the Reynolds-stress model (RSM) SSG/LRR-ω for turbulent boundary layer flows along walls with concave and convex surface curvature. During the last decade, only a few new test cases of wall-bounded flow with curvature have been studied, most of them using DNS/LES. This is in contrast to the importance of surface curvature effects on the lower side of modern transonic airfoils. Moreover, this is in contrast to the large number of experimental and numerical studies that have been performed for the improvement and validation of turbulence models (RANS, hybrid RANS/LES, wall-modeled LES) for turbulent boundary layer flows subjected to pressure gradient, separation and reattachment.

RANS turbulence modeling for flows with significant streamline curvature was mainly pursued for models based on the Boussinesq hypothesis. Linear eddy-viscosity models cannot capture the effect that convex curvature reduces turbulence, whereas concave curvature amplifies turbulence. Empirical modifications have been proposed to alter the growth rate of turbulence, e.g., for the Spalart-Allmaras model (SA) and for the SST model (see [5,6]). For a RSM, which remedies the need for the Boussinesq hypothesis, the need for curvature correction(s) is still open. The production tensor of the Reynolds stresses is exact and able to capture the effects of mean-streamline curvature. However, there are other tensorial terms involving modelling, viz., (i) the turbulent transport of the Reynolds stresses due to velocity and pressure fluctuations, (ii) the pressure-strain-correlation (i.e., redistribution), and (iii) dissipation. The different model contributions of the SSG/LRR-ω model are studied. Regarding (i), different models for the turbulent transport, the generalised gradient diffusion hypothesis (GGDH) and the simple gradient diffusion hypothesis (SGDH) are considered. Analytical investigations highlight the importance of the Reynolds stress anisotropy to capture curvature effects [5]. Moreover, a sensitisation to curvature using the idea by Zeman [8] is investigated. Concerning (ii), the different redistribution models LRR, SSG, and blended SSG/LRR model are considered.

The present work reviews existing test-cases from the 1970s and 1980s and gives an assessment regarding their suitability for the validation of curvature effects. The selected cases are the flows by Gillis & Johnston (1983) and by So & Mellor (1975). Moreover, the case by Monson & Seegmiller (1992) is used, as this case was used for the design of the rotation-correction for the Spalart-Allmaras model (SA-RC) by Shur et al. (2000).

For the selected cases, a computational set-up (geometry/boundary of the computational domain, boundary conditions) is developed based on the information given in the corresponding publications. For this purpose, the position of the inflow boundary is determined to match the boundary layer properties (boundary layer thickness, shape factor, skin-friction coefficient C_f) at different reference positions upstream of the curvature region. Moreover, the shape of the wall opposite to the curved wall of interest is designed to match the streamwise distribution of the pressure coefficient C_p measured in the experiment. For this, a gradient-based optimisation method was developed and applied. The re-design of the opposite wall was necessary to account for three-dimensional effects in the wind tunnel experiment (e.g., corner vortices, boundary layers on the spanwise wind-tunnel side walls) and to account for local effects due to special devices used in the wind-tunnel like suction boxes, which cannot be described by an exact boundary condition in a CFD solver.

The results for the convex-curvature turbulent boundary-layer flow by [1] are shown in figure 1. The model ingredients of the SSG/LRR-ω (GGDH, blended SSG/LRR redistribution model) were found to yield best agreement with the experimental data among the possible options. The GGDH is superior to SGDH, which is plausible as it benefits from the wall-normal fluctuation v'^2 and the importance of the different Reynolds normal stresses in curved flows (see [5]). The blended SSG/LRR redistribution model was found to give better agreement with the experimental data than SSG and LRR model alone. Additionally, a sensitisation of GGDH on curvature (denoted CC-1) based on the work by Zeman [8] was developed, which was found to yield a small improvement for the predicted Reynolds stresses in the outer boundary layer.

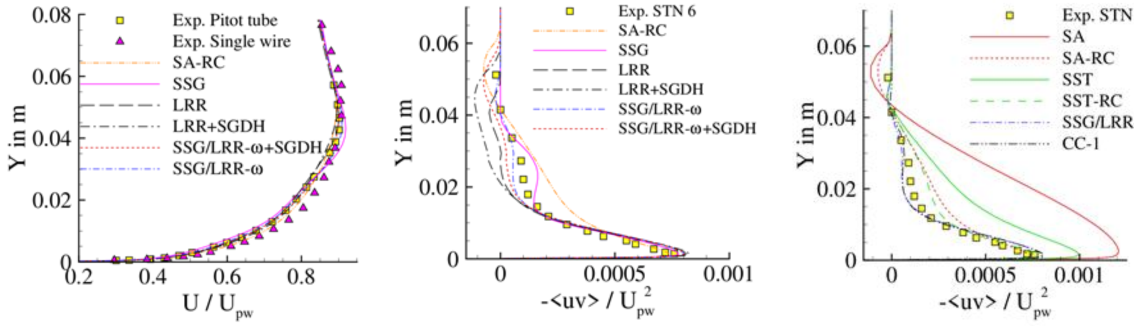

Figure 1: Convex-curvature turbulent boundary-layer flow by Gillis & Johnston (1983) [1]: Study of effect of redistribution model (LRR, SSG, SSG/LRR) and turbulent transport model SGDH, GGDH (left and middle) and curvature sensitisation of GGDH inspired by Zeman [8] (denoted by CC-1).

Moreover, for the flow by Gillis & Johnston [1], the SSG/LRR-ω model was found to yield a superior agreement with the experimental data compared to SA-RC and SST-RC. For the testcase by Monson [3], similar results were obtained. For the concave-curvature case by So & Mellor [2], the SSG/LRR-ω model was also found to yield good agreement with the experimental data, except for effects due to the presence of Görtler vortices, which could not be captured.

To conclude, the SSG/LRR-ω model was found to yield overall good agreement with the experimental data for different validation cases of turbulent boundary-layer flows with convex and concave streamwise surface curvature and mild streamwise pressure gradients.

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