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# Numerical simulation of turbulent wake of a flat plate subjected to adverse pressure gradient

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**Abstract.** Results are presented of a numerical study of the flat plate wake evolving under adverse pressure gradient. They include both results of the computational experiments aimed at supporting high accuracy of the performed scale-resolving simulations of the flow and results of the simulations aimed at quantitative evaluating of the effect of the adverse pressure gradient on the mean flow and statistical characteristics of the wake.

## 1. Introduction

The paper presents some recent results of the three-year German-Russian project “Wake in Adverse Pressure Gradient”, which ultimate goal consists in creating of a reliable combined (experimental and numerical) database on turbulent wakes developing under the influence of adverse pressure gradient. This is needed for improvements of the existing RANS models known to be incapable to predict characteristics of this type of flow, which is typical of high-lift wings of modern commercial airplanes in the take-off and landing stages [1] when the wakes of the slat and main wing are subjected to the strong APG, caused by the deflected flap.

The paper outlines results of the scale resolving simulations (zonal RANS-IDDES) of the experimental flow model designed and manufactured in the course of the project at the Technische Universität Braunschweig (TU BS). It is organized as follows.

In Section 2, a brief description of the experimental setup is presented along with some details of the computational problem statement and numerical aspects of the simulations performed. In Section 3, results of the simulations are presented and discussed. Finally, in Section 4 major conclusions based on the performed studies are formulated.

## 2. Computational problem setup and numerical aspects of the computations

Experimental flow model which detailed description could be found in [2] was designed by TU BS. It includes a flat plate as a wake generator and two pairs of symmetrically installed liner foils creating Adverse Pressure Gradient (APG), which intensity may be controlled by varying the distance,  $h$ , from the upper and lower liner foils to the center plane of the test section. In the experiments the free stream velocity  $U_0$  is varied from 24m/s to 48m/s. This corresponds to the variation of the Reynolds number based on the plate length  $L = 1.058$  m and  $U_0$  from 1.6 to 3.2 million. Corresponding Mach number is less than 0.1, which justifies using the incompressible flow assumption.

Simulations were performed with the use of the zonal RANS-IDDES approach. In the framework of this approach entire computational domain is divided into RANS and IDDES sub-domains (see Fig. 1). In the RANS sub-domain, the  $k-\omega$  SST model [3] is applied, whereas in the IDDES one the

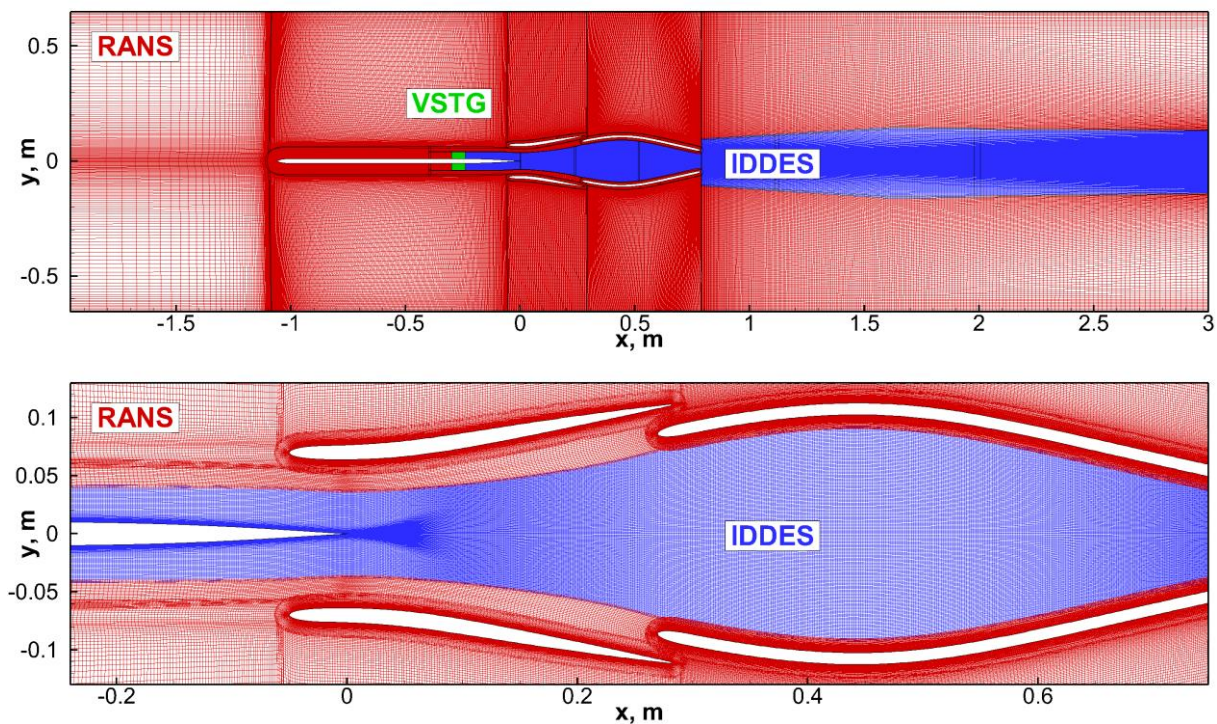


IDDES approach [4] is employed with the same underlying RANS model. The RANS sub-domain extends from the inlet boundary of the domain to some section in the flat plate boundary layer and also includes the outer part of computational domain and the attached boundary layers forming on the liner foils. The IDDES sub-domain covers the downstream part of the flat plate boundary layer and the entire wake, which is the focus region in this study. For triggering a rapid transition from RANS to IDDES, the Volume Synthetic Turbulence Generator (VSTG) [5, 6] is used at the RANS-IDDES interface. As a result, in the downstream part of the attached FP boundary layer the IDDES performs as Wall Modeled LES (WMLES) and in the wake it functions as a pure LES [4]. In the baseline simulation the RANS-IDDES interface was set at  $x_{int} = -0.3$  m and the span size of the domain  $L_z$  was set equal to 0.1 m (effect of the choice of these parameters is discussed in Section 3).

The boundary conditions used in the simulations were as follows.

On the plate and liner foil surfaces no-slip conditions were applied. At the inflow, uniform profiles of all the flow quantities except for the pressure were specified, and at the outflow boundary a constant pressure was imposed. The upper and lower boundaries were treated as the slip walls, and in the spanwise direction periodic boundary condition were imposed, which assumes the 2D mean flow character in the experiment.

The computations were performed with the use of the in-house code of the Saint-Petersburg Polytechnic University “Numerical Turbulence Simulation” (NTS code) [7]. This is a cell-vertex finite-volume code accepting structured multi-block overset grids of the Chimera type. The incompressible branch of the code used in present simulations employs the flux-difference splitting method of Rogers and Kwak [8]. In the RANS sub-domain the inviscid fluxes in the governing equations are approximated with the use of a 3<sup>rd</sup>-order upwind-biased scheme and in the IDDES sub-domain a 4<sup>th</sup>-order central scheme is used. The viscous fluxes are approximated with the 2<sup>nd</sup>-order central scheme. For the time integration, an implicit 2<sup>nd</sup>-order backward Euler scheme with sub-iterations is applied. The time step  $\Delta t$  was chosen to ensure less than 1.0 Courant number.



**Figure 1.** Computational domain, grid, and RANS and IDDES sub-domains in XY-plane.

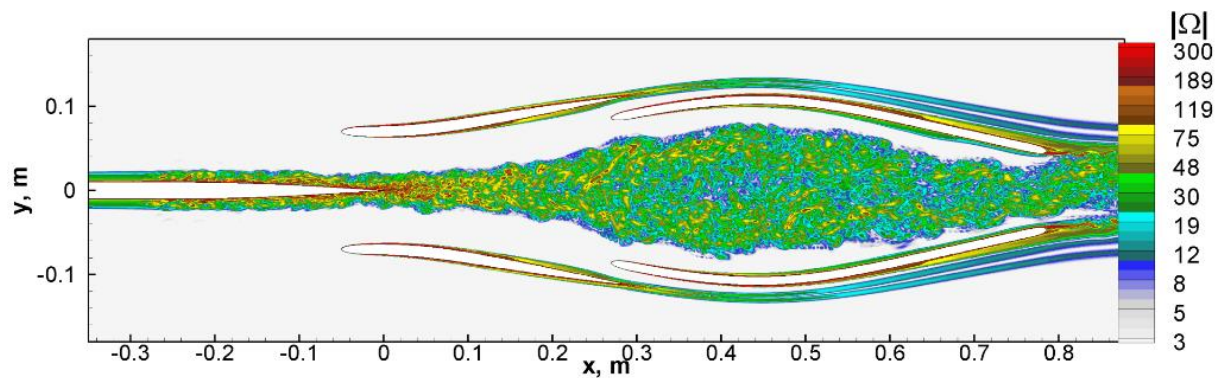
Upper frame: entire domain; lower frame: zoomed in wake region.



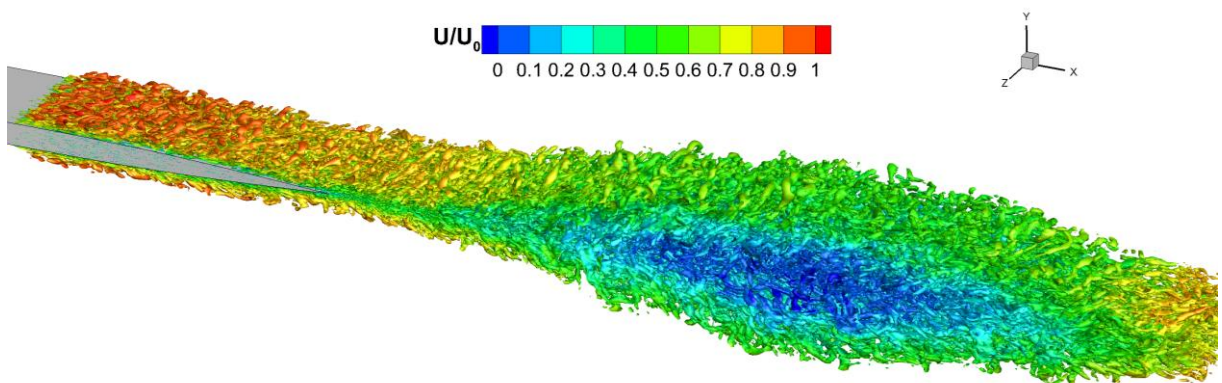
Two computational grids were used. The first, baseline, grid in XY-plane is shown in figure 1. The grid is clustered near the plate and liner foils walls so that the size of the first near wall step in the wall-normal direction would be less than 1.0 in wall units. In the IDDES sub-domain the grid steps in the streamwise and spanwise directions,  $\Delta x$  and  $\Delta z$ , are equal to  $2 \cdot 10^{-3} \text{ m}$  and  $10^{-3} \text{ m}$ , respectively, which corresponds to  $\Delta x/\delta = 0.13$ ,  $\Delta z/\delta = 0.06$  ( $\delta$  is the thickness of the boundary layer at the RANS-IDDES interface for the case with  $\text{Re} = 1.6\text{M}$ ). Total number of cells in this grid is about 28 million. Refined grid has 1.6 times reduced steps in  $x$ - and  $z$ - directions  $\Delta x = 1.25 \cdot 10^{-3} \text{ m}$ ,  $\Delta z = 6.25 \cdot 10^{-4} \text{ m}$  ( $\Delta x/\delta = 0.08$ ,  $\Delta z/\delta = 0.04$ ) in focus region and about 50 million cells total.

### 3. Results and Discussion

Figures 2-3 present flow visualizations from the simulation performed with the use of the baseline values of the RANS-IDDES interface location and span size of the domain at  $h = 0.07 \text{ m}$ . They visibly display fine-grained resolved turbulent structures in the IDDES sub-domain (both in the attached flat plate boundary layer and in the wake), thus suggesting a plausible functionality of the VSTG and IDDES in the WMLES and LES modes. Other than that, the visualizations clearly reveal presence of an extended stagnation region in the wake, which is a peculiar feature of the wakes subjected to APG.



**Figure 2.** Instantaneous field of vorticity magnitude.

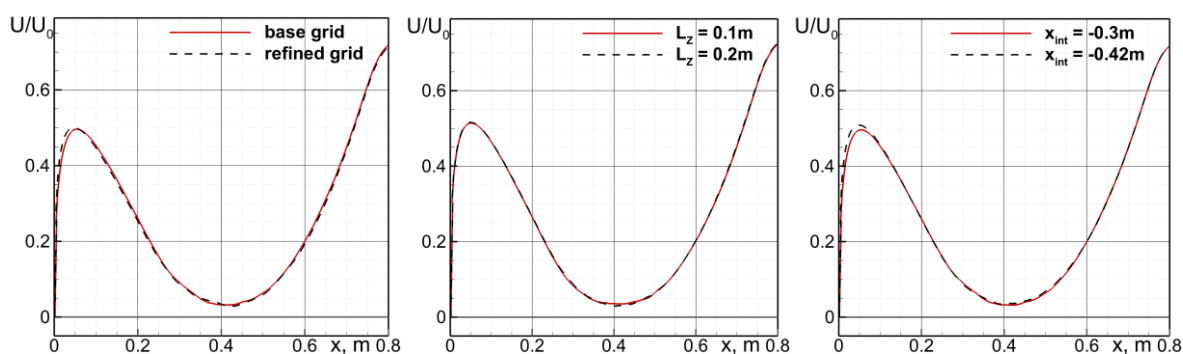


**Figure 3.** Instantaneous isosurface of Q-criterion colored by streamwise velocity.

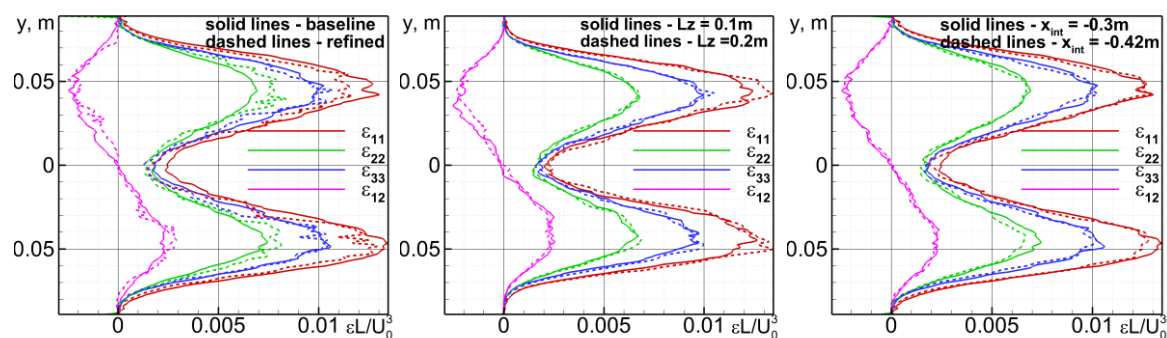
Reliability of the results of the simulation with the baseline numerical setup has been investigated by a set of numerical experiments aimed at indicating and, if needed, elimination of potential sources of inaccuracies. Particularly, dependence of the LES solutions on the computational grid, on the span size of the computational domain, and on the position of RANS-IDDES interface has been examined. It has been shown that the difference of the mean flow predictions on the baseline and 1.6 times refined grids, in the baseline and two times widen computational domain in the spanwise direction and with the two considered locations of the RANS-IDDES interface is negligible and shows up only in the very beginning of the wake (see Fig.4). This applies also to the turbulence statistics including

Reynolds-stress anisotropy and different terms of the Reynolds stress transport equations: convection, production, redistribution, turbulent transport (triple-correlations, pressure diffusion).

Moreover, virtually grid-converged results are obtained for the rate of viscous dissipation of the turbulent kinetic energy  $\varepsilon$  and the individual components of the dissipation rate tensor  $\varepsilon_{ij}$  (see Fig. 5). A possibility of accurate computation of the latter quantities on the grids with the steps much larger than the Kolmogorov length scale is achieved thanks to the special post-processing procedure based on the balance of the transport equations for the Reynolds stresses proposed in [9]. This possibility is especially important since the dissipation rates cannot be directly measured by PIV in the experiments but are crucial for improvement of Reynolds Stress Transport (RST) RANS models.

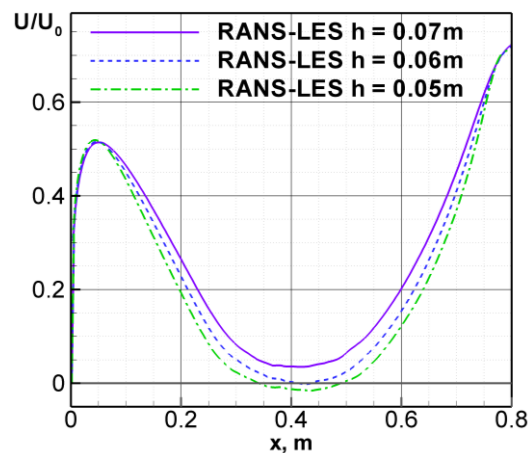


**Figure 4.** Effect of computational grid (left), spanwise size of the domain (central) and of position of RANS-IDDES interface (right) on predicted profiles of wake mean velocity.

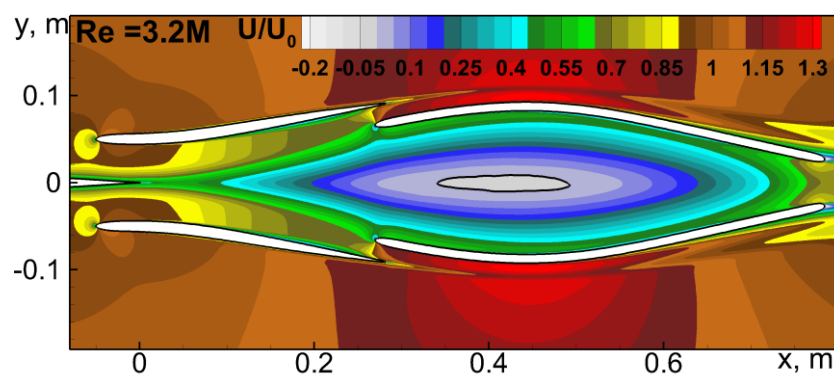


**Figure 5.** Effect of computational grid (left), spanwise size of the domain (central) and of position of RANS-IDDES interface (right) on predicted individual components of the dissipation rate tensor at  $x = 0.4$  m.

The most challenging feature of the wake subjected to APG, which cannot be captured by any of available RANS models including the RST ones is forming of the so called hanging or off-body recirculation zone at high levels of APG. In order to check whether the approach to turbulence representation outlined above is capable of doing this, in addition to the baseline simulation at  $h = 0.07$  m, two other simulations were carried out at  $h = 0.06$  and  $0.05$  m, respectively. Analysis of results of these simulations firmly confirms this capability. It particular, results of computations presented in figure 6 suggest that gradual increase of the APG first leads to a full stagnation of the mean flow in the mid wake region and, at some point, causes forming of the enclosed zone of reversal flow (figure 7). Other than that, the simulations show that design of the flow model created by TU BS indeed ensures a simple and reliable control of the level of APG imposed on the wake.



**Figure 6.** Effect of the distance between the centreline and the leading edge of the upstream liner foils  $h$  on the distribution of the streamwise velocity along the wake symmetry plane.



**Figure 7.** Mean velocity contours at  $h = 0.05$  m. Black lines in the contour plots show boundary of reversal flow.

#### 4. Conclusions and outlook

The paper presents some recent results of zonal RANS-IDDES simulations of the turbulent wake subjected to adverse pressure gradient at conditions of experiments conducted concurrently at the Institute of Fluid Mechanics of the Technische Universität Braunschweig in the framework of the joint German-Russian project “Wake in adverse pressure gradient”. They include both results of the computational experiments aimed at evaluation of accuracy of the performed scale-resolving simulations and of the numerical study aimed at quantitative prediction of the effect of the adverse pressure gradient on the mean flow and statistical characteristics of the wake. The former firmly confirm the reliability of the simulations (both the mean flow and the turbulence statistics in the wake are shown to be virtually independent the grid resolution, the spanwise size of the domain, and the position of the RANS-IDDES interface) and the latter support adequacy of the RANS-IDDES approach and, particularly, its capability of capturing the off-body recirculation zone in the mid-region of the wake at strong APG.

#### Acknowledgements

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## References

- [1] Rumsey C L and Ying S X 2002 Prediction of high lift: review of present CFD capability *Progress in Aerospace Sciences* **38** 145-80
- [2] Breitenstein W, Scholz P, Radespiel R, Burnazzi M, Knopp T, Guseva E, Shur M and Strelets M 2019 A Wind Tunnel Experiment for Symmetric Wakes in Adverse Pressure Gradients *American Institute of Aeronautic Science and Technology Forum* (07.-11.01.2019, San Diego, CA, USA)
- [3] Menter F R 1994 Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications *AIAA Journal* **32** 1598–605
- [4] Shur M L, Spalart P R, Strelets M Kh and Travin A K 2008 A hybrid RANS-LES approach with delayed-DES and wall-modelled LES capabilities *Int. J. Heat and Fluid Flow* **29** 1638-1649
- [5] Shur M L, Spalart P R, Strelets M Kh and Travin A K 2014 Synthetic Turbulence Generators for RANS-LES Interfaces in Zonal Simulations of Aerodynamic and Aeroacoustic Problems *Flow, Turbulence and Combustion* **93** 63-92
- [6] Shur M, Strelets M and Travin A 2017 Acoustically adapted versions of STG *Notes Num. Fluid Mech. and Multidisciplinary Design* **134** 62-9
- [7] Shur M, Strelets M and Travin A High-order implicit multi-block Navier-Stokes code: Ten-years experience of application to RANS/DES/LES/DNS of turbulent flows [https://cfd.spbstu.ru/agarbaruk/doc/NTS\\_code.pdf](https://cfd.spbstu.ru/agarbaruk/doc/NTS_code.pdf)
- [8] Rogers S E and Kwak D 1991 An upwind differencing scheme for the incompressible Navier-Stokes equations *Appl. Numer. Math.* **8** 43–64
- [9] Dejoan A and Leschziner M A 2005 Large eddy simulation of a plane turbulent wall jet *Phys. of Fluids* **17** 025102