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Zonal RANS-IDDES of asymmetric curved wake subjected to adverse pressure gradient

E.K. Guseva [1], M.L. Shur [1], A.S. Stabnikov [1]✉, P. Ströer [2], A.K. Travin [1]

[1] Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg, Russia;

[2] DLR (German Aerospace Center), Institute of Aerodynamics and Flow Technology, Göttingen, Germany

✉ an.stabnikov@gmail.com

Abstract. Results are presented of high-fidelity scale-resolving simulations of an asymmetric curved turbulent wake subjected to adverse pressure gradient based on the zonal RANS-IDDES approach to turbulence representation. The work is performed within the framework of a joint German-Russian project "Complex Wake Flows" and presents a continuation of the computational/experimental studies of the straight symmetric wakes carried out by the same team during 2017-2019. The addition of asymmetry and longitudinal curvature to the flow model made it more representative in terms of reproducing the real wakes behind the three-element high-lift wing configurations used during takeoff and landing of an aircraft. The reliability of the obtained results (both the mean flow parameters and the turbulent statistics) is supported by the grid-refinement study, whereas their comparison with the similar results of the RANS computations reveals a considerable discrepancy. This suggests the necessity of the improvement of the RANS models, which is planned for future work.

Keywords: turbulent wakes, adverse pressure gradient, scale-resolving simulations of turbulence, streamline curvature

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Материалы конференции
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Зонный RANS-IDDES расчет асимметричного криволинейного турбулентного следа, подверженного неблагоприятному градиенту давления

Е.К. Гусева [1], М.Л. Шур [1], А.С. Стабников [1]✉, Ф. Штрёер [2], А.К. Травин [1]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;

[2] DLR (Немецкий Аэрокосмический Центр), Институт аэродинамики и технологии потоков, г. Гёттинген, Германия

✉ an.stabnikov@gmail.com

Аннотация. Представлены результаты расчетов асимметричного криволинейного турбулентного следа, подверженного воздействию неблагоприятного градиента давления, с использованием вихреразрешающего зонного RANS-IDDES подхода к моделированию турбулентности. Работа выполнена в рамках совместного Германо-Российского проекта «Течения в сложных следах». Надежность полученных результатов расчета средних и пульсационных характеристик рассматриваемого следа подтверждается сеточной независимостью полученного решения, в то время как сравнение этих результатов с результатами расчетов, выполненных в рамках уравнений RANS, свидетельствует о необходимости усовершенствования RANS-моделей турбулентности.

Ключевые слова: турбулентные следы, неблагоприятный градиент давления, вихреразрешающие подходы к моделированию турбулентности, продольная кривизна линий тока

Финансирование: Работа выполнена при финансовой поддержке РФФИ и Немецкого научно-исследовательского сообщества в рамках научного проекта № 21-58-12002.

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Introduction

Optimization of the high-lift wings employed in the modern commercial airplanes to ensure sufficient lift for low-speed operations (take-off and landing) requires multi-variant computations. Currently they are performed based on the Reynolds-Averaged Navier-Stokes (RANS) equations which have been for many years and still remain the only approach to such computations affordable at the practically meaningful (high) Reynolds numbers. However, in contrast to the wings in cruise flight conditions, the accuracy of the available RANS turbulence models for the high-lift systems at low speed is unsatisfactory, especially near the maximum lift [1]. A major reason is complexity of the corresponding flow-pattern. One of its most challenging feature are turbulent wakes of the upstream wing elements significantly affected by the streamlines curvature and subjected to a strong adverse pressure gradient (APG) induced by the downstream elements. Particularly, the APG causes thickening of the wake, its stagnation or even formation of a reversed flow regions (off-surface separation), which leads to a reduced flow turning and to a loss in lift. Hence, the improvement of the RANS turbulent models is needed, which would ensure the reliable prediction of the complex wake flows. This requires detailed high-fidelity experimental and computational (based on the scale-resolving simulations – SRS) data on the mean characteristics and the turbulence statistics of such flows.

This motivated a joint German-Russian research project “Complex Wake Flows” aimed at the accumulation of such a database and, ultimately, at the development of improved RANS models capable of the accurate prediction of the flows over the high-lift systems. This project presents a direct continuation of the computational/experimental studies of the evolution of the straight symmetric turbulent wakes carried out by the same team during 2017–2019 (see, e.g., [2–4]). The addition of the asymmetry and longitudinal curvature to the flow model implemented in the current project made it more representative in terms of reproducing the real wakes of the three-element high-lift wings.

The preceding paper [5] described the results of the RANS-based aerodynamic design of the experimental flow model of a complex curved turbulent wake with strong curvature and APG effects, which experimental investigation is planned on at the Technical University of Braunschweig (TU BS). In the present paper, we present the first results of the computational part of the project, namely, the results of the high-fidelity SRS of the flow over this model. Sections 2 and 3 below outline, respectively, the wake configuration proposed in [5] and the computational approach used in the simulations. After that, in Section 4, results of the computations are presented and discussed.

Asymmetric curved wake flow model

The design proposed in [5] is based on the currently available at TU BS experimental model of the straight symmetric wake subjected to APG [2] (see left frame in Fig. 1), which allows minimizing the additional manufacturing efforts. Unlike the straight wake, in the curved wake model (right frame in the figure) the Flat Plate (FP) generating the wake is mounted at non-zero angle of attack relative the direction of the flow at the inlet of the wind tunnel test section. Just as in the straight wake, the APG is created by a pair of symmetrically installed thin airfoils ("liner foils") placed right downstream of the trailing edge of the FP. However, further downstream, instead of the second pair of the symmetric liner foils, the curved wake model includes an inclined flat plate and a liner foil with deflected flap. The key geometric parameters of the model (the angles of attack of the FP and of the downstream plate and the length and deflection angle of the flap) are adjusted so that, on the one hand, there would be no separation of the flow from either the FP leading edge or from the inner surface of the liner foils and, on the other hand, the APG and the curvature effects in the wake would be strong enough to cause a large stagnation region and to significantly affect the wake turbulence. The latter is confirmed by Fig. 2, which reveals a strong difference of the eddy viscosity fields in the wake predicted by the Spalart-Allmaras (SA) RANS model [6] and its enhanced version (SARC model [7]) known to be capable of realistic prediction of the curvature effect not accounted for in the original model [6]. Note that the curved wake model shown in Fig. 1, which simulations are conducted in the present study, slightly differs from that proposed in [5]. Namely, the angle of deflection of the flap of the second lower liner foil is reduced by ~ 3° with corresponding adjustment of the angle of the upper flat plate to ensure the same "exit" cross-section of the model. This is done in order to prevent the flow separation not only from the inner surfaces of the liner foils but also from the outer surface of the flap, which could cause difficulties both in the experiments and in the simulations.

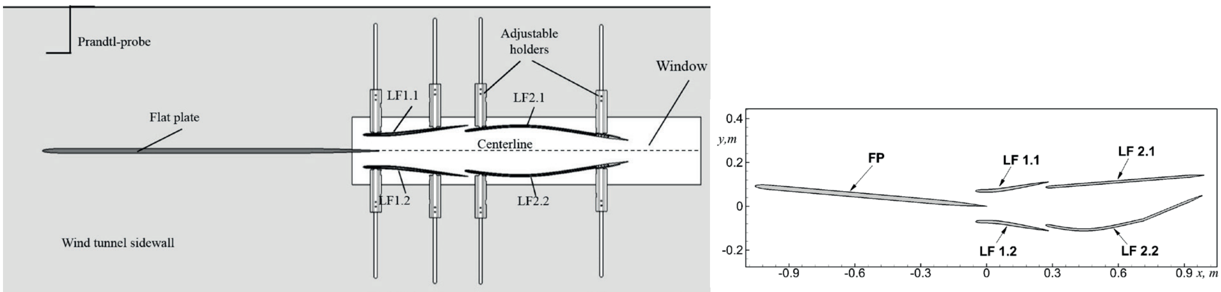

Fig. 1. Sketch of experimental model of straight wake installed in TU BS wind tunnel [2] (left) and asymmetric curved wake model analyzed in the present work (right)

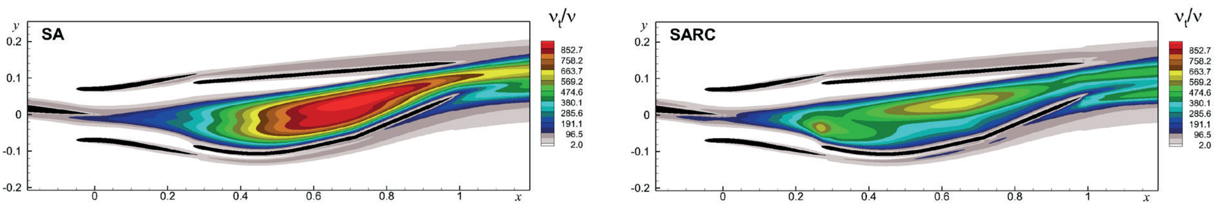

Fig. 2. Fields of normalized eddy viscosity in the curved wake predicted by SA (left) and SARC (right) models

Computational approach and some numerical details

In general, the SRS approach employed in the present work for the computations of the asymmetric curved wake is similar to the approach successfully used in the preceding project [2–4] for the simulation of the straight symmetric wake. It is based on the zonal RANS-LES model with the hybrid IDDES method [8] used for the representation of turbulence in the LES zone. In the presence of resolved turbulence, the IDDES functions as LES with wall modeling (WMLES) in the attached boundary layers and as "pure" LES away from walls. Within the zonal RANS-IDDES, the computational domain is manually subdivided into two RANS and IDDES subdomains (zones) which are shown in Fig. 3 together with the entire computational domain and grid in *XY*-plane.

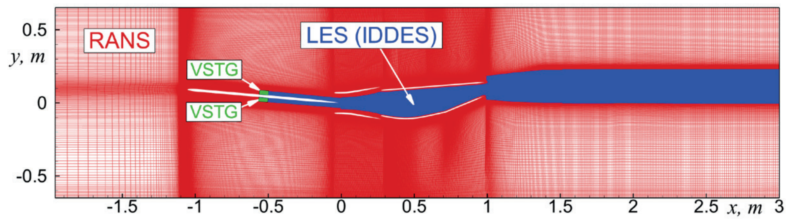

Fig. 3. Computational domain, RANS and IDDES subdomains, and baseline grid in *XY*-plane

Specifically, the RANS zone (red in Fig. 3) includes the outer (inviscid) part of the computational domain, the initial part of the FP boundary layers, and the boundary layers forming on the liner foils. The IDDES zone (blue in Fig. 3) covers the rest (downstream) part of the FP boundary layers and the FP wake, which is the focus region in this study. To introduce resolved turbulent structures into the IDDES subdomain, which is essential for ensuring a rapid transition from the fully modeled turbulence (RANS sub-domain) to mostly resolved turbulence (IDDES sub-domain) the Volume Synthetic Turbulence Generator (VSTG) [9, 10] is used at the RANS-IDDES interface (in Fig. 3, the area of non-zero VSTG source term is shown in green).

In the RANS zone, the k-ω SST RANS model of Menter [11] is applied, which serves also as the underlying RANS model for the IDDES.

The simulations are performed at the Reynolds number 1.6 million based on the FP length L (1.058 m) and the free stream (inlet) velocity U_0 (25 m/s). Corresponding Mach number is as small as ~ 0.07, which justifies using the incompressible flow assumption.

The boundary conditions used in the simulations are the same as those employed in the straight wake simulations (see [3] for details). Particularly, in the spanwise direction the periodic boundary conditions are imposed, and in order to check whether the chosen span size of the domain is sufficient to ensure span-size independent mean and statistical flow characteristics, two simulations are carried out in the computational domains with the span size L_z = 0.1m and 0.2 m, respectively.

The computational grids used in the present study are the structured Chimera-type grids with 25 overlapping blocks. The “baseline” grids have around 35 or 70 million cells total, depending on the span size of the domain. In addition, grid-sensitivity of the obtained solution is analyzed by carrying out a simulation at L_z = 0.1 m on the “refined” grid which steps in the focus region are reduced compared with the baseline grid by a factor of 1.3 in all the three spatial direction (this grid has ~ 64 million cells total).

The computations are performed with the use of the in-house CFD code “Numerical Turbulence Simulation” (NTS code) [12]. The incompressible branch of the code used in the present study employs the flux-difference splitting method of Rogers and Kwak [13]. In the RANS sub-domain, the inviscid fluxes in the governing equations are approximated with the use of a 3rd-order upwind-biased scheme and in the IDDES sub-domain a 4^{th}-order central scheme is used. The viscous fluxes are approximated with the 2^{nd}-order central scheme. For the time integration, an implicit 2^{nd}-order backward Euler scheme with sub-iterations is applied. The time-step Δt is chosen to ensure less than 1.0 value of Courant number.

Results and Discussion

Sample results of the simulations are shown in Figures 4—7.

In particular, Fig. 4 (left frame) presents a visualization of results of the simulations on the baseline grid in the form of the instantaneous isosurface of the Q-criterion revealing the vortical turbulent structures resolved by the simulation. Both, in the attached boundary layers downstream of the VSTG and in the FP wake the size of the smallest structures is consistent with the grid used, which suggests a correct functionality of both the VSTG and the IDDES in WMLES and pure LES modes. Besides, the figure clearly displays strong asymmetry and curvilinearity of the wake and the presence of a large “hanging” stagnation region caused by the APG.

Convincing additional evidence of the credibility of representation of the wake turbulence in the simulations is the presence of an extended inertial region in the computed spectra of turbulent fluctuations (Fig. 4, right frame) and an increase in the length of this region with grid-refinement due to a decrease of the size of the smallest resolved turbulent structures.

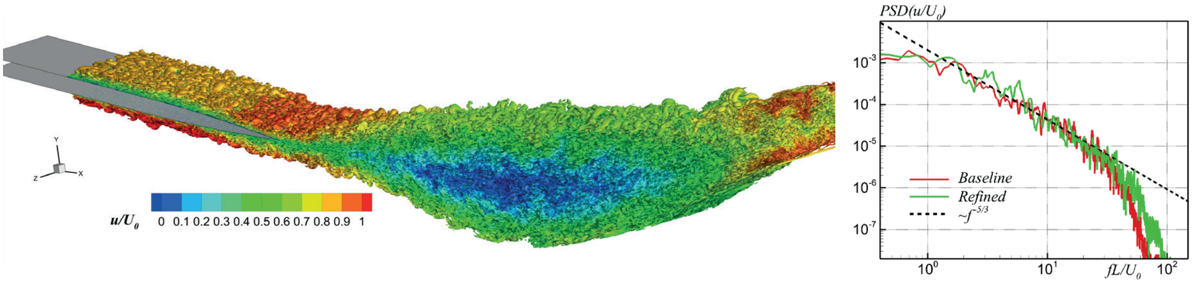

Fig. 4. Isosurface of Q-criterion "colored" by streamwise velocity (baseline grid, L_z = 0.1m) and spectra of streamwise velocity fluctuations obtained on baseline and refined grids (x = 0.7 m, y = 0)

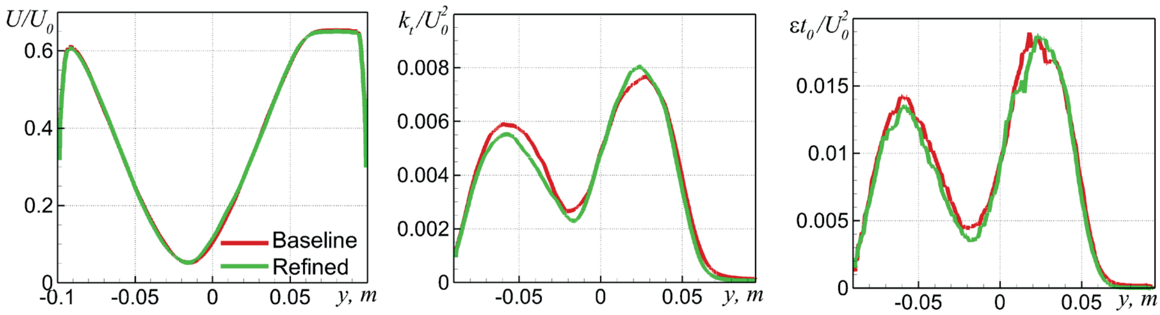

Fig. 5. Profiles of mean velocity, turbulent kinetic energy and its dissipation rate in the mid-wake section (x = 0.5 m) from simulations on baseline and refined grids

Other than that, the Q-isosurface in Fig. 4 does not reveal any large-scale vortical structures with the size of the order of the span-size of the "narrow" computational domain L_z = 0.1 m, which indicates that this L_z-value is sufficient for getting span-size independent solution for the flow under consideration. This is directly confirmed by the comparison (not shown) of the results of the simulations carried out in the narrow and wide (L_z = 0.2 m) domains: both the mean flow parameters and the turbulent statistics obtained in these simulations virtually coincide with each other. As for the grid sensitivity of the predicted flow characteristics, it can be judged by Fig. 5 which compares the profiles of the mean streamwise velocity, the resolved turbulent kinetic energy (TKE), and its dissipation rate extracted from the simulations on the baseline and refined grids. One can see that thanks to the high-order numerics used, the relatively coarse baseline grid ensures accurate (virtually grid-converged) prediction of even the turbulence dissipation rate, which is known to be the most grid-sensitive characteristic of turbulent flows.

In Fig. 6, we compare the mean velocity and the TKE fields obtained by the zonal RANS-IDDES for the straight wake [3] and for the curved wake considered in the present work. The figure shows that the APG-induced stagnation regions in the both wakes are of similar streamwise extent and, roughly, have the same values of the minimum velocity, $U_{min}/U_0 \approx 0.07$, but the lateral size of this region in the curved wake is significantly narrower than in the straight one. Probably this effect and therefore higher velocity gradients is the cause of the tangibly higher TKE levels in the curved wake predicted by the simulations (see lower row in Fig. 6).

Finally, considering that the ultimate goal of the present project consists in improving the accuracy of RANS turbulence models for the wakes in APG, we have evaluated accuracy of some already existing models by comparing the corresponding 2D RANS predictions of the curved wake characteristics with the predictions of the high-fidelity zonal RANS-IDDES approach.

The steady RANS computations of the wake were performed with the use of three RANS models, which currently are widely used for the computation of aerodynamic flows: the eddy viscosity models SARC [7] and k-ω SST [11], and the Reynolds-stress transport (RST) LLR-SSG-ω model [14]. Figure 7 presents the comparison of the RANS results obtained with the use of these models with the results of the zonal RANS-IDDES computations. The figure suggests that none of the three RANS models is capable of accurate prediction of the mean velocity field in the wake.

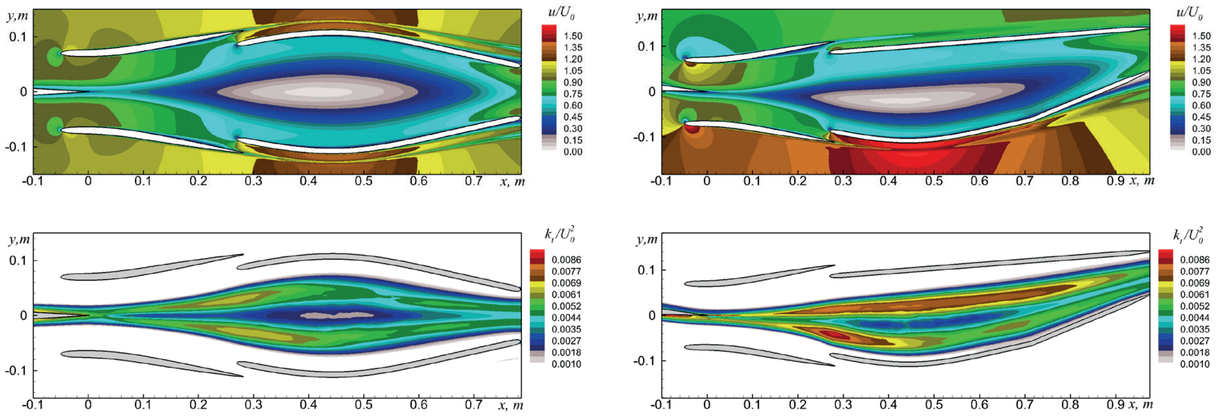

Fig. 6. Zonal RANS-IDDES predictions of mean velocity and TKE fields in the symmetric straight wake [3] (left) and in the asymmetric curved wake considered in the present study (right)

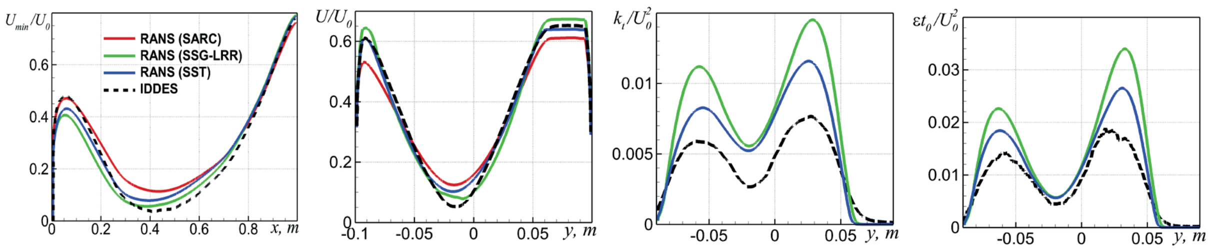

Fig. 7. Comparison of RANS-based and zonal RANS-IDDES predictions of curved wake characteristics: streamwise distributions of the minimum mean velocity in the wake and profiles of mean velocity, TKE and its dissipation rate in the mid-wake section x = 0.5 m

Other than that, two of these models, which potentially can claim to the prediction of the TKE and its dissipation rate (the two-equation model [11] and the RST model [14]), strongly overestimate these quantities. This confirms the necessity of the RANS models improvement in order to achieve satisfactory predictions of the characteristics of complex turbulent wakes typical of the low-speed flows over high-lift configurations.

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THE AUTHORS

GUSEVA Ekaterina K.
katia.guseva@inbox.ru
ORCID: 0000-0002-7117-2454

SHUR Mikhail L.
mshur@cfd.spbstu.ru
ORCID: 0000-0002-9223-1687

STABNIKOV Andrey S.
An.stabnikov@gmail.com
ORCID: 0000-0001-7011-6197

STRÖER Philip
philip.stroeer@dlr.de

TRAVIN Andrey K.
atravin@cfd.spbstu.ru
ORCID: 0000-0003-3995-5085

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