RANS-based design of experimental flow model for investigation of complex curved turbulent wakes subjected to adverse pressure gradient

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Abstract. Results are presented of a series of RANS computations aimed at creating a new experimental flow model of a curved turbulent wake evolving under adverse pressure gradient. In the course of the computations, key geometric parameters of the model (the angle of attack of a flat plate generating the wake and the shape and the angles of attack of liner foils creating the pressure gradient) were varied in a wide range. The purpose was to find the parameters ensuring desirable features of the flow, namely, a considerable wake curvature and its strong deceleration leading to formation of a large stagnation or even a reversal flow region, on the one hand, and no flow separation either from the flat plate or from the surfaces of the liner foils, on the other hand. As a result, the design satisfying all these demands has been found. This design will be implemented and studied in the framework of recently launched joint German-Russian project “Complex Wake Flows” which presents a continuation of an earlier similar project devoted to symmetric wakes.

1. Introduction
Modern transport aircrafts employ high-lift systems to provide the necessary lift for low-speed operations (take-off and landing regimes). The combination of a leading-edge slat and a trailing-edge single slotted Fowler flap is currently the state-of-the-art system. The trend in further development is to simplify devices while improving high-lift performance [1]. The related aerodynamic design still remains a technical challenge. While flow computations based on RANS (Reynolds Averaged Navier-Stokes equations) are now an integrated part of wing design for cruise flight, reliability of the RANS turbulence models for high-lift systems at low-speed has not yet been achieved [2]. This is explained by a complexity of the flow, which combines turbulent boundary layers, curved wakes generated by the elements located upstream, and the confluent flow of upstream element wakes and boundary layers on downstream elements, all subjected to a strong adverse pressure gradient (APG). The APG causes thickening of the wake, its stagnation and even formation of reversal flow regions. This latter feature (so-called off-surface separation) results in reduced flow turning and hence in a significant loss in lift.

Reliable RANS-prediction of all these flow features is impossible without high-fidelity experimental and computational (based on scale-resolving simulations) data on the flow characteristics needed for validation and improvement of RANS turbulence models used in the design process. Such data are planned to be accumulated in the course of a collaborative German-Russian research project...
“Complex wake flows”, which presents a direct continuation of a similar project devoted to investigations of the symmetric wakes (see, e.g., papers [3-5]).

In this paper we presents results of the first stage of the new project, namely, results of a series of RANS calculations aimed at aerodynamic design of the experimental flow model of a complex curved turbulent wake evolving under adverse pressure gradient. Its rest part is organized as follows. In Section 2, details of flow model are presented along with a computational problem statement and some numerical aspects of the computations performed. In Section 3, the influence of streamlines curvature in the proposed design is shown. Finally, in Section 4 major conclusions are formulated.

2. Flow model design
In order to minimize additional manufacturing efforts, design of the new asymmetrical curved turbulent wake model is based on the currently available model of symmetrical wake subjected to APG designed and manufactured in at the Technische Universität Braunschweig (TU BS) [3]. It includes a Flat Plate (FP) as a wake generator and two pairs of symmetrically installed Liner Foils (LF) creating Adverse Pressure Gradient (APG), which intensity may be controlled by varying the distance from the upper and lower liner foils to the center plane of the test section (fig. 1).

![Figure 1. Sketch of experimental flow model installed in TU BS wind tunnel [3](https://example.com/image.png)](image.png)

Particularly, the effort comprised a manual variation of the key geometric parameters of the existing model (the angle of attack of a flat plate and the shape, length, and the angles of attack of liner foils creating the pressure gradient), carrying out RANS computations of thus obtained configurations and choosing the design with a significant asymmetry of the wake and with APG strong enough to cause a large stagnation region but not cause a separation of the flow from either the flat plate or from the surfaces of the liner foils.

The computations were performed with the use of the in-house code of the Saint-Petersburg Polytechnic University “Numerical Turbulence Simulation” (NTS code) [6]. 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 the present study employs the implicit flux-difference splitting method of Rogers and Kwak [7]. The inviscid fluxes in the governing equations are approximated with the use of a 3rd-order upwind-biased scheme. The viscous fluxes are approximated with the 2nd-order centered scheme.

The size of the computational domain corresponded to the size of work section of the wind tunnel shown in Fig.1 above, and the grids used in the computations satisfied well-known requirements to RANS grids.
Computations were carried out at Reynolds number based on the inlet velocity \( U_0 \) and the flat plate length \( \text{Re} = 3.2 \text{M} \) [3] with the use of two RANS models, namely, Spalart-Allmaras model (SA) [8] and its modification with the rotation-curvature correction (SARC model) [9].

Boundary conditions used in the simulations were as follows. On the plate and liner foil surfaces, no-slip conditions were imposed. 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 set. The upper and lower boundaries were treated as the slip walls.

Figure 2 shows some examples of the streamwise velocity fields computed for “unsuccessful designs” which were considered in the course of the manual adjustment of the geometry aimed at finding a satisfactory design. It shows that these designs do not meet requirements to the target flow model formulated above: they either do not ensure sufficiently strong wake deceleration or result in a massive separation of the flow from the upper downstream liner foil.

![Streamwise velocity field and streamlines predicted by SA RANS for three sample unsuccessful designs](image)

**Figure 2.** Streamwise velocity field and streamlines predicted by SA RANS for three sample unsuccessful designs

Figure 3 presents the finally found target design. The shape and sizes of the flat plate and of the upstream pair of the liner foils in this design are identical to those in the previously studied symmetric wake model (Fig.1). Thus, the new design requires only two relatively simple new elements: the straight upper downstream liner foil and an elongated trailing edge flap of the downstream liner foil.
Figure 3. Geometry of proposed design for investigation of an asymmetric curved wake subjected to APG

At the same time, as seen in Fig. 4, where the streamwise velocity field computed for the newly proposed design is shown, it satisfies all the above stated demands. In particular, it creates a wake with a considerable asymmetry (this is supported by results of SARC-based computations presented in the next section) and rather strong deceleration which results in formation of a large stagnation region. Other than that, there is no flow separation from either the flat plate leading edge or from the inner surfaces of the liner foils (only a tiny separation at the outer part of the lower downstream liner foil is observed).

Note that although the minimum velocity in the stagnation region is very close to zero ($U/U_0 = 0.07$), the RANS computation does not predict the reversal flow in the wake. However, it is known that RANS models typically delay formation of the off-body flow reversal zone [5], and so it is very likely that such a zone will appear in experiments and in the scale-resolving simulations.

Figure 4. Streamwise velocity field and streamlines predicted by SA RANS for proposed design

3. Streamline curvature effect

In order to evaluate the effect of the streamline curvature in the new wake configuration, its additional computation was carried out with the use of the SARC model [9], which is capable of realistic prediction of this effect on turbulence, which is not accounted for by the original SA model. A comparison of results of the two models’ predictions is shown in Figs. 5-6. The figures display a considerable difference of the two RANS solutions and, therefore indicate a rather strong curvature effect in the proposed design. In particular, the curvature correction results in a strong decrease of the turbulent viscosity in a large part of the wake. Hence, the proposed new design of the wake flow model is a good starting point for the experimental study and numerical simulations of the complex curved wakes subjected to APG.
4. Conclusions and outlook
The paper presents results of SA and SARC RANS computations of a complex curved turbulent wake subjected to adverse pressure gradient designed for further experimental and high-fidelity computational studies in the framework of the joint German-Russian project “Complex Wake Flows”. These results demonstrate that the proposed design allows generating a curved wake subjected to adverse pressure gradient strong enough to ensure formation of extensive stagnation region with no undesirable side-effects.
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