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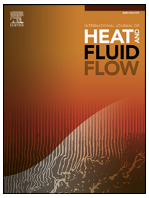

Evaluation of grey area mitigation tools within zonal and non-zonal RANS-LES approaches in flows with pressure induced separation

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ABSTRACT

Hybrid RANS-LES computations of the separated flow over a wall-mounted hump are presented, which employ different grey-area mitigation techniques in the framework of a structured and an unstructured flow solver. Two zonal approaches using different synthetic-turbulence generators at the RANS-LES interface, as well as a non-zonal approach based on a shear-layer-adapted subgrid scale are compared in detail with validation data from a wind-tunnel experiment. Irrespective of the applied flow solver, the different methods are shown to be similarly effective in reducing the grey area compared to the basic hybrid RANS-LES model, and thus provide satisfying mean-flow predictions of the pressure-induced separation.

1. Introduction

Wall-bounded flows with non-fixed separation caused by an adverse pressure gradient (APG) feature several complex phenomena, such as turbulent boundary layer separation, reattachment of the separated shear layer, and recovery of the reattached turbulent boundary layer further downstream. These are common for many aerodynamic and industrial flows (e.g. wings/turbine blades near maximum loading) and present a serious challenge not only for RANS modelling but also for hybrid RANS-LES approaches. For the latter, the major difficulty in predicting such flows is associated with a strong delay of transition from modelled to resolved turbulence in the separated shear layers called the "grey area" issue (see Mockett et al., 2015a) resulting in a significant deviation of the predicted mean flow quantities and turbulence statistics from the experimental data. Note that the term "transition" refers here to a change of the modelling state (RANS vs. LES) of an already turbulent flow, and not to the classical "laminar-turbulent" transition. Although this difficulty is common to all hybrid RANS-LES methods, its origin and possible remedies are quite different for zonal and non-zonal methods.

In non-zonal ("DES-like") approaches, which rely on the natural instability of the separated shear layers, the delay of transition to developed 3D turbulence occurs because this instability is "blocked" by an excessive level of eddy viscosity in the initial region of the shear layers. This results from the convection of eddy viscosity from the attached upstream boundary layer treated by RANS, as well as from a too strong generation of modelled turbulence in the separated region treated by LES. The latter is due to grid anisotropy (coarse in the spanwise and streamwise directions) typically used in this region and to the Smagorinsky-type subgrid modelling in classic DES, which was originally calibrated for developed 3D turbulence and therefore yields an overly large production term in 2D shear flow. Thus, in order to resolve the issue, one should ensure a considerable decrease of the eddy viscosity in the early shear layers (see, e.g. Shur et al., 2015, Mockett et al., 2015b).

For the zonal approaches, the issue results from a too slow transition from fully modelled turbulence in the upstream RANS zone to mostly resolved turbulence in the downstream LES zone (actually Wall-Modelled LES or WMLES zone). In this case, accelerating the transition process is only possible by improving the methods to inject artificial turbulence at the RANS-WMLES interface, which is a key element of zonal approaches.

Note finally that independently of the modelling approach, the efficiency of any grey-area mitigation tool is considerably affected by the grid resolution and the numerical discretization errors inherent to the flow solver. All these considerations have motivated the present study, aimed at comparing the performance of zonal and non-zonal hybrid RANS-LES approaches in different flow solvers for flows with APG-induced separation and reattachment.

The two considered zonal RANS-WMLES approaches employ the SST-based Improved Delayed Detached Eddy Simulation (IDDES) of Shur et al. (2008) in the WMLES zones, which are geometrically fixed throughout the simulation (thus, the term 'zonal'). The simulations performed differ both in the numerical solver and in the method used for the generation of turbulent content at the

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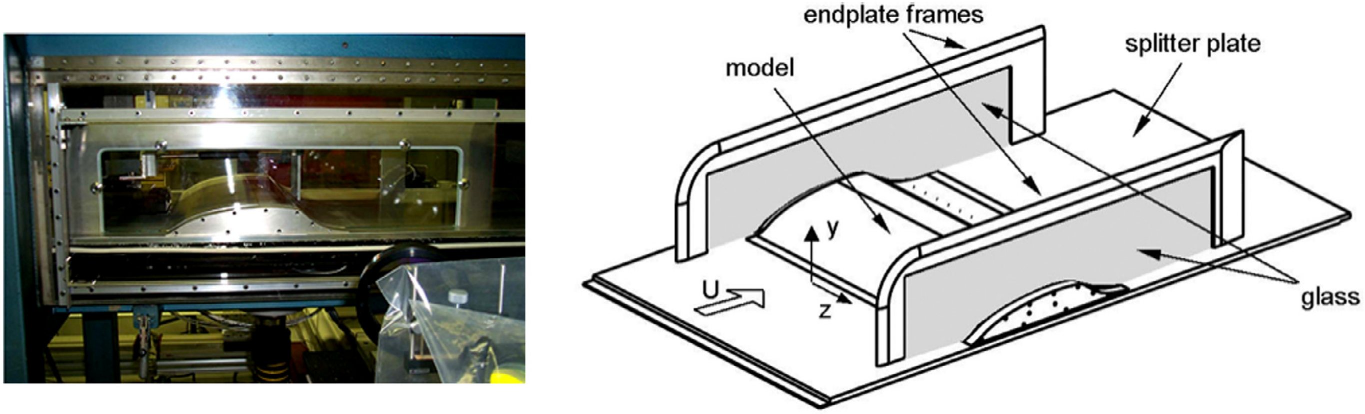

Fig. 1. Photo and sketch of the experimental setup.

RANS-WMLES interface. The first approach employs the unstructured DLR-TAU code (Schwamborn et al., 2008) with the Synthetic Eddy Method (SEM) by Jarrin et al. (2009), whereas the second one applies the Synthetic Turbulence Generator (NTS STG) developed by Shur et al. (2014) within the block-structured NTS in-house code.

The non-zonal hybrid approach which is used only within the NTS code is the SST-based Delayed Detached Eddy Simulation (DDES) of Spalart et al. (2006) combined with the recently proposed shear-layer-adapted (SLA) definition of the subgrid length-scale (Shur et al., 2015).

The performance of the three hybrid models is evaluated based on the 2D wall-mounted NASA hump test case (see Fig. 1), which had been purposefully designed as a CFD validation test case by Greenblatt et al. (2006). The key features of the flow (separation of the boundary layer from the hump, reattachment of the separated shear layer, and relaxation of the reattached boundary layer) are exactly the features we focus on in the present study.

2. Numerical approaches

The two research groups of DLR and NTS used their own numerical solvers and partly different physical-modelling approaches to simulate the common 2D hump test case. The following sections give a brief outline of these methods.

2.1. Flow solvers

DLR used its unstructured compressible finite-volume solver TAU, employing the recent implementations of the Synthetic-Eddy Method (SEM) by Jarrin et al. (2009) and the low-dissipation low-dispersion (LD2) scheme by Löwe et al. (2016). The latter is based on a 2nd-order energy-conserving skew-symmetric convection operator that is combined with a minimal level of 4th-order artificial matrix dissipation for stabilization. Moreover, the central flux terms employ an additional gradient extrapolation that effectively increases the discretization stencil and is used to reduce the dispersion error of the scheme. Both ingredients are essential for accurate WMLES results with the unstructured TAU code (Probst et al., 2016a). Note that in the present zonal RANS-WMLES computations, the LD2 scheme is only active in the respective WMLES region downstream of the interface. The temporal discretization is based on an implicit dual-time stepping scheme which is also of 2nd-order accuracy.

The simulations carried out by NTS were performed using the in-house NTS code, which is described in Shur et al. (2004). It is a cell-vertex finite-volume code accepting structured multi-block overset grids of Chimera type. The incompressible branch of the code employed here uses the flux-difference splitting method of Rogers and Kwak (1988). The approximation of the inviscid fluxes depends on the turbulence representation approach: in the zonal RANS-WMLES computations, it uses a 3rd-order upwind-biased scheme in the RANS zone and a 4th-order central scheme in the WMLES zone, whereas for the global DDES the hybrid (3rd-order upwind-biased/4th-order central) scheme of Travin et al. (2002) is used. The viscous fluxes are approximated with the 2nd-order central scheme. For the time integration, an implicit 2nd-order backward Euler scheme with sub-iterations is applied.

2.2. Basic hybrid RANS-LES approaches

The non-zonal simulation performed by NTS employs the Delayed Detached Eddy Simulation (DDES) of Spalart et al. (2006) which extends the classic Detached Eddy Simulation with a ‘RANS shielding function’. This shielding function is designed to keep the hybrid length scale in attached boundary layers (e.g., upstream of the hump) in RANS mode ($l_{hyb} \approx l_{RANS}$), and to allow LES mode ($l_{hyb} \approx l_{LES} = C_{DES}\Delta$) only in separated or wake flows. While the subgrid filter width Δ in the original DDES is determined by the maximum local grid-edge length, Δ_{max}, it can be replaced by other filter definitions to tackle the grey-area problem (see Section 2.3).

For the zonal approaches with injection of synthetic turbulence, the hybrid RANS-LES methods need to be able to resolve the attached boundary layers upstream of separation. Both DLR and NTS achieve this by using the Improved Delayed Detached Eddy Simulation (IDDES) of Shur et al. (2008) which further extends the DDES by a wall-modelled LES (WMLES) branch in the hybrid length scale:

$$l_{hyb} = \tilde{f}_d \cdot (1 + f_e) \cdot l_{RANS} + (1 - \tilde{f}_d) \cdot l_{LES}.$$

Here, the blending function $\tilde{f}_d = \max\{(1 - f_{dt}), f_B\}$ provides the mechanism to automatically switch between RANS ($f_{dt} = 0$), pure LES ($f_{dt} = 1$ and $f_B = 0$), and WMLES ($f_{dt} = 1$ and $0 \leq f_B \leq 1$) modes, additionally involving a more complex filter-width definition to compute l_{LES}. Note that in the zonal simulations of DLR, the WMLES mode is enforced by manually setting the shielding function f_{dt} to 1 downstream of the pre-defined RANS-LES interface. However, this measure of precaution can be omitted without negatively affecting the results, as shown by the NTS simulations (see Section 4). Finally, the empirical “elevating” function f_e increases the modelled Reynolds stress near the RANS-LES interface to ensure a continuous log-layer in WMLES (see Shur et al., 2008 for details).

All hybrid approaches chosen in the present study use the k–ω SST model of Menter (1994) as their RANS basis.

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