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Source term based synthetic turbulence inflow generator for eddy-resolving predictions of an airfoil flow including a laminar separation bubble

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ABSTRACT

The present paper addresses the issue of the strong dependency of eddy-resolving simulations for turbulent flows on the employed inflow conditions. Thus, the objective of this study is to analyze the influence of the inflow conditions on the external wall-bounded flow past the SD7003 airfoil and more precisely on the form and size of the laminar separation bubble. Motivated by the typically coarse resolution of the inlet region of the computational domain used for hybrid simulations, the synthetic turbulence is introduced within the flow field by a flexible source term treatment. The generated turbulent fluctuations are taken into account in the momentum equation by source terms and hence allow a shift from the inlet to a finer resolved region, where the damping of small structures due to the grid resolution is negligible. To provide a proper formulation of a synthetic turbulence inflow generator (STIG), the digital filter concept of Klein et al. (J. Comp. Phys. 186, 652–665, 2003) is merged with a large-eddy simulation (LES) as well as a hybrid LES-URANS method. The synthetically generated velocity fluctuations are distributed in an area of influence which is in accordance with the digital filter concept of the STIG. An automatic calculation of the dimension of the influence region is ensured by the employment of the integral scales which are used during the generation of the synthetic turbulence inflow generator inflow. The definition of the required input quantities for the STIG in case of the flow past a SD7003 airfoil at $\mathrm{Re}_c = 60{,}000$ and an angle of attack $\alpha = 4^\circ$ are based on experimental data including a turbulence intensity of $\mathrm{TI} = 0.28\%$. Due to separation, transition and subsequent reattachment this is a demanding test case in which the shape and the size of the separation bubble strongly depends on the oncoming turbulence. The reference velocity profiles of the experimental measurements are compared with a wall-resolved LES and hybrid simulations performed on two grids with a coarser resolution. The evaluation of the results of the simulations applying the STIG and without turbulence intensity showed an improved level of agreement between the STIG based simulations and the experiment. Moreover, the turbulence intensity is varied to understand the behavior of the LSB in more detail.

1. Introduction

As a result of increasing computational resources, eddy-resolving turbulence simulations become more and more common for industrially relevant applications. The information on large-scale flow phenomena such as massive separation or vortex shedding which vary in space and time are very important in order to enhance the performance of complex constructions. An appropriate simulation technique for the prediction of such complex flow structures is the large-eddy simulation (LES). However, for wall-bounded flows the required resolution has to follow the recommendation of Piomelli and Chasnov [1] defined in terms of $y^+_{1\mathrm{st}} < 2$, $\Delta x^+ = \mathcal{O}(50\text{–}150)$ and $\Delta z^+ = \mathcal{O}(15\text{–}40)$ not feasible in the near-future for airfoil flows at realistic Reynolds numbers (Re). The resulting computational grid which fulfills these specifications would require about 10^{11} control volumes (CV) for typical $\mathrm{Re} = 10^7$ of aerodynamic configurations [2]. Contrary to LES, the (unsteady) Reynolds-averaged Navier-Stokes (RANS/URANS) approach is able to capture a certain number of flows at high-Re on coarser grids. However, for flows deviating from the modeling assumption used during the derivation, even state-of-the-art RANS approaches are not able to deliver satisfying results. Therefore, the complementary advantages and drawbacks of both techniques lead to the obvious idea to benefit from synergy effects due to the coupling of both methods. Following this concept many researchers have paid an

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increased attention towards hybrid LES-URANS methods leading to a vast variety of concepts such as the improved delayed detached-eddy simulation by Shur et al. [3], the scale-adaptive simulation by Menter and Egorov [4] or the partially-integrated transport model by Chaouat and Schiestel [5] to mention only a few. In the present study the unified hybrid LES-URANS method by Breuer et al. [6] and Jaffrézic and Breuer [7] is applied. The behavior of this hybrid technique was carefully evaluated for a wide range of complex internal flows such as the periodic hill [7,8] as well as three-dimensional diffusers [8,9]. As recognized during the evaluation of the predictions for the external flow past a SD7003 airfoil [9,10], a strong dependency of the shape and size of the laminar separation bubble on the applied turbulence intensity (TI) of the oncoming flow was observed. Regarding experiments which can be found in the literature for the SD7003 airfoil flow, the spectrum of the measured turbulence intensity varies significantly. In an exemplary manner the experiments of Ol et al. [11] with TI $\approx$ 0.1%, Windte et al. [12] with TI = 0.16% and Hain et al. [13] with TI = 0.28% show the discrepancies concerning the turbulence intensity of the oncoming flow. Therefore, it is not astonishing that the measured separation points are highly scattered between $x_{\text{sep}}/c = 0.18$, $x_{\text{sep}}/c = 0.30$ and $x_{\text{sep}}/c = 0.35$, respectively[1]. Thus, in order to enable a comparison between the measurements and the simulations, the hybrid method was merged with a synthetic turbulence inflow generator (STIG) based on the digital filter concept by Klein et al. [14]. The first hybrid simulations applying the STIG at the inflow were performed for the channel flow and the periodic hill flow underlining the general applicability of the fusion of both concepts [15,16].

It has to be mentioned that a variety of literature is available for the topic of synthetic inflow generators, which cannot be reviewed here. For example, instead of using the three-dimensional filters proposed by Klein et al. [14], Xie and Castro [17] apply a two-dimensional filter. Furthermore, in contrast to the originally proposed Gaussian shape of the digital filters [14], they employ an exponential function [17]. The first modification increases the efficiency of the generation of the turbulent inflow content and the latter is motivated by the typical shape of correlations of inhomogeneous flow fields. The adopted approach of Xie and Castro [17] was used by Kim and Xie [18] to investigate the aerodynamics effects of a pitching airfoil with different levels of incoming turbulence intensity.

In association with hybrid methods the application of synthetic turbulence profiles as a volume forcing within the momentum equation at the crossover region between the RANS and LES area was investigated in various publications. An obvious concept to introduce synthetic fluctuations is the method proposed by Spille-Kohoff and Kaltenbach [19], where additional source terms in the wall-normal momentum equation are introduced at different planes in the streamwise direction. Based on a target distribution of the Reynolds shear stresses which can be provided by RANS pre-simulations or measurements, the flow field is forced to a desired downstream distribution due to the discrete amplification of additional velocity fluctuations. The amplifications are controlled by a function which compares the target value of the Reynolds shear stresses with the actual flow state. The method is successfully applied by Keating et al. [20] for a plane channel flow. The investigations showed that a certain number of control planes is required to reach after an acceptable development length a high level of agreement with a simulation applying periodic boundary conditions. Keating et al. [21] extended the application of the forcing term approach for a segregated hybrid method and added synthetic turbulence based on the method by Batten et al. [22]. The results for a turbulent boundary layer with a favorable pressure-gradient applying the additional amplification of the velocity fluctuations showed a shorter development length than without the employment of the triggering mechanism, where an unphysical relaminarization of the flow was observed.

An extension of the approach by Spille-Kohoff and Kaltenbach [19] was proposed by de Laage de Meux et al. [23] which takes the anisotropy of the flow into account and is at least theoretically independent of the coupling direction of the URANS and LES domain. However, due to the fact that de Laage de Meux et al. [23] only evaluated the method for the coupling between an upstream RANS region and a downstream LES area, the statement of the authors that this concept can be applied for every coupling direction must be verified by further investigations.

A different source term method was published by Davidson and Billson [24]. In order to avoid the modeled stress depletion (MSD) which is typically recognized by a kink in the mean velocity profile, the authors introduced an additional forcing term in the momentum equation of the LES generated by a STIG at the crossover region between the RANS and the LES domain. The method is used for the simulation of the plane channel flow. The synthetic turbulence is based on a modified von Kármán spectrum and the required input quantities consisting of an integral length scale and a velocity scale are taken from a DNS. The predictions considering the applied source term deliver an enhanced level of agreement with the DNS data of the mean velocity compared with the hybrid simulations without additional turbulent fluctuations. However, an overestimation of the velocity profile away from the wall is observed. As shown by the authors, the application of an increased integral length scale decreases the discrepancies between the hybrid simulation and the DNS for the velocity profile and thus illustrates the importance of suitable input quantities for a STIG.

A completely different application of source terms was suggested by Xiao and Jenny [25], where two grids with different resolutions are coupled. According to the different resolution requirements of RANS and LES, Xiao and Jenny [25] used two separate grids where the control volumes are distributed in such a manner that reasonable simulations either for the near-wall region by RANS or for the core of the flow by LES are achieved. Due to the introduction of source terms depending on the LES predictions within the momentum equation of the RANS calculation (and vice versa), a consistent crossover between both simulations is ensured.

Thus, the main motivation for the application of forcing terms within a hybrid simulation is twofold. As briefly sketched in the literature overview, very often some extra terms are introduced at the crossover between regions applying different simulation concepts in order to avoid inconsistencies and mismatches. On the contrary, source terms can also be applied to guarantee appropriate inflow conditions. In the context of the present unified hybrid method used for the simulation of the flow past the airfoil SD7003, the second case is on hand since the hybrid technique works with a dynamically adjusted interface definition disclaiming additional source terms at the crossover between URANS and LES. The source terms are solely introduced in front of the airfoil to set the same free-stream turbulence intensity as measured in the experiment by Hain et al. [13]. Hence, the employment of additional synthetic turbulence does not address the issues to solve the MSD problem occurring at the interface between RANS and LES as presented by some authors mentioned in the short overview before.

When inflow boundary conditions using synthetic turbulence are set at the inflow of the computational domain the coarse resolution typically applied in this region leads to a damping of small fluctuations and subsequently to a blurred flow. In order to circumvent the problem of the coarse resolution at the inlet region, an appropriate measure is to apply source terms within the computational domain which allow the introduction of artificial

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[1] The chord length of the airfoil is denoted c.