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A zonal RANS–LES method for compressible flows

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ABSTRACT

A zonal Reynolds-averaged Navier–Stokes (RANS) – large-eddy simulation (LES) method for compressible flow problems is presented and applied to generic flow problems. The quality of the method is shown by comparing zonal RANS–LES results, pure LES, pure RANS, and direct numerical simulation (DNS) data. For the transition from the RANS to the LES regime the zonal RANS–LES approach uses a synthetic eddy method combined with control planes downstream of the embedded LES interface. This combined approach reduces the RANS-to-LES transition length to less than three boundary-layer thicknesses. At the embedded LES outflow interface a reconstruction of the turbulent eddy viscosity ensures a smooth LES-to-RANS transition. The numerical scheme of the zonal RANS–LES method is validated for compressible zero-pressure gradient boundary-layer flow and then applied to the fundamental problem of a shock-wave turbulent boundary-layer interaction (SWBLI). For both problems, a smooth transition of mean flow quantities from the RANS to the LES regime was achieved and the low frequency pressure signals were transferred without spurious disturbances from the LES to the RANS domain. For the SWBLI case the time- and spanwise averaged pressure, wall-shear stress, and Reynolds-stress distributions agree well with the pure LES and DNS reference data. This zonal method can be directly extended to more intricate flow problems.

1. Introduction

Despite enormous computer power most computational fluid dynamics (CFD) applications are based on solutions of the Reynolds averaged Navier–Stokes (RANS) equations using turbulence models of varying complexity. The reason for the RANS popularity is obvious. The methods are straightforward to apply for a wide range of external and internal flow cases and computationally efficient such that nowadays they are used for design and/or optimization analysis and for problems where experimental data are hard to be obtained [7,51]. However, whenever the flow problem no longer satisfies the condition of a turbulent equilibrium flow, i.e., when the streamlines are strongly curved, pronounced adverse pressure gradients are encountered, or transition or relaminarization occur, the quality of the results is clearly reduced [27,23]. Although numerous modifications and new concepts of turbulence modeling, i.e., algebraic Reynolds-stress models, non-linear eddy-viscosity closures, etc., were proposed over the last decades [49,18], a clear breakthrough in RANS models to be applicable to non-equilibrium flows has not been found, yet.

In the large-eddy simulation (LES) concept only the dissipative scales of turbulence, which are assumed to have a more isotropic character than larger scales in a shear-driven flow, are modeled while the eddies carrying the bulk of energy of the flow are resolved. Therefore, unlike the RANS ansatz the LES concept can be applied to non-equilibrium flow problems due to the resolution of the relevant turbulent scales. However, in the proximity of walls the number of grid points rises drastically since the time and length scales of the energy containing eddies become very small. This prevents LES from being immediately applied to large scale flow problems.

Since in the method of direct numerical simulation (DNS) all flow scales are resolved due to a sufficiently high grid resolution, no modeling is required [38]. That is, the DNS method represents the physically and mathematically most reliable approach to fundamentally analyze turbulent flows. Unfortunately, due to the necessity of resolving all relevant time and length scales of a turbulent flow the application of DNS is limited to low Reynolds number flows. It is an excellent method for fundamental research to improve the detailed knowledge of turbulence and to develop new models to describe the mean turbulent flow structure. However, due to the enormous computer power required, which will not be available in the next decades, DNS will not be used to investigate any industrial or technologically relevant flow problem [44].

When technical flow problems are tackled it is obvious that large regions of the flow domain, where the turbulent flow is in equilibrium, e.g., in attached flows over slender bodies, can be computed by the RANS ansatz. There are, however, regions in the

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flow domain which require a higher-order turbulence description, i.e., an LES, to capture relevant flow physics. This is, for instance, the case when a pronounced adverse pressure gradient generated by a shock wave interacts with the boundary layer such that the flow separates and the dissipation and production in the turbulent flow are no longer in equilibrium. The detailed analysis and accurate prediction of such a flow pattern is quite essential, e.g., at transonic flows over wings or supersonic flows in air intakes to mention just a few, since the overall aerodynamic efficiency is impaired by this shock-wave/turbulent boundary-layer interaction (SWBLI) phenomenon [26,1]. Therefore, it makes sense to combine RANS and LES simulation methods to reduce the computational effort on the one hand, and to ensure a physically reliable solution in the entire flow domain on the other hand.

An overview of hybrid and/or zonal RANS–LES approaches is given in [16]. There are at least two techniques to couple RANS with LES in hybrid computations. The first approach uses a continuous turbulence model, which switches from RANS to LES to close the system of equations in a unified domain, such as the detached-eddy simulation (DES) proposed by Spalart et al. [45]. Various methods exist in the literature which follow this concept. Generally, the transition from RANS to LES is triggered by the local grid size, which means that wherever the mesh is fine enough to resolve relevant energy containing eddies the eddy viscosity of the RANS model is reduced. In standard DES simulations RANS–LES interfaces are often located in free shear layers being shed from sharp corners where the disturbances are strongly amplified and the transition to physical turbulence is short. In wall-bounded shear layers, which encounter a local flow separation being caused only by an adverse pressure gradient and without any drastic geometric alteration, the shear layer instability mechanism may not suffice to strongly generate turbulent eddies in the outer shear layer while the modeled turbulence of the RANS part decreases. In the RANS part of the flow only the large scale unsteadiness and the Reynolds shear stress provided by the turbulence model are included whereas the resolved eddies of the LES part do also contribute to the shear-stress budget. The transition from RANS to LES is locally not properly described and hence, it deteriorates the downstream flow field. In this zone, where the resolved eddies grow, the flow can be considered in an artificial numerical transition state. The development of turbulent structures is highly grid dependent and the propagation of structures from a coarse to a fine grid region might not be properly described.

The second technique uses two or more predefined separate computational domains being linked via an overlapping zone where the transition from RANS to LES and vice versa occurs. In the defined RANS region a coarse mesh is applied and in the LES regions a fine mesh allows the required resolution of the turbulent flow features. The interface conditions for the RANS and LES regimes constitute the major challenge of this zonal technique. For the transition from RANS to LES the information of the turbulent flow of the RANS domain must be used to generate physically and mathematically relevant turbulent eddies in the sense of the discrete Navier–Stokes equations within the overlapping zone of the RANS and LES domains. Richez et al. [40] applied predefined RANS and LES regions to compute the incompressible flow over an airfoil, however, without using a special formulation of the RANS-to-LES boundary condition. Schlüter et al. [41] used a large-eddy simulation where the turbulent fluctuations were scaled and superimposed on a mean velocity profile obtained from a RANS solution. This approach is computationally expensive and a proper scaling for flows over complex geometries may not be available. Another possibility is to apply the synthetic-eddy method (SEM) by Jarrin et al. [19] or the synthetic homogeneous turbulence method by Kraichnan [25], which was extended to inhomogeneous flows by Smirnov et al. [42] and Batten et al. [3]. A similar method based on the specification of autocorrelation lengths was developed by Klein et al. [22] and di Mare et al. [12]. Pamiès et al. [32] extended the method of Jarrin et al. [19] by decomposing the inflow plane of an incompressible flat plate boundary layer into several zones depending on the wall distance. At each zone turbulent eddy shapes are prescribed in the sense of Marusic [30].

Following the idea of Keating et al. [21] and de Prisco et al. [9] this development region can be significantly shortened by combining a synthetic turbulence generation method (STGM) with controlled forcing [46] that is applied downstream of the LES inlet. For incompressible flows, this method provided transition lengths of about two to three boundary-layer thicknesses. The idea of Keating et al. [21] will be pursued for compressible flows in this paper. For the LES-to-RANS transition an interface condition is required that computes at the RANS inflow a proper turbulent viscosity besides the averaged flow quantities provided by the upstream LES flow domain. The approach of König et al. [24] can be used to reconstruct the required turbulent viscosity based on LES or DNS data without the requirement to solve the transport equations in the entire LES domain.

It goes without saying that the quality of the solutions based on the second zonal techniques depends on the formulation of the embedded RANS–LES and LES–RANS boundaries. In the following, it will be shown that this problem can be convincingly solved also in highly compressible flows. To be more precise, the purpose of this study is twofold. First, a zonal RANS–LES method to determine compressible flow fields in which the shock-wave/turbulent boundary-layer interaction phenomenon plays an essential role is presented. Second, it will be evidenced that the solutions of the zonal method possess the same accuracy like the results of pure LES or DNS methods. Note that the analysis does not focus on the maximum computational efficiency. The purpose of this work is to present a method validated by generic flow problems that can be extended to more realistic flow problems. That is, for instance a high-lift configuration [10,47,54] is considered, where the LES zone is restricted to the slat area an order of magnitude saving of computing time can be expected to be achieved.

The paper is organized as follows. In Section 2, the numerical flow solver, the synthetic turbulence generation method, and the turbulent reconstruction method are described. That is, the zonal RANS–LES method is introduced in detail. Subsequently, in Section 3 the flow problems, i.e., the compressible flat-plate flow and the shock-wave/turbulent boundary-layer interaction (SWBLI), are described. Section 4 contains the results. First, the validation of the zonal method is discussed based on the findings of the flat-plate flow and then, a detailed comparison of the results of the SWBLI problem of the zonal RANS–LES method with pure LES and reference DNS data is presented. Finally, some concise conclusions are drawn.

2. Zonal RANS–LES method

2.1. Flow solver

The Navier–Stokes equations of a three-dimensional unsteady compressible flow are discretized by a mixed centered upwind AUSM (advective upstream splitting method) scheme [28] at second-order accuracy for the Euler terms and the non-Euler terms are discretized second-order accurate using a centered approximation. The temporal integration is done by a second-order explicit 5-stage Runge–Kutta method.

The LES formulation is based on the MILES (monotone integrated LES) approach [5] to model the impact of the sub-grid scales. A detailed description of the fundamental LES solver is given by Meinke et al. [31] and the convincing quality of its solutions in