NUMERICAL MODELING OF SYNTHETIC TURBULENCE GENERATION BY USING ZONAL RANS/LES METHOD

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Abstract A synthetic turbulence generation (STG) method for flows at low and high Reynolds and Mach numbers to provide LES inflow boundary conditions of zonal RANS/LES method simulations is presented. The present method separates the LES inflow plane into three sections where a local velocity signal is decomposed from the turbulent flow properties of the upstream RANS solution. Depending on the wall-normal position in the boundary layer the local flow Reynolds and Mach number specific time, length, and velocity scales with different vorticity content are imposed on the LES inflow plane. The STG method is assessed by comparing the resulting skin-friction, velocity, and Reynolds-stress distributions of zonal RANS-LES simulations of subsonic and supersonic flat plate flows with available pure LES, DNS, and experimental data.

INTRODUCTION

Most of the industrial CFD simulations at high Reynolds numbers are nowadays based on solutions of the RANS equations. The reasons for their application are obvious since they are simple to apply and computationally efficient. Therefore, they are used for the flow analysis at design and offdesign conditions, for optimization, and large scale flow cases where experimental data may not be easily obtained. However, in most of the practically relevant flow problems the condition of a turbulent equilibrium is not satisfied, i.e., when strong pressure gradients or flow separation occurs, which impairs the results obtained by one- and two-equation turbulence models [1, 2]. The alternatives to RANS modelling are direct-numerical and large-eddy simulation (DNS and LES).
An overview of hybrid RANS-LES approaches is given in [3]. 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. [11]. 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. However, the development of physical turbulent structures is hence 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 that are 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 LES regions a fine mesh is used to allow the required resolution of the turbulent flow features. The interface conditions used 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 applied 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. That is, the mean velocity distribution of the RANS solution and turbulent fluctuations are imposed at the inflow boundary of the embedded LES domain. There exist several possibilities to generate such turbulent fluctuations at the inflow boundary [6]. The method of Keating et al. [5] and de Prisco et al. [7] significantly shortened this development region by combining a synthetic turbulence generation (STG) method with controlled forcing [12] that is applied downstream of the LES inlet. For incompressible flows, this method provided transition lengths of about two to three boundary-layer thicknesses. A similar method was applied by Roidl et al. [8, 9, 10] to successfully analyze a supersonic shock-boundary-layer interaction and the buffet phenomenon at a transonic airfoil, respectively. Pami`es et al. [6] expanded the method of Jarrin et al. [4] by dividing the inflow plane of an incompressible flat plate boundary layer in several zones depending on the distance from the wall.

SYNTHETIC TURBULENCE GENERATION METHOD

The method is based on the work of Jarrin *et al.* [4] and Pamies *et al.* [6], called synthetic eddy method (SEM), which describes turbulence as a superposition of coherent structures. These structures are generated over the LES inlet plane by superimposing the influence of virtual eddy cores that are defined in a specified volume around the inlet plane that has the streamwise, wall-normal, and spanwise dimensions of the turbulent length-scale l_1, the boundary-layer thickness at inlet δ_0, and the width of the computational domain L_z, respectively. N virtual eddy cores are defined at positions x_m^i inside of the virtual box and their local influence on the velocity field is defined by a shape function σ

which describes the spatial and temporal characteristics of the turbulent structure. The normalized stochastical velocity fluctuation components $u_m^{'}$ at the coordinate x_m at the LES inflow plane reads

$$u_m^{'}(x_{1,2,3},t) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \varepsilon^i f_{\sigma^m}(\tilde{x}_n), \tilde{x}_n = \frac{x_n - x_n^i}{l_n}$$

where the superscript i denotes a virtual eddy core, ε^i the random sign, and m, n=1,2,3 the Cartesian coordinates in the streamwise, wall-normal, and spanwise direction, respectively. The shape function f_{σ^m} has a compact support on $[-l_n, l_n,]$ where l_n is a length scale which satisfies the normalization condition $\frac{1}{\sqrt{2\pi}} \int_{-1}^{1} f_{\sigma^m} d\tilde{x}_m = 1$.

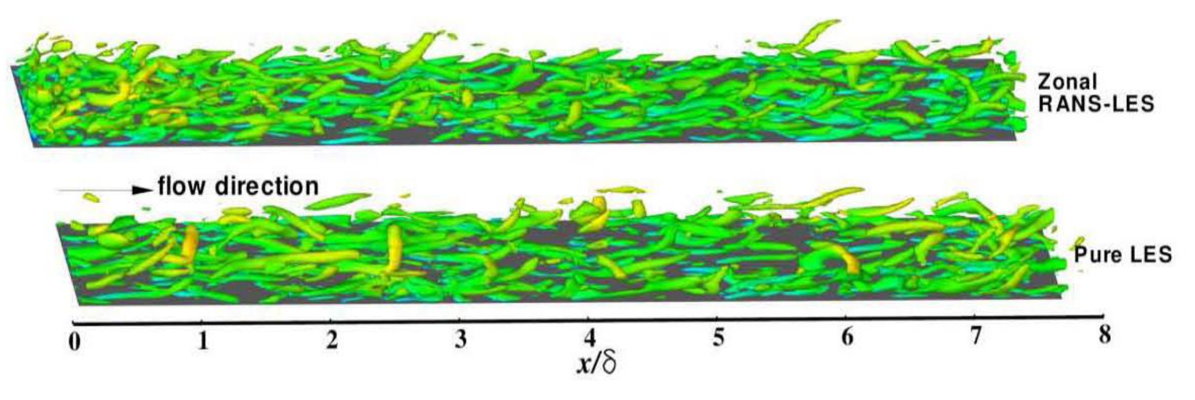

Figure 1. Coherent turbulent structures based on the λ_2-criterion with mapped-on local Mach number for subsonic flat-plate boundary layer.

Coherent turbulent structures based on the λ_2-criterion in the subsonic boundary layer with mapped-on Mach number contours are visualized in Fig. 1 for the zonal RANS-LES solution and the pure LES. A synthetic turbulence generation method for a zonal RANS-LES method for sub and supersonic flows has been introduced. The STG method has been validated by computing a subsonic boundary-layer flow at $M = 0.4, \mathrm{Re}_\theta = 1400$ and a supersonic flow boundary-layer flow at $M = 2.3, \mathrm{Re}_\theta = 4200$, respectively. The zonal RANS-LES solutions have been compared with pure LES, pure RANS, DNS, and experimental data.

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