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Influence of synthetic inlet turbulence on the prediction of low Mach number flows

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ABSTRACT

Time-resolved numerical simulations of fluid flows, such as Large Eddy Simulations (LES), have the capability of simulating the unsteady dynamics of large scale energetic structures. However, they are known to be intrinsically sensitive to inflow conditions the modeling of which may become a crucial ingredient of the computational model. The present work reports LES of both reactive and non-reactive turbulent channel flows. The flow configuration and associated conditions correspond to those associated with a reference experimental database that has been gathered at the French aerospace Laboratory of Onera. The focus of our study is placed on the influence of synthetic inlet turbulence in this experimental geometry, i.e., the principal aim is to investigate the sensitivity of the flow dynamics and mixing to inflow conditions. The analysis undoubtedly confirms that, even with properly set mean velocity and turbulence kinetic energy profiles as available from experimental data, both non-reactive and reactive flow fields still remain very sensitive to the choice of the synthetic turbulence model. This sensitivity is illustrated for four distinct turbulent inflows obtained from *white noise* (WN), *digital filter* (DF) by Klein et al. (2003), *random flow generator* (RFG) by Smirnov et al. (2001), and *synthetic eddy model* (SEM) by Jarrin et al. (2009). Finally the results obtained for reactive flow conditions clearly emphasize the influence of the retained model on the chemical reaction rate statistics. This conclusion confirms how relevant are the developments devoted to synthetic turbulence for the computational investigation of turbulent combustion.

1. Introduction

It is well known that a subject of great importance for fluid flow numerical simulations is the prescription of correct and realistic boundary conditions. For outflow conditions, it appears that the use of a buffer zone [6] or an advective boundary condition [35], or even a combination of both, may adequately describe several flow conditions of practical interest. The present work is focused on low Mach number flows and the main difficulty is thus concentrated on the settlement of the inlet velocity field. In contrast, for compressible flows, specifying the fourth variable (pressure, density, temperature or characteristic wave) may also become a critical issue which raises a wide range of additional specific difficulties. In such conditions, elaborate strategies should be used to avoid pressure wave reflections, see for instance Rudy and Strikwerda [40]; Thompson [47]; Poinsot and Lele [36]; Albin et al. [1]. The specification of inflow boundary conditions may also raise several issues. Most flows encountered in real applications are, indeed, spatially developing turbulent flows. Hence, they pose a great challenge for numerical simulations due to the need to prescribe time-dependent turbulent inflow data at the upstream boundary. For steady Reynolds-Averaged Navier–Stokes (RANS) simulations, simple analytical or experimental profiles are retained for mean velocity components and turbulent characteristics. For LES or Direct Numerical Simulations (DNS), however, the inflow data should consist of an unsteady fluctuating velocity signal representative of the turbulent velocity field at the inlet.

A basic technique to generate such a turbulent inflow data consists in taking a mean velocity profile with superimposed random noise. The major drawback of such a methodology is that the resulting inflow data do not exhibit any spatial and/or temporal correlations. The energy generated is, also, uniformly spread over all wave numbers and, due to the lack of large scale energy-containing structures, *turbulence* is quickly dissipated [19].

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In principle it may be possible to predict turbulence via a LES technique by starting from a quiescent flow or with the mean flow field obtained from RANS simulations. Unfortunately, a very long time is required for a turbulent flow to spatially and temporally develop [45]. Ideally, the simulation of the upstream flow entering a computational domain would provide realistic inlet conditions to the simulation of interest. However, due to the computational cost, the domain cannot be extended upstream indefinitely, and approximate turbulent inlet conditions must therefore be specified.

There are several ways to remedy this situation, and the existing methods belong to two principal categories: *(i) mapping or recycling methods*, in which some sort of turbulent flow is pre-computed, prior to the main calculation, and subsequently introduced at the domain inlet, and *(ii) synthetic turbulence methods*, in which some form of random fluctuation is generated, modulated according to experimental data, and combined with mean inflow. Other appealing strategies have been introduced in the literature, some of them are based on Fourier techniques, and others rely on the Proper Orthogonal Decomposition (POD) introduced by Lumley [29], see for instance Druault et al. [12].

The present manuscript is organized as follows: first a brief description of recycling methods is provided. Further, synthetic turbulence generators are presented, and the four methods considered in the present work are detailed: (i) the *white noise* (WN), (ii) the digital filter (DF) method proposed by Klein et al. [21], (iii) the *Random Flow Generator* (RFG) introduced by Smirnov et al. [45] and (iv) the *Synthetic Eddy Method* (SEM) of Jarrin et al. [19]. The synthetic turbulence generators have been implemented in a low Mach number Navier–Stokes solver, the main features of which are presented, including a brief description of both mathematical and numerical aspects. As a preliminary step of verification and validation, the methods are applied to the description of homogeneous isotropic turbulence. The computational programs are then further assessed by analyzing their capabilities of generating a fluctuating signal which reproduces a given stress tensor and features an energy spectrum similar to the one associated with a fully developed turbulent flow spectrum. The former means that the inflow data generator should be able to reproduce an anisotropic turbulent velocity field at the inlet. The paper ends with the application of the above-mentioned synthetic turbulence generators to the numerical simulation of high speed non-reactive and reactive turbulent mixing layers, which were experimentally studied by Moreau and Boutier [32], see also Magre et al. [31]. Comparisons with available experimental data are provided.

2. Literature review

The specification of realistic turbulent inflow boundary conditions remains a challenging issue for both LES and DNS. This is quite a contrast to RANS or URANS applications for which a scale separation argument is implied between the unsteadiness of the mean flow field and the associated turbulent fluctuations. The quantities being computed in RANS or URANS are thus steady or varying on a characteristic time scale that is much larger than the computational time step. Such a scale separation argument does not hold for DNS or LES which therefore require a special treatment of turbulent fluctuations at inlet conditions. A review of some of the existent methods that deal with the specification of such turbulent inflow conditions is provided below.

2.1. Mapping methods

The most accurate method to specify turbulent fluctuations for either LES or DNS would probably consist in running a suitable precursor simulation with the purpose of providing the main simulation with accurate boundary conditions. However, such a procedure has been used only when the turbulence at the inlet can be regarded as a fully developed or a spatially developing boundary layer. In these cases periodic boundary conditions in the mean flow direction can be applied to the precursor simulation. In general, the simulation of the precursor flow is initialized with a mean velocity profile perturbed with a few unstable Fourier modes. Instantaneous velocity fluctuations in a plane positioned at a fixed streamwise location are extracted from the precursor simulation and prescribed at the inlet of the main simulation at each time step.

In practice, periodic boundary conditions can only be used to generate inflow conditions for homogeneous flows in the streamwise direction, which restricts their applications to simple fully developed flows. A more flexible technique to generate inlet conditions, also based on the procedure of recycling the velocities in a plane located several boundary layer thicknesses downstream of the inlet, has been proposed by Lund [30]. In this framework, the velocity field at the re-scaling station is decomposed into mean and fluctuating components; scaling is applied to the mean and to the fluctuating parts in the inner and outer layers to account for the different similarity laws that govern both regions. The scaled velocity is then re-introduced as a boundary condition at the inlet of the computational domain. The use of such a methodology results in a spatially evolving boundary layer simulation that is capable of generating its own inflow data.

Another strategy has been followed by Li et al. [26] who proposed a procedure to reduce the storage requirement, as well as the computational cost associated with a precursor calculation. A spatially developing turbulent mixing layer, originating from the mixing of a low-speed and a high-speed boundary layer flow at the end of a splitter plate, is simulated within the LES context. However, instead of simulating the precursor boundary layer flow fields, only a time series of instantaneous velocity planes with duration approximately equal to the integral time scale of the flow is extracted from a boundary layer simulation. The resulting signal is converted into a periodic one using a classic windowing technique, and it is used, as many times as required, to obtain converged statistics in the main simulation. This methodology is beneficial from both the computational and storage points of view, since the precursor simulation is run over a short duration only and the data used to generate the inflow correspond to a few integral time scales of the flow. For the investigated mixing layer simulation, the periodicity involved by the inflow decays rapidly, in approximately 25 per cent of the total length of the computational domain. However, Li et al. [26] reported that the resort to this procedure for wall-bounded flows, where destabilizing effects remain relatively weak, might require a longer transition region to weaken the effects of the periodicity condition that is involved in the inflow prescription.

Finally, Bodony [6] noted that the method introduced by Lund [30], i.e., random uncorrelated fluctuations superimposed on a mean velocity profile, is very sensitive to the initialization of the flow field. Bodony [6] also stated that the generation of fully developed turbulence cannot be obtained from such a strategy and, hence, proposed a more robust variant of the original method of Lund [30], where the flow field is initialized thanks to synthetic turbulence with prescribed energy spectrum and shear stress profile.

To conclude it is noteworthy that other mapping techniques have been proposed in the context of hybrid RANS-LES simulations. For instance, Schlüter et al. [42] fed the LES of a combustor with the Favre-averaged mean velocity field $\tilde{u}_i$ issued from a RANS solution together with a fluctuating component $u_i - \widetilde{u}_i$. The latter is extracted from a database which was generated from an auxiliary LES computation and the corresponding turbulent fluctuations are