Computers & Fluids 93 (2014) 116–128

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Evaluation of scale resolving turbulence generation methods for Large Eddy Simulation of turbulent flows

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ARTICLE INFO

Article history:
Received 29 April 2013
Received in revised form 23 October 2013
Accepted 9 January 2014
Available online 28 January 2014

Keywords:
Inlet boundary
Turbulence generation
LES
Turbulent boundary condition

ABSTRACT

Large Eddy Simulation (LES) has become an attractive simulation method even for technical processes and it usually provides space and time resolved fluctuations of a significant portion of the spectrum. However, in contrast to a RANS simulation an accurate LES requires the definition of suitable initial and boundary conditions, which includes turbulent structures with physically sound spatial and temporal correlations. Such turbulent structures are usually generated artificially at the boundary. Three different algorithms for generating turbulent fluctuations are evaluated in the present work. The investigated methods are Filtered noise [1], Diffused noise [2] and an Inverse Fourier approach [3,4]. These techniques were developed for generating inflow data for LES and have already been used in published research [5–15], e.g. for investigating turbulent combustion processes. In the present work the turbulent statistics i.e. energy spectra and velocity correlations as well as derived quantities such as turbulent kinetic energy and subgrid scale viscosity are investigated in more detail in a comparative fashion for the generated turbulent velocity fields. As a simple test case, the decay of turbulence in a cubical box, is considered here to provide information on the initially generated turbulence as well as its temporal evolution. The results are analyzed in detail and are compared to experimental data. Turbulence fluctuations generated by Filtered noise and Diffused noise lead to similar results. The resulting energy spectra and velocity correlations agree generally well with experimental data despite some discrepancies at very early times after initialization. The Inverse Fourier approach yielded good agreement at all times, but at increased computational cost. In addition, the implementation of Filtered noise and Diffused noise might be easier for most cases of practical interest. In particular, the Diffused noise approach can be used for the generation of inhomogeneous turbulence on arbitrary grids.

1. Introduction

Turbulent fluid motion plays a central role in most flow configurations of technical interest and it introduces special requirements for their simulation. One possibility to capture turbulent fluctuations is the use of Large Eddy Simulation (LES) providing a partially space and time resolved solution at moderate computational effort. Depending on the grid and time resolution, a significant portion of the turbulent spectrum is resolved and this (also considering the coupling of turbulence with other processes such as combustion) usually leads to more predictive simulations when compared to RANS approaches.

A crucial element of any numerical simulation is the definition of proper boundary conditions. The suitability of the prescribed physical quantities at the domain boundaries is essential for getting accurate results. Since in LES turbulent structures are resolved both in space and time, the velocity field at the inlet has to contain space and time dependent fluctuations superimposed on the mean velocity. These fluctuations have to be physically meaningful making the definition of inflow boundary conditions a challenging task. The spectral content of the velocity signal and the spatial and temporal correlation of the eddies are two characteristic properties, which have to be satisfied. Different techniques for generating turbulent data at the inflow plane of the simulation domain were developed to fulfill the requirements of turbulent inflow conditions

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http://dx.doi.org/10.1016/j.compfluid.2014.01.013
0045-7930/

Nomenclature

C_s	Smagorinsky constant	$\mathcal{R}$	random number
CFD	Computational Fluid Dynamics	*RANS*	Reynolds averaged Navier–Stokes
Co	Courant number	$S_{i,j}$	strain rate
D	diffusion coefficient	t	time
DN	Diffused Noise	$\mathcal{T}$	rate of transfer of turbulent kinetic energy
$\mathcal{D}$	dissipation of turbulent kinetic energy	u_i	velocity
E	specific kinetic energy	u_{rms}	root-mean-square velocity
f	longitudinal velocity correlation	$\delta_{i,j}$	Kronecker delta
FN	Filtered Noise	Δ	filter width
FT	Fourier transform	ε	dissipation rate
g	transverse velocity correlation	ϕ	phase of Fourier mode
HIT	homogeneous isotropic turbulence	κ_j	wave number vector
IF	Inverse Fourier approach	κ_e	wave number of most energetic scales
k	turbulent kinetic energy	κ_{kol}	wave number of most dissipative scales
L_{int}	longitudinal integral length scale	ν	kinematic viscosity
M	size of active grid	σ_i	direction of Fourier mode
M_i	number of elements of simulation domain	τ	integral time scale
NRC	numerical reference case	$\tau_{i,j}$	stress tensor
$\mathcal{P}$	production of turbulent kinetic energy	η	Kolmogorov length scale
r	separation distance between correlated points	$\langle\rangle$	time average
R	auto-correlation function		

[1,2,4,16–19]. Performing an auxiliary simulation is one possible way of defining suitable inflow turbulence. The simulation domain is extended upstream from the inlet to allow the turbulence to develop naturally. The additional computational effort, which increases the cost and time of the whole simulation is the main drawback of this procedure [2]. Another possibility is to artificially generate turbulent fluctuations. In this context one way is to apply an inverse Fourier transform on a predefined energy spectrum function [20,21]. The velocity can then be determined from the calculated Fourier coefficients. This algorithm is used for validating the numerical setup in Section 4.1. The method generates velocity fields which satisfy a desired energy spectrum and continuity, but the algorithm is difficult to implement, particularly for anisotropic turbulence [1] or arbitrary grids. A comparative study of different inflow boundary conditions including recycling and rescaling as well as precursor-like approaches was presented by Pronk and Hulshoff [22]. The algorithms were applied and evaluated for a boundary layer flow on a flat plate. A detailed review on different techniques for the generation of turbulence at inlet boundaries was presented by Tabor and Baba-Ahmadi [23].

For the present work three different methods for generating artificial turbulence – proposed by Klein et al. [1], Kempf et al. [2] as well as Billson et al. [3] and Davidson [4] – are investigated in more detail. The approach of Klein et al. [1] is based on digital filtering of random data and is referred to as Filtered Noise (FN). Kempf et al. [2] diffuse random noise to obtain correlated turbulent structures. Hence the algorithm is denoted Diffused Noise (DN) in the following. The turbulence generation method proposed by Billson and Davidson is based on random Fourier modes of a prescribed energy spectrum. The algorithm is designated Inverse Fourier approach (IF) in the remainder of this text. These algorithms were developed for generating turbulent inflow data and have widely been used in research on different issues ranging from flame modeling in gas turbines to turbulent jet flows. Several examples of their application are found in [5–15]. However the characteristics of the generated turbulence has not been investigated in detail yet. Knowing the properties of the turbulent inflow data, such as spectral content, can improve the understanding of problems, which might occur in the simulation. E.g. the dissipation of turbulent kinetic energy strongly depends on the velocity gradients of the smallest resolved length scales. If an artificially generated turbulence field does not contain eddies at these scales the dissipation will be underpredicted considerably. Thus the aim of the present work is to investigate the quality of the three algorithms with respect to the following issues:

- Does the generated velocity field fully represent the characteristic energy spectrum for homogeneous isotropic turbulence (HIT)?
- Does the generated velocity field reproduce physically correct longitudinal and transverse velocity correlations?
- How do the turbulent properties develop in time during the decay of turbulence in a box?
- Which characteristics of the different algorithms have to be considered for their application?

2. Fundamentals

2.1. Simulation theory

For the present analysis it suffices to consider constant property flows at low Mach numbers. Then, the conservation equations for mass and momentum reduce to [24]

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

and

$$\frac{\partial u_j}{\partial t} + \frac{\partial u_i u_j}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j}\right) \tag{2}$$

where u, p, ρ and ν are velocity, pressure, density and kinematic viscosity, respectively. For the present investigation LES are performed where these equations are spatially filtered in order to separate larger and smaller length scales. Those smaller length scales, which are not resolved directly have to be considered by subgrid scale closure. In this context the standard Smagorinsky model is one of the most frequently used approaches. It is based on Boussinesq's hypothesis of the eddy viscosity, which describes a propor-