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On the generation of synthetic divergence-free homogeneous anisotropic turbulence

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Highlights

- Traditional methods used for the generation of synthetic turbulence are reviewed.
- The mechanisms embedded in the DSRFG method are discussed in detail.
- Two new approaches to the generation of homogeneous divergence-free velocity fields are proposed.
- An anisotropic field characterized by prescribed spectra and length scales is successfully synthesized.

Abstract

It is well known that the generation of appropriate unsteady boundary conditions represents an important component of successful Large Eddy Simulations in turbulent flows. In particular, when Computational Wind Engineering applications are considered, a recurrent problem consists in imposing turbulent fluctuations characterized by given spectra and length scales at the inlet boundary. In the present contribution, firstly, currently available techniques for the generation of synthetic turbulence are revised with a focus on their mathematical formulation. Then, two new approaches for the generation of homogeneous turbulence are proposed. The first one can be seen as a correction over existing techniques which allows to control the obtained length scales. The second method, conceived to generate anisotropic turbulence characterized by arbitrary harmonic content in both time and space, is designed to be computationally efficient, to guarantee the divergence-free condition and to ensure a good approximation of the resulting turbulence integral scales. Finally, the procedure is validated by synthesizing a homogeneous turbulent field characterized by time and length scales typical of the atmospheric boundary layer showing good results.

Keywords: Synthetic turbulence; Random fields; LES; Inflow conditions

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1. Introduction

The generation of unsteady synthetic turbulent flow fields represents an important step in the setup of Large Eddy Simulations (LES) in turbulent flows. In particular, it is well known that the characteristics of the incoming turbulence can greatly affect the aerodynamic behavior of immersed bodies and deeply contribute to determine both the time-averaged and the fluctuating pressure fields recorded on their exposed surfaces.

As pointed out in numerous experimental and numerical studies [1–5], the interaction between the incoming disturbances and the flow field developed around an immersed body is established mainly by means of two mechanisms. On the one side, small scale turbulence directly contributes to destabilize the shear layers detached from the body corners so generally leading to a shortening of the separated zones. On the other side, large scale turbulence interacts with the body in a quasi-static way leading to unsteady variations of the apparent wind attack angle. Besides such extreme cases, for turbulent structures characterized by length scale comparable to the immersed body size, the interaction can become extremely complex. In this case, the incoming disturbances directly interact with the vortex development and shedding mechanisms so affecting their detachment frequency and coherence. In such a context, the development of appropriate boundary conditions for LES becomes a crucial point for the setup of accurate numerical simulations.

Numerous techniques have been proposed throughout the literature aiming at producing appropriate unsteady boundary conditions for LES. In particular, two main approaches are generally followed: recycling/rescaling methods and synthesis methods [6]. The first approach requires a database of velocity and pressure fluctuations to be used as inlet condition for the numerical simulation [7]. The database can be obtained by means of either a precursor simulation or wind tunnel measurements. If a precursor simulation is adopted, the computational cost of the LES, needed to obtain a fully developed turbulent field, could be remarkable and comparable to the main simulation. When such a strategy is adopted, a large amount of data needs to be stored and the resulting energy spectrum and spatial correlations might be difficult to be controlled *a priori*.

The second approach consists in artificially generating the turbulent fluctuations by using random sequences and can be, in turn, particularized into three main categories. In the first category of synthesis methods, the spectrum of the wind velocity fluctuations is used in order to build a trigonometric series with Gaussian random coefficients [8]. The main advantage of this procedure is that the Power Spectral Density, PSD, of the resulting velocity field can be controlled in the generation procedure. The main shortcoming is represented by the fact that, in order to control spatial correlations, the field cannot be generated independently at each point, so rendering the procedure inefficient for parallel computations. In addition, the resulting velocity field does not respect the divergence-free (solenoidal) condition. A modification of such procedure allows to take into account the divergence-free condition [9,10] making use of the Taylor hypothesis of frozen turbulence. In such case, direct control over the resulting spectral content is lost while the disadvantages of the previously presented procedure, related to its non-optimal behavior in parallel computations, remain unsolved.

The second category of synthesis methods is represented by the Vortex Method and the Synthetic Eddy Method [11–13]. These methods generate a velocity field correlated both in space and time but no explicit control is provided over the obtained spectra.

Finally, the third category of synthesis methods is mainly based on the work presented by Kraichnan [14] which, indeed, represents the ancestor of a multitude of techniques which, due to their flexibility and computational efficiency, constitute the most widely spread and promising turbulence generation techniques adopted today [15–17,4,5]. By using such an approach, the spectral content of the resulting field can be controlled and the solenoidal condition can be easily enforced.

In the present paper, some of the most important turbulence generation techniques belonging to such group are critically revised from a theoretical point of view, with particular emphasis on the generation of anisotropic turbulence. Then, aiming at ameliorating the control over the obtained synthetic turbulence characteristics, two new methodologies are proposed: the first one can be seen as a correction over existing techniques while the second one is conceived in order to generate anisotropic turbulence characterized by arbitrary harmonic content in both time and space. Similarities and differences between the new methodologies and the existing ones are discussed in detail with a focus on their mathematical formulation.

The paper is organized as follows: in Section 2 some of the existing techniques for the generation of synthetic random flow fields based on Kraichnan method are briefly recalled. In Section 3, some methodological remarks on the generation of turbulence characterized by imposed spectra and integral scales are provided. In Section 4 and in