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Evaluation of the proper coherence representation in random flow generation based methods

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A R T I C L E I N F O

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A B S T R A C T

The interest in synthetic methods relies in the fact that reliability of methodologies such as large eddy simulations (LES) or direct numerical simulations strongly depends on how well the developed turbulence is characterized, which generally leads to computationally expensive simulations. Turbulence generation methods allow the initialization and up-keeping of the velocity fluctuations field to promote the observed/needed turbulence in the flow.

In this work the methodology known as 'modified discretizing and synthesizing random flow generation' (MDSRFG) jointly with a LES method is analyzed for its use in the study of tall building aerodynamics. A comparison with other generation techniques, that are closely related by their features and their conceptual origins, is presented with particular emphasis on the correct representation of the coherence of the velocity field. Particularly, an expression for the coherency function for the MDSRFG is derived.

After an analysis and revision of these generation methodologies, the turbulent air flow around a rectangular prismatic model is computationally simulated. A comparison of the results obtained from different methods is performed. The resulting wind loads on the model, along with the statistical characteristics of the flow, show that the MDSRFG technique allows to represent a field of spatially correlated velocities correctly.

1. Introduction

A problem that remains a challenge in the area of computational fluid dynamics (CFD) is the proper representation of turbulence scales. In this regard, the LES method its variants have been extensively used to evaluate the interactions between submerged bodies and the surrounding fluid in motion. However, LES methods require appropriate boundary conditions at domain inlets since the upstream turbulence characteristics directly affect the aerodynamic behavior of immersed bodies. As was previously stated by Li and Melbourne (1999), the fluctuating pressure and peak pressure distributions on bluff bodies are strongly dependent on free stream turbulence intensity, while the inflow turbulence length scale is the least important parameter (Mariotti et al., 2016). In particular, the characteristics of the flow field around rectangular bodies is still under intensive research in order to quantify the reliability of CFD results. In this regard, results with significant dispersion were reported in the literature (Bruno et al., 2014; Ricci et al., 2017), being the inflow turbulence setting one of the main influencing parameters.

Several methodologies have been proposed for this purpose and they can be classified into two general groups: *precursor simulation methods* and *synthesis methods*. Within the last, three different techniques can be found, i.e., the *synthetic random Fourier method* (Kraichnan, 1970; Smirnov et al., 2001; Huang et al., 2010; Castro and Paz, 2013; Aboshosha et al., 2015; Patruno and Ricci, 2017), the *synthetic digital filtering methods* (Klein et al., 2003; di Mare et al., 2006; Xie and Castro, 2008; Kempf et al., 2012; Kim et al., 2013) and the *synthetic coherent eddy* methods (Jarrin et al., 2006; Pamiès et al., 2009; Poletto et al., 2013). An exhaustive review of these approaches can be found in Tabor and Baba-Ahmedi (2010) and Wu (2017) articles.

The so-called synthetic random Fourier methods (SRFM) are the set of

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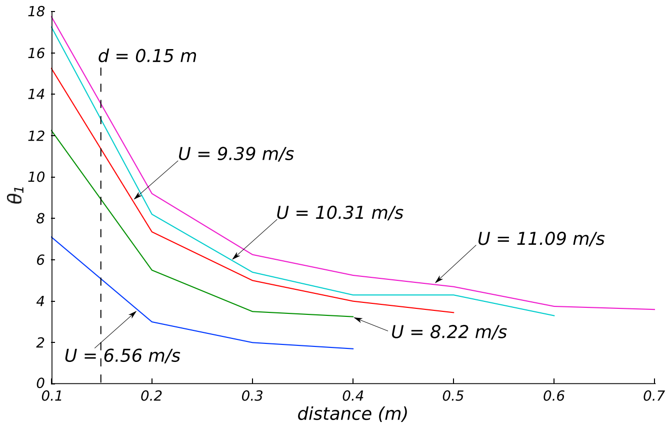

Fig. 1. θ_1 variation for the analyzed points ($L_u = 0.358$, $L_v = 0.112$, $L_w = 0.057$).

procedures derived mainly from the work of Kraichnan (1970). Kraichnan was able to represent homogeneous isotropic turbulence as a sine and cosine wave sum, while the velocity amplitude corresponding to each wave vector $\boldsymbol{k_n}$ is computed in a random way. This formulation allows to reproduce (in average) the statistics corresponding to the isotropic turbulence in a simple model. Because of this, many formulations were based on the Kraichnan methodology or some of its variants. It was used in studies on sound dispersion (Karweit et al., 1991; Bechara et al., 1994), inflow turbulence generation in simulations of wind passing buildings and other structures (Maruyama et al., 1999; Tamura and Ono, 2003; Li et al., 2015; Zhang et al., 2015) and vehicles (García et al., 2015) to name a few.

Based on the Kraichnan's process for homogeneous isotropic turbulence synthesis, Smirnov et al. (2001) proposed a procedure to generate anisotropic turbulence called random flow generation (RFG). Although this procedure is simple and gives an isotropic turbulent field, it is not possible to control its associated spectrum. This property is important since as it was shown by Huang et al. (2010), the synthesized fluctuations follow a Gaussian spectral model where frequencies in the inertial subrange (those of great interest in the area of the wind engineering) are discarded. The methodology proposed by Huang et al., called DSRFG (for discretizing and synthesizing random flow generation) allows to generate random fluctuating velocity fields from any prescribed spectrum. Later, Castro and Paz (2013) revisited this approach, modifying intervening parameters in order to provide temporal correlation to the formulation. The resulting modified DSRFG (known as MDSRFG) method was used in other works (Li et al., 2015; Ricci et al., 2016, 2017).

Recently, other researchers have contributed to the RFG methodology in order to improve it. Aboshosha et al. (2015) proposed a scheme called 'consistent discrete RFG' (CDRFG) with the aim of improving the coherence function of the synthesized velocity series. According to them, the DSRFG technique produces fluctuating velocities with high correlation. This conclusion arises when analyzing the coherence function obtained by the DSRFG method which does not decrease exponentially with increasing frequencies but remaining approximately constant with a value close to 1. According to Aboshosha et al. this unrealistic frequency-independent coherence is mainly due by the fact that the parameter responsible for modeling the spatial correlation is not a function of the frequency but a constant parameter, related to the integral length scale of the turbulence. Thus, by means of a parametric analysis they rescaled the components of the position vector by a parameter that depends mainly on the frequency.

Table 1
Parameters used for the generation of synthetic turbulence (Aboshosha et al., 2015).

frequencies	$f_{\min} = 1.0$ Hz, $f_{\max} = 100$ Hz
discretization	$\Delta_f = 1.0$ Hz, $M = 100$, $N = 50$

In this article a brief review of the recent methodologies related to the MDSRFG technique is made in Section 2. In particular, the spatial correlation that characterizes the field of synthesized velocities obtained by this technique is discussed. A further improvement is introduced by performing an analysis of the participating parameters and an expression for the coherency function for the MSDRFG is obtained (Section 3). The turbulent air flow around a rectangular prismatic model is computationally simulated and the results obtained from various methods are compared (Section 4). Finally, conclusions are given in Section 5.

2. Synthetic turbulence flow generation methods

Whilst there is an important amount of work performed on this subject, this work is focused on the analysis of three approaches: the DSRFG, MDSRFG and CDRFG methods. The reason behind this comparison resides in that these methodologies share common features and origins while performing differently in relation to the intervening parameters.

2.1. DSRFG method

Huang et al. (2010) proposed a turbulence synthesis technique known as discretizing and synthesizing random flow generation method (DSRFG). This approach proved to have an important advantage with respect to its predecessor, the random flow generation (RFG) technique by Smirnov et al. (2001): it allows to synthesize fluctuating velocity fields from any prescribed spectra. According to the DSRFG method, a homogeneous and isotropic turbulent velocity field $\boldsymbol{u}(\boldsymbol{x}, t)$ can be synthesized as follows:

$$u_i(\boldsymbol{x}, t) = \sum_{m=1}^{M}\sum_{n=1}^{N} p_i^{m,n}\cos\left(\tilde{k}_j^{m,n}\tilde{x}_j + \omega_{m,n}t\right) + q_i^{m,n}\sin\left(\tilde{k}_j^{m,n}\tilde{x}_j + \omega_{m,n}t\right), \quad (1)$$

where $u_i(\boldsymbol{x}, t)$ represents the longitudinal u, transverse v and vertical w velocity components, for $i = 1, 2$ and 3 respectively; $\boldsymbol{x}$ is a reference Cartesian coordinate system, t is time and

$$\mathbf{p}^{m,n} = \frac{\boldsymbol{\zeta} \times \mathbf{k}^{m,n}}{|\boldsymbol{\zeta} \times \mathbf{k}^{m,n}|}\sqrt{a\frac{4E(k_m)}{N}}, \quad (2)$$

$$\mathbf{q}^{m,n} = \frac{\boldsymbol{\xi} \times \mathbf{k}^{m,n}}{|\boldsymbol{\xi} \times \mathbf{k}^{m,n}|}\sqrt{(1-a)\frac{4E(k_m)}{N}}, \quad (3)$$

$$\tilde{\mathbf{x}} = \frac{\mathbf{x}}{L_s}, \quad (4)$$

$$\tilde{\mathbf{k}}^{m,n} = \frac{\mathbf{k}^{m,n}}{k_0}, \quad (5)$$

with $\omega_{m,n} \in N(0, 2\pi f_m)$, $f_m = k_m U_{\text{avg}}$, a is a random number uniformly

Table 2
Values used in coherence computation.

Point	U [m/s]	I_j	L_j
z_1	6.56	0.263	0.194
		0.211	0.036
		0.153	0.008
z_2	8.22	0.230	0.270
		0.194	0.066
		0.153	0.023
z_3	9.39	0.213	0.327
		0.184	0.094
		0.152	0.042
z_4	10.31	0.202	0.374
		0.178	0.122
		0.152	0.066