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SynInflow: recent advancements in the generation and application of inflow turbulence

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SUMMARY:
The generation of appropriate inflow conditions is an important aspect in the setup of scale-resolving Computational Fluid Dynamics, CFD, simulations for Wind Engineering. The present contribution summarises the work-flow developed by the authors for the synthetic generation and application of synthetic turbulence. In particular, the approach is based on two subsequent steps. Firstly, the synthetic turbulent field is generated aiming at ensuring the fulfilment of desired target values for turbulence intensity and integral length scales in each spatial direction, for all velocity components. In particular, the turbulent velocity field is generated using the Prescribed-wavelength Random Flow Generator^3, *PRFG*^{3}, which also imposes the divergence-free condition as well as approximate momentum conservation. Then, in the second step, the synthetic turbulent velocity field is corrected by means of the Variationally Based Inflow Correction Method, *VBIC*, aiming at moderating the insurgence of undesired spurious pressure fluctuations at the inlet patch. Additionally, further recent developments for both *PRFG*^{3} and *VBIC* are touched on. A boundary condition denoted as *SynInflow* for OpenFOAM implementing the approach is available at https://site.unibo.it/cwe-lamc/en.

Keywords: Computational Wind Engineering; Inflow conditions; Synthetic turbulence

1. INTRODUCTION

The use of scale-resolving Computational Fluid Dynamics, CFD, simulations for Wind Engineering applications is rapidly growing due to the increase of available computational resources. Nevertheless, setting up such kind of numerical models still poses relevant challenges. In particular, when the object of the study is immersed in a turbulent flow such as the Atmospheric Boundary Layer, ABL, the incoming turbulence must be correctly applied as inflow condition. To this purpose, numerous techniques have been developed in the last years, showing varying degree of success (Plischka et al., 2022; Wu, 2017). Reasonably good results can be obtained with many available techniques, some of the most widely adopted being (Huang et al., 2010; Kornev and Hassel, 2007; Poletto et al., 2013). Nevertheless, at the current stage of development, a rational approach to inflow generation is called for, grounding on theoretical considerations the characteristics which must be respected to ensure a successful transmission of the inflow within the computational domain. Such aspect is not automatic nor irrelevant: the synthetic turbulent field applied at the inflow patch of CFD simulations must be correctly propagated within the computational domain, governed by the Navier-Stokes equations and subjected to appropriate Boundary

Conditions, BCs. Failing to take such aspects into account inevitably leads to unwanted modifications of the synthetic flow downstream the inflow patch and spurious pressure fluctuations. In this contribution, we detail two techniques developed in recent years by the authors. The first one, denoted as Prescribed-wavelength Random Flow Generator^3, *PRFG*^{3}, is a synthetic turbulence generator which produces divergence-free synthetic fields characterized by approximate momentum conservation and appropriate statistical characteristics. The second one, denoted as Variationally Based Inflow Correction Method, *VBIC*, is needed in order to moderate the insurgence of spurious pressure fluctuations at the inflow patch, generated despite the good properties of *PRFG*^{3}. Both procedures have been implemented in a boundary condition for OpenFOAM denoted as *SynInflow* available at https://site.unibo.it/cwe-lamc/en, which allows to generate anisotropic inhomogeneous synthetic flows with ease. Two significant ongoing improvements to *PRFG*^{3} and *VBIC* are also tuched on. The first one aims at improving the spectra produced by *PRFG*^{3}, while the second generalizes *VBIC* providing additional flexibility.

2. *PRFG*^{3} AND *VBIC*

Similarly to all spectral methods, *PRFG*^{3} builds the turbulent velocity field, $\boldsymbol{u}^s$, as

$$\boldsymbol{u}^s(\boldsymbol{x},t) = \sum_{n=1}^{N} \left[\boldsymbol{p}^n \cos(\boldsymbol{k}^{nT}\tilde{\boldsymbol{x}}) + \boldsymbol{q}^n \sin(\boldsymbol{k}^{nT}\tilde{\boldsymbol{x}}) \right], \tag{1}$$

being $\boldsymbol{k}^n$ the wavevector, $\boldsymbol{p}^n$ and $\boldsymbol{q}^n$ amplitudes, while $\tilde{\boldsymbol{x}} = [x_1 - Ut, x_2, x_3]$, in which the time-averaged velocity is assumed to be oriented in the x_1-direction and of magnitude U. As it is well-known, using such a form the convection operated by the time-averaged field is automatically taken into account, satisfying linearized momentum equations. The divergence free-condition requires $\boldsymbol{k}^n$ to be orthogonal to $\boldsymbol{p}^n$ and $\boldsymbol{q}^n$. It must be noticed that Eq. (1) is the 3d Fourier representation of the velocity field, which can be deduced from its 3d Power Spectral Density, PSD, if the effect of phases is disregarded (leading to a gaussian process). Actually, imposing the 3d-PSD of each i-velocity component, $S_i(\boldsymbol{k})$, allows to impose the turbulence intensity as well as all three integral length-scales (three intensities and nine integral length scales in total), being the correct integral time-scale automatically obtained. The main steps of the *PRFG*^{3} method are thus

1. define the 3d-PSD for each velocity component;
2. discretize the 3d-PSD obtaining a list of $\boldsymbol{k}^n$ and the corresponding energies for each velocity component, $\boldsymbol{E}^n$;
3. for every $\boldsymbol{k}^n$ extract $\boldsymbol{p}^n$ and $\boldsymbol{q}^n$ in agreement with $\boldsymbol{E}^n$.

Actually, the divergence-free condition imposes realizability constraint in the last step, so that a correction procedure is actually needed on the $\boldsymbol{k}^n$ and $\boldsymbol{E}^n$ obtained in step (2), before proceeding to step (3), in order to obtain real-valued fields. It can be noticed that the procedure requires the knowledge of the 3d-PSD, which is generally not known. In the original version of the procedure, the following simple form has been proposed

$$S_i(\boldsymbol{k}) = \prod_{j=1}^{3} S_i^j(k_j), \tag{2}$$

which is, the 3d-PSD is calculated from marginal 1d-PSDs, for which the classical von Kàrmàn or Kaimal spectra can be adopted, simply by means of a product. The approach substantially imposes the integral length scales in the three coordinate directions. Further details regarding the procedure can be found in (Patruno and Ricci, 2018). The proposed spectrum works well and it is simple, but it has been found to lead to larger-than-expected integral scales in diagonal directions.

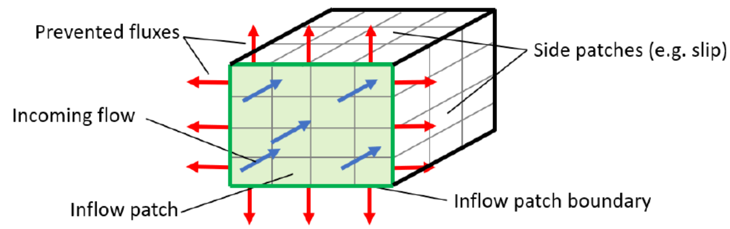


Figure 1. Scheme representing the effect of BC mismatches: fluxes required by the synthetic field might be prevented by the BCs confining with the inflow patch.

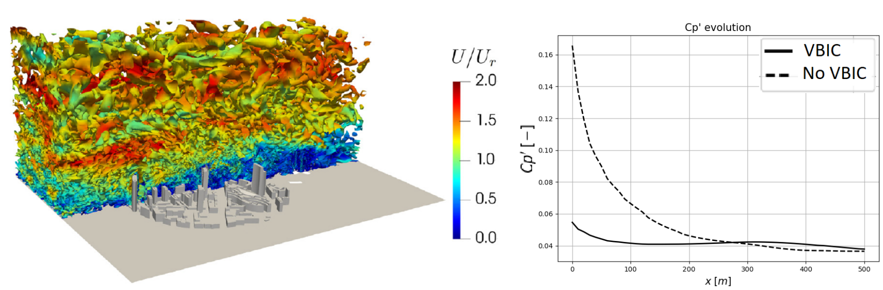
Finally, before applying the synthetic velocity as Dirichlet BC at the inflow of the CFD simulation, correction are applied in order to solve for BCs mismatches (see Fig. 1) and reimpose the divergence-free condition, which might be partially lost for inhomogeneous fields (see Bervida et al. (2020)). Such corrections are such that

$$\boldsymbol{u} = \boldsymbol{u}^s + \boldsymbol{u}^c, \tag{3}$$

where $\boldsymbol{u}$ is the actually-applied velocity field, $\boldsymbol{u}^s$ is the synthetic field obtained, for instance, using *PRFG*^{3} and $\boldsymbol{u}^c$ are velocity corrections to be determined. Such corrections must be of minimal norm in order to preserve $\boldsymbol{u}^s$ as much as possible. In the original *VBIC* procedure, for the matter of convenience and simplicity, it is assumed

$$\boldsymbol{u}^c = [0, u_2^c, u_3^c], \tag{4}$$

so that the u_1 velocity component is not involved in the correction procedure. Further details on *VBIC* can be found in (Patruno and Miranda, 2020). An example of ABL generated by the described procedure and the moderating effects of *VBIC* on spurious pressure fluctuations can be observed in Fig. 2. The *VBIC* procedure can be applied to any synthetic velocity field and, as such, it is not required to use it in conjunction with *PRFG*^{3}.



(a) (b)

Figure 2. Synthetic turbulence generation: (a) example of obtained ABL flow and (b) pressure fluctuation C_p', moderation due to VBIC.

3. FURTHER ADVANCEMENTS

The description of *PRFG*^{3} and *VBIC* provided in the previous section is extremely concise and not exhaustive, but it is sufficient to highlight the following points amenable to further developments

1. the 3d-PSD is a fundamental ingredient of the *PRFG*^{3} procedure and the currently adopted approach based on the product of marginal spectra shall be considered only as a convenient simple solution, which might be still improved. It is necessary to generalize known 1d-PSD for wind, in order derive a 3d-PSD which eliminates the aforementioned problem of larger-than-expected integral scales in diagonal directions. Promising results have been already obtained;

2. the correction strategy of *VBIC* is currently built forcing null corrections over the u_1 velocity component. Also this aspect might be further refined, and a two steps *VBIC* is currently under development, able to provide enhanced flexibility to the procedure.

4. CONCLUSIONS

In this contribution, an overview of the work-flow developed by the authors for the generation and application of synthetic turbulence suitable for use as inflow condition for scale-resolving CFD simulations is presented. The procedures have been implemented for OpenFOAM and the source code as well as documentation and relevant examples made available. The developed approaches allow to gain very good control over the generated fields, leading to a good matching of the target turbulence intensity and integral scales, as well as reduced spurious pressure fluctuations at the inflow. Further ongoing developments are also touched on, which are expected to further ameliorate the obtained results.

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