Atmospheric turbulent layer simulation providing unsteady inlet conditions for large eddy simulation

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ABSTRACT

The aim of this work is to bridge the gap between experimental approaches in wind tunnel testing and numerical computations, in the field of structural design against strong winds. This paper focuses on the generation of an unsteady flow field, representative of a natural wind field, but still compatible with CFD inlet requirements. A simple and "naïve" procedure is explained, and the results are successfully compared to some standards.

1 INTRODUCTION

Inlet conditions for Large Eddy Simulations are of the utmost importance, as it determines a large part of the fluid behaviour within the computational domain. Tabor and Baba-Ahmadi (2010) gave a good overview of the different techniques, classifying them as *synthesised turbulence methods* and *precursor simulation methods*.

The first category presents the critical limitation of not achieving a flow field inlet 100% compatible with CFD requirements (temporal and spatial fluctuations, divergence-free, spectrum). For instance, the method developed by Jin *et al.* (1997) is not divergence-free. These requirements are of great importance when the purpose of the computations is to generate pressure fields on obstacles. Some regularisation methods have to be introduced, as for instance the Synthetic Eddy Method (Jarrin *et al.* (2006)).

The second category of techniques is due to Spalart and Leonard (1985). The idea of these methods is to generate inflow condition using CFD itself, as a genuine simulation of turbulence. The inflow of this precursor domain is obtained through a rescaling of the flow field extracted from a downstream location. Nevertheless, even with different stages of simplification (Lund *et al.*, (1998), Nakayama *et al* (2012)), those techniques are still complicated and not easy to implement. Additionally, they seem more adequate to small scale turbulence (*Re* about 2.10^3)), which does not correspond to structural design against strong winds (*Re* about 4.10^7).

This paper deals with a more "naïve" precursor model. The idea is to draw inspiration from the wind tunnel testing community, with the use of roughness blocks lying on the floor. The large *x*-axis dimension of the wind tunnel is replaced by a short cyclic domain, in order to convert the large domain issues into a duration matter. Similarly to atmospheric turbulent layer which is driven by geostrophic wind (instead of a horizontal pressure gradient), our flow is naturally driven by the upper boundary condition, acting as a conveyor belt. Re-introducing a flow field extracted downstream becomes straightforward.

The final aim of the method being building dimensioning to high winds, our reference will be an international code concerning these issues: Eurocode I (EN-1991-1-4): "Actions on structures – Wind actions". This code proposes a systematic approach to describe some of the wind characteristics; we will focus on these characteristics in order to validate –or not– the approach.

2 DESCRIPTION OF THE METHOD

2.1 *Aim of the simulation*

In order to compute the extreme loads on a building, CFD calculations have to immerse it in a turbulent atmospheric air flow. Eurocode I (EN-1991-1-4) proposes a systematic and simple approach to describe this air flow: a log-law profile for the mean wind speed, associated with an inverse log-law profile for turbulence intensity.

$$V(z) = V_b k_r \ln\left(\frac{z}{z_0}\right) \tag{1}$$

$$I\%(z) = \frac{\sigma_u}{U} = \frac{k_I}{\ln\left(\frac{z}{z_0}\right)} \tag{2}$$

Wind speeds distributions are Gaussian and the spectrum of turbulence is driven by a modified Von Karman model:.

$$S(z,\nu) = \frac{\sigma_u^2}{\nu}\frac{6.8\, f(z,\nu)}{\left(1+10{,}2\, f(z,\nu)\right)^{5/3}} \qquad \text{With} \quad f(z,\nu) = {}^{\nu L(z)}\!\big/_{U(z)} \tag{3}$$

The turbulence scale L is also given by Eurocode:

$$L(z) = 300.\left(\frac{z}{200}\right)^{0.67+0.05\ln(z_0)} \tag{4}$$

There is no mention of correlation length within the Eurocode. Another regulation, the English code ESDU 75001, gives the correlation lengths:

$$L_u^x(z) = 560\left(\frac{z}{\delta}\right)^{0.35} \qquad \text{With} \quad \delta = 1000.\, z_0^{0.18} \tag{5a}$$

$$L_v^x(z) = 280\left(\frac{z}{\delta}\right)^{0.48} \tag{5b}$$

$$L_w^x(z) = 0{,}7z \tag{5c}$$

Our target is to generate an unsteady flow corresponding to this wind model, with a roughness length equal to z_0 =5 cm.

2.2 *Geometry and boundary conditions*

The domain used is a 20x10x20m^3 box. On the ground, the roughness is modelled by random cubic elements: their size and density are given by some “rule of the thumb” from the experimental wind-tunnel community (h between $0.z_0$ and $30.z_0$, area density around 10%). Special attention is focused on the lateral homogeneity (the largest cubes mustn’t be grouped on the left or on the right). Figure 1 shows the roughness cubes at the bottom of the computational domain for this study.

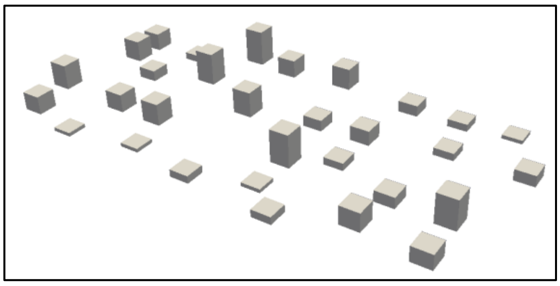

Figure 1: Geometry of the roughness-cubes lying on the floor

Boundary conditions are *no slip* on the ground and on the roughness-cubes. Because the cubes are randomly located, a lateral force can appear on the ground. In order to compensate this force and to guide the flow within the *x*-axis, the lateral boundaries have to block the flow: *symmetry* boundary condition is chosen on these boundaries. Concerning the inlet and outlet, *cyclic* is used to re-introduce the flow field as it is. The upper-boundary condition is also *no slip* on the “roof”, but with a moving wall (67.5 m/s instead of 0 m/s on the ground). This value of 67.5 m/s has been obtained through a try-and-error process (the flow being Reynolds quite independent, the results of the simulation are proportional to this moving roof speed). Figure 2 sums up these boundary conditions.

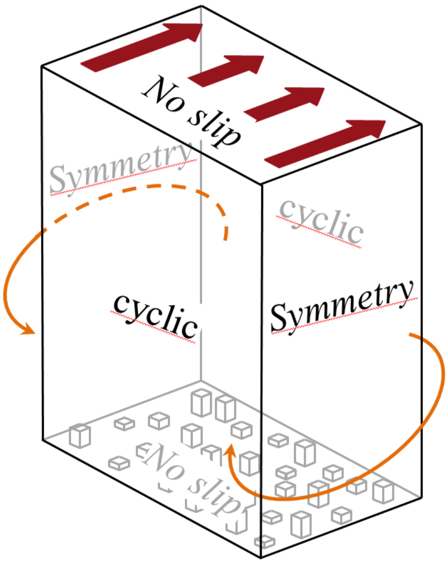

Figure 2: Boundary conditions

2.3 Running OpenFOAM

The mesh density is uniform with a 25cm grid step. In order to slightly reduce the cells number, a pinch of grading is introduced in the upper half space (last upper cell is 50cm; see Figure 3 Left).

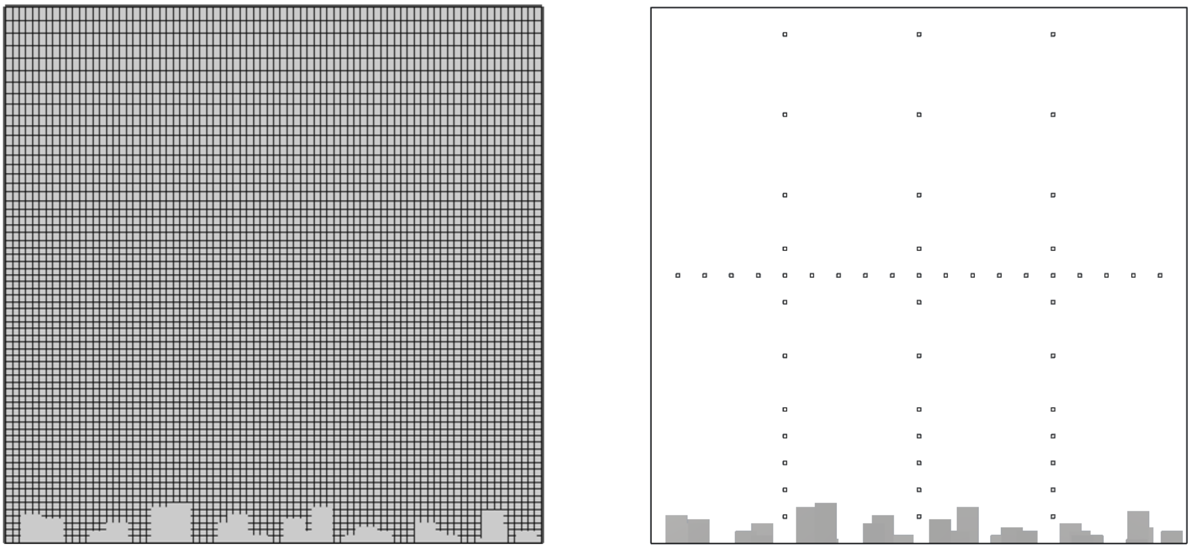

Figure 3: x-*projection of computational domain:*
Left: meshing and roughness cubes. Right: probe locations

`Pimplefoam` is run in order to optimize the time step: max Co is 10, with a time step close to 4.10^{-2} s. Time scheme is `Crank-Nicholson`, spatial scheme is `Gauss Linear` (and `Gauss LinearUpWindV GradU`). Subgrid turbulence model is `oneEqEddy`. Solver for pressure is `GAMG`, and `PBiCG DILU` for U and k. Initial condition is a uniform field U equal to 67.5 m/s.

3 RESULTS

3.1 Spatial and temporal extraction method

Many probes are placed onto a x-constant plane in order to evaluate the success of the method to generate an atmospheric boundary layer: three vertical lines to estimate the flow homogeneity and the vertical gradient, and a uniform horizontal line to assess the horizontal homogeneity and correlations (see Figure 3 Right).

A time span of 300 seconds is first run. During this first period, the flow is rapidly decreasing (from uniform 67,5m/s), starting to brake from the ground. 300 seconds turns out to be a good time span in order to achieve a global equilibrium. Then the statistics are evaluated over a 300s window, which is half the meteorological international standard.

3.2 First check

Visual inspection (Figure 4) shows a first validation: the flow field looks like one could expect.

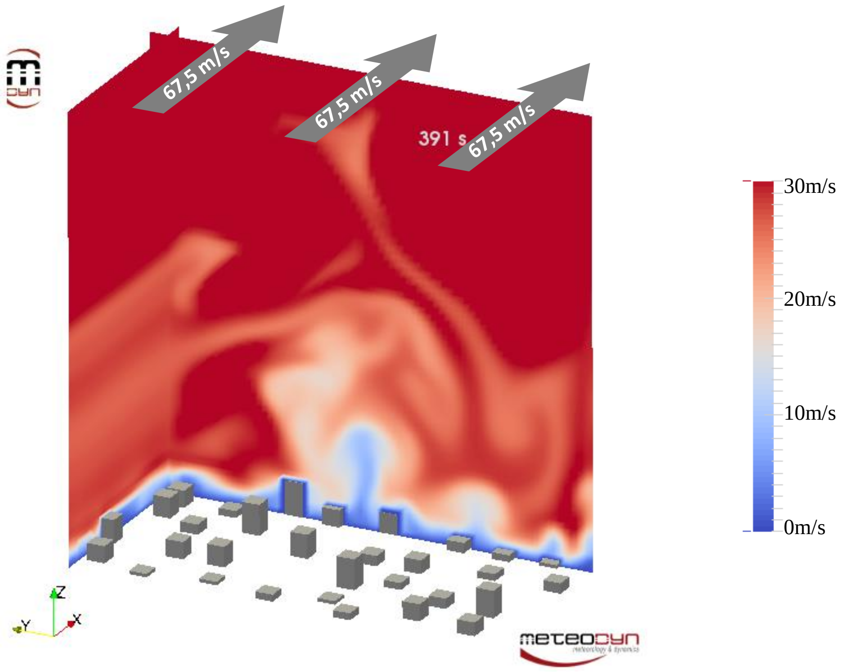

Figure 4: Instant wind field sections in the computational domain.

3.3 Results; comparison with Eurocode

The flow is quite homogeneous: at 10m high, the mean wind speed and turbulence intensity do not depend of the lateral position (see Figure 5), at least in the central part of the flow (one half centered span).

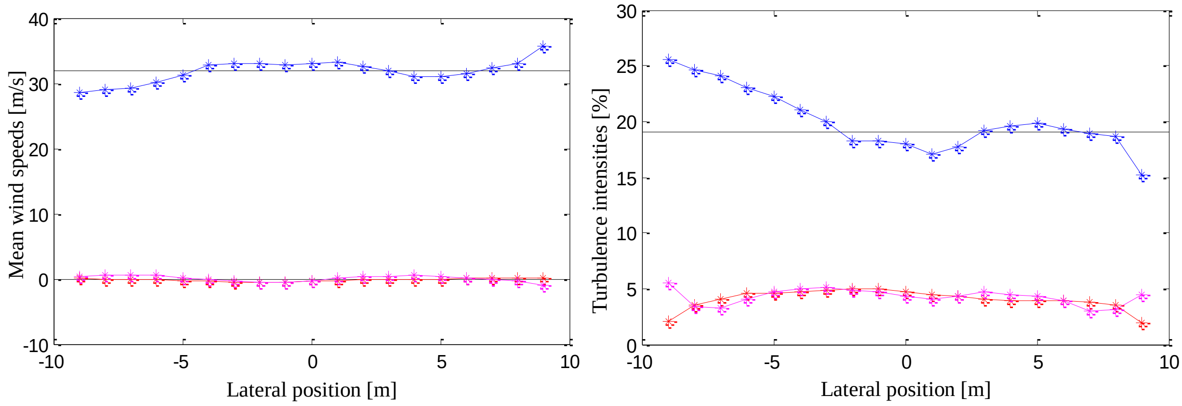

Figure 5: Horizontal gradient of mean wind speeds (left) and turbulence intensities (right).
Blue: u-component; red: v-component; purple : z-component

Densities are found symmetric, close to Gaussian (Figure 6).

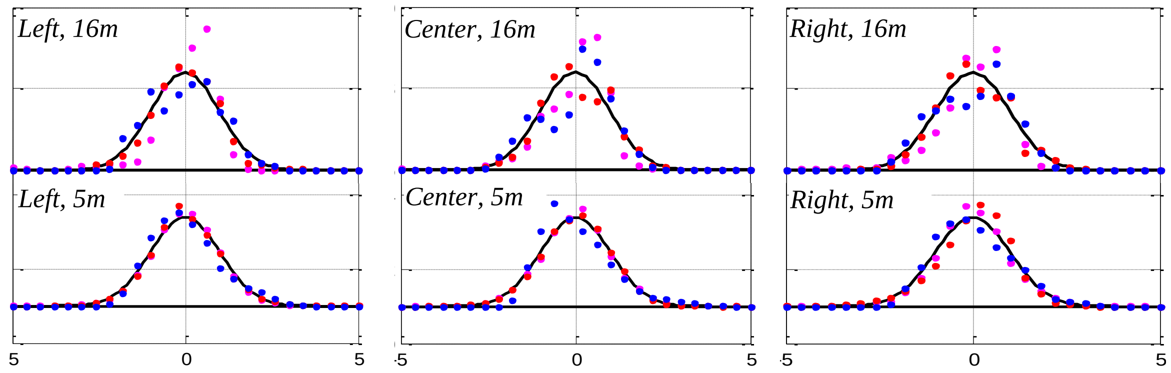

Figure 6: normalized distribution of u, v *and* w *fluctuating components.*
First line: 16 m high. Second line: 1m high
Left: 5m to left wall. Middle: center of computational domain. Right: 5m to right wall.

Vertical gradients (mean wind speed, Figure 7, and turbulence intensity, Figure 8) exhibit excellent fit with the Eurocode model. In those figures, the results from LES are compared with the Eurocode gradients (equations (1) and (2)), with a roughness length of $z_0 = 5$ cm and a based velocity equal to 31.6 m/s. This based velocity is found to be directly proportional to the top boundary condition speed.

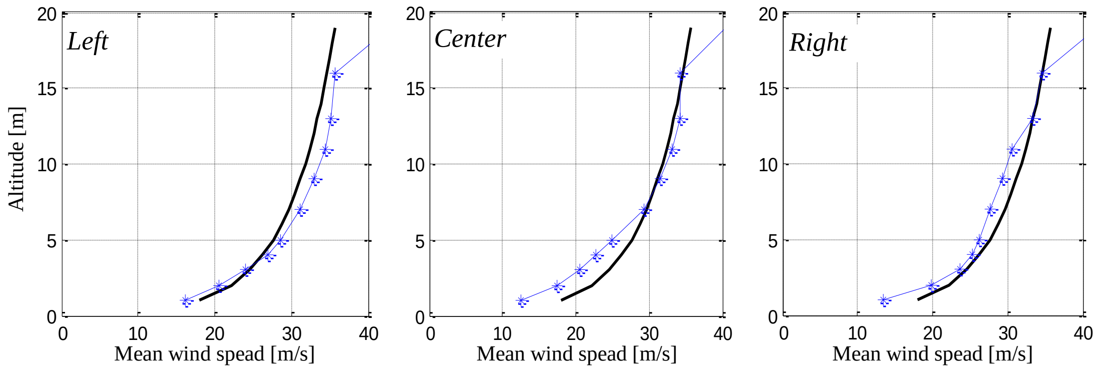

Figure 7: vertical gradient of mean wind speed. Blue stared: LES results. Black line: Eurocode

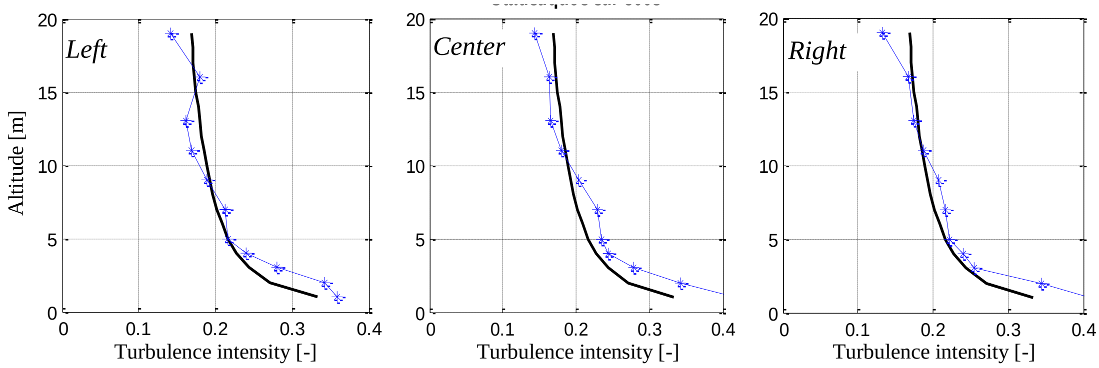

Figure 8: vertical gradient of turbulence intensity. Blue stared: LES results. Black line: Eurocode

Power density spectra are computed at different locations within the domain. Results are plotted Figure 9 (blue line), as well as Eurocode model (bold black line, equation (3)). The peak of energy is slightly shifted to low frequencies, corresponding to a turbulence length scale slightly larger than the one proposed by Eurocode (equation (4)). Nevertheless, the global balance between high and low frequencies is not accurately reproduced: low frequencies are over estimated whereas high frequencies are underestimated. This behaviour might be linked with the LES filtering of high frequencies.

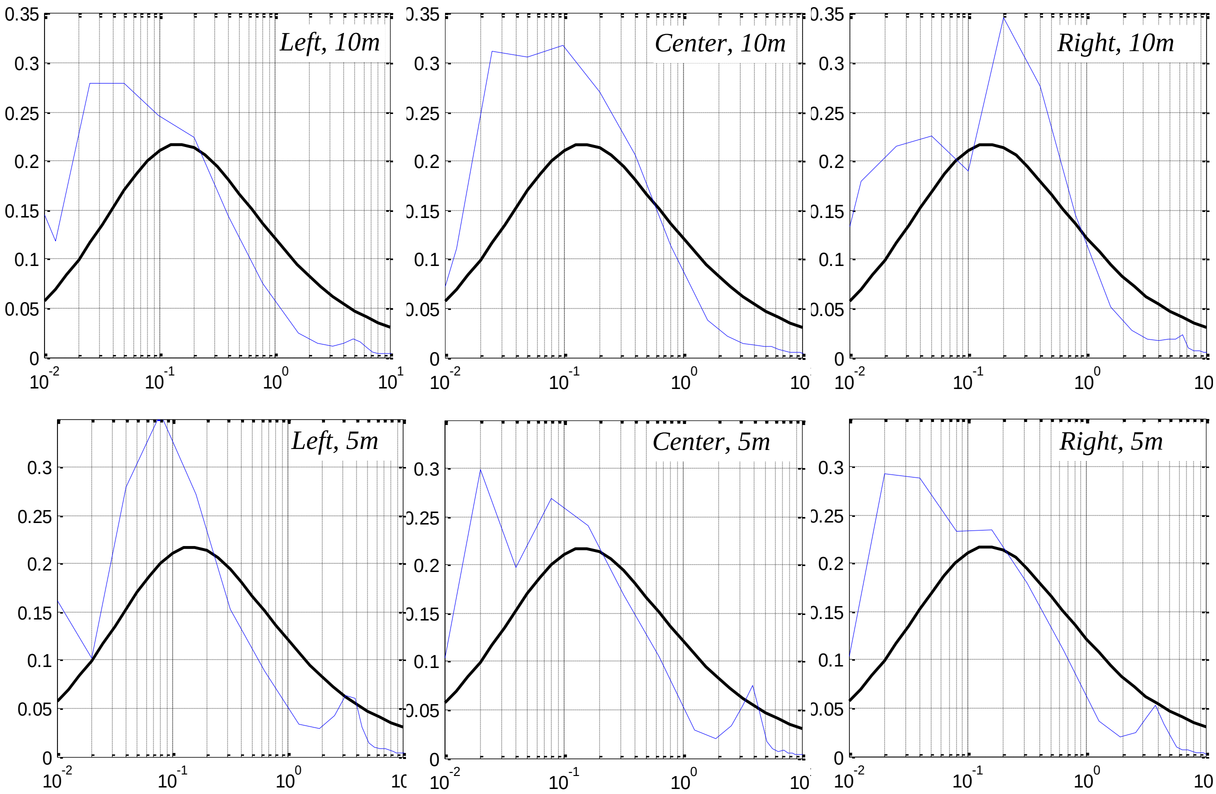

Figure 9: Normalized power densities versus reduced frequency

Close to ground (5m high), there is a second peak energy at a reduced frequency around 4. This might be the "signature" of the domain size: 10 m long, about 28m/s, makes a cycling frequency equal to 2.8 Hz, corresponding to a reduced frequency (equation (3) and (4)) of $\frac{2.8\times 44}{28} = 4.4$.

3.4 Correlations; comparison with ESDU

Streamwise correlation length is evaluated thanks to Taylor hypothesis: the temporal correlation (of fluctuating component *u*, *v*, and *w*) is calculated and compared with a negative exponential (Figure 10). The parameter of this negative exponential is given by formulae (5a) (135m at 10 m high, 105m at 5 meter high), divided by the local mean wind speed (given on Figure 7).

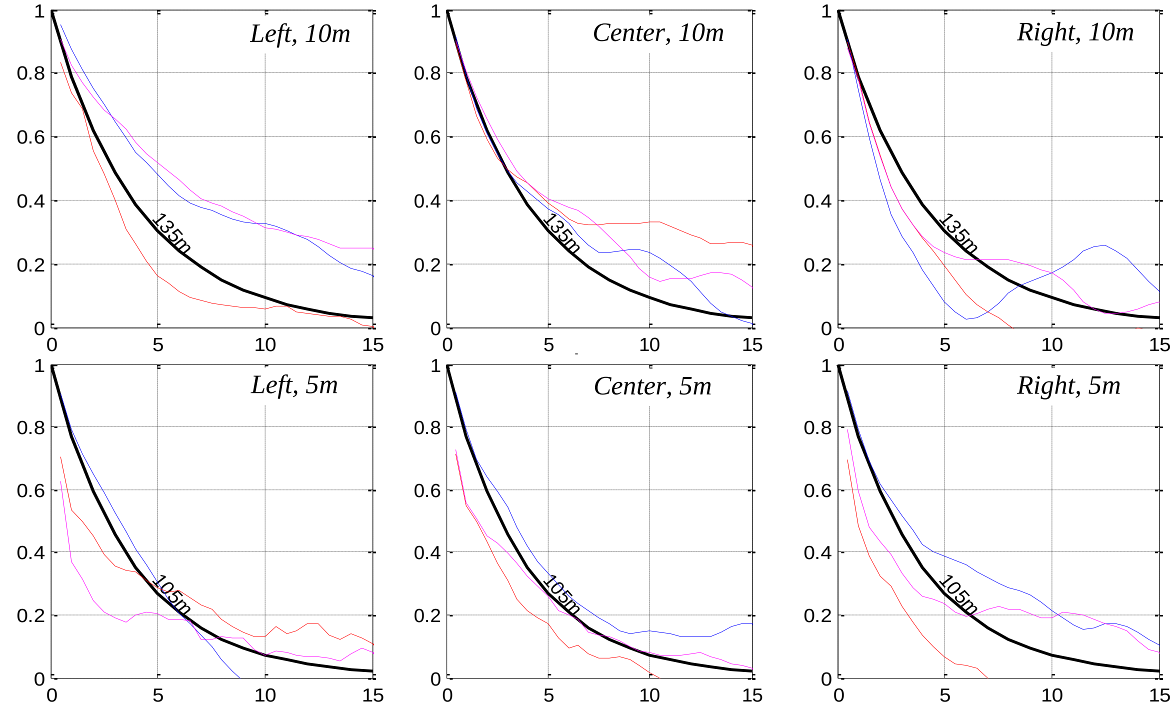

Figure 10: Stream wise correlation analysis
Top: 10m high. Bottom: 5m high. Left/middle/right = left/center/right

Agreement is very good for axial component *u*, especially at the middle of the domain. For the other two components (*v* and *w*), situation is not so satisfactory: for ESDU, correlation lengths are different for different axis (equations (5b) and (5c)), whereas in our LES calculation they seem to be the same.

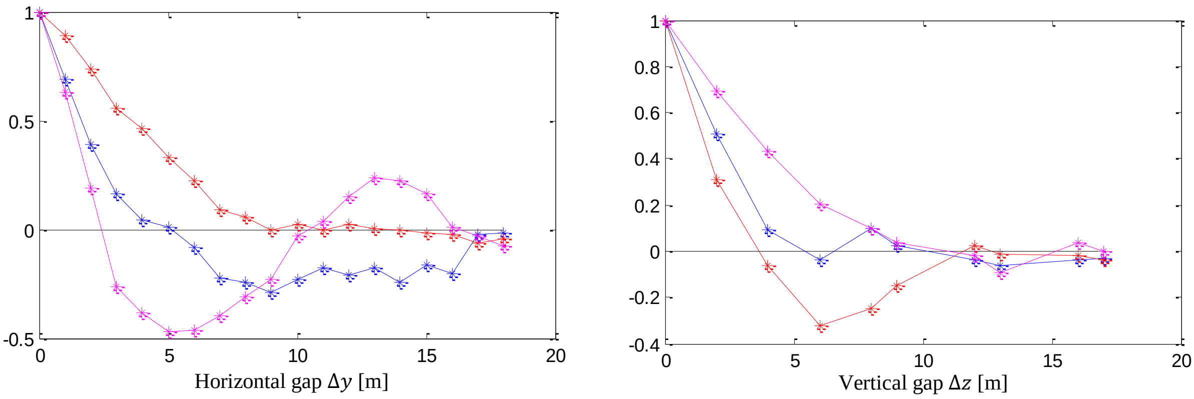

Figure 11: Lateral and vertical correlation for the three components
Blue for u*-component; Red for* v*-component; Purple for* w*-component*

Lateral and vertical correlation lengths are much smaller: we can estimate from Figure 11 around 5m, which is a quarter of the width and height of the domain. These correlation lengths seem limited by the domain size much more than any other aspect.

4 CONCLUSIONS

A new solution for generating unsteady inlet conditions for Large Eddy Simulation is presented in this paper. This solution, which draws its inspiration from the wind tunnel testing community, is as simple as possible and straightforward to implement using OpenFoam. The flow field generated can be directly used as inlet conditions for Large Eddy Simulations.

The results are compared with international standards concerning wind engineering (Eurocode 1 and ESDU 75001). Densities are found symmetric, close to Gaussian, and the flow is homogeneous (no lateral fluctuations). Vertical gradients of mean wind speed and turbulence intensity exhibit excellent fit with the Eurocode model. Stream-wise correlation length is about 120m which agrees with ESDU; lateral and vertical correlations are much smaller (about 4~5m). The main discrepancies concern the power spectral density: low frequency domain is a bit over energetic while there is a lack of high frequencies. This misbalance might be linked with the LES filtering of high frequencies.

Acknowledgements

The author greatly acknowledges Alberto Passalacqua for his GeekoCFD live distribution. Thanks also to Bernhard Gschaider for his kind help using swak4foam, and all the CFD online community for their discussions and nice exchanges.

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