A method for the numerical modelling of wind induced forces on tall buildings on a commercial basis

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Introduction

In this paper we investigate the current technical viability on a commercial basis for modelling wind induced forces and moments on a tall structure in an urban environment using computational fluid dynamics (CFD). The parameters determining the above question are accuracy of the computation, time and the costs involved for such a study.

To test the viability, we have performed calculations using a range of turbulence models provided within a commercial software package, namely, a transient formulation of the k-epsilon model (URANS), a large eddy simulation (LES) and a detached eddy simulation (DES). A novel way of representing the large scale upstream turbulence to match the observed wind spectrum has also been examined. This approach is necessary in order to capture the large scale turbulence impinging on the building and hence the fluctuating forces on it.

A previously completed atmospheric boundary layer (ABL) wind tunnel study on a sky riser in a city centre (Figures 1 and 2) was compared with the CFD results.

Phase 1: Initial CFD simulation for modelling wind loads on tall structures

A logarithmic upstream velocity profile varying with height was applied. This profile was similar to the one produced in the wind tunnel (Equation 1) and ignored the turbulence at the inlet as the expected vortex shedding around the bluff body was assumed a local effect, i.e. dependent on the wind direction, building exposure and the building geometry. Also, it was assumed that the vortices created by the surrounding buildings will have a more significant effect on the building of study than the upstream turbulence.

\[ \overline{U_z} = \frac{\mu^*}{\kappa} \log \left( \frac{z + z_0}{z_0} \right) \]  

Where \( \overline{U_z} \) is the mean velocity varying with height \( z \), \( \mu^* \) is the friction velocity, \( \kappa \) the Van Karman universal constant and \( z_0 \) is the equivalent roughness height.

However for this particular study we chose a wind direction such that there are no obstacles upstream of the building of interest and our assumptions proved to be invalid.

A comparison of the streamwise wind loading for different turbulence models, namely URANS and DES and the wind tunnel data (Graph 1), shows that although the numerically determined mean force is close to wind tunnel measurements, the fluctuating loads differ significantly! This indicates that the large scale upstream turbulence seems to be an important factor in generating a similar dynamic response.
Phase 2: Re-scaling of forces from previous CFD calculations using an analytical expression of velocity

Before trying various methods to generate upstream turbulence to match the spectral distribution of velocity generated within the wind tunnel, an approximation of the velocity was derived using a series of sinusoidal signals. This signal was scaled to fit a similar turbulence intensity and spectral distribution and added to the mean velocity profile in the ABL (Equation 2). This approximation of the inlet signal was then translated into dynamic pressures and integrated over the upstream facing side of the studied building. As expected it was found that the dynamic response is similar (Graph 2) and hence simulating the upstream large scale turbulence is crucial to getting a correct answer.

\[ u_{t,z} = \sum_{z=0}^{Z} \sum_{k=1}^{N} A_k \sin(2\pi f_k t + \theta_k) + \bar{u}_z \]  

Equation 2

**Phase 3: Generation of upstream turbulence**

Different methods have been proposed over the years on how to implement upstream turbulence. The most common technique is to generate a coherent velocity and turbulent energy profile using a set of low level obstacles. There are variations to this method, but numerically modelling a wind tunnel setup is unlikely to offer a practical way forward, solely because it is computationally expensive, as the obstacles, normally a series of blocks, have to be meshed individually. The other drawbacks are that the eddy sizes are limited to the obstacles’ dimensions, i.e. only high frequency turbulence is generated, the time spent in finding the correct combination of obstacles and the inability of introducing time-varying large scale turbulence.
Over the past years a technique to describe the velocity profile statistically, with particular interest for LES was developed by various authors [2,3,4]. One of these more recent approaches is to generate a random set of numbers on a 2D plane which are filtered using a normalized exponential weighting function [4]. The filter ensures that the spatial correlations observed in the atmospheric boundary layer are maintained [1]. The filter in time uses a very similar function and was previously used by Hanna et al. [3] for a 1D time-varying inlet condition.

The advantages of this method are that the turbulent field is generated analytically in space and time and can be easily checked prior to the CFD analysis. The parameters used to generate the desired velocities are the ones that have to be matched, i.e. the mean velocity profile, the integral length and time scale and the turbulence intensity.

Synthetic inlet conditions were used for this case study created using a simplified formulation of the velocity vector to only the streamwise velocity component as follows:

\[
\begin{align*}
u_{x,z,t} &= \bar{u}_z \left(1 + I_z \left[u_{x,z}^{\text{new}} \sqrt{(1 - f_t^2)} + u_{x,z,t-1} f_t \right]\right) \\
\end{align*}
\]  

(3)

Where \(u_{x,z,t}\) is the instantaneous velocity perpendicular to the x-z plane, \(\bar{u}_z\) the mean velocity and \(I_z\) the turbulence intensity varying with height \(z\), \(u_{x,z}^{\text{new}}\) is the new randomly generated velocity fluctuation, \(u_{x,z,t-1}\) the velocity fluctuation data from the previous time step and \(f_t\) the filter in time [3]. In order to establish a coherent time series of the velocity it was found that the time step to velocity ratio in the time filter ought to be less than 0.1. The expression for \(u_{x,z}^{\text{new}}\) is generated form a set of normalized random data and filtered as described by [4]:

\[
\begin{align*}
u_{x,z}^{\text{new}} &= \sum_{j=-N}^{N} \sum_{k=-N}^{N} f_j f_k n_{\text{rand}}_{j,k} \\
\end{align*}
\]  

(4)

Where \(f_j\) and \(f_k\) are the normalized spatial filters, \(n_{\text{rand}}_{j,k}\) the normalized two dimensional random data and \(2N\) the filter length proportional to the integral length scale \(L\) and grid size \(\Delta\) such that \(4N = L/\Delta\).

The motivating factors behind simplifying the velocity description were three-fold. First, it is three times faster to execute, secondly, the fluctuations in one direction will trigger coherent fluctuations in the cross-stream directions and finally, it should provide us with enough information whether this technique can be easily used and whether it produces the desired effect.

**Phase 4: Statistical inlet conditions**

Initially a number of tests were carried out on a single tall building using a laminar and LES turbulence model in order for the difference in the dynamic response due to the turbulence model and the newly formulated inlet conditions to be investigated. It was found that the impinging response of either turbulence models was in the same order of magnitude, but that only the LES formulation could predict the expected vortex shedding downstream of the obstacle.

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**Graph 3**: Wind spectra at reference height taken from wind tunnel measurements.

**Graph 4**: Wind spectra at reference height computed from CFD inlet conditions.
Before using the synthetic inlet conditions, the wind spectra, i.e. the wind tunnel data (Graph 3) and the CFD inlet conditions (Graph 4) were compared.

The more distorted profile from the synthetic inlet is due to the sampling size between the two sets of data, with the wind tunnel data being composed of 512000 measurements and only 4096 time steps being used for the synthetic inlet condition. Although the CFD spectrum is not an exact match, it provides an indication whether the response of the building is now similar to the measured data.

This revised inlet condition was used with a standard LES turbulence model [Star-CD version 4]. Ensuring that the mean Courant number was below 0.75 it was found that the agreement between the CFD predictions and wind tunnel measurements is reasonable (Graph 5).

The underestimation of the peaks in the CFD simulation is likely be caused by the change of the velocity vector in the cross-stream direction and hence the turbulence intensity is reduced in the streamwise direction. Furthermore, it seems that the integral length scale was underestimated. A re-run with an overestimation of turbulence at the inlet and correct integral length scale is expected to show better agreement or the computation of the cross-stream velocity components at the inlet boundary.

**Conclusions**

It was shown that when large scale turbulences are not introduced at the inlet boundaries of the fluid domain that the large scale force fluctuations are not captured. In order to have similar force fluctuations due to wind loading a method to generating upstream turbulence has to be formulated.

Upstream turbulence generated using non-statistical methods does not capture the necessary wind spectrum and is computationally and time expensive, whereas when generated using a statistical formulation, the spectral distribution can easily be matched with no additional computational expenses.

By combining the statistical formulation of turbulence at the inlet condition with LES, eddies are maintained whilst being transported downstream, resulting in the required response of the building of study to wind loading.

Our test case was decomposed into 4 million fluid cells. When simulating 7 minutes of real time wind, spread over 16 CPUs took 4 days for a given wind direction. If that same model was spread over 100 CPUs and simulated for 1 hour of real wind, i.e. this would be a representative sample to match the required wind spectrum, we would expect a wind direction to take one week. To achieve a turnaround of two weeks with 36 wind directions is therefore likely to require access to around 2000 CPUs.

**References**


