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# Wind-Induced Human Comfort: Outline of a Computational Procedure

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## Abstract

Environmental wind at pedestrian locations is an important factor in the human experience within the built environment. This paper outlines a complete computational procedure for the prediction and assessment of the pedestrian level wind environment. This tool is intended to be used for exploring possible solutions to excessive winds prior to conducting time consuming wind tunnel testing. The current method has been calibrated by subjective site assessment.

## Introduction

Aurecon, Building Sciences has recently provided environmental wind assessment for a prominent tower in the Perth CBD of approximately 250m height (see figure 1). In Perth, strong afternoon south westerly winds occur regularly in the warmer months, leading to unacceptably windy conditions at the base of this tower.

Figure 1. Photo of the Perth city skyline showing a prominent office tower (centre left). Image source: commons.wikimedia.org

Subjective on-site wind assessment was used to calibrate the computational model presented in this paper.

## Assessment Criteria

A variety of wind assessment criteria have been proposed in the literature [1,5,7,9,15,16,18,20,21,24,25,32]. Each is generally a relationship between a series of velocity thresholds, their probability of occurrence and the average human physical response obtained from subjective testing.

In this research the Lawson comfort criteria [18], amended with input from Isyumov and Davenport [16] are used for assessment of pedestrian wind comfort. This criteria is based on the exceedance of a Gust Equivalent Mean (GEM) velocity occurring less than 5% of the year (approximately once per week during daylight hours [20]). The assessment of pedestrian wind safety is based on the probability of exceeding a GEM less than once per annum. These assessment criteria are listed in table 1.

| **Comfort criteria (exceedance once per week)** | | |
|---|---|---|
| Uncomfortable | >10m/s | Uncomfortable for all spaces |
| Fast walking | 10m/s | Areas quickly transited |
| Leisurely walking | 8m/s | General walking |
| Short period sitting/standing | 6m/s | Bus stops, building entrances |
| Long period sitting/standing | 4m/s | Sitting, eating and drinking |
| **Wind Safety Criteria (exceedance once per annum)** | | |
| Unsuitable for general public | 15m/s | Including elderly, cyclists and children |
| Unsuitable for able bodied | 20m/s | Unsafe in for all uses |

Table 1. Summary of environmental wind comfort and safety criteria.

Assessment criteria based on GEM velocities were chosen for three reasons. First, the importance of including gusts effects when assessing wind comfort and safety is well known [20]. Secondly, as discussed below, the GEM can be estimated from mean CFD results. Finally, the GEM is referenced to mean velocity, making the application of statistical analysis to the mean meteorological data somewhat more straightforward.

## Statistical Analysis of Meteorological Data

Recorded wind data is obtained from the meteorological station closest to the site of interest and adjusted for terrain category and height effects. The wind speed data is filtered for 16 cardinal directions and probability distributions fitted to hourly mean velocities at a 10m reference height.

To assess wind comfort a Weibull distribution (1) is fitted to the hourly mean velocities in each direction following the procedure outlined by Aynsley et. al. [2]. This Weibull distribution will be used to estimate wind comfort criteria using gust equivalent mean velocities with a moderate probability of exceedance. The Weibull distribution is given by

$$P(\overline{U},\theta) = A(\theta)\exp\left[-\left(\frac{\overline{U}}{C(\theta)}\right)^{k(\theta)}\right] \qquad (1)$$

where k(θ) and C(θ) are the Weibull coefficients for the θ azimuth and A(θ) is the marginal probability of the wind direction occurring within the θ azimuth sector.

Given there are difficulties in using a Weibull distribution to predict extreme events, the Generalised Extreme Value (GEV) distribution was also fitted to the meteorological data to assess wind safety. Here the Gumbel (GEV Type I) probability distribution [11,12] (equation (2)) is applied to the ten largest hourly mean velocities for each year of recorded data following the procedure outlined in Holmes [14]. The Gringorten correction [10] was also applied to this procedure. Ten datum points per year were selected such that a probability of 0.1 corresponds to the probability of exceedance of the hourly mean velocity once per year, as required for the wind safety assessment criteria. No attempt was made to separate velocity data for downburst and synoptic weather events. The Gumbel distribution is given by

$$F(U,\theta) = A(\theta)\exp\left[-\exp\left(-\frac{(U-u(\theta))}{a(\theta)}\right)\right] \quad (2)$$

where a(θ) and u(θ) are the Gumbel coefficients for the θ azimuth.

### Atmospheric Boundary Layer Modelling

Simulation of the Deaves and Harris model [6] of the Atmospheric Boundary Layer (ABL) was achieved by closely following the recommended procedure of Richards and Hoxey [26]. Specifically, the inlet conditions were implemented as

$$U = \frac{U_*}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \quad (3)$$

$$k = \frac{U_*^2}{\sqrt{C_\mu}} \quad (4)$$

$$\varepsilon = \frac{U_*^3}{\kappa(z+z_0)} \quad (5)$$

$$U_* = \kappa\frac{U_{ref}}{\ln\left(\frac{z_{ref}+z_0}{z_0}\right)} \quad (6)$$

where z is the vertical cell centre height above the ground level wall, κ is Von Karman's constant, $U_*$ is the frictional velocity, $C_\mu$ is 0.09, $U_{ref}$ is the reference velocity at a reference height of $z_{ref}$ and $z_0$ is the aerodynamic roughness length given by [31]

$$z_0 = 2\times10^{(TC-4)} \quad (7)$$

where TC is the terrain category as defined in the Australian Standard [31].

Often the upper boundary conditions matching these inlet conditions are erroneously omitted due to difficulties in their implementation in commercial CFD software packages [3,8,13,26,27,28,29]. These difficulties were overcome in this research by implementing the equations in the open source package OpenFOAM [22]. To maintain boundary layer shearing along the fetch the constant kinematic shear stress, τ, given by

$$\tau = U_*^2 \quad (8)$$

which was implemented on the upper boundary via

$$U_t = \frac{\tau}{\partial z_t \nu_{eff}} + U_{nt} \quad (9)$$

where $U_t$ is the velocity at the upper boundary patch face centre, $\nu_{eff}$ is the effective viscosity, $\partial z_t$ is the vertical distance from boundary patch face centre to cell centre of the immediately adjacent cell and $U_{nt}$ is the velocity at the same cell centre. Given the kinematic shear stress is constant in height for a neutral ABL, the gradient in turbulent kinetic energy is set to zero at the upper boundary. The gradient in turbulent dissipation at the upper boundary (10) is set as specified by Sumner and Masson [33],

$$\frac{\partial\varepsilon}{\partial z} = -\frac{U_*^3}{\kappa z_t^2} \quad (10)$$

Finally, the use of velocity based wall functions in OpenFOAM allows equation (3) to be implemented for the ground level wall function such that the cell centre immediately adjacent to the ground will exhibit velocity consistent with the atmospheric boundary layer profile.

To validate the implementation of the above described ABL conditions a test was set up mimicking the domain size, grid velocity conditions and turbulent length scale tested by Hargreaves and Wright [13]. It should be noted a Von Karman constant of κ = 0.4 is used for consistency with the sources of the equations [13,26] rather than the more conventional κ = 0.41 found in other fluid mechanic applications.

Figure 2 shows the results for the validation test at various stations along the fetch. The combination of each of the above boundary conditions is seen to maintain the boundary layer profiles over 4km. When considering the flow field within 5 reference lengths of the ground a small peak in turbulent kinetic energy can be seen (upper right image in figure 2). This is believed to be a consequence of the realizable k-epsilon turbulence model [30] deviating from the standard assumptions for the ABL [35]. This ~10% excursion from a constant turbulent kinetic energy profile is maintained along the fetch and is much smaller than that reported by Hargreaves and Wright [13]. This improvement is believed to be a consequence of the specification of turbulent gradients at the upper boundary. The current approach is suitable for engineering applications given the built environment will cause flow field changes that overwhelm this inconsistency; however further research is required to investigate the driving mechanisms of this observation and any possible improvements.

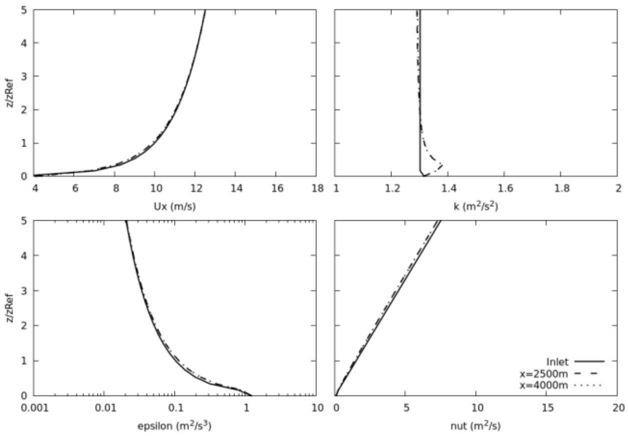


Figure 2. Neutral ABL maintenance of velocity and turbulent variables up to 5 reference lengths above the fetch.

### Computational Fluid Dynamic Method

Given the low Mach number flows in near-ground ABL flow, the governing equations solved in the CFD model are the steady, incompressible Navier-Stokes equations with constant laminar viscosity. Turbulence closure and hence turbulent viscosity is provided by the realizable k-epsilon turbulence model [30].

The numerical implementation is the finite volume method, on a co-located, hexahedral dominant mesh. The SIMPLE approach [23] is used for pressure-velocity coupling and the segregated equations are solved with the Gauss-Seidel family of matrix solvers. An overview of the numerical methods and finite volume implementation in OpenFOAM can be found in [17].

A hexadecagonal domain surrounds the building of interest (see figure 3) and is re-used for the wind simulations in sixteen directions. The building of interest has a near wall cell height of approximately 0.3m adjacent to regions of assessment and 0.6m across the remainder of the building, while the volume enclosing the region of assessment is meshed with hexahedral cell edges of approximately 0.15m. Features larger than 0.3m are therefore included in the geometry where possible. Surrounding buildings within approximately 2H of the building of interest are coarsely modelled where H is the height of the tallest building in the domain. The height and radius of the domain is set to approximately 5H and 7H, respectively. This satisfies the mesh and domain requirements of Tominaga et. al. [34], with the exception of the 10H outlet requirement. In this research the outlet boundary condition was set using the zero velocity gradient where the flux is outbound, while a fixed velocity (calculated from the pressure field) was applied to faces where the flux is inbound. This boundary condition is known as pressureInletOutletVelocity and is documented on the OpenFOAM website [22]. Use of this boundary condition allowed the outlet to be located 7H downstream of the building of interest without adverse effect on the solution while improving the computational expense.

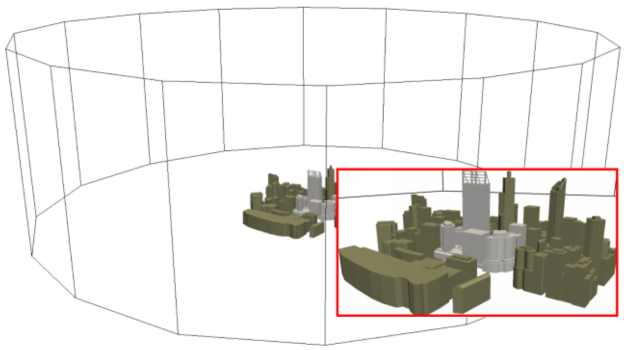

Figure 3. Domain surrounding Perth CBD. Note the terrain has been omitted from this image for clarity.

Steady simulations were conducted for ABL wind from each of the 16 directions. The reference velocity was set to 10m/s at a reference height of 10m. Each simulation was run until sampled velocities varied by less than 1%, often corresponding to residual levels of less than $10^{-2}$ and $10^{-3}$ for pressure and scalar transport equations, depending on the mesh size.

The GEM field values can estimated from the steady CFD solution using the equation of Bottema [4]. Here the continuous fields of mean velocity, $\overline{U}$, and turbulent kinetic energy, k, are used to calculate the $U_{GEM}$ by

$$U_{GEM} = \max\left(\overline{U}, \left(\overline{U} + g\sqrt{k}\right)/G\right) \qquad (11)$$

Where g is the peak factor and G is the gust factor. The peak factor relates the standard deviation in velocity to the maximum gust velocity and is typically 3.5 [1]. In this research $g = 5$ was calibrated for on-site experiences around the tower base, while the gust factor was taken to be $G = 1.85$.

The reference velocity $(U_{ref})$ required to produce each assessment criteria velocity $(U_{criteria})$ is then calculated by

$$\frac{U_{ref}}{U_{criteria}} = \left(\frac{U_{ref}}{U_{GEM}}\right)_{CFD} \qquad (8)$$

where $(U_{ref})_{CFD} = 10m/s$ and $(U_{GEM})_{CFD}$ is calculated as above. The probability of $U_{ref}$ occurring is calculated for each direction using either the Weibull or extreme value probability distribution for the comfort or safety criteria, respectively. The probabilities for each criterion are summed and the result assessed against the 5% probability of occurrence for every cell in the computational domain. The result is a three-dimensional field of environmental wind assessment criteria throughout the entire built environment. These results are typically reported on a horizontal cutting plane at pedestrian height (1.5m) above ground level.

On-site wind observations were made at 14:30 on Wednesday 22nd February 2017. Bureau of Meteorology reported wind conditions were SW to SSW winds at 17km/h. Subjective interpretation of local wind environment is shown in figure 3. Predicted results are shown in figure 4 where there is a clear correlation with the subjective reporting. Quantitative comparison between computational results and on-site wind speed measurements is not commonly available in the literature and will be the subject of future research.

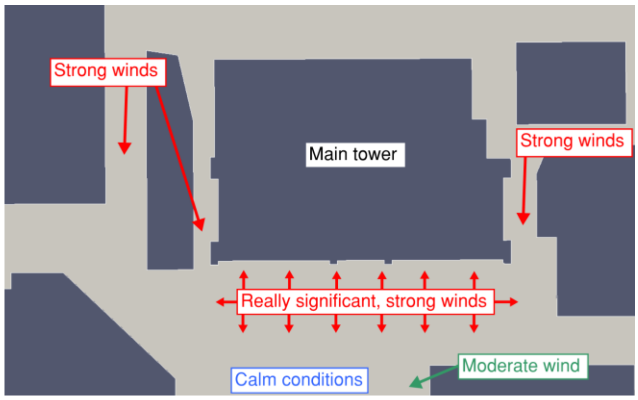


Figure 3. Subjective on-site wind observations at 14:30 on Wednesday 22nd February 2017.

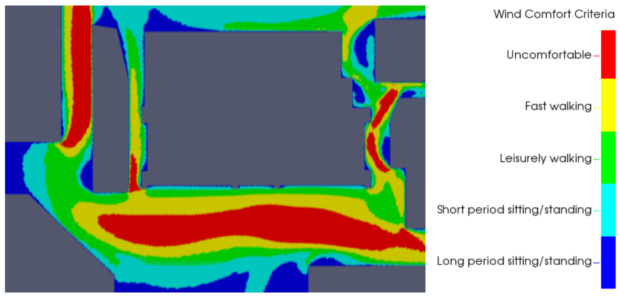


Figure 4. Computational assessment of wind comfort at 1.5m above podium (ground) level.

## Conclusions

An outline of a complete computational methodology to environmental wind prediction and assessment has been given. Maintenance of the modelled neutral ABL through an empty domain was attained by implementing all relevant inlet, wall function and upper boundary conditions. Further improvement to the turbulent kinetic energy profile near ground level may be the subject of future research.

Wind was simulated from 16 directions and probability analysis of the environmental wind was conducted using both Weibull and extreme value wind distributions. Assessment of wind comfort and safety was conducted for the overall wind probability fields at pedestrian height.

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