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Guidelines for Practical Application of CFD to Pedestrian Wind Environment in Australasia

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ABSTRACT

Computational Fluid Dynamics (CFD) application to wind engineering has significantly increased in the last two decades. Continued improvements in computing resources has enabled commercial assessment of the pedestrian wind environment as a valuable building design tool. This paper reviews available guidelines on the practical application of CFD to predicting pedestrian level winds in the built environment. Reference is made to the existing best practices for pedestrian wind effects in the Australasian wind engineering community. This is intended as a first step toward more comprehensive development of Australian/New Zealand CFD guidelines.

1. Introduction

Over the last 50 years substantial research has been conducted on the ability of CFD to model flows around building-like bluff bodies (Blocken 2014). Performance can be evaluated against the local amplification factor, $K = U/U_{ref}$ where U is the local velocity and U_{ref} is the free stream reference velocity (Blocken et. al. 2016). High amplification factor regions are important contributors to velocity exceedance probability, while low amplification factors occur in low speed wake regions. Fortunately, steady RANS simulations very accurately (within 10%) predict wind speeds in higher amplification factor regions, while deficiencies are generally restricted to low amplification regions (Blocken et. al. 2016). These favorable properties have led to RANS CFD gaining increased acceptance as a tool for pedestrian wind assessment.

When undertaking pedestrian wind environment simulations, the CFD user must make several choices which, if poor choices are made, can overwhelm any inadequacy of CFD models (Castro & Graham 1999). In the absence of sufficient guidelines, the quality of the application of CFD varies significantly subject to the experience of the consultant, with no basis for acceptance by authorities.

Authoritative guidelines have emerged from several working groups including the Architectural Institute of Japan (AIJ) and the European Cooperation in the field of Scientific and Technical Research known as COST (Yoshie et. al. 2007, Tamura et. al. 2008, Tominaga et. al. 2008, Britter & Schatzmann 2007, Franke et. al. 2004, 2007, 2011). Notably the Dutch Wind Nuisance Standard, NEN8100 (Willensen & Wisse 2007, NEN 2006) includes both wind tunnel and CFD assessment model requirements.

The current AWES (2014) Guidelines for Pedestrian Wind Effects (GPWE) and the AWES (2001) Quality Assurance Manual (QAM) mentions CFD and allows for its use, however an assessment method is only prescribed for wind tunnel studies. This paper reviews the AIJ and COST CFD guidelines and compares them to the current AWES wind tunnel test guidelines where applicable. Comments based on commercial experience are also provided. Discussion is restricted to choices associated with the finite volume CFD method rather than the larger topics of wind statistics and pedestrian wind assessment criteria.

2. Geometry

In both wind tunnel and CFD models there is a region of model validity, outside of which flow is undergoing conditioning. The AWES GPWE requires the minimum wind assessment area (thus minimum valid area) extend to $\min(H/2$, B/2), where B and H are the width and height of the building model respectively. To adequately condition the flow, minimum geometry specifications for the building model, surrounding structures, terrain, vegetation and overall domain must be defined.

The AWES QAM requires that overall building dimensions modelled within 2% accuracy and that architectural details of 1m or greater (at full-scale) are included. Neither the AIJ or COST guidelines make specific recommendations for the resolution of the 3D digital building model, however in practice the scale of architectural details in CFD models is limited by the mesh resolution (refer Section 3).

The AWES QAM requires modelling of major surrounding structures and topological features within a 300m to 600m radius with at least 10% accuracy in overall dimensions (architectural features are not required). The AIJ states that structures should be clearly modelled within $1 - 2H$ of the building model plus one additional street block in each direction. The effects of terrain geometry are omitted in the AIJ guidelines. The COST guidelines discuss surrounding structure effects but does not specify a required radius, instead stating that solution sensitivity to surrounding geometry should be investigated. The more specific AWES 10% accuracy requirement within 300m to 600m is recommended, however a height-based relationship between 300m and 600m should be considered in future.

Modelling of existing local vegetation is required by the AWES QAM for pedestrian wind studies; however, the AWES GPWE strongly discourages the use of vegetation to ameliorate excessive pedestrian wind speeds. Conversely, the AIJ guideline mentions tree planting as one of the most popular measures for improving the pedestrian wind comfort environment and recommends vegetation modelling methods are compared to Mochida et. al. (2006). The COST guideline states that the effects of vegetation are secondary to that of buildings and does not specify modelling requirements. Further clarification of vegetation modelling requirements is needed for an Australasian guideline.

The AWES QAM specifies a maximum 10% blockage ratio for the scale model building and surrounding structures in a wind tunnel working section. Both the AIJ and COST guidelines specify a 3% maximum blockage ratio, however these guidelines also require upper and lateral boundaries at least 5H away from the building model (when surrounding structures are included), often creating a much lower blockage ratio. Both guidelines also recommend the inlet is placed 5H upstream and the outlet at 10H and 15H downstream for the AIJ and COST guidelines, respectively. Commercial experience shows the AIJ minimum domain size recommendations are sufficient.

3. Mesh

The 3D computational grid (mesh) of cells (control volumes) has a significant influence on the accuracy of a CFD simulation. In the finite volume method hexahedral cells are desirable and the following specifications refer to the edge length of a cubic hexahedral cell.

There must be enough cells near rooftops, walls and corners of buildings in the assessment area to correctly reproduce separating flow characteristics. Both the AIJ and COST guidelines recommend a minimum grid size of 1/10th of the building scale, often resulting in cells between 0.5 and 5m in length. Further, both the AIJ and COST guidelines recommend there are at least 3 cells between the ground and pedestrian wind assessment height (typically 1.5m or more above ground). Commercial experience has shown that increasing this requirement to between 5 and 10 cells (i.e. 15cm to 30cm edge length) is beneficial in the resolution of flow near mullions, canopies and other thin surfaces that play a crucial role in pedestrian wind assessments.

Traditionally wall adjacent grid height requires careful tuning to retain a local Reynolds number (y^+) suitable for the chosen wall treatment. For buildings and structures Castro (2003) shows that wall functions have only a small effect on pedestrian wind speeds. First cell y^+ criterion on buildings and structures is therefore unspecified in the AIJ and COST guidelines. The interaction between terrain/ground plane adjacent cell height and terrain roughness is discussed further in Section 4.

Neither the AIJ or COST make specific recommendations on regional grid refinement, instead stating that systematic grid convergence studies should be attempted using Richardson extrapolation. Likewise, no specific grid quality criteria (e.g. for non-orthogonality, skewness, aspect ratio) are specified as different codes often handle numerical consequences of grid quality in different ways. The AIJ and COST do recommend limiting grid stretching as much as possible in the assessment regions, near separation points and across key shear layers.

While stopping short of guidelines, the following practical refinement strategies have evolved from commercial experience and may provide a satisfactory starting point for CFD practitioners.

- Cells in the far-field are refined with distance from the ground. Cells are refined to 2.5m within 20m of the ground, 5m edge length between 20m and 75m, and 10m edge length 75m to 100m. Cells above this height can be cubes of 20m edge length if taller buildings are not present.
- Suburban houses and other surrounding structures can often be meshed with 1.25m to 2.5m cubes and retain the 1/10th scaling law.
- Cells within 3m of the building model are refined to either 30cm or 15cm depending on the geometrical resolution required and the computing resources available. This refinement level should be extended across the valid pedestrian wind assessment area. Cells are refined to 65cm between 3m and 7m and 1.25m edge length between 7m and 20m from the building.

Total cell count for a city-scape using the above criteria is typically in the order of 10 million cells depending on the geometry complexity, size of the building and its surrounding structures.

4. ABL Maintenance

Generation and maintenance of ABL profiles in the approach flow depends on the inlet and, crucially, lower wall and upper boundary conditions. The AIJ guideline recommends a power law velocity and turbulence intensity profile consistent with AIJ (2004). Slip or symmetry-plane upper boundary conditions can be used as these profiles assume extension beyond the ABL gradient height of 2.7 to 4.5km (AS/NZS 1170.2). Note that this domain height is prohibitively onerous in many commercial applications. COST specifies Richards & Hoxey (1993) (RH) inlet profiles based on constant-shear ABL valid for partial height ABL simulations. Here maintenance through the domain crucially relies on either a constant shear upper boundary condition (as specified by RH) or by prescribing the inflow profile across the entire upper boundary (Blocken et. al. 2007). Jones et. al. (2017) found improved maintenance of turbulent profiles using the Sumner & Masson (2012) formulas for gradients at the upper boundary. Unfortunately, these upper boundary conditions are often erroneously omitted. It is therefore strongly recommended that proof is provided of mean velocity and turbulence intensity maintenance over an empty domain.

The AWES QAM requires approach mean wind speed and turbulence intensity profiles lie within 10% of Deaves & Harris (1978) values tabulated in AS/NZS 1170.2. Cermak & Cochran (1992) also show that constant shear stress requirements should be observed for wind tunnel tests of a partial height ABL. Figure 1 shows a theoretical comparison between AS/NZS 1170.2 and RH ABL profiles. Mean velocity profiles show excellent agreement across all terrain categories; however, differences appear in the turbulence intensity profiles when using the standard von Kármán constant, $\kappa = 0.4$. Possible deficiencies in the Deaves & Harris (1978) turbulence intensity profiles are currently being explored (Holmes 2017) which may lead to better agreement (refer Figure 1); however, for now, the RH inlet profiles can achieve the AWES QAM 10% accuracy requirement by tuning the von Kármán constant for each terrain category. Further investigation is required before definitive guidelines can be specified.

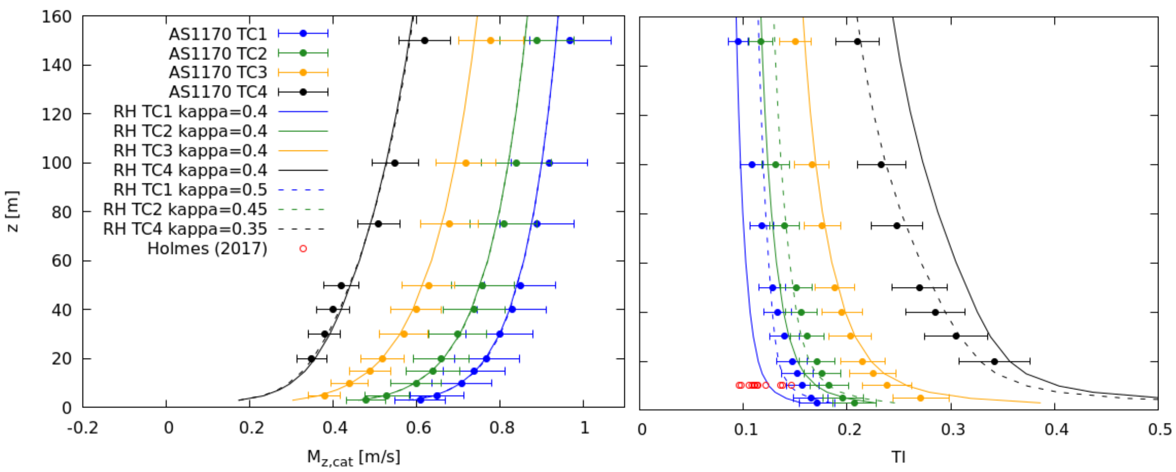

Figure 1: ABL velocity (left) and turbulence intensity (right) for Richards & Hoxey (1993) and AS/NZS1170.2 with 10% error bars. Cyclone Yasi data also shown for TC1 (Holmes, 2017)

The lower wall function should recreate the constant shear stress for consistency with the partial height ABL profile above. Both AIJ and COST present the lower wall treatment in terms of so-called rough-wall functions where the aerodynamic roughness is related to a roughness height $k_s \approx 30 \times z_0$. The AWES QAM and AS/NZS 1170.2 present aerodynamic roughness z_0 as a function of terrain categories 1 through 4. Several problems arise including the requirement that first cell height lies above the roughness height and that the wall function implementation in some commercial CFD codes cannot maintain the ABL (Hargreaves & Wright 2006). Again, it is recommended that proof is provided of mean velocity and turbulence intensity maintenance through an empty domain.

5. Turbulence Modelling & Numerical Convergence

The AIJ and COST guidelines recommend non-linear or Reynolds Stress models over standard k-ϵ turbulence models due to its well-known deficiencies. Realizable k-ϵ is recommended as a satisfactory baseline choice and is a common choice in published literature (Blocken et. al. 2004). Both the AIJ and COST guidelines do not recommend first-order upwind numerical schemes for convection terms in the transported variable equations, except during initialization of the flow fields.

Both the AIJ and COST recommend the solution variables are monitored for convergence to quasi-constant values. COST suggest scaled residuals (relative to the first iteration) should be reduced by at least four orders of magnitude. Practical experience shows the ability to achieve this will be a function of the flow configuration, boundary conditions and mesh size. Both residual and solution variable convergence criteria are recommended.

6. Effective Wind Speed and Direction

Willemsen & Wisse (2007) define effective wind speed for NEN8100 as

$$U_{Eff} = \overline{U} + g\sigma \tag{1}$$

where $\overline{U}$ is the mean wind speed, σ is the standard deviation and $g \in [0,3.5]$ is the peak factor. The NEN8100 uses $g = 0$. The AIJ and COST guidelines refrain from specifying a peak factor. Bottema (2000) reviews several effective velocity and peak factors in relation to the discomfort criteria employed. The AWES GPWE recommends the use of Melbourne (1978) criteria for wind safety where $g = 3.5$. It is tentatively suggested a peak factor $g = 3.5$ for wind safety is consistent with existing AWES guidelines; however, further research and agreement is required. It should be noted though that the assumption of a constant peak factor for local, complex flow fields is somewhat arguable (Gross 2014).

Finally, the AWES QAM requires assessment of at least 16 wind directions. AIJ recommends at least 12 wind directions (Yoshie et. al. 2007) while the number of wind directions is omitted in the COST guidelines. For consistency with AWES QAM at least 16 wind directions are recommended.

7. Conclusions

This paper has presented a brief comparison between the AWES QAM/GPWE and the AIJ and COST guidelines. Generally, the AWES requirements were generally found to be more specific, onerous and conservative. Recommendations were given to align potential CFD guidelines with the Australasian wind engineering community. Several comments were also provided based on practical consulting experience. It is desired that this paper is a first step toward more comprehensive discussion of CFD guidelines suitable for the Australian/New Zealand region.

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