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Quality assurance in assessing wind loading with scale resolving CFD simulations

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SUMMARY

Ensuring reliable predictions from turbulence-resolving CFD simulations remains a key challenge in wind loading applications. While methods such as LES and DES offer high physical fidelity, their flexibility in modelling choices, numerical setups, and user practices introduces variability that can affect accuracy and reproducibility. This creates a need for clear and practical quality assurance (QA) approaches to assess the reliability of such simulations. This study focuses on identifying and demonstrating a set of key QA checks for scale-resolving CFD applied to structural wind loading. Typical checks aim to cover essential aspects of the simulation, including domain setup, statistical convergence, and turbulence resolution. Here, we discuss a metric to verify the quality of inflow turbulence conditions in precursor simulations that aim to ensure consistency with target profiles. In addition, the index of resolution quality (IRQ) is presented as a practical metric to assess mesh adequacy around study buildings to confirm that the relevant turbulent structures are sufficiently resolved. Together, these checks provide a simple and effective framework for improving confidence in CFD-based wind loading predictions.

Keywords: *wind loading, CFD, quality assurance, dynamic structural loading, DES*

1. INTRODUCTION

With the growth of computational power and improved numerical methods, Computational Fluid Dynamics (CFD) tools have become more capable and widely used in engineering practice. They are now commonly applied to estimate wind loads and structural responses under a range of wind conditions. Among available approaches, turbulence-resolving methods such as Large Eddy Simulation (LES) and hybrid approaches (e.g., various variants of detached eddy simulation, DES) are particularly important, as they can capture the spectral nature of the key flow regimes that govern wind loading. However, their successful application is not straightforward and requires careful consideration of modeling choices.

A major challenge in using these advanced simulations is ensuring a consistent and high level of quality. CFD workflows can vary significantly depending on the solver, modeling assumptions, and practitioner preferences and biases. While this flexibility supports innovation and continuous development, it also introduces uncertainty in assessing accuracy and achieving reproducible results. As a result, beyond standard good practices, there is a need for clear and rigorous approaches to evaluate the quality of a simulation and to minimize both user-related and numerical errors.

Conventional verification of LES applied to atmospheric flows typically involves ensuring agreement between precursor simulations and theoretical boundary layer targets (e.g., ESDU), as well as demonstrating convergence in both precursor and building-resolved simulations. Here, attention is directed instead toward more advanced, non-routine diagnostic checks found in the literature that provide a more stringent assessment of solution quality, meanwhile complementing the traditional metrics.

2. METHODOLOGY

2.1. QA checks

This section discusses some advanced verification metrics found in the literature for both the approach flow development and for building-resolved simulations, and they consider the spectral content or statistics of the unsteady solution fields for velocity.

2.1.1. Approach flow verification

A two-step approach is used to define the wind loading flow conditions, where the first step involves precursor simulations in an empty domain to generate the inflow. These simulations are designed to match target profiles at the location of the most upstream building. The target profiles follow ESDU guidelines for mean wind speed (ESDU 82026, 2002a), turbulence intensity and integral length scales (ESDU 85020, 2002b; ESDU 86010, 2001), within a framework consistent with ESDU 01008 (2010).

The resulting profiles are then compared against the targets to ensure accuracy. The mean wind speed and turbulence intensity must be within 10% over the upper 75% of the building height, while the integral length scales should be within a factor of three. The length scales are determined using autocorrelations of velocity time series and applying Taylor's frozen turbulence hypotheses.

Additionally, the mesh resolution for approach flow simulations is evaluated for sufficiency by analysing the power spectral density (PSD) distribution ("spectra") from the velocity field time series measured at selected probe locations. Per Geleta and Bitsuamlak (2022), a cutoff frequency, n_c, is determined based on the local mesh size, Δ, and the total local spectra, $F(n_c)$:

$$\boldsymbol{\Delta} = \sqrt{\frac{\boldsymbol{\pi}}{\boldsymbol{n_c}}\boldsymbol{F}(\boldsymbol{n_c})} \tag{1}$$

Where the total spectra can be calculated by:

$$\boldsymbol{F}(\boldsymbol{n_c}) = \sum_{\boldsymbol{i=1}}^{\boldsymbol{3}} \boldsymbol{S_{ii}}(\boldsymbol{n_c}) \tag{2}$$

Equation (1) is then solved iteratively for n_c and this frequency is indicated on the spectra plots to indicate whether the cutoff frequency for the given mesh and resolved turbulence lies within the inertial subrange of the spectra (where the slope in log-log scale should be roughly $-\frac{5}{3}$), implying the largest, energy containing eddies have been resolved.

2.1.2. Index of resolution quality

Since mesh resolution strongly affects accuracy in LES/DES, a mesh sensitivity study is required. The index of resolution quality (IRQ), proposed by Celik et al. (2005), is used as a meshindependent metric to assess resolution adequacy. IRQ is defined as the ratio of resolved to total turbulent kinetic energy (see Equation (3)). The total turbulent kinetic energy is estimated using an extrapolation approach (see Equation (4)), where Δ is the cell size and p represents the numerical order of the method.

$$IRQ = \frac{k_{resolved}}{k_{total}} \tag{3}$$

$$k_{total} = k_{resolved} + |a_k| \cdot \Delta^{\mathrm{p}} \tag{4}$$

Using the resolved turbulence kinetic energy from solutions with two different mesh resolutions ("fine" and "medium"), which differ by a refinement factor, r, Equation (5) is used to calculate an estimate for a_k:

$$a_k = \frac{1}{\Delta_{fine}^{p}} \left(\frac{k_{resolved-fine} - k_{resolved-medium}}{r^p - 1} \right) \tag{5}$$

Ultimately, this metric can be evaluated at multiple probe locations near the building, or preferably reported as a field contour across the domain. A threshold of at least 75% is typically used to indicate sufficient resolution (Celik et al., 2005).

2.2. Simulation setup

The simulation setup follows internal tests and prior studies. The computational domain is defined to minimize boundary effects. Turbulence is introduced at the inlet using a synthetic generator to match the target inflow, with symmetry conditions on the sides and top, no-slip on solid surfaces, and a pressure outlet downstream. The mesh is designed to preserve turbulence, with refinement near the inlet and building, and its adequacy is confirmed using the cutoff frequency (approach flow in the open channel) and IRQ metric (main simulation).

Temporally, a small time step is used to maintain a low average Courant number for stability and accuracy. Flow quantities are sampled at each time step, with resampling applied if needed for spectral analysis. The total simulation time is chosen to ensure statistical convergence of the solution.

3. IRQ DEMONSTRATION

Figure 1 presents an example of QA checks for a generic case study for a tall building in a moderately sparse urban environment. As shown, IRQ values drop when a coarse mesh is used (top panel), while they remain close to 1 across most of the domain with a sufficiently refined mesh (bottom panel), indicating strong turbulence resolution. Lower values (though still above the 75% threshold in the refined case) are observed near the leading-edge roof region, where flow separation occurs and finer grid resolution is needed to capture smaller eddies. This quality check confirms that key turbulent structures are well captured and increases confidence in the predicted wind loading.

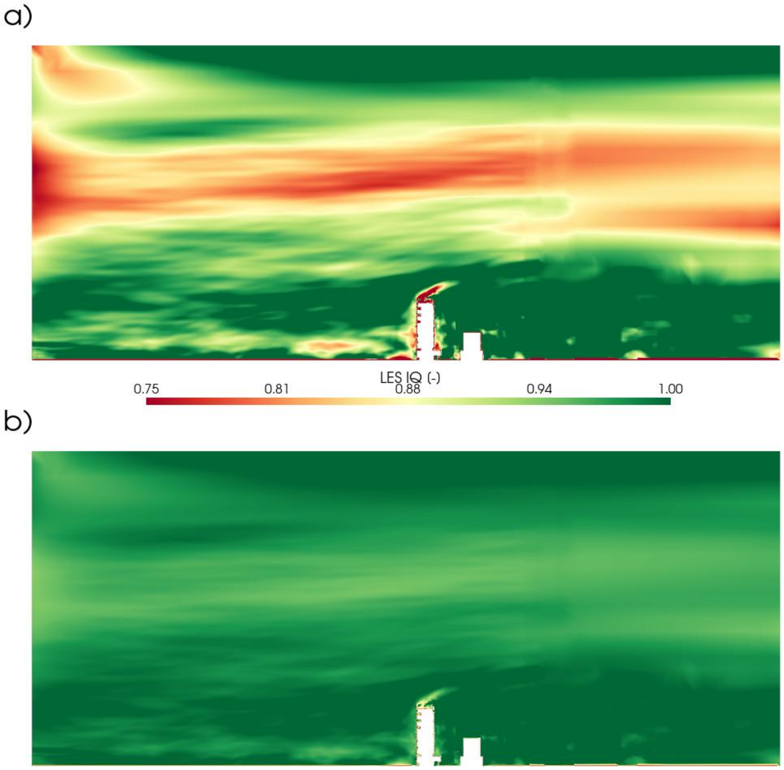

Figure 1: Example of a QA check for an internal project, showing the IRQ metric for mesh adequacy and turbulence resolution based on (a) coarse and (b) fine meshes.

4. CONCLUSION

This study highlights the importance of quality assurance in turbulence-resolving CFD for wind loading applications. A set of practical QA checks, including turbulence resolution, are presented and demonstrated. The sample results show that these checks provide a simple and effective way to assess simulation reliability, thereby improving confidence in CFD-based predictions for structural wind loading.

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