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Integrated LES Guidelines and Database for Validation of CFD Simulations in Urban Wind Environments: The Accumulation of AIJ Activities Post-RANS Guidelines

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SUMMARY

The rapid utilization of Large-Eddy Simulation (LES) for urban flow necessitates best practice guidelines (BPGs), building upon the Reynolds-averaged Navier–Stokes equations (RANS) simulation guidelines by Tominaga et al. [J Wind Eng Ind Aerodyn **96** (10-11), 1749–1761 (2008)]. A working group at the Architectural Institute of Japan (AIJ) developed comprehensive LES BPGs for the Pedestrian Wind Environment (PWE) and proposed a modeling strategy, numerical setups, quantitative criteria, and robust averaging times. Simultaneously, the AIJ compiled an expanded standardized benchmark database of 13 cases. These cases, ranging from isolated building cases to idealized building arrays and actual urban areas, include mean wind velocity, concentration, and temperature measurements. Data were converted from legacy formats, such as the previous Excel format, to standardized text-based formats (CSV/STL) and published openly on Zenodo. This integrated effort will significantly enhance the reliability and standardization of LES in computational wind engineering.

Keywords: *Large-eddy simulation, Best practice guidelines, Benchmark dataset, Urban wind environment, Computational wind engineering, Architectural Institute of Japan*

1. INTRODUCTION

Wind environment simulation in urban areas is crucial for addressing issues related to pedestrian comfort, air pollution, and thermal effects, all driven by the complex interaction between atmospheric boundary layer flows and dense building formations. Computational Fluid Dynamics (CFD) has served as an essential tool in Computational Wind Engineering (CWE) and provided detailed flow insights since the 1980s.

To institutionalize quality assurance, the Architectural Institute of Japan (AIJ) established a working group in 1997. In the first ten years, this effort culminated in the AIJ CFD guidebook (AIJ, 2016) and best practice guidelines (BPGs) published by Tominaga et al. (2008), which primarily focused on Reynolds-averaged Navier–Stokes equations (RANS) models for Pedestrian Wind Environments (PWEs). Simultaneously, the European Cooperation in Science and Technology (COST) initiative provided BPGs, mainly addressing RANS simulations, and a limited discussion of large-eddy simulation (LES; Franke et al., 2007). In the subsequent fifteen years, rapid advancements in computational resources fueled a dramatic increase in the use of LES for urban complex flow. LES is favored over RANS as it directly resolves grid-scale turbulent structures, offering higher accuracy for transient phenomena such as wind gusts. However, the broader application of LES has been hindered by its high computational cost and the absence of comprehensive, quantitative BPGs tailored specifically for PWE.

In response, the AIJ working group systematically developed quantitative LES guidelines and expanded their validation databases significantly. This study summarized these dual efforts: newly proposed LES BPGs (Okaze et al., under review) and a comprehensive benchmark database (Kikumoto et al., under review), which collectively aim to enhance the reliability and application scope of CFD in urban environments.

2. OVERVIEW OF LES GUIDELINES

The AIJ LES BPGs offer a systematic framework designed to ensure acceptable prediction quality for mean wind velocity, second-order turbulence statistics, and instantaneous wind speed (e.g., three-second averages) in PWE applications. The guidelines consist of two requirements: “Recommendations” (minimum required conditions) and “Notes” (suggestions for achieving higher quality).

- <u>Domain Size and Blockage</u>: The blockage ratio (ratio of the projected building frontal area to the domain cross-sectional area) must be set at 5% or less. This relaxation from the previous 3% RANS standard acknowledges the recent assessment practices. The inlet and lateral boundaries must be located at a distance of at least five times the maximum building height (H) from the outer edge of the target building.
- <u>Building Modeling</u>: Buildings within the primary assessment area (1–2H radius) and an additional street block (2–3H) must be reproduced. Buildings in the outer area (>3H) can be simplified (e.g., using urban roughness lengths or canopy models) but must retain their aerodynamic effect.
- <u>Grid Resolution</u>: LES requires significantly finer grids than the RANS model. The grid resolution around the target building must be 1/20 of the characteristic edge length or less. At typical urban scales, this corresponds to an actual spacing of approximately 0.5–5.0 m.
- <u>Near-Wall Treatment</u>: To prevent pedestrian-level evaluation points (1.5–5.0 m) from being directly affected by wall functions, computational grids should be arranged such that these points fall at or above the third computational cell from the ground surface.
- <u>Inflow Turbulence</u>: A boundary condition that explicitly expresses turbulent fluctuations is mandatory for LES, corresponding to a specific ground surface roughness category. The inflow profile properties (mean velocity, turbulence intensity, and integral length scale) should be aligned with standards or codes.
- <u>Subgrid scale (SGS) turbulence model</u>: Appropriate SGS turbulence models should be introduced to reproduce the effects of SGS stress on a resolved flow field.

- Spatial Discretization: A common and recommended practice uses second-order central differencing for advection terms, blended with a small weighting (5–10%) of the first-order upwind difference to suppress numerical oscillations while maintaining accuracy.
- Calculation Time and Convergence: Simulations require an initial spin-up period of at least five flow-through times to eliminate the dependence on initial conditions. The subsequent averaging period for statistical quantities should be sufficient for obtaining data equivalent to several samples of 10-min averages on an actual scale, ensuring consistency with meteorological observations. Unlike RANS, LES does not require excessively tight convergence criteria for Poisson's equation at any time step.

3. BENCHMARK DATA SET

The AIJ working group meticulously reconstructed and expanded the experimental database to serve as a high-quality foundation for CFD verification and validation. This comprehensive database consists of 13 benchmark cases (Cases A–M) compiled from existing and new wind tunnel and field measurements. These cases cover diverse scenarios, from simplified isolated models to complex real urban configurations, extending the scope to include advanced physics, such as pollutant dispersion and non-isothermal flows. The details of the benchmark cases are provided on the AIJ website (https://www.aij.or.jp/jpn/publish/cfdguide/index_e.htm).

We also addressed the fact that all experimental data, including previous cases, were converted from legacy formats such as Excel files to standardized, less dependency-prone text-based formats (CSV and STL). All datasets are publicly available via Zenodo under the Creative Commons Attribution 4.0 International license.

- Metadata: readme_case*.md files details of experiments and observations.
- Approach Flow: AF_case*.csv provides approach flow characteristics.
- Building Geometry: BD_case*.stl provides complex geometries. Several cases include terrain.
- Measurement Point: MP_case*.png draws measurement points in several cases.
- Results: RS-*.csv provides the measurement results. In several cases, they were separated into RS-WT_case*.csv (Wind Tunnel) and RS-FO_case*.csv (Field Observation).

4. FUTURE PERSPECTIVES

The LES BPGs and versatile benchmark database establish crucial platforms for advancing CWE research, focusing on accuracy, thermal physics, and computational efficiency.

4.1. Appropriate Inflow Turbulence on benchmark cases and Roughness Categories

The AIJ working group shared precursor LES-derived inflow turbulence databases for the relevant benchmark cases (H, K, and M). The continued development and open sharing of standardized turbulent inflow databases tailored to various roughness categories critically reduce the setup complexity and enhance the reproducibility of LES in diverse urban terrains.

4.2. Application to Pollutant Dispersion and Non-isothermal Flows

The expanded database, particularly benchmark cases H, J, K, L, and M, supports the validation of the advanced turbulence models for pollutant dispersions and/or non-isothermal flows. Continued research related to the modeling of turbulent scalar fluxes in RANS simulations should involve the effects of the large-scale periodic motion of flow and/or local stratification. In addition, the flow dynamics must be discussed under conditions in which high buoyancy forces locally exert a significant influence.

4.3. Benchmark of Efficient Computational Methods

Mitigating the high computational burden of LES is essential for practical applications. The Lattice Boltzmann Method (LBM) is highly suited for large-scale GPU parallelization and is also expected to be applicable to urban wind simulations.

5. CONCLUSIONS

The activities of the AIJ working group were introduced after Tominaga et al. (2008). Comprehensive efforts have yielded two major outcomes. First, the systematic development of comprehensive BPGs for LES in PWE provided a rigorous framework for setting up high-fidelity simulations (Okaze et al, under review). The second was the compilation and expansion of an extensive experimental benchmark database comprising 13 validation cases (Cases A–M). To enhance the usability of the CFD validation, the data were carefully curated, converted from legacy data formats, such as Excel files, into standardized, less dependency-prone text-based formats (CSV and STL), and made publicly available via Zenodo (Kikumoto et al., under review). These integrated efforts standardize the LES methodology, enable rigorous verification and validation against high-quality, open-access experimental and field data, and focus future research on enhancing the predictive accuracy for thermal stratification, turbulent dispersion, and computational efficiency.

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