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Transient Wind-Response Prediction of a High-Rise Building Using LES and Newmark-Beta Dynamics validated against Full-Scale Measurements

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Summary

This work presents a combined LES–measurement framework for predicting wind-induced accelerations of tall buildings in urban environments. High-fidelity large-eddy simulations of the Rotterdam city center were used to extract time-resolved aerodynamic forces on the New Orleans Tower. These loads were applied to a calibrated reduced-order structural model solved with Newmark-β integration. Full-scale acceleration measurements collected over ten years served as validation data. The LES-derived responses reproduce the observed direction-dependent vibration levels and capture key effects of shielding, wake turbulence, and vortex-induced fluctuations. The results demonstrate that coupling LES with in-situ data provides a reliable approach for assessing wind-induced building dynamics in complex urban settings.

Keywords: *Large-eddy simulation, wind-induced response, tall buildings, urban flow, structural dynamics, full-scale measurements*

1 INTRODUCTION

Reliable prediction of wind-induced responses of tall buildings requires models that capture the interaction between urban exposure, unsteady aerodynamics, and structural dynamics. Large-eddy simulation (LES) has advanced the modelling of building-scale flow phenomena, with several studies reporting good agreement with full-scale data Hochschild (2024); Hochschild et al. (2024); Ciarlatani et al. (2023). However, most validation efforts focus on façade pressures or integral loads, while only few studies couple LES-derived loading with structural dynamics models, and these typically rely on generic building archetypes or wind-tunnel data rather than full-scale measurements. To the authors' knowledge, no existing work combines high-fidelity urban LES, time-resolved sectional forces, and direct comparison with long-term in-situ accelerations of a real high-rise building. This work combines (i) in-situ measurements from an instrumented high-rise building, (ii) LES of the surrounding urban flow, and (iii) a reduced-order structural model solved with Newmark-β. Time-resolved LES-derived drag, lift, and moment components are applied as spatially coherent, distributed loads to the structural model, which filters the aerodynamic forcing according to the building's dynamic properties, as summarised in Figure 1. The resulting acceleration responses are then compared directly to full-scale measurements.

2 IN-SITU MEASUREMENTS

The New Orleans Tower has been instrumented with façade pressure taps, triaxial accelerometers at three different floor heights, and an ultrasonic anemometer on the roof. This instrumentation provides long-term data on wind conditions, pressure distributions, and dynamic response, enabling identification of the building's modal properties and the statistical characteristics of the along-wind and across-wind acceleration components. Moretti et al. (2022); Bronkhorst and Geurts (2020) have shown that the first two bending modes dominate the response, with eigenfrequencies of approximately 0.29 Hz in both principal axes and damping ratios in the range of 0.8–0.9%. The

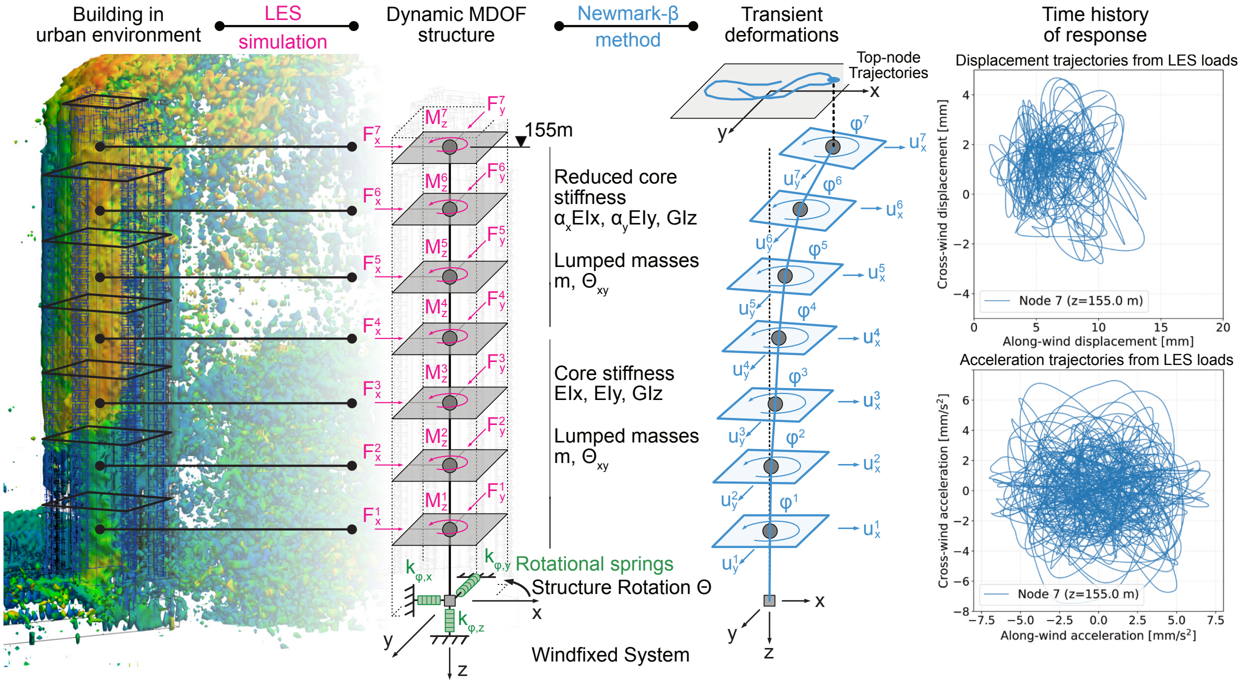

Figure 1: Determination of transient response based on LES-derived aerodynamic loads and exemplary results for trajectories of displacement and acceleration of the top node [Φ=130°, v(z=155m)=10m/s]

observed vibration patterns are characterized by strong coupling between the two axes, resulting in Lissajous-type motion rather than pure along-wind or cross-wind modes. Moreover, the highest vibration levels consistently occur in wind sectors influenced by upstream high-rise buildings, underscoring the importance of wake effects and directional turbulence in the urban environment, see Kemper et al. (2026). These full-scale data and its statistical analysis form the structural and aerodynamic reference for validating the LES-based response calculations presented in the subsequent sections.

3 LES SIMULATIONS

Large-eddy simulations were performed with the charLES solver (Cascade Technologies) using an implicit LES formulation of the filtered Navier–Stokes equations. Inflow conditions setup follows Hochschild et al. (2024) and is adapted for time-resolved load extraction. A detailed urban model of Rotterdam was generated within a radius of 1000 m around the tower, combining LoD 2.2 buildings from City4CFD in the near field ($R < 200$ m) with extruded LoD 1.2 blocks further away. The New Orleans Tower was remodelled with full geometric fidelity inside a domain of approximately $2.5 \times 1.8 \times 1.0$ km.

The block-structured mesh is locally refined around the tower and wake region (50–120 million cells, depending on refinement). Inflow conditions were generated with a synthetic turbulence method tuned to urban roughness and spectral properties. Simulations were carried out for wind directions where strong shielding and wake interaction were observed in the full-scale data. Surface pressures were integrated to obtain time series of base forces and moments (F_x, F_y, M_x, M_y, M_z), sampled at about 10 Hz in full scale. These signals capture buffeting, wake turbulence and vortex shedding.

Table 1: In-situ and numerical natural frequencies for the first six global modes.

	1-X [Hz]	1-Y [Hz]	1-T [Hz]	2-Y [Hz]	2-X [Hz]	2-T [Hz]
In-situ f_{IS}	0.282	0.291	0.638	1.332	1.527	2.054
Model f_{NUM}	0.279	0.290	0.656	1.367	–	2.208
Diff. $[(f_{\mathrm{NUM}} - f_{\mathrm{IS}})/f_{\mathrm{IS}}]$ [%]	-1.1	-0.3	2.8	2.6	–	7.5

1-X/2-X – first/second bending x', 1-Y/2-Y – first/second bending y', 1-T/2-T – first/second torsion

To compare LES and in-situ data, geometric (1:100) and temporal scaling based on the Strouhal law were applied. Forces and moments at the reference simulation velocity were rescaled to target wind speeds, consistently adjusting both velocity pressure and time scale. All series were transformed to ten minutes of full-scale time; for each simulated wind direction, ten such segments were extracted for statistical evaluation.

4 STRUCTURAL DYNAMIC AND NEWMARK-BETA

Structural properties were calibrated using full-scale measurements from the New Orleans Tower monitoring campaign. Table 1 compares the measured modal frequencies with those predicted by the numerical model. The initial stiffness and mass distributions were taken from the design-phase FE model. To align the model with the in-situ dynamic characteristics, rotational springs and stiffness-reduction factors α_x and α_y were introduced and tuned. Damping was represented using Rayleigh damping, with the coefficients chosen to match target frequencies of $f = 0.1\,\mathrm{Hz}$ and $0.3\,\mathrm{Hz}$ at a damping ratio of $\zeta = 0.9\%$.

The structural response was computed using a three-dimensional reduced-order model based on the first bending and torsional modes of the building. The coupled equations of motion were solved with a transient Newmark integration scheme, providing numerically stable acceleration time histories at all relevant frequencies. To interface the flow simulation with the structural model, the LES-derived drag, lift and moment components were mapped to seven structural nodes along the building height. This ensures a realistic vertical distribution of forces for different wind directions and preserves the directional dependence observed in the aerodynamic data. The resulting modal forces were used to compute floor-level acceleration responses, enabling direct comparison with in-situ measurements, see Figure 1.

5 COMPARISON OF DYNAMIC RESPONSES

Full-scale acceleration data collected over ten years were filtered according to wind direction and projected onto the building's principal horizontal axes x' and y'. Since these axes are fixed to the structure rather than the wind direction (x), the LES-based aerodynamic loads and the resulting Newmark-β responses were transformed consistently into the same x', y'-coordinate system. Comparisons were carried out for the ten wind directions for which LES simulations were available.

Figure 2 presents the maximum accelerations and corresponding standard deviations in the x' and y' directions for two representative wind directions. The agreement between simulation and full-scale observations is very good, demonstrating that the combined LES and structural-dynamics framework is able to reproduce the measured response characteristics with high fidelity.

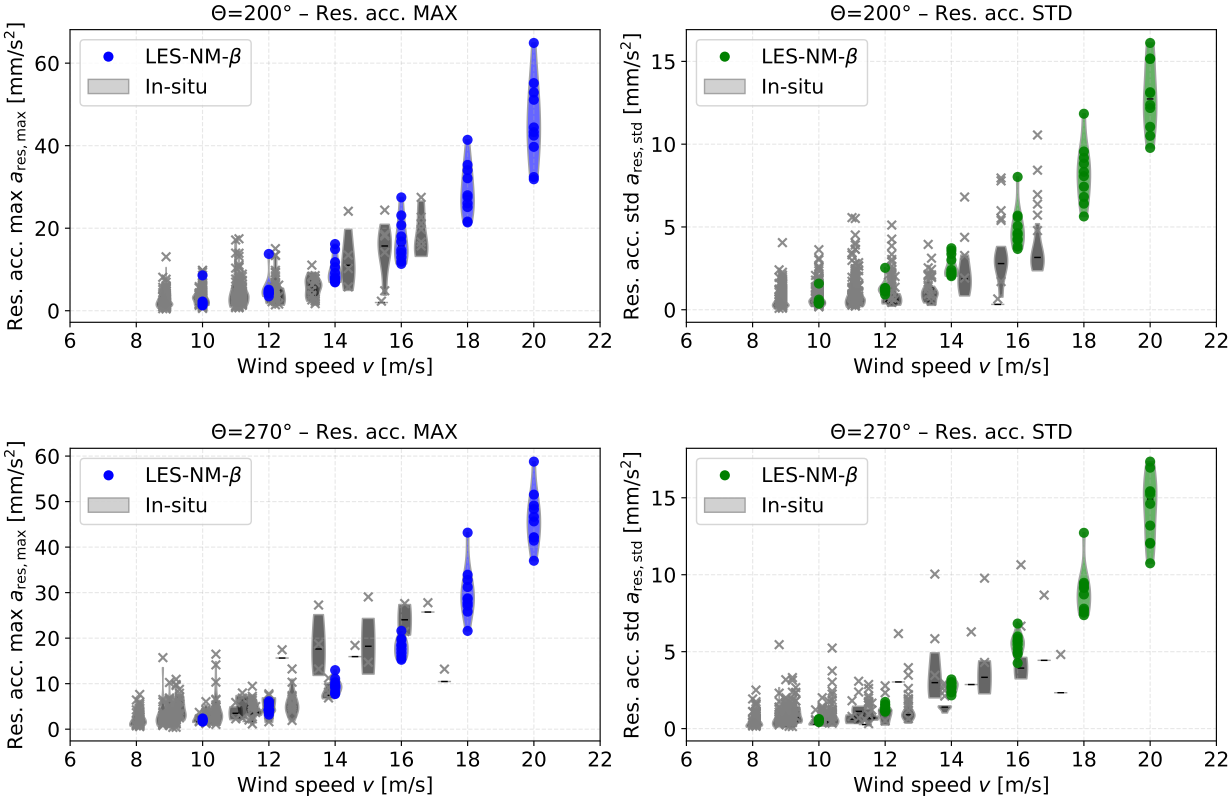

Figure 2: Comparison of LES-Newmark-β (LES-NM-β) results compared to in-situ accelerations for two exemplary directions

6 CONCLUSIONS

This paper presents a numerical workflow for reconstructing wind-induced accelerations of tall buildings from time-resolved aerodynamic loading produced by LES. In contrast to simplified code-based methods, the framework captures directional variability, wake effects and turbulence-induced fluctuations characteristic of dense urban environments. When validated against in-situ measurements from the New Orleans Tower, the LES–Newmark approach shows very good agreement and offers improved physical insight into the coupling between unsteady aerodynamics and building dynamics.

Ongoing work focuses on LES with more realistic roughness representation, comparison with wind tunnel tests using matched urban surroundings, and extending the dynamic model to include torsion–translation coupling and aerodynamic damping. The methodology is intended to support hybrid LES–measurement-based prediction models and to inform improved design provisions for wind-induced vibrations in tall buildings.

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