Physics-Regularized Residual Learning for Nonlinear Urban Turbulence Reconstruction

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Résumé

Airflow in urban environments is governed by the nonlinear dynamics of turbulent flow, including vortex shedding, shear-layer instabilities, and wake interactions across multiple spatial scales. While Reynolds-averaged Navier–Stokes (RANS) models provide computational efficiency, they systematically damp nonlinear turbulent structures that are resolved by Large Eddy Simulation (LES). Bridging this fidelity gap remains a central challenge in approximating complex flow dynamics efficiently.
We formulate this problem as learning a residual correction operator that maps low-fidelity RANS solutions to LES-consistent fields. Instead of directly approximating the high-fidelity solution, we adopt a residual learning strategy that models the discrepancy between RANS and LES predictions. This approach preserves large-scale flow structures while focusing the learning process on unresolved interactions.

To ensure physical consistency, the surrogate model is regularized using divergence-free constraints and gradient-based energy consistency terms, embedding structural properties of incompressible turbulence into the learning objective. Across multiple urban geometries and Reynolds regimes, the proposed framework significantly reduces velocity and turbulence prediction errors while accurately recovering coherent structures such as recirculation zones and shear layers. Leave-one-geometry-out experiments further demonstrate robust generalization to unseen layouts.
These results indicate that physics-regularized residual learning provides an efficient and scalable pathway toward LES-level turbulence approximation while preserving key nonlinear flow mechanisms

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