Multiscale Reduced-Order Modeling for Real-Time Flow Estimation

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Real-time estimation of unsteady flows from limited and noisy measurements is a key challenge in many areas of applied science and engineering, including haemodynamics and respiratory airflow. Addressing this challenge requires computational strategies that are both fast and robust, while capable of integrating physical models with measurement data. In this talk, we present RedLUM [2, 3], a multiscale and hybrid framework based on Reduced-Order Modeling and data assimilation techniques. The model relies on the incompressible Navier-Stokes equations, and the reduced-order framework is constructed intrusively using Proper Orthogonal Decomposition and Galerkin projection. Full-order solutions used to generate the reduced basis are computed with a finite volume discretization implemented in OpenFOAM [1], while the reduced-order model itself is built using the ITHACA-FV library [5, 4]. A central feature of the method is its stochastic closure model, which accounts for the unresolved dynamics introduced by basis truncation. This stochastic representation of the truncated modes is used as a physically informed prior in ensemble-based Bayesian data assimilation, enabling robust and adaptive flow estimation. The proposed methodology has already shown promising results on three-dimensional cylinder wake flows at Reynolds numbers ranging from 300 to 3900. It offers a solid foundation for future applications to complex systems, including those arising in biological contexts (e.g., digital twins for non-intrusive patient monitoring).

[1] *OpenFOAM | Free CFD Software | The OpenFOAM Foundation.* https ://openfoam.org/.

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[4] G. Stabile, S. Hijazi, A. Mola, S. Lorenzi, G. Rozza. *POD-Galerkin reduced order methods for CFD using Finite Volume Discretisation : vortex shedding around a circular cylinder.* Communications in Applied and Industrial Mathematics, **8(1)**, 210–236, 2017. doi :10.1515/caim-2017-0011.

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