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A Framework for Meshless Data-Driven Decompositions with RBF-Based Inner Products

Manuel Ratz[1, 2]; Samuel Ahizi[1,3]; Alessandro Parente[3,4,5] Miguel Alfonso Mendez[1,3]

[1] *the Von Karman Institute (VKI) for Fluid Dynamics*

[2] *U niversité Libre de Bruxelles (ULB)*

[3] *Universidad Carlos III de Madrid (ULB)*

[4]*Brussels Institute for Thermal-Fluid Systems and Clean Energy (BRITE)*

[5]*WEL Research Institute*

Abstract

Data-driven modal decompositions, such as Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD), are essential tools for feature extraction and dimensionality reduction in fluid dynamics. These techniques represent datasets as linear combinations of optimal modes or meet specific criteria. Various variants, like Spectral or Multiscale POD, have been developed to identify particular patterns or constrain the frequency content of each mode. Traditional algorithms for these decompositions are tailored for data organized on spatial and temporal grids, typical of outputs from cross-correlation-based Particle Image Velocimetry (PIV) or conventional mesh-based numerical methods in computational fluid dynamics (CFD).

Over the past decade, there has been a significant shift towards experimental and numerical methods that generate scattered data. This is the case of Lagrangian Tracking Velocimetry in experimental fluid dynamics and meshless Lagrangian methods such as Lagrangian Differencing Dynamics (LDD) or Smoothed Particle Hydrodynamics (SPH) in computational fluid dynamics. Computing modal decompositions on such data requires expensive and often inaccurate mapping onto regular grids before traditional algorithms can be deployed. This work proposes a meshless framework for computing all decompositions directly from scattered data. The approach uses Radial Basis Function (RBF) regression to efficiently build analytic representations of the velocity field from scattered data and compute inner products. The approach extends the first formulation for POD in [1] with a direct RBF formulation of inner products in space and time that adapts better to complex geometries. Meshless algorithms for POD, DMD, Spectral POD, and Multiscale POD are proposed. The method is tested on both experimental data using PTV and numerical data using SPH.

Keywords:

Reduced order modeling, Particle tracking velocimetry, Smoothed particle hydrodynamics, Meshless data assimilation, Radial basis function regression

References

[1] Tirelli, I., Mendez, M. A., Ianiro, A., Discetti, S. (2024) A meshless method to compute the proper orthogonal decomposition and its variants from scattered data. *Submitted to: Proceeding of Royal Society A.*