Proceedings of the 1st international Symposium on AI and Fluid Mechanics
Abstract No S5 A1

On the accurate identification of wall-bounded coherent structures via SHAP methodologies for 2D turbulent fields

[1,2]Samuel Molina*; [2]Andrés Cremades; [3]Sergio Hoyas; [1]José Cardesa; [1]François Chedevergne; [2]Ricardo Vinuesa

[1]ONERA – The French Aerospace Lab, Toulouse, France

[2]KTH Royal Institute of Technology, Stockholm, Sweden

[3]Universitat Politècnica de Valencia, Valencia, Spain

Abstract

Recent studies have demonstrated the potential of machine learning methods in predicting the temporal evolution and dynamics of turbulent flows [1,2], offering new tools to characterize this complex regime. Among these efforts, explainable artificial intelligence emerges as a means to uncover the underlying patterns learned by neural networks during training.

Building on this foundation, a game-theoretic SHAP-based algorithm has been applied to evaluate the relative importance of localized regions in predicting the future state of a given flow field [3,4]. The resulting areas of high importance, termed SHAP structures, draw an analogy with classical coherent structures in wall-bounded turbulence, such as Q events, streaks, and vortices. A three-dimensional (3D) comparison reveals that each type of classical structure is most relevant at specific wall-normal heights. SHAP structures, in addition, provide a unified perspective by highlighting the regions where classical structures are most influential [5]. This demonstrates the potential of SHAP-based methods to offer a more comprehensive, data-driven picture of turbulent flow dynamics.

This study explores the application of the SHAP methodology to two-dimensional (2D) slices of 3D flow data, where only longitudinal and wall-normal velocity components are available. This is a critical step towards faster analyses and reduced computational costs, while extending its applicability to experimental data from techniques like particle image velocimetry (PIV), which often provide only 2D measurements. A detailed comparison is presented between SHAP and classical coherent structures both derived from 2D slices on the one side, and the SHAP structures obtained from a 3D dataset that includes the transversal velocity component on the other side.

This work evaluates the viability of SHAP-based methods for turbulence characterization through 2D sampling, offering insights into their potential for generalization and application to experimental datasets.

Keywords: explainable artificial intelligence; SHAP; coherent structures; turbulent flow

References

[1] Solera-Rico A, Sanmiguel Vila C, Gómez-López M, Wang Y, Almashjary A, Dawson STM, Vinuesa R. β-Variational autoencoders and transformers for reduced-order modelling of fluid flows. Nat Commun. 2024 Feb 14;15(1):1361.

[2] Schmekel D, Alcántara-Ávila F, Hoyas S, Vinuesa R. Predicting Coherent Turbulent Structures via Deep Learning. Front Phys. 2022 Apr 13;10.

[3] Cremades A, Hoyas S, Deshpande R, Quintero P, Lellep M, Lee WJ, Monty JP, Hutchins N, Linkmann M, Marusic I, Vinuesa R. Identifying regions of importance in wall-bounded turbulence through explainable deep learning. Nat Commun. 2024;15(1):3864.

[4] Lellep M, Prexl J, Eckhardt B, Linkmann M. Interpreted machine learning in fluid dynamics: explaining relaminarisation events in wall-bounded shear flows. J Fluid Mech. 2022 Jul;942:A2.

[5] Cremades A, Hoyas S, Vinuesa R. Classically studied coherent structures only paint a partial picture of wall-bounded turbulence. [Preprint]. arXiv; 2024.