Implicit U-Net Enhanced Fourier Neural Operator for Long-Term Dynamics Prediction in Turbulence

Authors : Zhijie Li, Wenhui Peng, Zelong Yuan, Jianchun Wang

Abstract : Turbulence is a complex phenomenon that plays a crucial role in various fields, such as engineering, atmospheric science, and fluid dynamics. Predicting and understanding its behavior over long time scales have been challenging tasks. Traditional methods, such as large-eddy simulation (LES), have provided valuable insights but are computationally expensive. In the past few years, machine learning methods have experienced rapid development, leading to significant improvements in computational speed. However, ensuring stable and accurate long-term predictions remains a challenging task for these methods. In this study, we introduce the implicit U-net enhanced Fourier neural operator (IU-FNO) as a solution for stable and efficient long-term predictions of the nonlinear dynamics in three-dimensional (3D) turbulence. The IU-FNO model combines implicit re-current Fourier layers to deepen the network and incorporates the U-Net architecture to accurately capture small-scale flow structures. We evaluate the performance of the IU-FNO model through extensive large-eddy simulations of three types of 3D turbulence: forced homogeneous isotropic turbulence (HIT), temporally evolving turbulent mixing layer, and decaying homogeneous isotropic turbulence. The results demonstrate that the IU-FNO model outperforms other FNO-based models, including vanilla FNO, implicit FNO (IFNO), and U-net enhanced FNO (U-FNO), as well as the dynamic Smagorinsky model (DSM), in predicting various turbulence statistics. Specifically, the IU-FNO model exhibits improved accuracy in predicting the velocity spectrum, probability density functions (PDFs) of vorticity and velocity increments, and instantaneous spatial structures of the flow field. Furthermore, the IU-FNO model addresses the stability issues encountered in long-term predictions, which were limitations of previous FNO models. In addition to its superior performance, the IU-FNO model offers faster computational speed compared to traditional large-eddy simulations using the DSM model. It also demonstrates generalization capabilities to higher Taylor-Reynolds numbers and unseen flow regimes, such as decaying turbulence. Overall, the IU-FNO model presents a promising approach for long-term dynamics prediction in 3D turbulence, providing improved accuracy, stability, and computational efficiency compared to existing methods.

Keywords : data-driven, Fourier neural operator, large eddy simulation, fluid dynamics
Conference Title : ICFDM 2024 : International Conference on Fluid Dynamics and Mechanics
Conference Location : Sydney, Australia
Conference Dates : March 25-26, 2024