9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Mode Decomposition Methods for Analyzing Phase Mixing and ITG Dynamics

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Data-driven mode decomposition methods, such as Proper Orthogonal Decomposition (POD), Dynamic Mode Decomposition (DMD) and their multiresolution variants, have been widely used and developed in fluid mechanics, aeronautics, and plasma physics for coherent structure identification and dimensionality reduction [1,2,3]. In this study, we apply these methods to simple examples, phase mixing processes and Ion Temperature Gradient (ITG) turbulence data, examining their ability to extract dominant features [4]. The results highlight the strengths and limitations of each method in analyzing plasma dynamics, providing insights into their applicability in turbulence studies.

For the phase mixing case, we employ a 1D real space and 1D velocity space (1X1V) particle-in-cell simulation initialized with a perturbed Maxwellian distribution. The resulting data is analyzed using POD to investigate how well the dominant singular vectors can represent the evolving fine-scale structures in velocity space. Particular attention is given to the limitations of low-rank representations in capturing dynamics near $v = 0$, where fine structures persist over time. Based on the dominant vectors, we also conduct regression to reconstruct the temporal evolution of the mode amplitudes. This approach is expected to yield a compact representation of the system dynamics with high data compression.

In the ITG turbulence case, we analyze GENE [5] simulation data spanning the linear growth phase through nonlinear saturation. As the dataset encompasses different dynamical regimes, a precise demarcation between linear and nonlinear phases is challenging. To address this, we apply multiple decomposition techniques with the aim of identifying key interactions between zonal flows and drift waves embedded within the data. The effectiveness of each method in isolating coherent structures across these regimes will be examined, and comparative results will be presented to assess the interpretability and resolution of physical features across time.

Through these investigations, we aim to demonstrate the practical considerations involved in applying mode decomposition methods to plasma simulation data, particularly in contexts where multiple spatiotemporal scales and mixed dynamical behavior coexist.

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (Grant Nos. RS-2022-00155991, No. RS-2023-00254695), Korea Institute of Fusion Energy (CN2502-1), and the Korea Institute of Energy Technology Evaluation and Planning and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (Grant No. 20214000000410). Computing resources were provided on the KFE computer KAIROS, funded by the Ministry of Science and ICT of the Republic of Korea (EN2541).

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