LEVERAGING TURBULENCE DATA FROM FUSION EXPERIMENTS

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1. INTRODUCTION

Fluctuations of plasma density or electron temperature have been measured in many fusion plasma experiments. Their analyses have revealed various characteristics of low-k plasma turbulence and advanced our understanding of turbulence transport in fusion experiments. In this work, analysis methods for leveraging the measured turbulent fluctuation data are introduced. Depending on purposes and conditions, a proper analysis method or the combination of methods can be used to extract more information from turbulence data. The linear and nonlinear spectral methods can provide the frequency or wavenumber spectrum and detect high order couplings among fluctuation components. These methods would be effective when there exist a few dominant coupling processes per each coupled triad (or quartet) as in the weak turbulence regime. To deal with more complicated systems with the large number of nonlinear couplings, the statistical perspective and methods would be helpful. In addition, recent developments of the physics informed neural network allow leveraging turbulence data in novel ways including the prediction of a missing field and the validation of turbulence models. Below two selected examples of turbulence data analyses are provided, and more examples and detailed explanation of methods are given in the reference [1].

2. CHAOTIC BEHAVIOR OF PEDESTAL TURBULENCE REVEALED BY COMPLEMENTARY SPECTRAL AND STATISTICAL ANALYSES

The zonal flow generation via the modulational instability of drift waves is one possible route of the nonlinear saturation of drift wave turbulences [2,3]. A linearly unstable pump mode is saturated by the nonlinear energy transfer to the sidebands and the zonal flow. According to this scenario, the nonlinear oscillations between the zonal flows and the drift wave intensity can exhibit a chaotic behavior at the certain parameter regime [3].

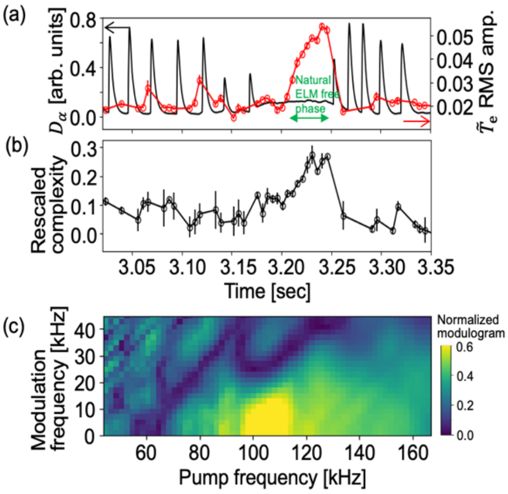

Figure 1. (a) The D_α emission (black) and the root mean square (RMS) amplitude of the normalized T_e fluctuation at the pedestal top. (b) The rescaled Complexity of the T_e fluctuation. (c) Modulogram for a fluctuation saturation period.

In the KSTAR H-mode plasmas, the growth and saturation of the broadband electron temperature (T_e) fluctuation near the pedestal top are observed for a short natural edge-localized-mode (ELM) free phase (see figure 1(a)) [4]. Modulogram, a kind of tricoherence to detect the four-wave coupling [1], of the T_e fluctuation reveals four-wave couplings among pump modes (~100 kHz), low frequency modulating modes (< 20 kHz), and the sidebands for the total integrated RMS amplitude saturation phase. As consistent with the theoretical observation [3], this strong nonlinearity might explain the more chaotic nature of the T_e fluctuation in this phase, which is revealed by a statistical method known as the Complexity-Entropy analysis [5]. The rescaled Complexity [4] of the T_e fluctuation is measured to tell whether the measured data is close to signals generated by a stochastic process or chaotic signals generated from deterministic systems having a low dimensional nonlinearity. It ranges from -1 to 1, and the higher value above 0 means the more chaotic behavior. The rescaled Complexity of the T_e fluctuation increases for the fluctuation saturation phase in accordance with the strong modulational coupling. This example shows that utilizing complementary spectral and statistical methods allows for extracting more comprehensive information from turbulence data.

3. MISSING VELOCITY FIELD PREDICTION USING PHYSICS INFORMED NEURAL NETWORK

Compared to plasma density and electron temperature fluctuations, accurate and high-resolution measurement of velocity fluctuation is more challenging in fusion plasmas. Direct measurement of the velocity fluctuation is often limited in the particular wavenumber or real space. Indirect methods utilizing two-dimensional density or temperature fluctuation measurements in time are vulnerable to noises.

Recently, the missing field prediction using the physics informed neural network (PINN) and measurements of other physically related fields has been demonstrated [6,7]. For the practical application for two-dimensional turbulent velocity field prediction in fusion plasmas, effects of the spatial resolution of available data are investigated in the Hasegawa-Wakatani system [1]. Among the density (n), potential (ϕ), vorticity (Ω) fields, only the density measurements, taken at regular spatial and temporal intervals, were provided to train PINN with additional constraints from physics laws. Figure 2 shows the summary of the PINN predictions as the spatial resolution of provided density data is varied. The PINN could capture the key characteristics of the potential field down to the 12 x 6 resolution case.

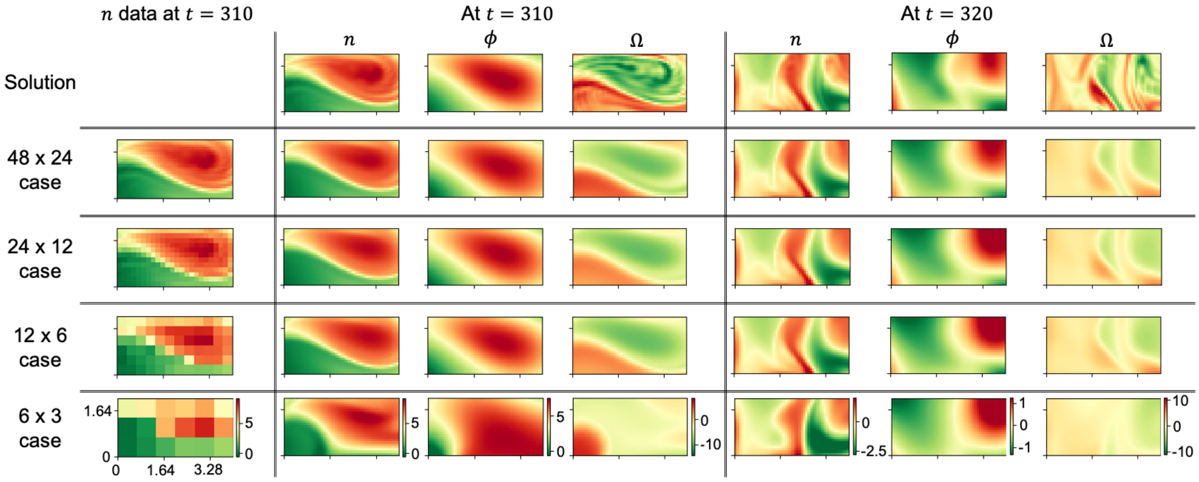

Figure 2. The PINN predictions of the density, potential, and vorticity fields in the Hasegawa-Wakatani system as the spatial resolution of provided density data is varied. Only the density measurements were provided to train the PINN with additional constraints from physics laws. The solution is shown at the top for reference.

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