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An approach toward extrapolative modeling of turbulent plasma transport

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Modeling of plasma turbulent transport is one of the most significant issues not only for fusion reactor development research, but also for understanding the essential physics of turbulent phenomena. Modeling with guaranteed extrapolability is necessary to predict transport phenomena in future reactors and unexplored parameter regions. To achieve the above goals, computer simulation based on kinetic theory is one of the most powerful and promising methods since it can predict transport while ensuring extrapolation based on first principles. However, kinetic theory-based simulations that deal with the time evolutions of the distribution functions in six- or five-dimensional phase space are not suitable for practical applications in terms of transport prediction because they are large-scale calculations using huge computational resources.

To reduce the computational resources, several reduced transport models with small computational costs have been developed [1-4]. These models are designed to reproduce the results of experiments and first-principles calculations and are beginning to be applied to reactor design and scenario analysis, realizing efficient transport prediction. On the other hand, since these models were developed based on existing experimental and simulation results, they are not guaranteed to be extrapolated and applied beyond the range of physical parameters to which they correspond. There are efforts to improve the extrapolability by developing predictive models based on the statistical and time series law properties of the results obtained from experiments and simulations, but there are issues with their general applicability.

Here, we regard the time evolution of turbulent flows obtained from laboratory plasma or computer simulations as solution trajectories in the corresponding theoretical space. These turbulent flows are realized on the solution space formed by these trajectories. For example, inertial manifolds in dissipative systems [5] and renormalized trajectories in quantum field theory [6] are a kind of subspace universally possessed by the system and they can be taken to form a reduced space like the solution space in the turbulent flow discussed above. Therefore, if it could be expressed this solution space that the system universally possesses, we may be able to construct a transport model with extrapolative properties. However, in plasma turbulent systems with infinite degrees of freedom, it is difficult to obtain such reduced solution space in the strict sense. Nevertheless, there is still a possibility that the solution trajectories of plasma turbulence form “effectively” reduced subspace. In other words, in a theoretical space in which the components of the integrated component of each mode of turbulent oscillation and the zonal flows, which are regarded as each axis of the space, the solution trajectories obtained from effectively form a finite dimensional subspace within a certain degree of error. Indeed, by constructing a functional model for each trajectory that represents the effective subspace discussed above, it is possible to create a model that is more accurate than conventional models, which are based on the average of many solution trajectories [7]. Furthermore, plotting the error in reproducibility on a space with the coefficient and exponential parameters employed in the model function as spatial axes also shows that the parameter fitting performed in conventional optimization is not taking locally unique optimal values on this space. The errors form a characteristic manifold on this parameter space, and the integral value of this manifold can be optimized to form a more general model function. The turbulence model constructed from this approach will be discussed with specific examples.

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