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Gyrofluid Simulation of Ion-Scale Turbulence in Tokamak Plasmas†

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Abstract. An improved three-field gyrofluid model is proposed to numerically simulate ion-scale turbulence in tokamak plasmas, which includes the nonlinear evolution of perturbed electrostatic potential, parallel ion velocity and ion pressure with adiabatic electron response. It is benchmarked through advancing a gyrofluid toroidal global (GFT_G) code as well as the local version (GFT_L), with the emphasis of the collisionless damping of zonal flows. The nonlinear equations are solved by using Fourier decomposition in poloidal and toroidal directions and semi-implicit finite difference method along radial direction. The numerical implementation is briefly explained, especially on the periodic boundary condition in GFT_L version. As a numerical test and also practical application, the nonlinear excitation of geodesic acoustic mode (GAM), as well as its radial structure, is investigated in tokamak plasma turbulence.

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Key words: Geodesic acoustic mode (GAM), zonal flow, ion temperature gradient (ITG) turbulence, gyrofluid simulation, tokamak.

1 Introduction

The study on turbulent particle and heat transport is of key importance for the improvement of confinement performance in magnetized fusion devices including current tokamaks/stellarators and the coming ITER. In a tokamak, plasma turbulence is rather copious in the spatio-temporal scale due to various linear and nonlinear instabilities. Typically the ion temperature gradient (ITG) driven turbulence is a representative of the ion-scale fluctuations. An important ingredient in turbulence is a poloidally and toroidally

†Dedicated to Professor Xiantu He on the occasion of his 70th birthday.

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symmetric, coherent structure, namely the so-called zonal flow. A remarkable progress on understanding ion transport in tokamak plasmas has been achieved in past years through the extensive investigations on the ITG turbulence and the zonal flow dynamics. It is the very zonal flow that may regulate the ion-scale turbulence and reduce the ion transport to the neoclassical level observed in present tokamak experiments. Meanwhile, another large-scale structure, the so-called geodesic acoustic mode (GAM), has also attracted much attention recently. The GAM is a class of toroidal eigenmode with finite low frequency [1–4], which is characterized in spatial structure by poloidally and toroidally symmetric potential and poloidally asymmetric density or pressure fluctuations. The latter gives rise to a time-dependent zonal flow in toroidal plasmas. On the other hand, the GAM is a damped oscillator with finite frequency coupling with axisymmetrical static potential (i.e., the stationary zonal flows). The level of zonal flows in toroidal ITG turbulence is strongly influenced by the collisionless damping of the GAMs [5]. Hence, the GAM dynamics have been intensively studied in toroidal plasma experiments and large-scale parallel simulations in light of theoretical analyses [6–23].

To study the turbulent transport in tokamak plasma with the dynamics of zonal flows and GAMs, advanced numerical simulations based on modern gyrokinetic theory have been developed as the first principal simulation: particle-in-cell (PIC) and Continuum (Vlasov) approaches. These methods benefit from the dramatic progress of computational capacity although they are very CPU-time-consuming. On the other hand, the conventional computational fluid dynamics (CFD) is still a very useful method in plasma turbulence simulation to illustrate the complex nonlinear plasma interaction. An improved fluid version, which could properly involve the most important kinetic effects such as the finite Larmor radius (FLR) and Landau damping, has also been proposed and extensively testified. It is noticed that while this approximated approach has shown the advance in understanding the saturation mechanism and fluctuation characteristics of turbulence, the adequacy of the existent gyrofluid models for calculating the zonal flow damping is quite questionable and becomes a crucial failing. The zonal flow is inadequately damped due to the inappropriate closure of the moment hierarchy so that the transport is overestimated. This is still a remaining problem and the improved model is being chased [24–27]. In this paper, we propose a new gyrofluid closure relation for the zonal flow and GAM components. A toroidal global ITG code accompanying with a local version is advanced to benchmark the model with the theoretical prediction of the zonal flow damping. As a practical application, the nonlinear excitation of the GAM and its radial spectral characteristics are investigated.

The remainder of this paper is organized as follows: the new gyrofluid closure relation is proposed in Section 2 with the nonlinear governing equations of toroidal ITG turbulence. The numerical implementation for both global and local versions is briefly explained in Section 3, the benchmarking tests are presented. In Section 4, the nonlinear excitation is numerically simulated as a practical application of the newly developed gyrofluid modeling and codes. Finally, the summary is given in Section 5.