§4. Construction of a Gyrokinetic Plasma Simulation Model for Electromagnetic Phenomena

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A new gyrokinetic plasma simulation model for electromagnetic phenomena was constructed [1]. In this model, the total characteristic method, where the δf particle-in-cell simulation model is complemented with the fluid model to satisfy the conservation properties, is applied to electrons. The total characteristic method was presented to improve the conservation properties, i.e., the conservation of particles, momentum, and energy, in the δf PIC simulation [2]. In the δf PIC simulation, the distribution function is expressed as the sum of the reference distribution and variation distribution. In the δf simulation, each Lagrangian marker represents a characteristic of the Vlasov equation. However, the characteristics which the Lagrangian markers do not represent are not considered in the δf simulation. In the total characteristic method, a fluid system provides characteristics complementary to those represented by the Lagrangian markers. The corrections to the Monte Carlo estimate of the source term propagate along the complementary characteristics provided by the fluid system.

In the new simulation model, the electromagnetic field is expressed by the scalar potential and the vector potential parallel to the magnetic field. The perpendicular components of the vector potential are neglected because we focus on incompressible perturbations of the magnetic field. For the low frequency phenomena, the gyrokinetic model provides a useful physical framework. The potentials are calculated from the gyrokinetic Poisson equation and the Ampère's law. The electric field component parallel to the magnetic field is calculated from the time derivative of the Ampère's law.

The real frequency and damping rate of the kinetic Alfvén wave for various electron beta values have been investigated with the new simulation model in 1-dimensional phase space. The number of grid points is 64, and the number of Lagrangian markers N=32768. The time step with the total characteristic method is restricted by the Courant condition for electrons. The computational time with the total characteristic method is at most roughly twice that with the conventional δf method. The real frequency and damping rate of the simulation results are compared with the theoretical values in Fig. 1. There is good agreement between the simulation results and theoretical values both for real frequency and damping rate. In Fig. 1, we see a discrepancy in the damping rate between the simulation and theory for β_e=0.2. For this case, the numerical convergence of real frequency and damping rate were investigated with respect to the number of marker particles using the total characteristic method and the conventional δf method. The results are compared in Fig. 2. It can be seen that the convergence with the total characteristic method is faster than with the conventional δf method.

We demonstrated that both the real frequency and damping rate of kinetic Alfvén wave were computed correctly for various electron beta values. We found that with respect to the number of marker particles, the numerical convergence of the real frequency and damping rate with the total characteristic method is faster than with the conventional δf method. Specifically, we demonstrated that the total characteristic method enables a simulation of a kinetic Alfvén wave with a grid size ten times larger than the electron skin depth, while the wave spuriously damps in the conventional δf simulation. For the application to fusion plasmas, it is important to simulate with a grid size larger than the electron skin depth. The gyrokinetic simulation model with the total characteristic method is useful for magnetically confined plasmas such as tokamak plasmas and helical plasmas.

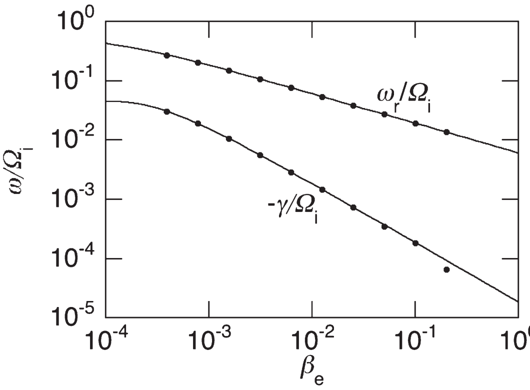

Fig. 1. Real frequency (=ω_r) and damping rate (=-γ) of the kinetic Alfvén wave in the simulation results are plotted with closed circles for various electron beta values. Solid curves represent the theoretical frequencies.

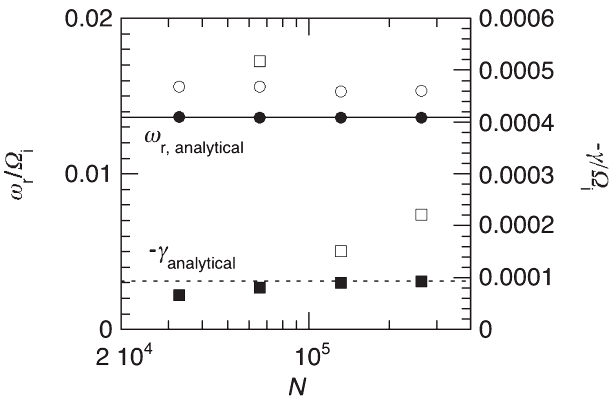

Fig. 2. Real frequency and damping rate versus number of marker particles. Solid line and dashed line represent analytical values of the real frequency and damping rate, respectively. Closed (open) circles and closed (open) squares represent the real frequency and damping rate in the simulation with the total characteristic method (with the conventional δf method).

[1] Y. Todo and A. Ito, Plasma Fusion Res. **2**, 020 (2007).
[2] Y. Todo, J. Plasma Fusion Res. **81**, 944 (2005).