§25. Development of 3D MHD Simulation Code for Magnetic Reconnection in an Open System

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Magnetic reconnection is a fundamental process to lead fast energy release. For instance, solar flares and geomagnetic substorms seem to be caused by magnetic reconnection. Because such high-temperature and low-density plasmas are collisionless, frozen-in condition holds macroscopically, and thus, reconnection can not take place. Collisionless reconnection requires microscopic processes which violate frozen-in condition. In order to clarify the mechanism of reconnection, we develop cross-hierarchy model to solve both microscopic and macroscopic physics consistently and simultaneously. Microscopic physics is described by particle simulation model, while macroscopic physics is expressed by MHD simulation model.

In this report, we explain the current situation of developing MHD code. We have developed the three-dimensional MHD code for a periodic boundary system, which is scheduled to be modified to one for an open boundary system. The basic equations to be solved are described in the dimensionless form, as follows:

$$\frac{\partial\hat{\rho}}{\partial\hat{t}} = -\hat{\nabla}\cdot(\hat{\rho}\hat{\mathbf{v}}),$$

$$\frac{\partial(\hat{\rho}\hat{\mathbf{v}})}{\partial\hat{t}} = -\hat{\nabla}\cdot(\hat{\rho}\hat{\mathbf{v}}\hat{\mathbf{v}}) - \hat{\nabla}\hat{P} + \hat{\mathbf{J}}\times\hat{\mathbf{B}} + \hat{\mu}\left(\hat{\Delta}\hat{\mathbf{v}} + \frac{1}{3}\hat{\nabla}\left(\hat{\nabla}\cdot\hat{\mathbf{v}}\right)\right),$$

$$\frac{\partial\hat{\mathbf{B}}}{\partial\hat{t}} = -\hat{\nabla}\times\left(\hat{\mathbf{B}}\times\hat{\mathbf{v}}\right) - \hat{\eta}\hat{\nabla}\times\hat{\mathbf{J}},$$

$$\frac{\partial\hat{P}}{\partial\hat{t}} = -\hat{\nabla}\cdot\left(\hat{P}\hat{\mathbf{v}}\right) + (\gamma-1)\left(-\hat{P}\,\hat{\nabla}\cdot\hat{\mathbf{v}} + \hat{\eta}\hat{\mathbf{J}}^2 + \hat{\mu}\frac{\partial\hat{v}_i}{\partial\hat{x}_k}\left(\frac{\partial\hat{v}_i}{\partial\hat{x}_k} + \frac{\partial\hat{v}_k}{\partial\hat{x}_i} - \frac{2}{3}\delta_{ik}\hat{\nabla}\cdot\hat{\mathbf{v}}\right)\right).$$

We adopt fourth-order central difference scheme for a spatial derivative, while we use forth-order Runge-Kutta-Gill method for a time integral.

We examine the numerical accuracy of this MHD code by applying it to tearing instability. It is well known that the linear growth rate γ of tearing instability is proportional to $\eta^{3/5}$ (η is electrical resistivity) [1]. In the first model, the initial magnetic field is assumed to be $B_{x0}(y)=\cos(2\pi y/L_y)$, where $(L_x, L_y, L_z)=(516, 68, 6)$ (L_x, L_y, and L_z are the mesh size for x, y, and z directions.). Figure 1 shows the growth rate γ of tearing mode (m=2) as a function of η. From the average slope of log(γ) we have the relation $\gamma\sim\eta^{0.50}$ and so the simulation results do not satisfy $\gamma\sim\eta^{3/5}$.

The reason may come from the fact that two current layers are very close to each other and so the growth rate is reduced by nonlinear coupling effect in the same way as double tearing modes [2]. In order to examine the nonlinear effect we simulate the tearing mode by using the initial magnetic field as

$$B_{x0}(y) = \begin{cases} \tanh\left[\left(y - L_y/4\right)/\left(L_y/32\right)\right] & \text{for } 0 < y < L_y/2, \\ \tanh\left[-\left(y - 3L_y/4\right)/\left(L_y/32\right)\right] & \text{for } L_y/2 < y < L_y, \end{cases}$$

Figure 2 displays the growth rate γ of tearing mode (m=2) as a function of η in the case, where, $(L_x, L_y, L_z)=(516, 132, 6)$ and two current layers are enough distant from each other. From Fig. 2, we find $\gamma\sim\eta^{0.58}$. The simulation results are consistent with the theory.

We have verified that our MHD code in a periodic boundary system is accurate. We are now developing MHD code for an open boundary system which is aimed to be connected with particle simulation code.

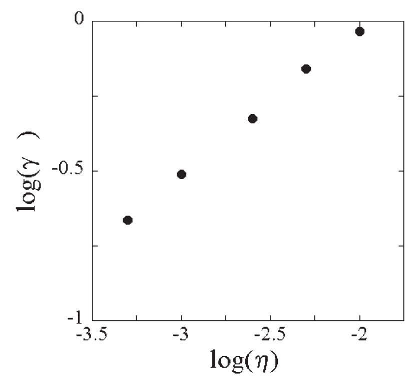

Fig. 1. Growth rate γ vs η. One current layer is very close to another one. We obtain $\gamma\sim\eta^{0.50}$.

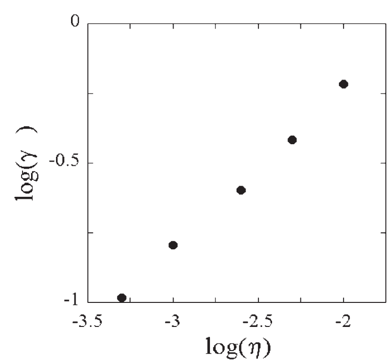

Fig. 2. Growth rate γ vs η. One current layer is distant from another one. We find $\gamma\sim\eta^{0.58}$.

References

[1] H. P. Furth and J. Killeen, Phys. Fluids **6**, 459 (1963).

[2] P. L. Pritchett, Y. C. Lee, and J. F. Drake, Phys. Fluids **23**, 1368 (1980).