§25. Simulation Study of Nonlinear Dynamics in Plasmas with Flows

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Flows, which universally exist in plasmas, couple with magnetic fields and create various fascinating structures. Driven magnetic reconnection is a typical example of such flow-magnetic field coupled system.

In a high-temperature collisionless plasma, such as the solar corona, the rate of magnetic reconnection (diffusion) is so small that the ideal magnetohydrodynamics (MHD) model applies in a macroscopic scale. The reconnection speed, however, is much higher if a small scale structure is created. In a small scale, dissipation due to ion chaotic motion plays an important role. A theory of fast reconnection requires self-consistent explanations of the structure bridging the macro and micro scale hierarchies. The Hall-MHD model can describe such a "mesoscopic" hierarchy. The Hall term added to the Ohm's law as a singular perturbation introduces an intrinsic length scale, viz., the ion skin depth $\ell_{\rm i}$. The $\ell_{\rm i}$ is the scale where ion exhibits chaotic motion. The chaos of particle orbit yields a collisionless resistivity (referred to as the chaos-induced resistivity) when the system of particles are viewed as a plasma.

In this study, we consider the Hall-MHD model including the chaos-induced resistivity. The Ohm's law is generalized as follows,

$$\boldsymbol{E} + \left(\boldsymbol{V} - \frac{\epsilon}{n}\nabla\times\boldsymbol{B}\right)\times\boldsymbol{B} = \frac{\eta}{R_{\rm m}}\nabla\times\boldsymbol{B} \qquad (1)$$

$$\eta(\boldsymbol{x},t) := 1 + \sum_j \alpha \exp\left(-\frac{1}{\epsilon^2}|\boldsymbol{x}-\boldsymbol{x}_j(t)|^2\right), \qquad (2)$$

where ϵ is the ratio of the ion skin depth to the system size, $R_{\rm m}$ is the magnetic Reynolds number, α is the magnitude of the chaos-induced resistivity, and $\boldsymbol{x}_j(t)$ is the position of the magnetic nulls. Because the magnetic nulls move as the field changes, the resistivity has dynamic inhomogeneous distribution.

We have performed simulations using the code developed in [1)] to study the effect of the Hall term and the chaos-induced resistivity. The parameters for the simulations are summarized in Table. I. Figure 1 shows the reconnection rate at the center of the dissipation region. The reconnection rate for $\alpha \neq 0$ is significantly large compared with that for $\alpha = 0$.[2)] We also observe that intermittent bursts of the reconnection rate occur corresponding to the sudden enhancement of the resistivity. Figure 2 shows the out-of-plane current distribution obtained by the Hall-MHD model with the chaos-induced resistivity. We see that the X-type structure is formed. The current sheet is formed in other cases. Only the Hall term or the chaos-induced resistivity does not lead the X-shaped configuration. We conclude that the Hall effect cooperates with the chaos-induced resistivity to yield such an X-type structure and leads the fast magnetic reconnection.

Table 1: Parameters for simulation. Taking $\alpha > 0$, the resistivity is enhanced ($\eta_{\rm max}$ is the maximum of the enhancement factor.)

Run	A	B	C	D	E	F
ϵ	0	0.1	0.1	0.1	0.05	0.05
α	0	0	1	0.1	0	1
($\eta_{\rm max}$)	1	1	3	1.2	1	3

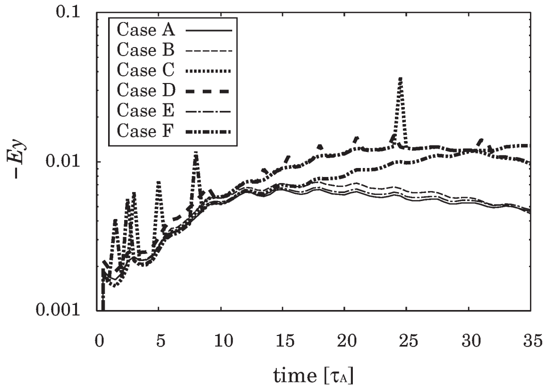

Fig. 1: Reconnection rate measured by the electric field at the center of the dissipation region.

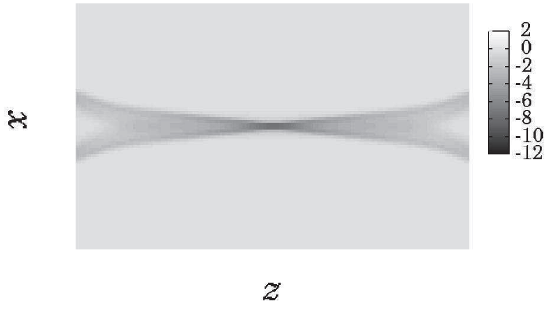

Fig. 2: X-type structure is obtained by using the Hall-MHD model with the chaos-induced resistivity.

References

1) Numata, R., Yoshida, Z., Hayashi, T. : J. Plasma and Fusion Res. SERIES 6 (2004) 130 ; Numata, R., Yoshida, Z., Hayashi, T. : Comput. Phys. Commun. 160 (2004) 291.

2) Numata, R., Furukawa, M., Yoshida, Z. and Hayashi, T. : submitted to Phys. Rev. Lett.