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Gyrofluid Energy Principle and Its Application to Fast Magnetic Reconnection

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Mechanism of fast magnetic reconnection in a gyrofluid model [1-4] is investigated by applying the energy principle to linear and nonlinear phases of a tearing instability. The energy principle is known as an sophisticated approach for studying ideal magnetohydrodynamic (MHD) stability, where the eigenvalue problem is shown to be self-adjoint and the most unstable mode is found by minimizing a potential energy. We show that this MHD energy principle can be extended to a gyrofluid model [4] by assuming nondissipative (or collisionless) and static plasmas (i.e., no flow and no diamagnetic drift at equilibrium state). By using the energy principle, we can prove rigorously that the ion's compressibility effect tends to diminish the growth rate (as is the case with ideal MHD) whereas the finite-Larmor-radius effect tends to enhance it. On the other hand, the stability boundary is not affected by them but determined by the incompressible-MHD potential energy with a destabilizing effect of the electron inertia. This energy principle is applied to collisionless tearing modes. By substituting a simple trial function that includes only two parameters and minimizing the potential energy with respect to them, the estimated growth rate is found to agree with the dispersion relations derived by asymptotic matching (Fig.1). The parameters are, in fact, related to the widths of two nested inner layers.

Nonlinear phase of magnetic reconnection is investigated by solving the gyrofluid model numerically, in which the displacement of magnetic field line becomes greater than the inner layer width (Fig.2). The explosive scaling of the reconnection rate, which is derived theoretically for an ideal two-fluid model [5], is consistently observed (Fig.3) when either the ion-sound gyroradius ρ_S or the ion gyroradius ρ_i is comparable to the electron skin depth d_e, even in the presence of a finite resistivity η. In this explosive phase, a local X-shaped current layer is spontaneously generated in common [Fig.2(a) and (b)], where the reconnection speed is closely related to the macroscopic shape of the layer and almost independent of the layer width. The reconnection speed is, therefore, insensitive to how small the microscopic scales, ρ_S, ρ_i, d_e and η, are [6]. On the other hand, in the cold plasma limit $\rho_S = \rho_i = 0$, an intermittent acceleration of the reconnection is observed due to the plasmoid instability [Fig.2(c)], which seems to be also explosive on average, but always falls below the aforementioned explosive scaling. The reconnection time extrapolated from this scaling is shown to be fast enough to explain the time scale of solar flares [6].

References

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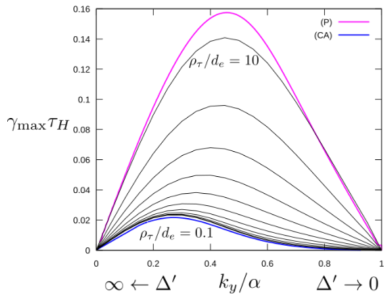

Fig.1 Maximum growth rate versus wavenumber for $d_e = 0.02, \rho_\tau/d_e = 0.1 \sim 10, \eta = 0$ where $\rho_\tau^2 = \rho_S^2 + \rho_i^2$. Analytic dispersion curves are (P) and (CA).

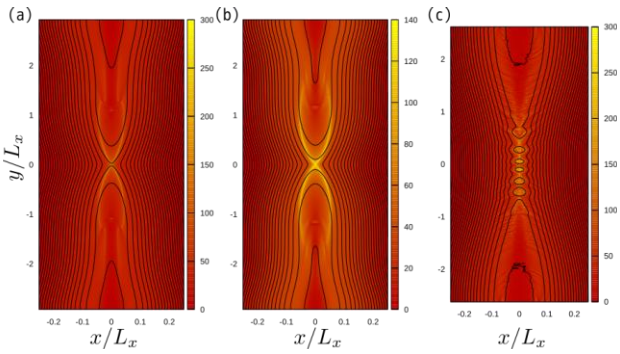

Fig.2 Magnetic field lines (solid lines) and current distribution (color bar) for (a) $d_e = \rho_S = 0.01, \rho_i = \eta = 0$ (b) $d_e = \rho_i = 0.01, \rho_S = \eta = 0$ (c) $d_e = 0.01, \rho_S = \rho_i = \eta = 0$.

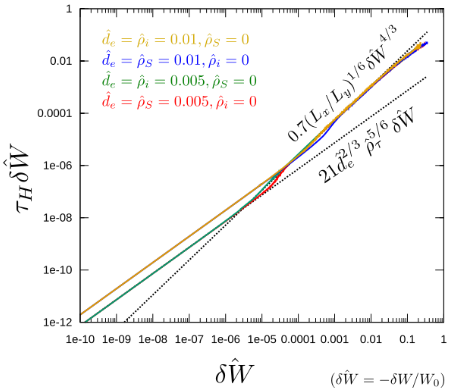

Fig.3 Transition from exponential decay of magnetic energy W to explosive one (when $\eta = 0$).