ハイブリッドシミュレーションモデルへの電子分極電流の組み込み

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Incorporating the electron polarization current in hybrid simulation model

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The rapid development of computational power in recent years makes the resolution of global magnetohydrodynamic (MHD) models of the earth magnetosphere to reach almost the ion kinetic scale. Obviously MHD models fail in such a situation and kinetic effects must somehow be incorporated into even a global model in the near future. This enables us to study how microscopic physics known to play the essential role in the key phenomena such as magnetic reconnection affects the global dynamics. The hybrid model, in which ions are treated as kinetic macroscopic particles whereas electrons are assumed to be a fluid, as well as the Hall-MHD model (the fluid counterpart of the hybrid) may be used for such purposes.

The hybrid and the Hall-MHD models are, however, tend to be numerically unstable when dealing with high frequency whistler waves. Actually, this severely limits the applicability of these models to small scale phenomena where whistler waves may play the role. Overcoming the problem certainly makes these model much more useful, for which understanding the reason for the numerical instability is crucial. By analyzing the linearized magnetic field induction equation including the Hall effect, we find that the problem becomes ill-conditioned for the whistler mode branch. More specifically, although one uses the induction equation to advance the magnetic field by using ion moment quantities, even a small numerical error in the ion velocity would be amplified for a wave on the whistler mode dispersion relation, which implies the existence of a numerical instability.

From physical point of view, we think that the reason for this is that the electron polarization current contribution, which is neglected in the conventional models, is essential for the whistler waves. We therefore investigate a way in which the effect of the electron inertia is appropriately incorporated to avoid the numerical instability without loosing advantages of the hybrid and Hall-MHD models. In these models, since the displacement current is ignored, there is no equation describing the time development of the electric field and thus one must invoke a generalized Ohm's law. We think that this problem is actually intimately linked to the question, how the electron inertia may be included properly. Namely, the polarization drift occurs due to slow time variation of the electric field which, however, involves averaging of very high-frequency (much higher than the electron cyclotron frequency) electric field fluctuations. An appropriate way to do this is obviously to solve the full set of Maxwell's equations including the displacement current. Under some reasonable approximations, we argue that it may practically be possible to use an analytic solution to Maxwell's equation in evaluating an averaged electric field and thus the polarization current carried by electrons. The advantage of using the analytic solution is that the simulation time step is not restricted by the high frequency waves. In this way, one effectively eliminates the high frequency fluctuations whereas the information may be used in taking the average. This enables us to include the electron polarization current properly, and may substantially extend the applicability of these models. Simulation results of the proposed model for standard linear and nonlinear test problems will be presented.