AMR-PIC Simulation on Solar Wind Interaction with Kinetic Scale Magnetosphere

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1 Introduction

Magnetic Sail is an advanced space propulsion system [1] which uses the interaction between an artificial magnetosphere around a spacecraft and solar wind plasmas. The solar wind is deflected in the magnetosphere and the momentum transfer results in the drag force exerted on the spacecraft. Recently, the Mini-Magnetospheric Plasma Propulsion (M2P2) [2], which is also called Magneto-Plasma Sail (MPS) [3], is suggested by Winglee et al. as a derivative system from Magnetic Sail. In the concept of M2P2 and MPS, the original magnetic field attached to a spacecraft is expanded by the injection of artificial plasmas from the spacecraft to form finally a huge magnetosphere. Such propulsion systems which use the solar wind energy are expected to achieve high energy conversion efficiency compared with conventional electric propulsion systems and many feasibility studies have been conducted.

Fujita [4] has revealed that the drag (thrust) force of a magnetic sail, which is exerted on the spacecraft from the solar wind, is characterized by the ratio of an ion Larmor radius of the solar wind at the magnetopause r_L to a representative length of magnetic field L. Figure 1 shows the schematic view of typical ion particle motions due to the difference in r_L/L. On the magnetohydrodynamics (MHD) scale (r_L/L<<1), the ion particle motions depend strongly on the magnetic field line and the momentum of ion particles turn into the drag force of the spacecraft as shown in Fig.1. On the other hand, on the ion inertial scale (r_L/L>>1), the electromagnetic interactions of ion particles with magnetic field become weak compared with the case of MHD scale because ion kinetic effect becomes dominant. Consequently, the thrust performance of magnetic sail decreases on the ion inertial scale. In the propulsion system of magnetic sail, at least the magnetospheric size of ion inertial scale or more is needed to obtain the thrust performance higher than conventional electric propulsion systems. Therefore, kinetic approaches which address the small-scale physical mechanism must be used to simulate the magnetic sail with such small magnetosphere of ion and electron inertial scale.

In the past study of magnetic sail, hybrid particle-in-cell (PIC) simulation methods have been conducted mainly in order to examine the solar wind flow field around magnetic sail and the thrust performance [4, 5]. The hybrid PIC simulations, in which ions are treated as super particles and electrons are assumed as fluid, can include the kinetic effect of ion particles. However, the solar wind flow field and thrust performance on the smaller magnetospheric scale than ion inertial, namely, electron inertial scale, have not been almost revealed. This is because the physical phenomena on electron inertial scale cannot be simulated by the hybrid PIC simulation method. On the other hand, full PIC plasma simulation methods [6], in which both electrons and ions are treated as super particles, are widely used in space plasma science and engineering. This method calculates plasma particles motions governed by motion equations and electromagnetic fields defined on the mesh of computational domain by Maxwell equations, self-consistently and alternately. This method includes the kinetic effect of not only ion but also electron particles. However, the computational load of PIC simulation is extremely higher than hybrid PIC or MHD simulations because the grid width of computational domain should be set to plasma characteristic lengths such as Debye length or Larmor radius in the full PIC simulations. Furthermore, over one hundred plasma particles per unit cell (grid) are needed for high accuracy simulations.

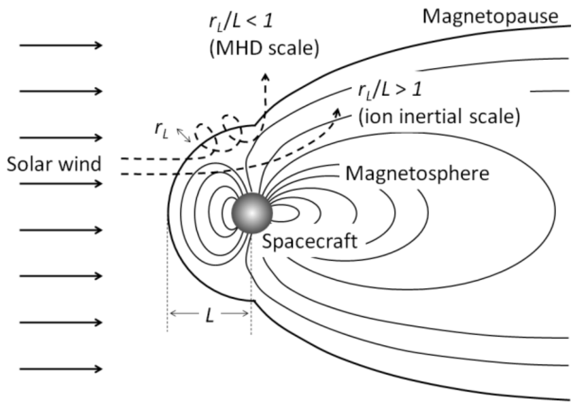

Fig. 1. Ion particle motion due to the difference on r_L/L.

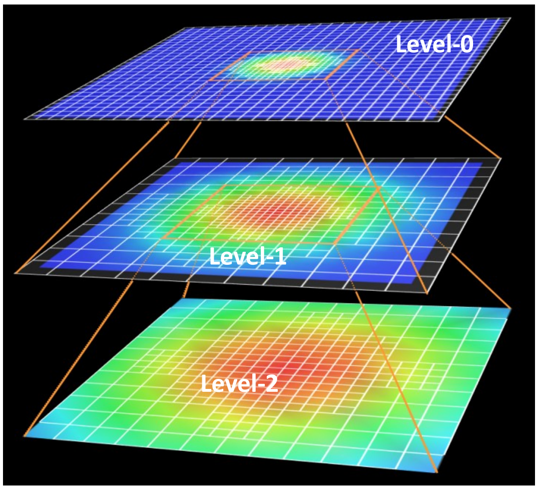

Fig. 2. Grid system of adaptive mesh refinement

Table 1. Working conditions

Number of Super Particles	32 pair/cell
m_i/m_e	25
q_i/q_e	1.0
T_i/T_e	1.0
ω_{ce}/ω_{pe}	8.0×10^{-2}
V_{Te}/c	5.0×10^{-2}
V_{in}/V_{Ti}	10.0
r_L/L	12.0

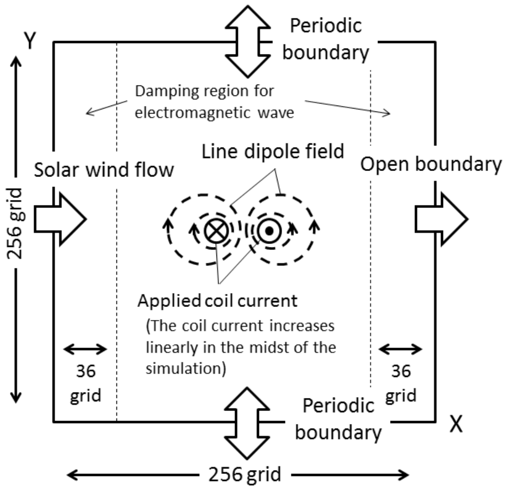

Fig. 3. Computational domain used in the two-dimensional AMR-PIC simulation.

Our research group has developed an adaptive mesh refinement PIC (AMR-PIC) simulation code in order to handle the problems as mentioned above. The AMR-PIC code is PIC simulation code which has method to modify the grid width of computational domain in the midst of the simulations temporally and locally as shown in Fig.2. The grid width is adjusted automatically in accordance with the physical values of intended plasma flow field. The AMR-PIC method can simulate the physical phenomena in which more resolution is needed, and can decrease the computational load such as memory and computing time compared to conventional PIC code with uniform grid width of computational domain.

Based on the above, the purpose of this study is to examine the interaction of solar wind flow field and kinetic scale magnetosphere around a magnetic sail by using AMR-PIC simulation codes.

2 Result of Two-Dimensional Simulation

The two-dimensional AMR-PIC simulation is conducted in order to examine the interaction of the solar wind plasma to the electron inertial scale magnetosphere. Table 1 and Fig.3 show the working conditions and computational domain used in this study. The nomenclature in the table is commonly-used. The scale parameter is set to the electron inertial scale (r_L/L = 12.0) although some solar wind parameters are set to arbitrary suitable for the electron inertial scale simulation. An interplanetary magnetic field is ignored in this study. The solar wind plasma flows from left to right direction and the dipole magnetic field is set on the centre of the computational domain in the figure. The line dipole field is excited by the applied current which increases linearly in the midst of the simulation. The damping regions for electromagnetic waves are set to the left and right boundary of the computational domain and top and bottom boundary are periodic condition.

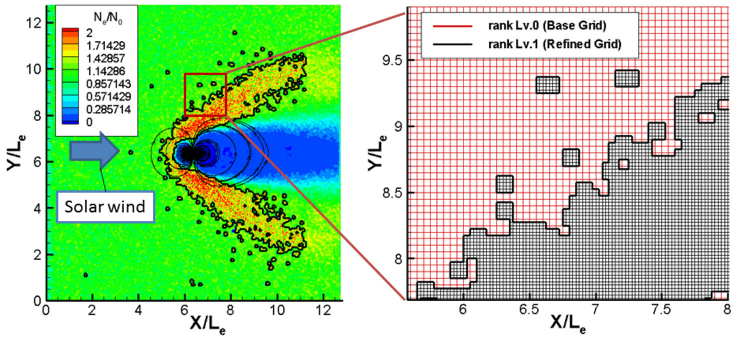

Fig. 4. Distribution of the electron number density, magnetic field lines and refinement grid at t = 10 [$1/\omega_{pe}$]

Figure 4 shows the distribution of electron number density normalized by the solar wind at upstream, magnetic field line and refinement grid at t = 10 [$1/\omega_{pe}$]. In this two-dimensional simulation, for simplicity, the mesh refinement level is set to one-step, two levels (Lv.0: base grid, X: 256 × Y: 256 grid, Lv.1: refinement grid, corresponding to X: 512 × Y: 512 grid) and the criterion of mesh refinement is set when the electron number density exceeds a critical limit. This criterion should correspond to some characteristic length like the Debye length or Larmor radius. The electron number density increase at the upstream of dipole magnetosphere like a bow shock formation. Moreover the wake region appears and the density decreases at the downstream of dipole field. These are the result of deflection due to the interaction of plasma particles to the dipole field. The grid width becomes finer where the electron number density increases as shown in this figure. Furthermore, it is shown that the memory cost (4GB to 1GB) and computational time (24 hours to 6 hours) are reduced by using the AMR-PIC code compared to the conventional PIC code with uniform finer grid (X: 512 × Y: 512 grid).

Acknowledgements

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