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Numerical simulation of a magneto plasma sail by using three-dimensional hybrid code

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Abstract. A magneto plasma sail (MPS) is a new propulsion system which has the possibility of realizing low-cost and short-time travel in planetary exploration and space trips in the near future. We investigate by using a three-dimensional hybrid code whether MPS could receive momentum force from the Solar wind and whether thrust power could be obtained. The hybrid code has some problems in calculating instability under the low-density plasma and has restrictions on grid size. We pay attention to these problems and we estimate the thrust power by calculating the momentum change and confirm that MPS could obtain thrust power from the Solar wind.

1. Introduction

A magneto plasma sail (MPS) is a new propulsion system which produces propulsive force by the interaction between the Solar wind and the artificial magnetic field inflated by the plasma injection. MPS is expected to have a high to thrust power ratio and specific impulse compared with chemical propulsion systems. Several investigations have been conducted on the mechanism of MPS and on the estimation of thrust power using numerical simulations. Asahi *et al.* [1], using MHD simulation code, have simulated the thrust production mechanism of MPS. Nishida *et al.* [2], also using MHD simulation code, have estimated the thrust power of a magnetic sail. We can use the MHD model when the ion Larmor radius (r_{L}) is comparable or smaller than the characteristic length (L). On the other hand, for the verification of MPS feasibility, we need the investigation at $r_{\mathrm{L}}/L \sim 1$ or $r_{\mathrm{L}}/L > 1$, so that ion kinetic simulations are required in order to address the feasibility issues. In this paper, we investigate the interaction between the Solar wind and an already inflated magnetic field by using a three-dimensional hybrid simulation code. With that, we try to clarify the physical phenomenon and to conduct the calculation of the propulsive force.

2. Simulation code

This hybrid code is based on the model given by Horowitz *et al.* [3] and treats ions as individual particles and electrons as a fluid. This approach is valid when the

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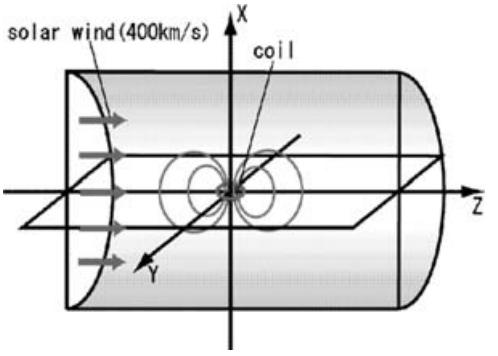


Figure 1. Simulation model.

system behavior is dominated by ion physics. The leap-frog method is adopted to solve the ion's equation of motion. We assumed quasi-neutrality and set the ion charge density equal to the electron charge density. So, the restrictions on the grid size and time step are imposed on the simulation calculations. The grid size must be greater than the ion skin depth $c/\omega_{\rm pi}$, and $\omega_{\rm ci}\Delta t$ must be less than 0.2, where $\omega_{\rm pi}$, and $\omega_{\rm ci}$ are the ion plasma frequency and ion cyclotron frequency, respectively. In the equation of Ampere's law, we adopted the Darwin approximation. The boundary condition adopted here for the field quantities is such that the spatial differences of the normal components are set to zero at the surface of the cylindrical calculation region.

3. Simulation model

The simulation model considered here is illustrated in Fig. 1. The grid number is $(x, y, z) = (80, 80, 80)$ and each grid size is 100 km. This size is the same as the ion skin depth. The initial magnetic field is located in the center of the system as a dipole configuration which has already been inflated by plasma injection. The magnitude of the magnetic field is 41 nT at 800 km from the dipole center. This corresponds to the condition balancing the dynamical pressures between the Solar wind and the dipole magnetic field. The solar wind flows in the positive Z direction with a density of 5×10^6 m^{-3} and a velocity of 400 km s^{-1}. The number of particles injected at every time step is 20 000. Therefore, the total number of particles is of two million, and this corresponds to ten particles existing in each cell. The time step Δt of $0.0001\omega_{\rm ci}^{-1}$ is used in this simulation.

4. Results

The numerical result of particle positions at 25.0 s is shown in Fig. 2, where they are projected onto the XZ plane. We confirmed that the momentum change of the solar wind by the dipole magnetic field is almost constant after 25.0 s. It can be seen clearly that the orbits of particles are deflected by the dipole magnetic field. Figure 3 shows the contour plot of magnetic field strength at 25.0 s. The magnetospheric boundary whose magnitude is 10 nT is seen in this figure. The distance between the center of the magnetic dipole and the ion deflected point is around 1600 km. This distance is defined as a characteristic length. So the ratio of the ion Larmor

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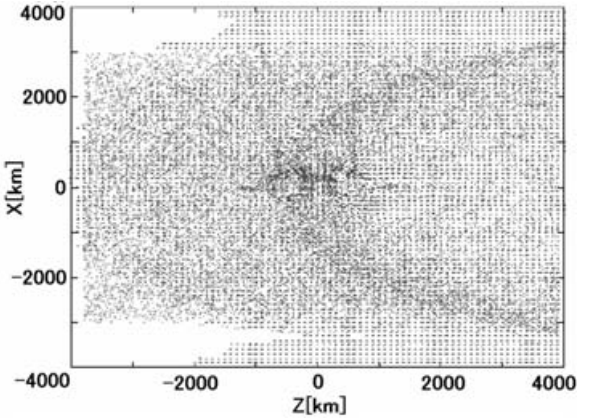


Figure 2. Ion particles and the vector plot of the magnetic field (t=25.0 s).

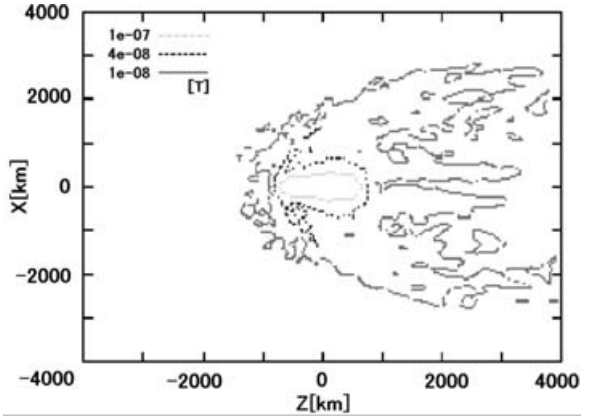


Figure 3. Contour plot of the magnetic field ($t = 25.0$ s).

radius to characteristic length r_{L}/L is 0.0625. In the range of this parameter, we can make a comparison among the simulation results obtained by using MHD code and hybrid code. Figure 4 shows the density distribution at 25.0 s. We cannot see the shock region near the ion deflected area, but the high-density region exists in the magnetospheric boundary which has a density five times grater than the density of solar wind. This result agrees well with the theoretical result.

In the case of analyzing plasma with a low density, such as the solar wind, it is unstable to calculate the electric field using the following equation (4.1) derived from electron momentum equation. This problem exists in the hybrid code using Darwin approximation [4]. In order to avoid this situation, we performed the following treatment. The threshold of density which is used for electric field calculation is increased by a factor of 10 from the original threshold. We adopted the density $10^5\ \mathrm{m}^{-3}$ as the threshold; this means that the Laplace equation (4.2) is used in the low-density region of less than $10^5\ \mathrm{m}^{-3}$:

$$E^n = \frac{1}{n}\left\{\frac{1}{\mu_0 Z_{\mathrm{e}}}\left(\nabla \times \mathbf{B}_{\mathrm{p}}^n\right) \times \mathbf{B}^n - \frac{1}{Ze}\mathbf{J}_{\mathrm{i}}^n \times \mathbf{B}^n - \frac{T_{\mathrm{e}}}{e}\nabla n_{\mathrm{i}}^n\right\} \tag{4.1}$$

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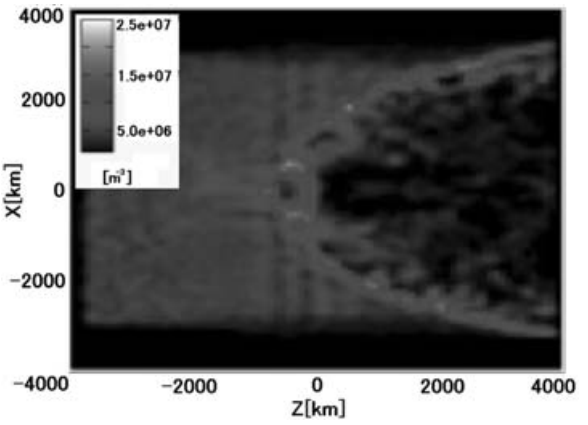


Figure 4. Ion number density distribution ($t = 25.0\,\mathrm{s}$).

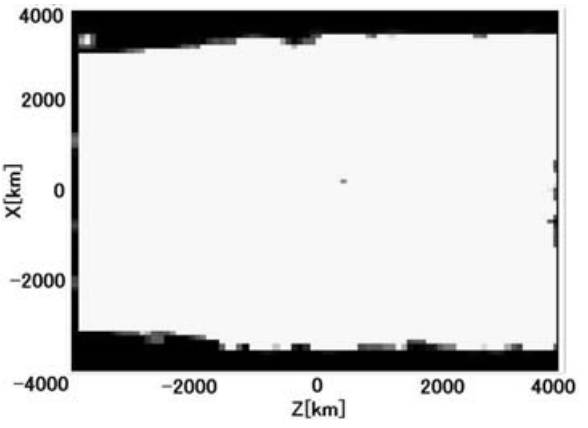


Figure 5. The region where (4.1) and (4.2) are used ($t = 25.0\,\mathrm{s}$).

$$\nabla^2 \mathbf{E} = 0 \tag{4.2}$$

In order to confirm the validity of this treatment, we examined the calculation regions in which (4.1) and (4.2) are used. In Fig. 5, the lighter region indicates the use of (4.1) in the calculation, and the other region indicates the use of (4.2) in the calculation. The region where (4.2) was used is very small and we can judge that this treatment has almost no influence on the calculated thrust power. We try to estimate the thrust power. However, because each grid size is very large, it is difficult to estimate the thrust power by using the Lorentz force generated at the coil loaded into the spacecraft. So we estimate the thrust power by calculating the change of momentum of the solar wind affected by the dipole magnetic field. Nishida *et al.* [2] have already shown that the thrust power calculated from the momentum change and thrust power calculated from the Lorentz force are almost the same value. So, in this simulation we estimated the thrust power by calculating the momentum change and we got the thrust power $F = 5000\,\mathrm{N}$ as a result. The

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calculated drag coefficient (C_d) is 3.7 using the following equation:

$$C_\mathrm{d} = \frac{F}{\frac{1}{2}\rho v^2 S}, \tag{4.3}$$

where ρ is the density, v is the velocity of the solar wind and S is the surface area of the cross section in the maximum magnetosphere.

5. Conclusion

In this simulation, we have obtained the result that the calculated drag coefficient (C_d) is 3.7. We assumed that the threshold of density which is used for the electric field calculation is $10^5\,\mathrm{m}^{-3}$. Considering the accuracy of calculation, a lower value is required. In the future, we are going to implement CAM-CL (current advance method cyclic leap-frog) method [4] in our code in order to calculate stably under the low-density condition. In our hybrid code, there is the restriction on the grid size and so we paid attention to satisfying the restriction: the grid size is equal to the ion skin depth. Thus, we have to develop a new calculation method adopting a smaller grid size than the ion skin depth in order to verify the feasibility of MPS with the small-scale magnetic field.

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