Multi-Scale Plasma Particle Simulation for the Development of Interplanetary Flight System

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Magneto Plasma Sail (MPS) is proposed as one of the innovative interplanetary flight systems. The propulsion of MPS is obtained as a result of multi-scale kinetic interactions between the solar wind plasma and a small-scale artificial magnetosphere created around the spacecraft. In the investigation of the multi-scale plasma interactions in association with MPS, plasma particle simulation can be a powerful tool. However, it is difficult to handle the multi-scale phenomena with the conventional particle simulation which adopts uniform spatial grid system. To conquer this difficulty we will establish the foundation and the methodology for the multi-scale plasma particle simulations by combining Adaptive Mesh Refinement (AMR) and Particle-In-Cell (PIC) methods. In the new AMR-PIC code, we introduced the fully threaded tree (FTT) structure for the AMR scheme and the Morton ordering for the parallelization needed for the high performance computing. In parallel to the tool development, we focus on the quantitative evaluation of the MPS thrust by performing hybrid particle simulations in which electrons and ions are treated as fluid and particles respectively. We could confirmed the magnetic field inflation by plasma injection from the simulation result that the magnetic field decays in the polar direction according to $B \propto r^{-2.3}$ while $B \propto r^{-3.0}$ for no plasma injection case, where r denotes the distance from the injection point, respectively.

Keywords: Magneto Plasma Sail, Particle-In-Cell simulation, adaptive mesh refinement, AMR, multi-scale simulation, interplanetary flight system, magnetic field inflation, plasma injection

1. Introduction

Magneto Plasma Sail (MPS) is an innovative propulsion system which makes the most use of the multi-scale kinetic interactions between the solar wind plasma and a small-scale artificial magnetosphere created around the spacecraft. The concept of using the interaction between the solar wind and the artificial magnetosphere for interplanetary flight system was originally proposed by Zubrin [1]. To increase the thrust performance, it is necessary to enlarge the size of the magnetosphere because a part of the energy of the solar wind interacting with the magnetosphere will be converted to the thrust. To inflate the artificial magnetosphere, Winglee proposed a concept of introducing a plasma injection from the spacecraft [2].

Inspired by the Winglee's MPS concept, JAXA started to investigate the basic principle of MPS and the

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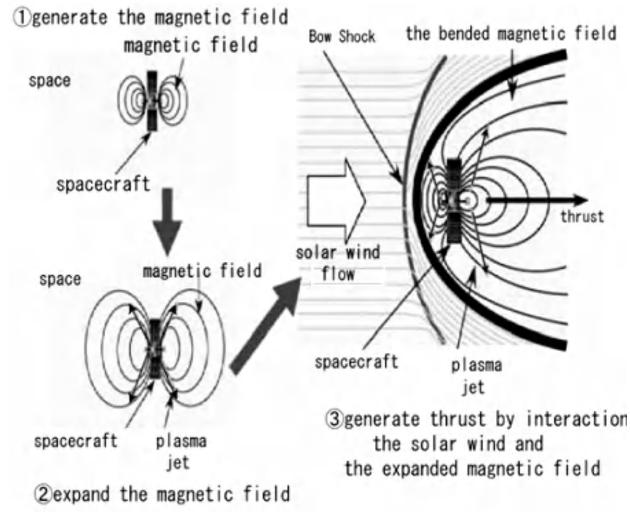

Fig.1 Schematic concept of Magneto Plasma Sail (MPS)

thrust performance [3]. The basic concept of MPS is shown in Fig. 1. A magnetosphere is artificially created as a result of the interaction between the solar wind and the dipole magnetic field which is generated by the coil at the spacecraft. To expand the magnetosphere, plasma is injected from the spacecraft so that the interaction region becomes large. In the process of the interaction, current layer structure is induced at the interface between the magnetosphere and the solar wind and it can modulate the original magnetic field at the current coil at the spacecraft. Then the net $\boldsymbol{J} \times \boldsymbol{B}$ force at the spacecraft becomes equivalent to the MPS thrust where $\boldsymbol{J}$ and $\boldsymbol{B}$ denote the current of the coil and the magnetic field at the coil, respectively.

In the previous studies, some MHD simulations were carried out for the understanding of the basic thrust mechanism as well as the dependence of the thrust performance on the plasma injection under the approximation of ideal MHD [4]. However, the fluid treatment of the solar wind as used in the MHD simulations does not seem appropriate when we consider the typical size of the artificial magnetosphere created around the spacecraft is approximately several tens kilometers and it is almost equivalent to the gyroradius of the solar wind ions. In such a situation, kinetic treatment of the solar wind is necessary in the analysis by including the effect of the finite Larmor radius. For this purpose, we started performing hybrid particle simulations in which ions are treated as particle while electrons fluid [5].

In addition to the plasma kinetic effect, we should consider multi-scale phenomena in the MPS analysis. As stated above, the MPS thrust at the local spacecraft is obtained as a result of macro-scale interaction between the magnetosphere and the solar wind. To evaluate the thrust quantitatively, we need a simulation system in which the above-stated macro phenomenon and the local MPS system can be simultaneously included.

With the conventional plasma particle simulations, however, it is difficult to handle the multi-scale phenomena because they adopt uniform spatial grid system. To simulate the multi-scale kinetic phenomena with particle model, we need to introduce non-uniform grid system. For this purpose, we started developing a new plasma simulation code by combining Adaptive Mesh Refinement (AMR) and Particle-In-Cell (PIC) methods. This challenging attempt was selected as a research project of the JST (Japan Science and Technology Agency) CREST (Core Research for Evolutional Science and Technology) in the research area of "high performance computing for multi-scale and multi-physics phenomena" in 2007 fiscal year. The research project which started at October in 2007 will continue for five years.

In parallel to the tool development, we have been examining the inflation of artificial magnetic field by plasma injection from the spacecraft. We already started the analysis by performing hybrid particle simulations. In addition to the current status of the development of the AMR-PIC simulation code, we will present some of the simulation results on the magnetic field inflation in the present paper.

2. Development of AMR-PIC Simulation Code

Toward the analysis of multi-scale phenomenon in association with MPS, we started to develop a new electromagnetic particle code with AMR technique. The AMR technique is effective to simulate the phenomena which include local micro-scale processes as well as global macro-scale processes with high-resolution. By using the AMR technique, we can subdivide and remove cells dynamically according to refinement criteria such as the characteristic length, for instance, the local Debye length. In development of the code, we introduced PIC method to the AMR grid system by using fully threaded tree (FTT) structure [6].

The basic concept of FTT is shown in Fig. 2. At the region where high spatial resolution is required, additional spatial grid system (Level L+1 shown in the figure) is locally created with a half size of the cell size used in the upper level (Level L). When the high resolution becomes unnecessary in a simulation run, the fields and particle information obtained in Level L+1 will be stored back to the Level L and the Level L+1 grid system will be automatically eliminated. Each cell consisting of one level of spatial grid system has pointers which indicate neighbors, parent, child cells as well as particles belonging to the corresponding cell. This subdivision of grid system level recursively takes place until the spatial resolution locally meets the refinement criteria.

We have already developed a proto-model of the AMR-PIC simulation code with the FTT method. Fig. 3 shows one example of mesh refinement for a test simulation in which a dense plasma cloud is locally placed at the center of the system. In the present model, we

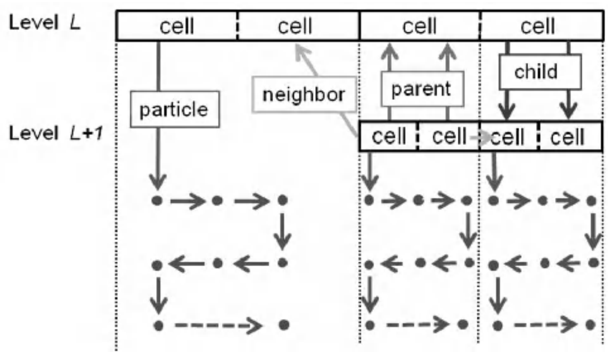

Fig.2 Concept of fully threaded tree (FTT) structure used in the AMR system.

monitored the local Debye length for the refinement criteria. As shown in the figure, three levels of spatial grid system are created and the grid system level with the highest spatial resolution is formed at the center where the plasma density is the maximum. By using this simulation system, we basically confirmed the AMR function with the FTT method including plasma particle.

In terms of memory resource required for simulations, the AMR-PIC method can save a large amount of memories in comparison with the conventional PIC method in which uniform mesh system is used. It is because AMR can set up fine mesh only where micro-scale phenomena take place in the simulation domain. Here is one example showing how much memories can be saved for the AMR-PIC code. When we consider a cubic simulation space consisting of 10^{15} uniform fine meshes, the conventional PIC codes require approximately 5,000 PB memories when we have 100 particles per mesh. If the fine meshes are only used for a region where a microscopic phenomenon occurs in the AMR-PIC simulation, the required memories are much reduced in comparison with the conventional PIC simulation. For example, if the region of the microscopic phenomenon occupies 10% of each spatial direction of the simulation space, namely 0.1% of total volume, then the required fine meshes are much reduced and the total memory size for the simulation become approximately 5 PB. Since the fine mesh region is much reduced, the total calculation time is also decreased. In addition, the spatial resolution for the microscopic phenomenon is maintained with the fine meshes in the AMR-PIC simulation.

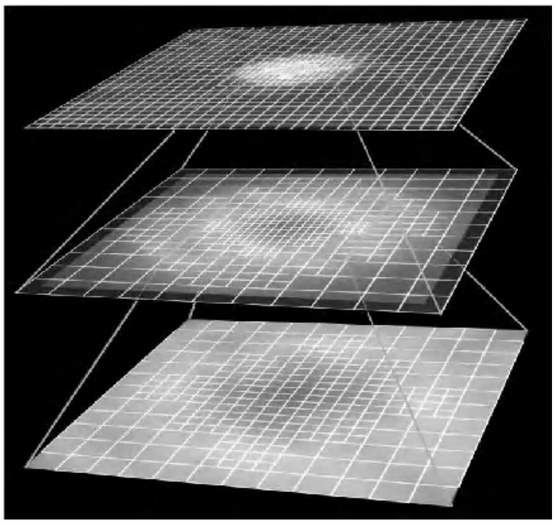

Fig.3 Mesh refinement for a model of dense plasma located at the center.

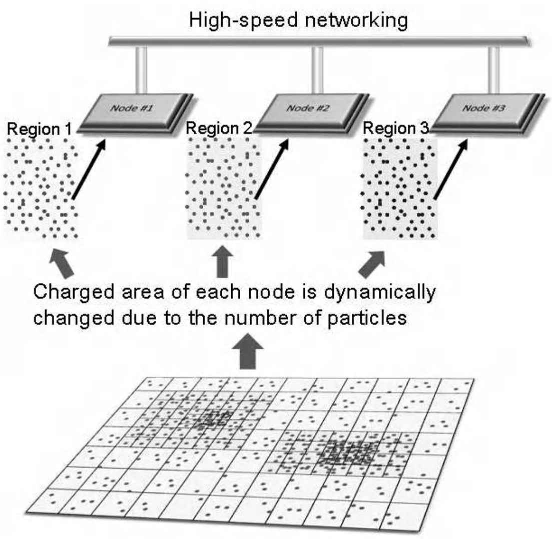

Fig.4 Concept of domain decomposition of simulation region for parallel computing.

Another important issue in the AMR-PIC code is the parallelization for the high performance computing. As shown in Fig. 4 we use domain decomposition model. In this model, each decomposed region is distributed to a node and plasma simulation is performed in each node by exchanging the fields/particle data at spatial boundaries. In order to obtain the maximum efficiency in the parallel computing, we have to achieve the load balancing among the multi-nodes. To do so, we need to monitor the number of particles in each decomposed region and dynamically change the region in charge of each node so that the number of particle roughly becomes constant. For this purpose, we use the Morton ordering method [7]. The evaluation of the parallel computing with the Morton ordering has been currently proceeding.

3. Hybrid Particle Simulation on the Magnetic Field Inflation

We have examined the magnetic field inflation process when Argon (Ar) plasma is injected into a dipole magnetic field generated by a current coil at the spacecraft [8]. The simulation model adopted in this study is shown in Fig. 5. Plasma is uniformly injected within an angle of 30° from the polar direction for different β_{in} values measured at the injection point. The plasma injection is schematically illustrated with three arrows as shown in Fig. 5. The ions are injected from a region with a finite thickness calculated by $v\,dt$ located at a distance of 1.0m from the center of the coil, where v and dt denote the initial velocity of injected ions and one time step, respectively. This region corresponds to the line of 1m position in Fig 5. The density and velocity of the plasma are N = 7.5×10^{19} /m^3 and v = 4.0 km/s, respectively. The zero-gradient electric field is adopted as the boundary condition.

The coil is located at the origin of the simulation model and it generates the dipolar magnetic field. We confirmed that the magnetic field is inflated in both near and far field region from the coil. When the plasma with $\beta_{in} = 1$ is injected, the magnetic field decays in the polar direction according to $B \propto r^{-2.3}$ while $B \propto r^{-3.0}$ for no plasma

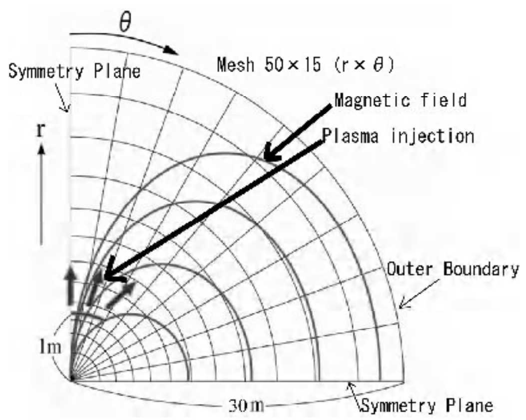

Fig.5 Simulation model for the magnetic field inflation by plasma injection.

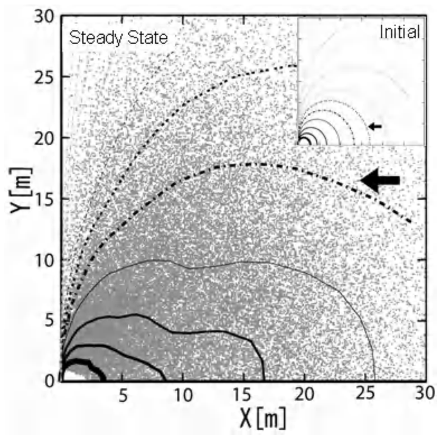

Fig.6 Profile of the magnetic field lines superimposed on the spatial distribution of injected ions.

injection case. Fig.6 shows a profile of the magnetic field lines for $\beta_{in} = 1$ at the steady state superimposed on the spatial distribution of injected ions. In comparison, the initial magnetic field lines are also shown at the upper right corner. The arrows in the figure indicate the field line with the same intensity. By comparing the location of the arrows in the figure, we can confirm that the magnetic field is inflated by the plasma injection and the magnetic field density B_z becomes high along the polar direction. Along the equatorial direction, however, the magnetic field lines are stretched in the outward direction. Therefore the magnetic field density B_z in the equatorial direction becomes small compared with the result without plasma injection. This may be associated with the outgoing ion flow which is observed at the equatorial region. The relation between the field extension and the outgoing flow is one of the issues we need to examine as a future work.

In order to obtain a higher performance of the MPS than that of other electric propulsion systems, it is necessary to inject plasma with a low β_{in} value of less than 10^{-6} which consists of very low density plasma. However, it is difficult to treat low density with the conventional hybrid particle code because the low density may cause the divergence of the local electric field. To avoid this electric field divergence in the simulation, we are modifying the conventional hybrid particle code so that we will be able to solve the field even if a region with low density plasma is created during a simulation run.

Meanwhile, MPS ground experiments have been carried out using a plasma chamber in JAXA/ISAS. In the experiments, formation of an artificial magnetosphere and inflation of the magnetosphere by plasma injection were observed as shown in Fig. 7. As shown in panel (b), we see the expansion of the magnetosphere by plasma injection. In order to understand the observations quantitatively, we also started hybrid particle simulations for the plasma chamber experiments by including the effect of neutral-ion collision.

4. Summary

We started a research project of multi-scale plasma particle simulation for the development of interplanetary flight system under the support of the JST/CREST. In the present paper, we first overviewed the MPS proposed as one of the innovative interplanetary flight systems. Secondly we briefly stated the development of a new electromagnetic particle code with AMR technique toward the analysis of multi-scale phenomenon in association with

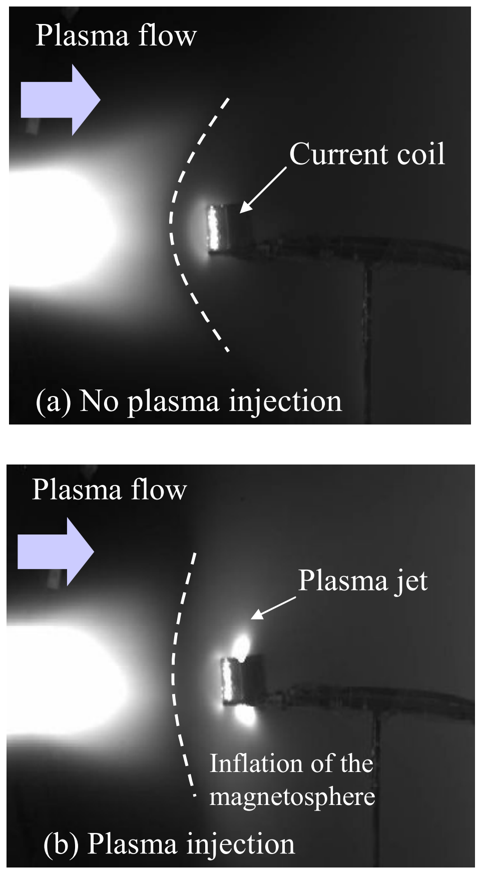

Fig.7 Snapshots of plasma chamber experiment. Panel (a) and (b) correspond to the profiles for no plasma jet and plasma jet injection from the coil location, respectively

MPS. We particularly focused on the fully threaded tree (FTT) structure introduced for the AMR scheme and the Morton ordering for the parallelization needed for the high performance computing. Thirdly, we showed some results on the inflation of the artificial magnetosphere created around the spacecraft by performing the conventional hybrid particle simulations. As observed in the plasma chamber experiments conducted in JAXA/ISAS, we could basically confirm the inflation of the magnetosphere by plasma injection from the spacecraft. For cases of plasma injection with lower density, however, we need to modify the conventional hybrid simulation scheme so that numerical divergence of electric field can be avoided at the low density region. In addition to the completion of the AMR-PIC simulation code, quantitative evaluation of magnetosphere inflation by injecting plasma with lower β_{in} is needed in the next step.

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[1] R.M. Zubrin and Andrews, D.G., Journal of Spacecraft and Rockets, Vol.28, pp.197-203, (1991).
[2] R.M.Winglee, et al., Journal of Geophysical Research, 105, No.21, 067-078, (2000)
[3] H. Yamakawa et al., Acta Astronautica, Vol. 59, No. 8-11, pp.777-784, (2006).
[4] H. Nishida, et al., Journal of Spacecraft and Rockets, Vol.43, pp.667-672, (2006).
[5] Y. Kajimura, et al., Journal of Plasma Physics, Vol 72(6), pp977-881 (2006).
[6] A. M. Khokhlov, J. Comput. Phys. 143, 519(1998).
[7] S. Warren and J.K. Salmon, Computer Physics Communications, 87, 1-2, 266-290 (1995).
[8] Y. Kajimura, I. Funaki, I. Shinohara, H. Usui and H. Nakashima, Proc. of the 4th Asian Joint Conference on Propulsion and Power, C4-3, (2008).