Numerical Simulation of Dipolar Magnetic Field Inflation due to Equatorial Ring-Current*)

Yoshihiro KAJIMURA, Ikkoh FUNAKI[1], Iku SHINOHARA[1], Hideyuki USUI[2], Masaharu MATSUMOTO[2] and Hiroshi YAMAKAWA[3]

Akashi National College of Technology, Akashi, Hyogo 674-8501, Japan
[1]*Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan*
[2]*Kobe University, Kobe, Hyogo 657-8501, Japan*
[3]*Kyoto University, Uji, Kyoto 611-0011, Japan*

(Received 22 November 2012 / Accepted 7 December 2013)

Magneto Plasma Sail (MPS) is one of the next generation space propulsion systems which generates a propulsive force using the interaction between the solar wind plasma and an artificial inflated magnetosphere generated by a superconductive coil. In the MPS system, the magnetosphere as a sail must be inflated by the plasma injection from the spacecraft in order to obtain the thrust gain. In the present study, the magnetic inflation concept is numerically tested by so-called ion one-component plasma model. As a simulation result, the magnetic moment of the system is drastically increased up to 45 times that of the coil current at plasma-β = 20 and r_{Li}/L (radius of gyro motion / characteristics length of the magnetic field) = 0.01, and this is the first successful magnetosphere inflation obtained by numerical simulation. Corresponding maximum thrust gain is also estimated to be about 45.

Keywords: magneto plasma sail, magnetic inflation, one component plasma model

DOI: 10.1585/pfr.9.2405008

1. Introduction

Plasma confinement in a dipolar magnetic field is one of important issues for fusion plasma in RT-1 [1] and space plasma in the geo-magnetosphere. In the dipolar magnetic field, a confined charged particle does not only gyrate and bounce, but also undergoes an azimuthal drift. This drift current is an effect of the gradient and curvature of the dipole magnetic field. The ring current associated with the drift flows in the same direction of the coil current, hence it can increase the magnetic moment of a system (magnetic inflation). Our research group proposed to use this magnetic inflation process for next space propulsion system: Magneto Plasma Sail (MPS) [2]. MPS generates a propulsive force using the interaction between the solar wind plasma and an artificial inflated magnetosphere generated by a superconductive coil. Figure 1 shows the conceptual illustration of MPS. Nishida has simulated the thrust transfer mechanism of MPS by using ideal MagnetoHydroDynamics (MHD) model, wherein magnetic inflation is achieved by a plasma injection from the spacecraft [3]. Within the framework of the ideal MHD formulation, if the MPS spacecraft is surrounded by a radial super-Alfvenic flow from the injected plasma, no information should be transferred upstream (i.e., to the spacecraft). This implies that the Lorentz force cannot be transferred to the MPS spacecraft [3]. Kajimura has also evaluated the obtained thrust of MPS by using Hybrid Particle-in-Cell (PIC) model [4]. The maximum thrust gain by MPS (thrust force by MPS divided by the sum of thrust by pure magnetic sail and thrust by plasma jet) is limited to around unity, i.e., MPS with plasma jet is not effective. To improve the situation of MPS, the magnetosphere inflation by plasma equilibrium uses currents by trapped particles to increase the magnetic moment of an MPS spacecraft. So the above magnetic inflation concept using ring current due to injected thermal plasma is numerically tested by so-called ion one-component plasma model. In this model, we neglect the electrostatic effect, and only one particle species (ions) is treated explicitly. The existence of other species of particles (electrons) is only implicitly assumed to guarantee the charge neutrality. Figure 2 shows a magneto-

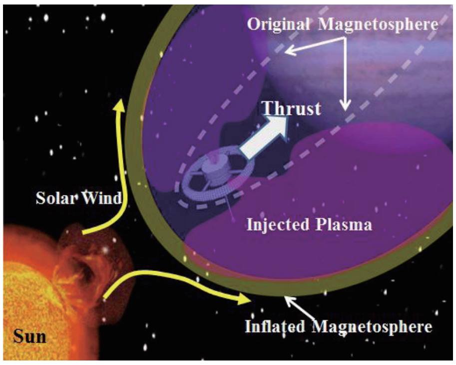

Fig. 1 The conceptual illustration of MPS.

author's e-mail: kajimura@akashi.ac.jp
*) This article is based on the presentation at the 22nd International Toki Conference (ITC22).

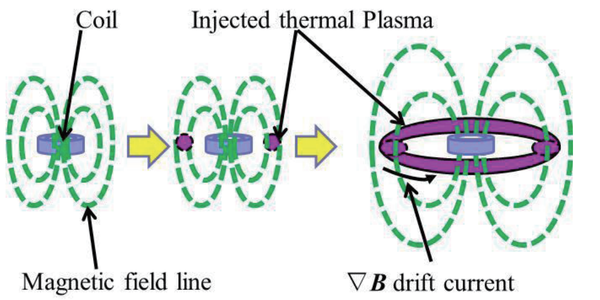

Fig. 2 Magnetosphere inflation processes: inflation due to equatorial ring current.

sphere inflation processes due to equatorial ring-current. In the present paper, in order to evaluate the magnetic moment induced by the equatorial ring current and to estimate the corresponding thrust of MPS with inflated magnetosphere due to the equatorial ring current, the ion particle simulation by using modified One Component Plasma (OCP) model is conducted.

2. Numerical Method (Modified One Component Plasma Model)

2.1 Governing equation

The modified One Component Plasma (OCP)model basing on the original model [5] consists of the equations of motion of ion particles (1) (2) and Maxwell's equations (3). The magnetic field is calculated using Eq. (4) from the vector potential $\boldsymbol{A}$ which satisfies the Maxwell equation. The boundary condition for Eq. (4) is adopted the zero-gradient condition. The ion current density $\boldsymbol{J}$ is calculated by the PIC method. The OCP model neglects the displacement current and the electric field under the quasi-neutral approximation. In the present study, we are interested in the temporal change in the magnetic field, which depends only on the transverse component of the ion current. The Eq. (5) solved by the successive over-relaxation (SOR) method is used in order to satisfy the divergence free condition of magnetic field. Figure 3 shows the flow chart of the OCP simulation.

$$m_i \frac{\mathrm{d}\boldsymbol{V}_i}{\mathrm{d}t} = q_i(\boldsymbol{V}_i \times \boldsymbol{B}), \tag{1}$$

$$\frac{\mathrm{d}\boldsymbol{X}_i}{\mathrm{d}t} = \boldsymbol{V}_i, \tag{2}$$

$$\nabla^2 \boldsymbol{A} = -\mu_0 \boldsymbol{J}, \tag{3}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}, \tag{4}$$

$$\nabla \cdot \boldsymbol{A} = 0. \tag{5}$$

3. Simulation of Equatorial Ring Current

3.1 Simulation condition and parameters

The simulation model adopted for the present study is shown in Fig. 4. A coil with a 2.0-m radius (spacecraft) is

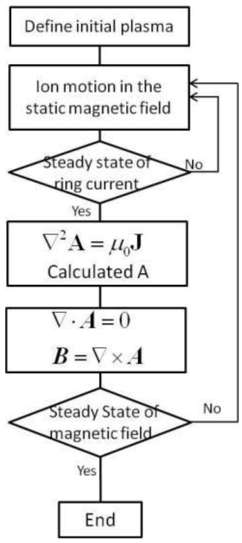

Fig. 3 Flow chart of modified OCP model.

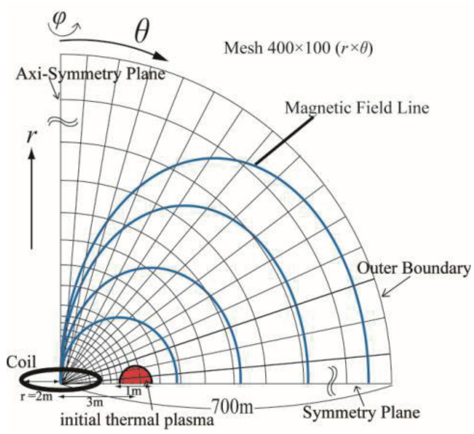

Fig. 4 Simulation model.

located at the origin of the simulation model, and it generates a dipolar magnetic field that is analytically calculated from the coil current. The hydrogen ions are injected continuously in the initial thermal plasma region, as shown in Fig. 4. This injected region is located at a distance of 3.0 m from the coil center. The initial volume of the injected thermal plasma is set unique value under the given plasma beta as shown in Table 1. The ion particles run away from the outer boundary are again injected in the initial defined plasma region. The other parameters are listed in Table 1. The collision effect among ions is not included in the present simulation since the cost of each simulation run becomes very large for reaching the steady state.

3.2 Simulation results

Figure 5 shows the time evolution of ion particle distributions (a) initial and (d) steady state for $\beta = 15$. Released ions start gyrating, bouncing and drifting motions, and the last motion induces an equatorial ring current. It is found that the ring current expands radially due to the

Table 1 Simulation Parameters.

(a) Plasma parameters	
Injection Plasma	H
Density [m^{-3}]	$3 \times 10^{15} \sim 3 \times 10^{21}$
Velocity $= V_0$ [m/s]	0.0
Ion temperature [eV]	1～10000
(b) Field parameters	
Magnetic moment [Tm^3]	1.58
Radius of coil [m]	2.0
Current of coil [Aturn]	1.0E+05
(c) Dimension less parameters	
r_L/L (use thermal velocity, B at the Injection point)	0.01～1.0
Thermal plasma β	0.1～100
(d) Simulation parameters	
dx [m]	0.03～13
dt	0.01 ($1/\omega_{ci}$)
mesh number (r*θ)	400*100

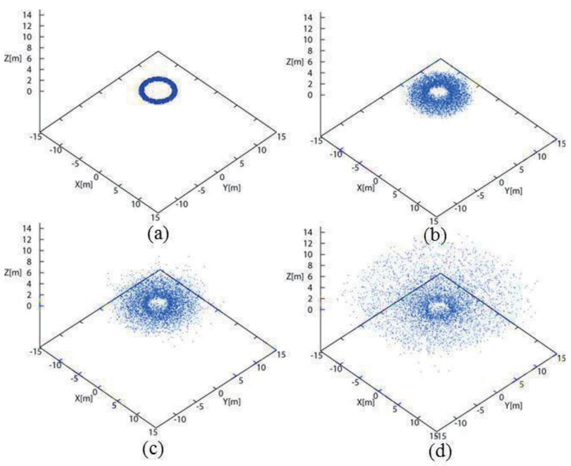

Fig. 5 Time evolution of ion particle distributions (a) initial and (d) steady state for β = 15: time increases from left to right.

hoop stress, resulting in a rather broad ring current region. Figure 5 (d) shows a steady state, in which force balance is established in both the radial and azimuthal directions. Figure 6 shows the time evolution of magnetic field line (a) initial and (d) steady state for β = 15. It can be seen the magnetic field inflation due to the equatorial ring current injected near the coil. From such steady solutions, the magnetic moment is calculated using equatorial ring current density. The results of the M/M_0 (the ratio of the magnetic moment due to the ring current to the initial magnetic moment of the coil) depending on β and r_L/L are plotted in Fig. 7. For large r_L/L ($r_L/$: ion gyro radius at the injection point, L: characteristics length of magnetic field gradient)

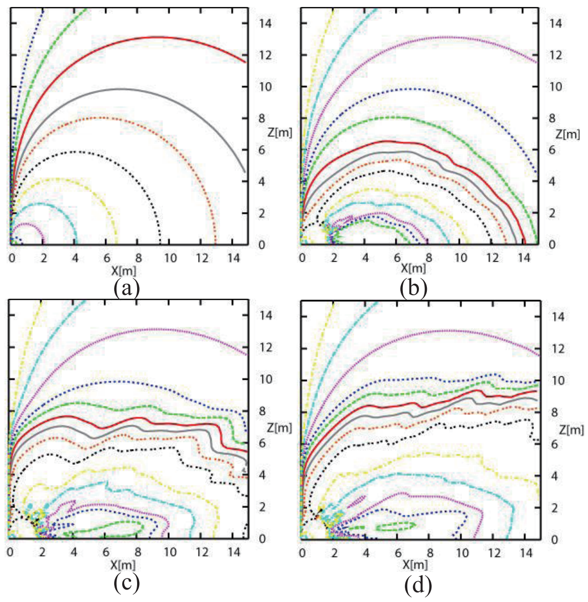

Fig. 6 Time evolution of magnetic field line: time increases from left to right (β = 15).

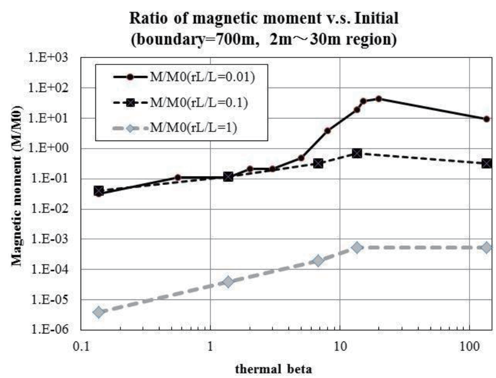

Fig. 7 Ratio of magnetic moment due to equatorial ring current to the initial magnetic moment v.s. initial thermal beta.

value of 1.0, injected thermal ions are not trapped in the magnetic field hence the magnetic moment induced by the ring current is quite small. On the other hand, for small r_L/L of 0.01, injected thermal ions are well confined in the magnetic field hence the magnetic moment induced by the ring current increase with the increase of beta value. The maximum value of the ratio of the magnetic moment to the initial magnetic moment of the coil is 45 for β = 15. However, even if the plasma with small r_L/L value is injected, the confinement of the injected plasma and increase of the magnetic moment induced by the ring current is not achieved in case for the plasma with too high beta. If the local beta becomes larger than unity by increasing the beta (density) of injected ion, the ions are not confined well and the magnetic moment generated by the ion ring current does not increase.

The thrust estimated in Fig. 8 is calculated by using Eq. (6) where n_{sw}, m, v_{sm} and L_{inf} are number density of so-

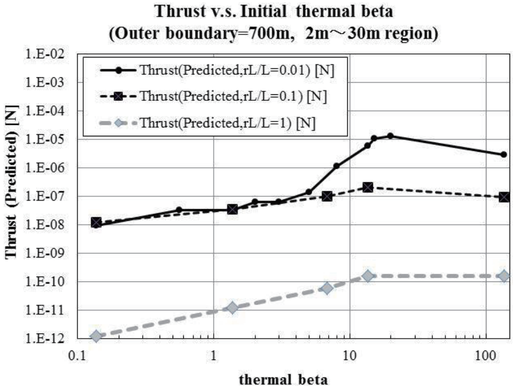

Fig. 8 Thrust v.s. initial thermal beta.

lar wind, mass of hydrogen ion, velocity of solar wind and inflated magnetosphere size, respectively. The drag coefficient C_d is calculated from the approximate formula in Eq. (7) for the drag coefficient as summarized by Fujita [6] where r_{Li} is the ion gyro radius at the magnetopause. The increase of the magnetic moment induced by the equatorial ring current is considered as in Eq. (8). Corresponding maximum thrust gain is also estimated to be about 45. The thrust estimated in the present parameters is 0.013 [mN].

$$F = C_d \cdot 0.5 \cdot n_{sw} m v_{sw}^2 (\pi L_{inf}^2), \tag{6}$$

$$C_d = \frac{3.4}{(r_{Li}/L_{inf})} \cdot \exp\left(\frac{-0.22}{(r_{Li}/L_{inf})^2}\right)(r_{Li}/L_{inf} > 1), \tag{7}$$

$$L_{inf} = \left(\frac{\mu_0 (M + M_0)^2}{8 n_{sw} m v_{sw}^2}\right)^{1/6}. \tag{8}$$

In order to confirm the validity of the present simulations, the delta t and grid size in the simulations were adjusted to 200%, 100%, and 50% of their original values in the present studies. As a result, the thrusts obtained were in error by less than factor 1.5 owing to these changes. The strength and the direction of the Interplanetary Magnetic field (IMF) have been taken into consideration in the present simulation. However there is no influence for the increase of the magnetic moment.

4. Summary

The magnetic moment induced by the equatorial ring current and the corresponding thrust of MPS with inflated magnetosphere due to the equatorial ring current have been estimated by the ion particle simulation by using modified OCP model. The magnetic moment of the system is drastically increased up to 45 times that of the coil current at plasma-β = 20 and r_{Li}/L (radius of gyro motion / characteristics length of the magnetic field) = 0.01, and this is the first successful magnetosphere inflation obtained by numerical simulation. Corresponding maximum thrust gain is also estimated to be about 45. The simulation for larger magnetic moment of the coil should be conducted in order to confirm whether if the better confinement under the strong magnetic field can be achieved. Furthermore, we need to consider solar wind flow in the simulation of magnetic inflation.

Acknowledgement

We gratefully acknowledge the support and advice of the MPS research group members in Japan. Simulations were supported by the Engineering Digital Innovation Center of the Japan Aerospace Exploration Agency (JAXA) and the KDK system of the Research Institute for Sustainable Humanosphere (RISH) at Kyoto University as a collaborative research project. This study was also supported by the Japan Science and Technology Agency (JST) and Core Research for Evolutional Science and Technology (CREST).

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