Two-dimensional Particle-In-Cell Simulation of Magnetic Sails in Formation Flight

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Magnetic sail is a propulsion system of spacecrafts which is equipped with a large superconductive coil to generate an artificial magnetosphere, which blocks solar wind particles approaching the coil and changes their momentum into thrust of the spacecraft. In order to obtain larger magnetosphere, formation flight of magnetic sails is proposed, and two-dimensional full particle-in-cell simulations are conducted on a small-scale magnetosphere to investigate the structure of magnetosphere and thrust characteristics of magnetic sails in formation flight. The magnetic sails in formation flight make a larger magnetosphere than that in single flight, resulting in larger thrust. The maximum thrust in formation flight is calculated as 2.5 times larger than that in single flight, which is caused by the diamagnetic current.

Nomenclature

$\mathbf{B}$	= magnetic flux density vector, T
$\mathbf{B}_{\mathrm{MS}}$	= magnetic flux density vector generated by onboard superconductive coil, T
c	= speed of light, m/s
$\mathrm{d}t$	= time step, s
$\mathrm{d}x$	= grid spacing, m
$\mathbf{E}$	= electric field vector, V/m
e	= elementary charge, C
$\mathbf{F}_{\mathrm{MS}}$	= thrust vector by magnetic sail, N/m
I_{coil}	= coil current, A
$\mathbf{I}_{\mathrm{coil}}$	= coil current vector, A
$\mathbf{J}$	= plasma current vector, A
L_{MP}	= cross-sectional length of magnetosphere, m
m_e	= mass of electron, kg
m_i	= mass of ion, kg
N_{SW}	= number density of solar wind plasma, /m^3
q_e	= charge of electron, C
q_i	= charge of ion, C
T_{SW}	= solar wind plasma temperature, eV
$\mathbf{x}_e$	= position vector of electron, m

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$\mathbf{x}_i$ = position vector of ion, m
V_{SW} = velocity of solar wind plasma, m/s
v_e = velocity of electron, m/s
v_i = velocity of ion, m/s
$\mathbf{v}_e$ = velocity vector of electron, m/s
$\mathbf{v}_i$ = velocity vector of ion, m/s
γ_{SW} = electon-ion temperature ratio of solar wind plasma
λ_D = Debye length, m
μ_0 = permeability of vacuum, N/A^2

I. Introduction

The solar wind in interplanetary space is a high-speed plasma flow from the sun, which has a lot of potential to be the propellant of spacecrafts. Magnetic sail which is originally proposed by Zubrin and Andrews[1] utilizes the solar wind to generate its thrust. A large loop of superconductive coil on the spacecraft produces an artificial magnetosphere in space, which reflects solar wind particles approaching the coil and changes their momentum into a corresponding force in order to accelerate the spacecraft in the antisunward direction (Fig. 1). Inspite of its propellantless thrust characteristics, it has been regarded as an unrealistic propulsion system which needs an extremely large superconductive coil. Winglee et al.[2] proposed the idea of enhancing magnetosphere with a compact superconductive coil using a plasma jet, which may reflect more solar wind particles and then generate larger thrust. The concept is called a mini-magnetoplasma propulsion (M2P2) or a magnetoplasma sail (MPS). Their investigation showed that the idea is effective, which provides a significant improvement in force even on a small-scale magnetosphere based on magnetohydrodynamic (MHD) simulations of solar wind flow around the spacecraft.

However, it was revealed that the fluid model is not valid for such a small-scale magnetosphere which is comparable to the ion Larmor radius of solar wind plasma. Khazanov et al.[3] conducted both MHD and kinetic simulations on a small-scale magnetosphere, which showed that the ion kinetic effect needs to be considered in the practical estimation of the thrust. Although several numerical simulations such as MHD simulation by Nishida et al.[4] and hybrid particle-in-cell (PIC) simulation by Kajimura et al.[5] were conducted under the assumption that MPS generates a large magnetosphere (>100 km), the condition is feasible in terms of the present technology of superconductive coils and payload capacity to launch.

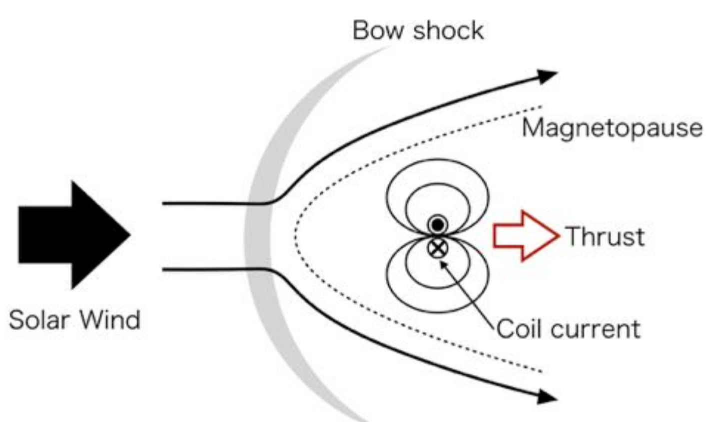

Figure 1. Schematic illustration of magnetic sail.

Ashida et al.[6,7] performed two-dimensional and three-dimensional full PIC simulations, which treat both ions and electrons as particles. Since a superconductive coil is set to realistic size and it generates a small-scale magnetosphere compared to the ion inertial length, the Larmor motions of solar wind particles need to be considered. As a result of the three-dimensional full PIC simulation of MPS, the maximum thrust and thrust-mass ratio were calculated as 6.5μN and 3.3×10^{-5}mN/kg, respectively, using a 200 kg superconductive coil of 4.0 m in diameter. However, they are much smaller than those of other existing propulsion systems. Moreover, the thrust-mass ratio must be even smaller than this estimation when the mass of cooling systems or bus systems is taken into account. In order to make the magnetic sail concept implemented, some effective breakthroughs are desired. Baba et al.[8] proposed the multipole-type MPS using two spacecrafts at the same time, which gives slightly high thrust gain than that in previous studies. This result indicates that a "formation flight" concept using a plural number of magnetic sails may generate larger net thrust.

The objective of this study is to propose the formation flight of magnetic sails and reveal thrust characteristics in the concept. Here we assume that the magnetic sail (not M2P2 or MPS) has a compact superconductive coil and the length of corresponding magnetosphere is comparable to the ion Larmor radius, where both ion and electron kinetics need to be considered. Therefore, two-dimensional full PIC method is employed in order to follow the motions of particles.

The structure of magnetosphere and thrust characteristics of magnetic sail making solo flight are obtained as a comparison, and then those of magnetic sails in two formation patterns are also examined, which evaluates the superiority of formation-flight concept.

II. Numerical Model

Full-PIC simulation involves ions and electrons in order to consider the kinetic effects of them such as Larmor motion and charge separation. The simulation solves following equations of motion for both ions and electrons:

$$\frac{\mathrm{d}\mathbf{v}_{i,e}}{\mathrm{d}t} = \frac{q_{i,e}}{m_{i,e}}\left(\mathbf{E} + \frac{\mathbf{v}_{i,e}}{\gamma c}\times(\mathbf{B}+\mathbf{B}_{\mathrm{MS}})\right), \tag{1}$$

$$\frac{\mathrm{d}\mathbf{x}_{i,e}}{\mathrm{d}t} = \frac{\mathbf{v}_{i,e}}{\gamma}, \tag{2}$$

where $\gamma = \sqrt{1+v_{i,e}^2/c^2}$ is the Lorentz factor. The magnetic field generated by the onboard coil is inserted into the equation as a background magnetic field, which is shown in Eq. (1). Buneman-Boris method[9] is employed for tracing the motion of each particle. Note that the simulation particle is called a super particle, which represents several charged particles. Second spline is adopted as a form-factor which denotes the amount of effect from a super particle to grid points. Density decomposition method[10] calculates the current density at each grid point satisfying the charge conservation law. Following Maxwell's equations are solved implicitly using an implicit method[11]:

$$\frac{\partial\mathbf{B}}{\partial t} = -c\nabla\times\mathbf{E}, \tag{3}$$

$$\frac{\partial\mathbf{E}}{\partial t} = c\nabla\times\mathbf{B} - 4\pi\mathbf{J}. \tag{4}$$

The computational domain used in the 2-D full-PIC simulations is shown in Fig. 2. The area is 800 m $\times$ 800 m, which is partitioned into 160 grids $\times$ 160 grids. The grid spacing is set to 5 m so that it does not exceed the debye length of solar wind ($\mathrm{d}x \leq \lambda_D/3$). Solar wind particles flow into the domain from the inflow boundary (left-hand side of Fig. 2) with the parameters of $N_{\mathrm{SW}} = 5.0\times10^6$ /m^3, $V_{\mathrm{SW}} = 5.0\times10^5$ m/s, and $\gamma_{\mathrm{SW}} = 1.35$, which are the typical values of the solar wind at 1 AU (astronomical unit)[6,12,13]. Other three edges are set to outflow boundary. The weight of each super particle and the mass ratio m_i/m_e are set to 1.25×10^6 and 25, respectively. The time spacing $\mathrm{d}t$ is 5.8×10^{-8} s.

Two different formation styles of magnetic sails, Formation A and Formation B are considered as shown in Fig. 3. The type using only one coil is called Single, which is set for comparison. Superconductive coils of 2 m in diameter are set at the coordinates in meters: $(x, y) = (0, 0)$ for Single, $(x, y) = (0, 0), (25, 0), (50, 0)$ for Formation A, and $(x, y) = (0, 0), (25, 25), (25, -25)$ for Formation B. Since the spacecraft obtains the maximum thrust when the magnetic moment of the coil directs at the solar wind flow direction[6], all of coils in Single, Formation A, and Formation B are set to follow that. The current on each coil is 3.0×10^6 A for Single, 1.0×10^6 A for Formation A, and Formation B, which aims at making the comparison of thrust

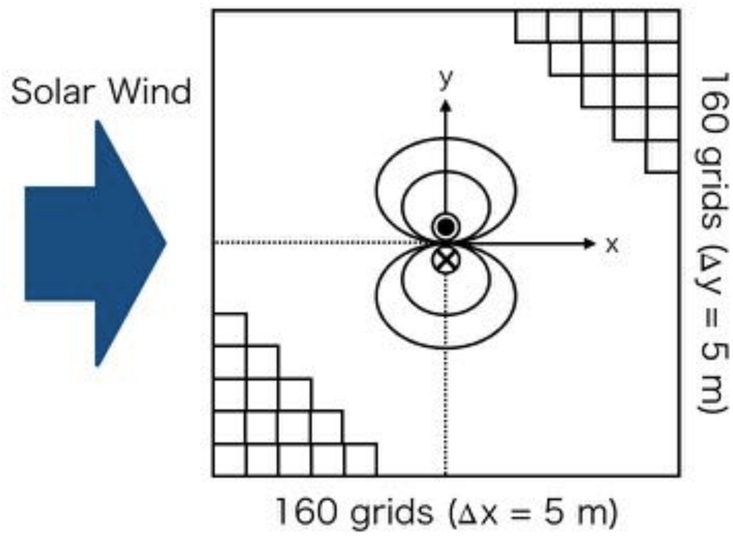

Figure 2. Computational domain of 2-D PIC Simulation.

characteristics more clear by letting the sum of coil current in each formation be the same value. Since the current on the loop coil is regarded as a pair of opposite currents in the domain, the magnetic field around coils is calculated using Biot-Savart law and inserted into Eq. (1) as a background magnetic field.

Magnetic sail acquires the Lorentz force as thrust which is generated between the coil current and magnetopause currents induced by $\mathbf{E} \times \mathbf{B}$ drift motion of electrons. Thus, the thrust in each formation is calculated as follows:

$$\mathbf{F}_{\mathrm{MS}} = \left(\sum_i \sum_j \frac{\mu_0 \mathbf{J}_{i,j} \times \mathbf{r}}{2\pi r^2} \right) \times \mathbf{I}_{\mathrm{coil}}, \tag{5}$$

where r is the distance between the plasma current and coil current, $\mathbf{J}_{i,j}$ is the plasma current vector at the coordinates $(x, y) = (i, j)$, respectively.

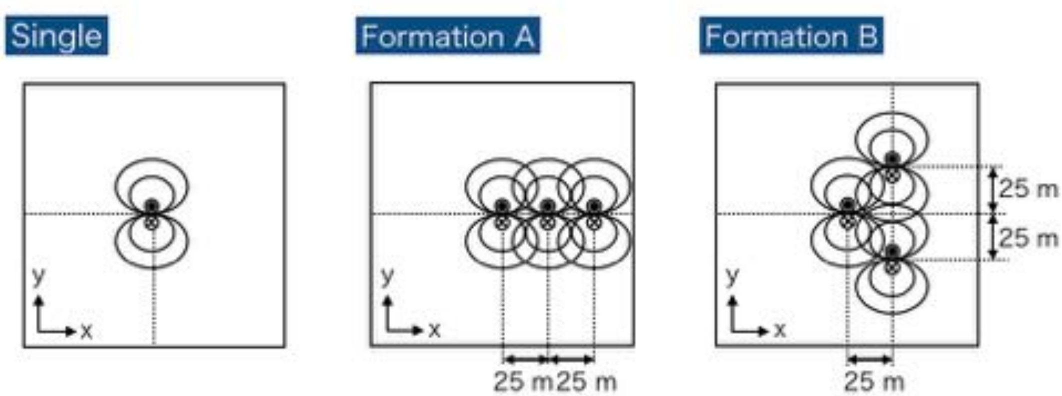

Figure 3. Disposition of magnetic sails.

III. Result

A. Structure of Magnetosphere around Magnetic Sails

Figures 4(a) to 4(c) and 4(d) to 4(f) show the density distribution of ion and electron, respectively, in Single, Formation A, and Formation B. The low-density regions (cavities) of ion and electron are formed around the spacecrafts because of the deflection of particles by the magnetic field of the onboard coils. Since electrons are subject to magnetic field beside ions, the cross-sectional length of the electron cavities is larger than that of the ion cavities. Furthermore, the high-density regions of electron in the upstream of spacecrafts indicate that the mirror magnetic field reflects electrons approaching the coil, which induces charge separation and corresponding electric field. Comparing three different cases, it is obvious that the formation style impacts on the structure of magnetosphere around magnetic sails. However, there is not significant difference in the size of cavities.

The electric field induced by the charge separation and the magnetic field around coils make electrons drift in $\mathbf{E} \times \mathbf{B}$ direction which corresponds to z direction in Fig. 5. The current induced by the $\mathbf{E} \times \mathbf{B}$ drift of electrons is called a magnetopause current, and the intensity depends on the magnitude of electric field and magnetic field. Since the thrust of magnetic sails is closely related to the magnetopause current, the structure of magnetosphere affects the thrust characteristics.

The density distribution of current is shown in Figs. 4(g) to 4(i). The cross-sectional length of magnetosphere is defined as the peak-to-peak length of the current. As a result, the length is measured as 120 m in Single, 125 m in Formation A, and 130 m in Formation B. Therefore, it is revealed that the magnetosphere can be enhanced slightly by the concept of formation flight, which may capture more ions and obtain larger thrust. Moreover, the diamagnetic current is induced in the downstream of spacecrafts in Formation B. Since there are high-density regions of electron in y direction which is caused by the mirror effect, the gradient of electron density is high in Formation B, resulting in inducing diamagnetic current. This current enhances the magnetosphere and generates larger Lorentz force between the current and the coil current.

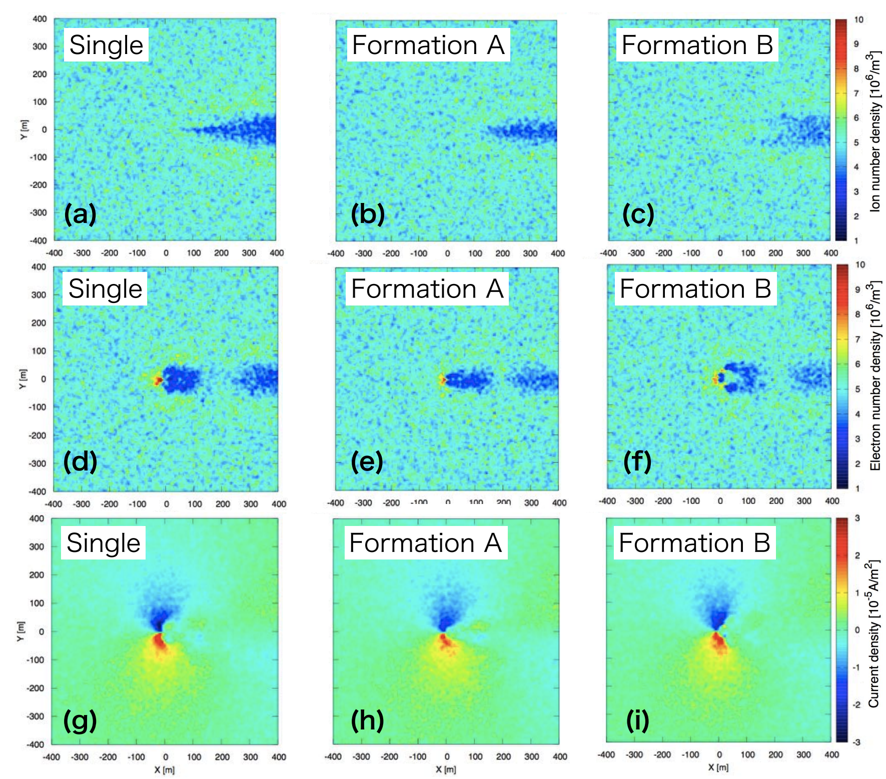

Figure 4. Density distribution of ion, electron, and current.

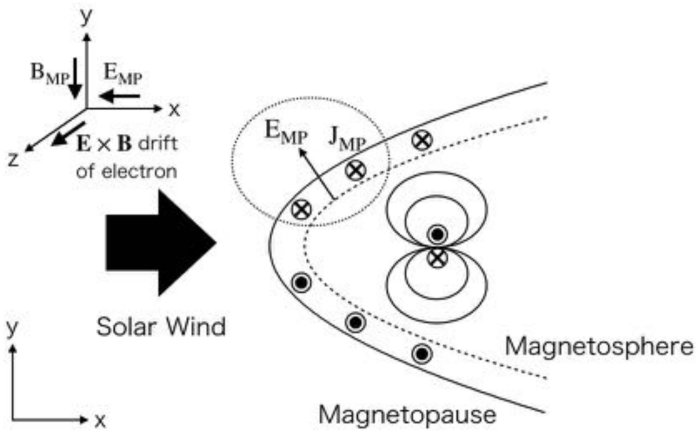

Figure 5. Schematic illustration of the magnetopause current around magnetic sail.

B. Thrust Characteristics of Magnetic Sails

Table 1 shows the results of thrust estimation. Note that each thrust value of Formation A and Formation B in Table 1 is sum of the thrust which is obtained by all of the spacecrafts in formation. The thrust in formation flight is larger than that of Single: 2.1 times larger in Formation A and 2.5 times larger in Formation B. This result indicates that the formation flight concept contributes to the enhancement of thrust. Formation B has the maximum thrust, which is caused by the diamagnetic current.

The relationship between the cross-sectional length of magnetosphere and the thrust is shown in Fig. 6, finding a positive correlation, which is consistent with the idea that the larger magnetosphere, the larger thrust the spacecraft obtains because the number of solar wind plasma to be captured increases.

Table 1. The result of thrust evaluation.

Single	Formation A	Formation B
2.6×10^{-5} N/m	5.3×10^{-5} N/m	6.6×10^{-5} N/m

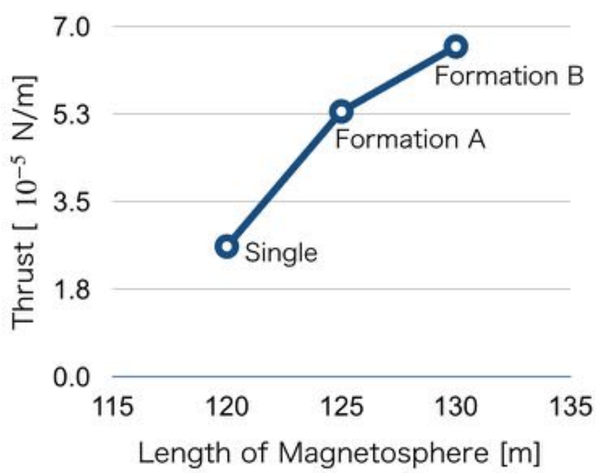

Figure 6. Relationship between the length of magnetosphere and the total thrust.

IV. Conclusion

In this study, we proposed the concept of formation flight of magnetic sails aiming at enhancing the magnetosphere and obtaining large thrust. Two-dimensional full-PIC simulations of magnetic sails with a ion-Larmor-radius-scale magnetosphere were performed in order to take kinetic effects of ions and electrons into account, which enabled to obtain the structure of magnetosphere and thrust characteristics of magnetic sails in formation flight.

The result showed that the cross-sectional length of magnetosphere in formation flight is enhanced slightly compared to that in Single case: 1.04 times in Formation A and 1.08 times in Formation B. Magnetic sails in formation flight obtained larger thrust than that in Single: 2.1 times in Formation A and 2.5 times in Formation B. Formation B gained the maximum thrust, which is caused by the diamagnetic current in the downstream of spacecrafts. These results revealed that formation flight is efficient in terms of enhancing the cross-sectional length of magnetosphere and converting the momentum of solar wind into thrust.

In future work, further numerical simulations of magnetic sails and MPSs in formation flight should be performed in order to find more effective formation styles. Furthermore, formation flight of small-sized magnetic sails equipped with permanent magnets can be examined which may achieve the high thrust-mass ratio.

Acknowledgments

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