ABSTRACTS (PH D THESIS)

Study on Propulsive Characteristics of Magnetic Sail and Magneto Plasma Sail by Plasma Particle Simulations

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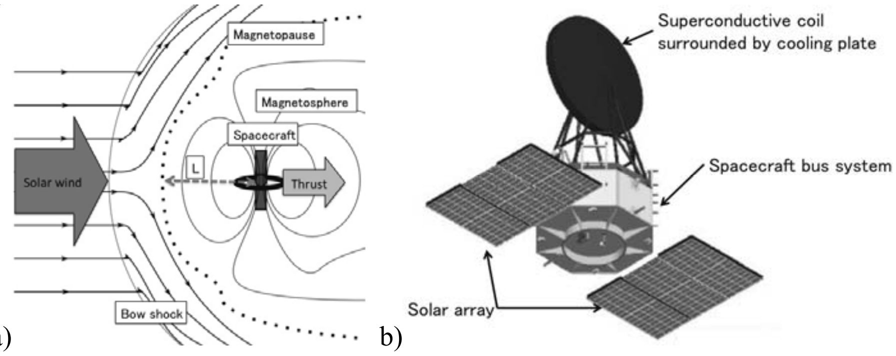
Magnetic Sail is a spacecraft propulsion system that generates an artificial magnetosphere to block solar wind particles and uses the imparted momentum to accelerate a spacecraft (Figure 1). The derivative of Magnetic Sail, Magneto Plasma Sail inflate the artificial magnetosphere by a plasma injection from the spacecraft. The momentum caught by the inflated magnetosphere is transfer to the spacecraft as a larger thrust. However, the propulsive characteristics of magnetic sail and magneto plasma sail has not been quantified even thought the many previous works were carried out. This is because the large computational efforts is required to simulate the momentum transfer process including the plasma kinetics and the scaling law of the propulsive characteristics cannot be obtained under the one simulation model.



a) b)

Figure 1 a) schematic illustration of Magnetic Sail and b) spacecraft model of Magneto Plasma Sail.

In the present study, the plasma flow around Magnetic Sail and Magneto Plasma Sail is simulated from the ion inertial scale, where ion Larmor motion is comparable with the artificial magnetosphere size, to the electron inertial scale, where electron Larmor radius and Debye length are comparable with the magnetosphere size. The steady-state model of plasma flow around magnetic sail including ion kinetic effects had to be developed by using Flux-Tube model to enable us to drastically shorten the simulation time required to reveal the propulsive characteristics with various parameters. Using the high performance computing techniques and the recently developed peta-scale supercomputer, the highly parallelized simulation code based on Full Particle-in-Cell (PIC) model was also developed to take the electron kinetic effects into consideration.

Three type of simulation: three-dimensional Flux-Tube model, two-dimensional Full-PIC model and three-dimensional Full-PIC model are hence performed to reveal scaling law of the propulsive characteristics of Magnetic Sail and Magneto Plasma Sail. The thrust of magnetic sail is approximately proportional to the magnetic moment of onboard superconductive coil on the electron inertial scale even though the thrust is approximately proportional to the 2/3 power of the magnetic moment on the ion inertial scale (Figure 2). The thrust changes from the electron inertial scale to the ion inertial scale nonlinearly. The empirical formula of thrust was obtained by the combination of Flux-Tube model and Full-PIC model. It was also revealed that these propulsive characteristics are caused by the finite Larmor motion and charge separation between ion and electron. The solar wind that is a natural phenomenon changes its parameters such as number density and velocity every moment. The propulsive characteristics about solar wind variation were also examined. The thrusts on the electron inertial scale and the ion inertial scale are proportional to the 1.15 power of number density and the 0.67 power of number density, respectively. This propulsive characteristics cause the difference in the flexibility of the interplanetary flight missions by magnetic sail since the average plasma density is inversely proportional to square of the sun-spacecraft distance. It was also revealed that the magnetic sail on the ion inertial scale, which thrust is inversely proportional to the 1.3 power of the sun-spacecraft distance is more suitable for the deep space flight than the magnetic sail on the election inertial scale, which thrust is inversely proportional to the 2.3 power of the sun-spacecraft distance.

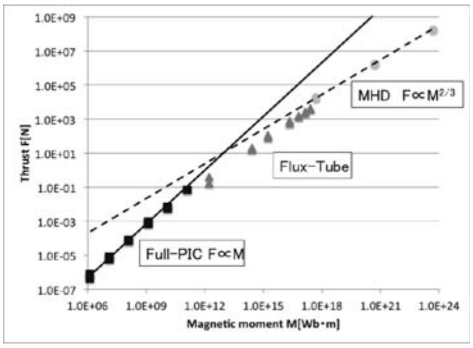
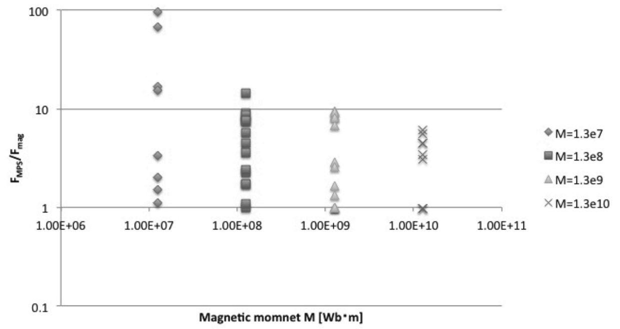


Figure 2 thrusts of magnetic sail with various magnetic moments.

Two- and three-dimensional simulations demonstrate the increase in thrust of Magneto Plasma Sail utilizing plasma injection. It becomes clear that the increase in thrust is dependent on the Larmor radius of injection plasma and the plasma energy at injection point. By simulations with various plasma parameters and one-dimensional theoretical analysis, we examined the parameters that maximize a thrust. The maximum increase (thrust of MPS / thrust of magnetic sail) is 97 but the thrust gain (thrust of MPS / (thrust of magnetic sail + thrust of plasma jet)) is only 0.4 by same condition. On the contrary, the maximum thrust gain 5.2 is obtained and the relation of trade-off between the increase in thrust and the thrust gain is revealed (Figure 3).



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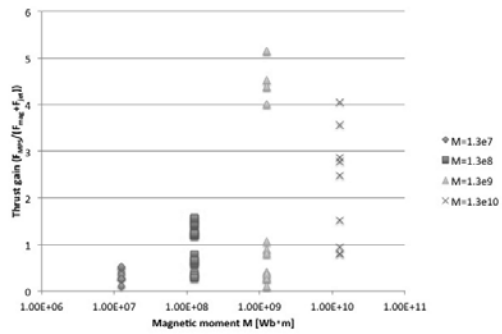

b)

Figure 3 a) thrust increase and b) thrust gain of Magneto Plasma Sail.

Moreover, the propulsive characteristics other than thrust: thrust-mass ratio, thrust-power ratio and specific impulse, were also examined. The thrust-mass ratio is approximately constant on the electron inertial scale and gradually decreases on the ion inertial scale as the magnetic moment of the onboard coil becomes large. The thrust-power ratio is mainly depends on the plasma injection velocity and, when the thrust gain is large the thrust-power ratio is also large. However, it was revealed that the high thrust-mass ratio, the high thrust-power ratio and specific impulse couldn't be achieved simultaneously. Under the limitation of the present technology and the propulsive characteristics, the feasible demonstration missions of Magnetic Sail and Magneto Plasma Sail are also proposed. The optimized trajectory obtained by Genetic Algorithm shows that large acceleration is obtained even the small-scale Magnetic Sail by the flight via an inner planet. The artificial halo orbit at Lagrange points are also proposed as the candidate of the magnetic sail mission.

Concluding the present thesis, the scaling law of the propulsive characteristics of Magnetic Sail and Magneto Plasma Sail are successfully revealed, with a few suggestions for realization of future interplanetary missions.