論文の内容の要旨

論文題目　Characterization on Momentum Transfer Process of Magneto-Plasma Sail by MHD Analysis

（磁気プラズマセイルにおける推力発生機構の電磁流体解析）

氏名　西田　浩之

Magneto-Plasma Sail is a propulsion system utilizing the solar wind. This propulsion system creates a strong magnetic field using a super-conducting coil and plasma jets, and this magnetic field works as a “sail” catching the solar wind momentum. The momentum caught by the magnetic field is transferred to the spacecraft as thrust. However, the thrust performance of this propulsion system has not been quantified because the momentum transfer from the solar wind to the spacecraft has not been clarified. Especially, the momentum transfer process has not been clarified even in the ideal MHD approximation which is the simplest model, and so Magneto-Plasma Sail is still under discussion.

In the present study, the whole flow field of Magneto-Plasma Sail were simulated using the ideal magnetohydrodynamics, and the momentum transfer from the solar wind to the spacecraft was studied. In addition, an idea for improving the performance of Magneto-Plasma Sail was proposed.

A portion of magnetohydrodynamic flow field around Magneto Plasma Sail can be considered in the force-free condition. Hence, characteristics of the ideal MHD equations were analytically investigated in the quasi-one dimension under the force-free condition. Results of this investigation showed that when the plasma flow was super-sonic wave flow, a plasma flow accelerates with expanding even though the plasma flow velocity is slower than the MHD wave speed. Here, the MHD waves are the characteristic waves in the ideal magnetohydrodynamic plasma.

To study the momentum transfer process, the interaction between plasma flows and magnetic fields has to be precisely simulated in a wide-range space. Before going into such simulation, the simulation of the magnetic field inflation without the interaction with the solar wind was carried out. The simulation was conducted assuming the realistic configuration of Magneto-Plasma Sail; a superconducting coil surrounds the spacecraft and two plasma jets are injected from two magnetic poles. Especially, the plasma inflow boundary conditions were carefully implemented. The closed magnetic field and the open magnetic field are created around the spacecraft, and the dipole magnetic field decreasing as the distance r^{-3} is inflated to the field decreasing as r^{-2} at the sufficient distance from the spacecraft. It is clarified that the flow field of Magneto-Plasma Sail is similar to the flow field of the Sun.

The whole flow field and magnetic field around Magneto-Plasma Sail were simulated to investigate the momentum transfer from the solar wind to the spacecraft. When the Mach number is defined using MHD wave speed, simulation results showed that Magneto-Plasma Sail could generate thrust only when sufficient low Mach number plasma jet was used. When higher Mach number plasma jet is used, Magneto-Plasma Sail can not generate thrust. In this case, the injected plasma jet accelerates to a plasma flow which is faster than the MHD wave and the termination shock surrounding the spacecraft is formed. This result showed the MHD wave played an important role in the momentum transfer process. The MHD wave transporting the information has to propagate from the interaction region with the solar wind to the spacecraft for thrust generation.

Magneto-Plasma Sail utilizing one-way single plasma jet was proposed to improve the thrust performance of Magneto-Plasma Sail, and this concept was validated by the numerical simulation. Using one-way single plasma jet permits the solar wind momentum to be transferred to the spacecraft even if the high Mach number plasma jet is used. In addition, when the one-way single plasma jet is injected to the Sun, the spacecraft can make use of not only thrust by Magneto-Plasma Sail but also thrust generated by the plasma jet. Simulation results indicated that smaller nozzle exit area could improve the thrust performance of Magneto-Plasma Sail. However, it is predicted that the optimum nozzle exit area exists for maximizing thrust by Magneto-Plasma Sail, therefore it is not always good to adopt a small nozzle exit area.

Finally, the ion kinetic effect and the nonideality effect were discussed. The ion kinetic effect prevents both the effective magnetic field inflation and the momentum transfer. However, further studies on the ion kinetic effect are required, because many waves other than the MHD waves are significant in the interaction in the ion kinetic scale, hence the mechanism of the momentum transfer is different from that in the MHD scale. The nonideality effects (i.e. the effect of the finite electric conductivity and the Hall effect) deform the structure of the inflated magnetic field. The electric resistivity is not significant, judging from previous research results. However, there is no knowledge about the Hall effect on Magneto-Plasma Sail, and so studies on the Hall effect are needed in future works.