Imaging of Plasma Flow around Magnetoplasma Sail in Laboratory Experiment

Kazuma UENO, Tomohiro AYABE[1)], Ikkoh FUNAKI[2)],
Hideyuki HORISAWA[1)] and Hiroshi YAMAKAWA[3)]

Department of Space and Astronautical Science, The Graduate University for Advanced Studies (Sokendai), Kanagawa 229-8510, Japan

[1)]Department of Aeronautics and Astronautics, Tokai University, Kanagawa 259-1292, Japan

[2)]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa 229-8510, Japan

[3)]Research Institute for Sustainable Humanosphere, Kyoto University, Kyoto 611-0011, Japan

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A solar wind plasma flow around a miniature Magnetoplasma sail spacecraft (MPS) was experimentally studied. When a miniature MPS spacecraft, consisting of a 75 mm-diameter solenoidal coil and two 20-mm-diameter MPD arcjets, was immersed in a flow simulating the solar wind, a magnetosphere was formed around the miniature MPS spacecraft. From the magnetic probe measurement, the magnetospheric size of a Pure Magnetic Sail (without plasma injection) and that of the miniature MPS was 90 mm and 115 mm, respectively for 0.06 T-magnetic field at coil center, and a plasma jet (17.2 km/s velocity and 3.2×10^{19} m^{-3} density) was injected in the case of MPS. It is hence found that the magnetosphere size was increased by 28% when the magnetic field by a coil was inflated by a plasma jet from the MPD arcjets.

Keywords: Space Propulsion, Magnetic Sail, M2P2, Laboratory Experiment, Magnetoplasmadynamic Arcjet.

1. Introduction

Fast trips to the outer solar system require an innovative space propulsion technique. In order to satisfy this requirement, many next-generation spacecraft propulsion systems were proposed and have been intensively researched. One of those propulsion systems is an electromagnetic (EM) Sail, which obtains a propulsive force by the interaction between the solar wind plasma and an artificial magnetic field produced around a spacecraft. A propulsion system using such an interaction was firstly proposed by Prof. Zubrin; this is called as Pure Magnetic Sail (Pure MagSail).

Illustrations of electromagnetic sails are shown in Fig. 1a). Pure MagSail uses only a coil onboard the spacecraft for the production of the magnetic field. When the solar wind is introduced to a magnetic field by a coil, a magnetosphere is formed, and the region of the solar wind and the region of the magnetic field are divided by a magnetopause. Since the solar plasma flow to Pure MagSail is blocked by the magnetosphere, the momentum of the plasma flow is changed and then it is transferred to the coil through electromagnetic process, and the spacecraft is propelled. In order to produce a large thrust level, it is necessary to produce a large magnetosphere. Zubrin estimated that an unrealistically large coil is required to propel a Pure Magsail (for example, 32km-coil for 20-N-thrust [3]). Thus Pure MagSail, which needs a large electromagnetic coil, is not suitable for a spacecraft system.

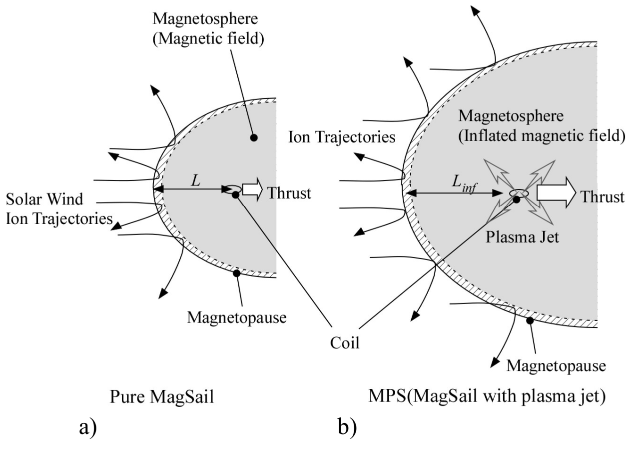


Fig. 1 Concepts of Pure Magnetic Sail and Magnetoplasma Sail.

To overcome the demerit of Pure MagSail, Mini-Magnetospheric Plasma Propulsion (M2P2) was proposed by Prof. Winglee in 2000. M2P2 at first produces a small magnetosphere by a small coil, and then

author's e-mail: ueno.kazuma@jaxa.jp

a plasma jet is emitted from inside the magnetic field. As a result, the magnetic field is inflated like a balloon and the large magnetic field is formed around the spacecraft. In this way, M2P2 obtains a large-scale magnetosphere (10-100 km in diameter) by a coil with an assistance of a plasma jet from a spacecraft [4]. In the cases of both M2P2 (MPS) and Pure MagSail, a large thrust level is given when a large-scale interaction between the plasma and the magnetic field is available. The scale length of the interaction is expressed by the magnetospheric size, which is defined as a distance from the spacecraft to the magnetopause. L and L_{inf} in Fig.1 are used in this paper to denote the magnetospheric sizes of Pure MagSail and MPS, respectively.

As a result of the interaction between the enlarged magnetic cavity and the solar wind, the solar wind will lose its momentum. If the momentum change of the solar wind were transferred to the MPS spacecraft, then, the spacecraft could obtain the propulsive force. However, this momentum transferring process is considered skeptical by many researchers [5]. To check the thrust production capability of the M2P2/MPS system, we are now working on the scale model experiment. Our special effort in experiment is directed to satisfy the similarity law associated with the plasma flow of Magnetoplasma Sail; this approach is necessary to step up from the first M2P2 experiment by Winglee [6] to demonstrate Magnetoplasma Sail.

In this study, plasma flows around a miniature MPS spacecraft were studied using an MPS Ground Simulator. The flow field was taken by a CCD camera, and the magnetic field measurement was conducted with a single-axis magnetic probe to evaluate the magnetosphere formed around the miniature MPS spacecraft.

2. Experimental Facilities

MPS Ground Simulator, shown in Fig.2, consists of a high-power magnetoplasmadynamic (MPD) solar wind simulator (SWS) and a miniature MPS spacecraft. The miniature MPS spacecraft has a 75 mm-diameter solenoidal coil and two small MPD arcjets (MPD_Inf) for plasma jet injection. All of these devices are operated in a quasi-steady mode of about 1 ms duration. Hence, a pulse forming network is arranged for the MPD arcjets in spite of employing a plasma gun. Although the plasma gun was frequently used to experimentally simulate geomagnetospheric physics [7,8], it is not suitable for our study because it is usually operated in a short pulse discharge (~10 μs) without any steady period. In this experiment, the miniature MPS spacecraft was located at a position 600 mm-downstream from the SWS. The 40-turns-coil, which is 75 mm in inner diameter and 40 mm in length, produces 0.08-T magnetic field at the coil center when the 0.14-kA discharge current is applied. The

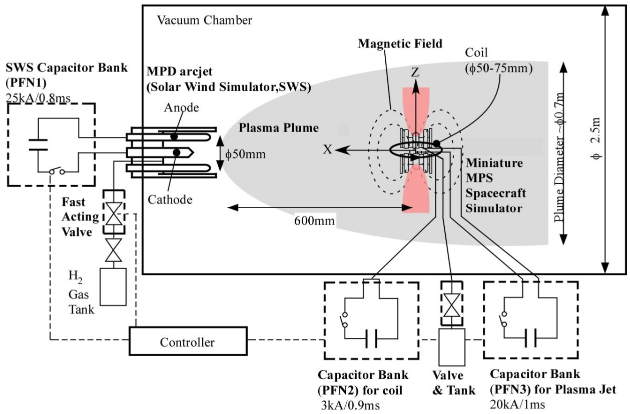


Fig. 2 Experimental Facilities.

20 mm-diameter MPD arcjets to produce high density plasma are installed at the coil center. In this experiment, H_2 gas is used for source of the plasma jet and supplied to each combustion chamber of MPD_inf by two small electromagnetic valves.

A shutter camera was used for the visualization of the flow around MPS. A steal camera was also used with its shutter opened. The camera was located outside the chamber and the interaction was taken through the glass flange.

In order to confirm the magnetic field inflation and the interaction between the magnetic field and the solar wind, the magnetic field produced by the MPS is measured with a single-axis magnetic probe. The magnetic probe consists of a small coil, an amplifier, and an integration circuit, and the magnetic flux density is obtained by integrating an output from the magnetic probe.

3. Design of Scale-model Experiment

For the scale model experiment of MPS, we have to find non-dimensional scaling parameters that characterize the plasma flow around an MPS spacecraft. Some conditions on the scaling parameters that are satisfied in space must be satisfied in the laboratory experiment as well. Important scaling parameters and conditions are summarized in Table.1.

In Table.1, the scaling parameters and conditions for pure MagSail and MPS spacecraft are compared with that of the geomagnetic field. So far, we did not consider the effect of the interplanetary magnetic field in spite of the fact that it would affect the geometry and the stability of the magnetic field around spacecraft. The most significant difference between the geomagnetic field and the MagSails resides in the condition for r_{Li}/L, which is the ratio between the ion Larmor radius at the magnetopause and the size of the magnetosphere; r_{Li}/L indicates how strongly the ion particles couple with the magnetic field. In the case of the geomagnetic field, the condition r_{Li}/L <<1, corresponding strong plasma-to-magnetic-field coupling, leads to the fluid-like behavior accompanied by the bow shock. The coupling in the case of MagSails is moderate because r_{Li}/L ~1, hence ion particle gyro-movement may make a flow field that is different from the geomagnetic field.

To describe the physics of the magnetic field inflation process, the most important parameter is r_{Li}/L_{inf}. In this parameter, L_{inf} is the frozen-in point where the dynamic pressure of the plasma jet equal to the magnetic pressure. Strictly speaking, L_{inf} is defined as a distance from the coil center to a typical frozen-in point. The B-field inflation process requires small ion gyration radius because the B-field inflation is possible only in the MHD scale. Hence, two inequalities, r_{Li}/L_{inf} <1 and L_{inf} <L, are included in Table.1.

From Table.1, it is understood that the conditions for the scale model experiment are fairly satisfied except for *Rm*, magnetic Reynolds' number. *Rm* in our experiment is much smaller than in space because 1) the size of the magnetic cavity must be smaller than the size of the space chamber as L~0.1 m, and 2) electric conductivity is small due to the low electron temperature and the collision of electrons with neutral particles in the laboratory.

4. Experimental Results & Discussion

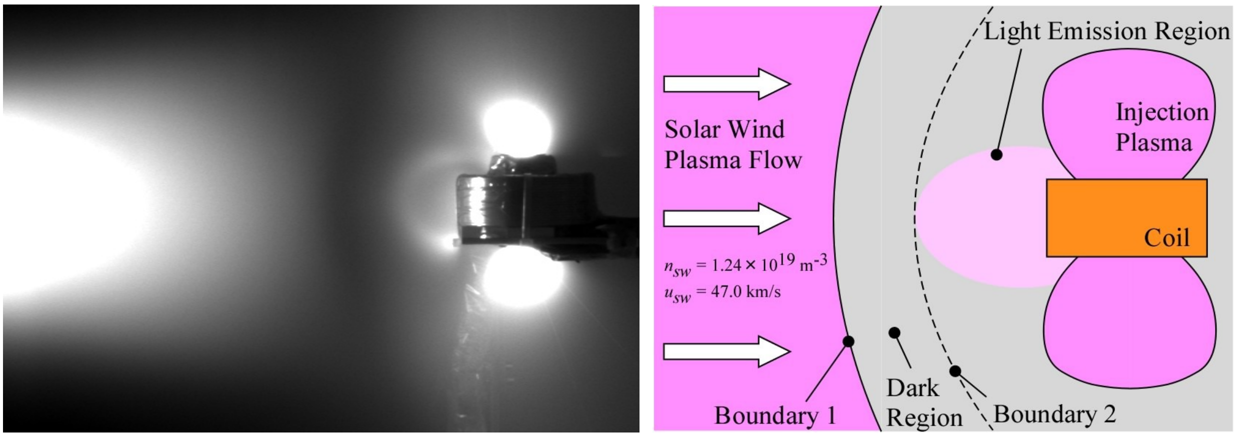
CCD images of a plasma flow around the miniature MPS are shown in Fig. 3. The solar wind comes from left side of Fig. 3a) and interacts with the magnetic field produced by the miniature MPS. We can find the plasma jets are injected to the upward and downward directions from the coil as is depicted in Fig. 3b). In Fig.3 a), a relatively dark region and a light emission region in front of the coil appear. The light emission region originates from a plasma trapped in the magnetic field. The dark region is caused by the interaction between the solar wind plasma and the magnetic field of MPS. The outer and inner edges of the dark region are called as boundary 1 and boundary 2, respectively.

In order to confirm the effect of plasma jets on the magnetic field, CCD images of MPS and Pure MagSail (MPS without plasma jet) were shown in Fig. 4 and Fig. 5. In these figures, X-axis is defined as a line from the coil center to SWS. There are dark regions in both images, and boundary 1 is positioned at X= 120 mm for both cases. However, the shapes of boundaries in Fig.4 and that in Fig.5 are different. The shape of boundary 1 is relatively sharp in Fig. 4, whereas the shape of boundary 1 in Fig.5 is relatively rounded. Boundary 2 of Pure MagSail is located at X= 90 mm in Fig. 4. On the other hand, boundary 2 of MPS is at X= 100 mm in Fig.5. Thus, it is found that the position of boundary 2 is changed by 10 mm due to the injection of plasma-jet from inside of the magnetic field. During the interaction between the solar wind plasma and the magnetic field, the magnetic

Table. 1 Scaling parameters in space and laboratory.

Parameters	Geomagnetic field		Pure MagSail / MPS	
	in space	in laboratory*	in space	in laboratory
Solar wind parameters				
Density	10^6 m^{-3}	10^{20} m^{-3}	10^6 m^{-3}	> 10^{18} m^{-3}
Velocity	400 km/s	500 km/s	400 km/s	< 60 km/s
Electron /ion temperature	10 eV	5-20 eV	10 eV	1 eV
Plasma duration	-	10 μs	-	0.8 ms
Coil parameters				
Magnetic moment	8x10^{15} Tm^3	4x10^{-5} Tm^3	10~ 100 Tm^3	~10^{-5} Tm^3
Size of magnetic cavity, L	10^{19} km	< 0.1 m	~300 km	~ 0.1 m
Magnetic flux density at magnetopause	40 nT	-	40 nT	0.8 mT
Duration of coil exciting current	-	> 10 μs	-	0.9 ms
Plasma parameters for inflation				
Density of injection plasma	-	-	T.B.D.	> 10^{19} m^{-3}
Velocity of injection plasma	-	-	T.B.D.	~ 20 km/s
Electron /ion temperature of injection plasma	-	-	T.B.D.	1 eV
Mass flow rate	-	-	T.B.D.	0.05 g/s
Plasma duration	-	-	-	1 ms
Non-dimensional parameters				
Mach number	~ 8	> 1	~ 8	> 1
Ratio of ion Larmor radius to L (r_{Li}/L)	<< 1	< 1	~ 1	~ 1
Ratio of skin depth to L (δ/L)	<< 1	<< 1	< 1	< 1
Magnetic Reynolds' number (*Rm*)	~10^{12}	~10^3	~10^8	~ 20
Frozen-in point dist. to L (L_{inf}/L)	-	-	<1	<1
Ratio of r_{Li} to L_{inf} (r_{Li}/L_{inf})	-	-	<1	<1

*Data from Yur, G. et al., *J. Geophys. Res.*, **100**, 23,727, 1995.



a) b)

Fig. 3 CCD image of the flow around Magnetoplasma Sail (a)) and explanation of the field (b)), Solar Wind: u_{sw}=47 km/s, n_{sw}=1.24x10^{19} m^{-3}, Coil: B_S=0.06 T, Injection plasma: u_{inj}=17.2 km/s, n_{inj}=3.2x10^{19} m^{-3}.

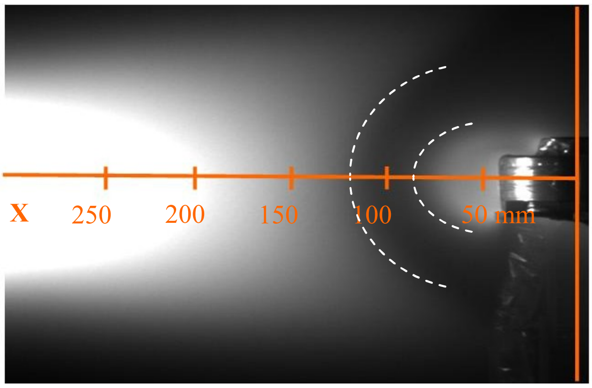


Fig. 4 CCD image of the flow around Pure Magnetic Sail (u_{sw}=47 km/s and n_{sw}=1.24x10^{19} m^{-3}), B-field at Coil center: B_S=0.06 T, without plasma injection.

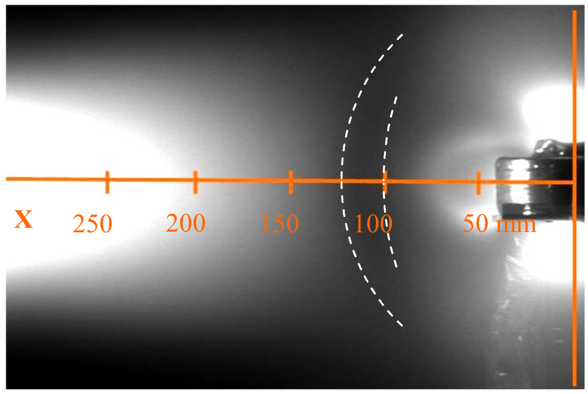


Fig. 5 CCD image of the flow around Magnetoplasma Sail (u_{sw}=47 km/s, n_{sw}=1.24x10^{19} m^{-3}), B-field at Coil center: B_S=0.06 T, with injection plasma (u_{inj}=17.2 km/s and n_{inj}=3.2x10^{19} m^{-3}).

field strength distribution was measured with the single-axis magnetic probe. The magnetic flux distributions normalized by the initial (dipole) magnetic field are shown in Fig. 6. In the case of Pure MagSail, the magnetic flux density is up to 1.3 times as large as the original dipole magnetic field at X= 70 mm. In the outer region (X> 70 mm), the density asymptotically approaches to zero. The same tendency of the magnetic flux distribution was reported in the research of geomagnetic field, and in Fig.6, the point, where the normalized magnetic flux density is unity, corresponds to the position of a magnetopause. It is thus found that the magnetopause of Pure MagSail is found around X= 100 mm. This is consistent with the fact that the induced current on the magnetopause produces a magnetic field, which compresses the magnetic field inside the magnetosphere (X<100 mm). The current along the magnetopause is induced by the different behaviors of charged particles, i.e. ion and electron, when the particles penetrated into the magnetic field. The size of the

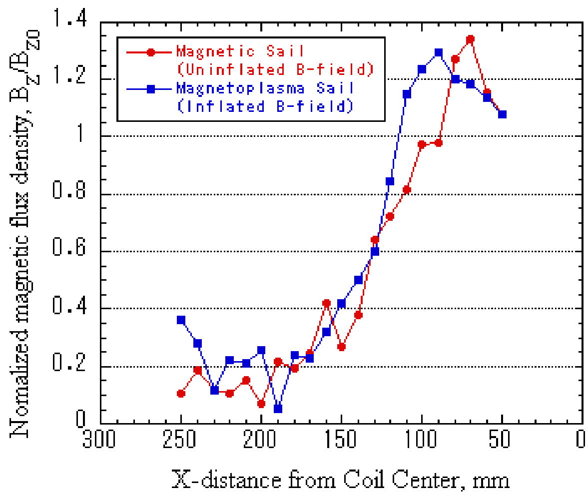


Fig. 6 Magnetic flux density (B_z) of Pure MagSail and Magnetoplasma Sail along the X-axis; B_z was normalized by the magnetic field without the interaction with the solar wind (B_{z0}).

magnetopause is considered to correspond to the size of magnetosphere. From theses results, the magnetic field is enlarged from 90 mm to 115 mm by the plasma jet, and the expansion rate of the magnetic field is about 28%. In Fig. 6, the distribution of Pure MagSail is the same as that of MPS for X= 50-60 mm. Thus, the magnetic field of MPS in this region is not inflated and the inflation starts from X= 60 mm. The inflation of magnetic field by the plasma jet was also confirmed from the imaging of the flow and the measurement of magnetic field.

5. Summary

Scale model experiment of Magnetoplasma Sail (MPS) was conducted in laboratory. When a miniature MPS spacecraft, consisting of a 75 mm-diameter solenoidal coil and two 20-mm-diameter MPD arcjets, was immersed in a flow simulating the solar wind, a magnetosphere was formed around the miniature MPS spacecraft. The plasma flow around a miniature MPS was taken by a CCD camera and a magnetic flux density distribution was measured by a single-axis magnetic probe. Comparing with the magnetopause in the case of Pure MagSail (without an injection of plasma jet from the miniature MPS), the magnetospheric size was enlarged in the case of MPS. The maximum expansion rate of the magnetic field is about 28%

In the next step, we are going to investigate: 1) the similarity law of MPS spacecraft by parametric survey of the plasma and magnetic field conditions, 2) optimization of the magnetic field inflation process, and 3) thrust characteristics of a miniature MPS spacecraft for a variety of the plasma and the magnetic field parameters.

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