Multi-Coil Magnetic Sail Experiment in Laboratory

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Magnetic Sail is a space propulsion system capturing the solar wind stream with an artificial magnetic field to produce thrust. Conventional magnetic sail use a coil magnetic field with a single-coil and that configuration is suitable for proof-of-concept. Multi-Coils Magnetic Sail generates a more complicated magnetic field than the conventional magnetic field. In this paper, Multi-Coils Magnetic Sail scale model consisted of three 22 mm-diameter coils was developed and direct thrust measurement of the Multi-Coils Magnetic Sail was conducted to observe thrust production with the multi-coil configuration using Magnetoplasma Sail Ground Simulator in ISAS/JAXA.

Key Words: Magnetic Sail, Deep Space Propulsion, Magnetosphere, the Solar Wind, Experiment

Nomenclature

B	:magnetic flux density (T)
B_0	:magnetic flux density at the center of the coil (T)
C_d	:thrust coefficient
e	:elementary charge (1.6×10^{-19} C)
F	:thrust (N)
I	:coil current (A)
L	:standoff distance of magnetic cavity (m)
M	:magnetic moment (Tm^3)
M_i	:ion Mach number
m_i	:mass of proton (1.67×10^{-27} kg)
N	:number of turns
n	:number density (m^{-3})
R_m	:magnetic Reynolds number
r_{Li}	:ion Larmor radius (m)
r_{coil}	:coil radius (m)
S	:representative area of magnetic cavity (m^2)
u	:velocity (m/s)
δ	:skin depth (m)
μ_0	:permeability in vacuum (1.26×10^{-6} H/m)

Subscripts

v	:ion
inf	:after inflation
mp	:magnetopause
f	:frozen-in point
sw	:solar wind

1. Introduction

A conventional Magnetic Sail use a single coil to produce an artificial magnetic field capturing the solar wind. An efficient capturing with the magnetic field increase a force on the coil and the spacecraft deploying the coil is accelerated towards the solar wind direction. In order to increase Magnetic Sail thrust, it is necessary to expand a magnetosphere or improve efficiency of capturing the solar wind. Multi-Coil Magnetic Sail concept is the latter approach. In this paper, Multi-Coil Magnetic Sail was developed and its thrust was measured with thrust stand directly to confirm thrust generation of Multi-Coil configuration.

2. Multi-Coil Magnetic Sail

Multi-Coil Magnetic Sail is 50 mm-outer-diameter multiple-coils consisted of three small coils which is 22 mm-diameter, 20 mm-height and 20 number of turns. The details of coil parameters are determined by referring our conventional magnetic sail, a single coil (50 mm-diameter, 20 mm-height and 20 number of turns). The small coils are connected in series. The total wire length and the total weight of Multi-Coil Magnetic Sail is about the same length and weight as the conventional coil. Thus, conventional experimental facility and

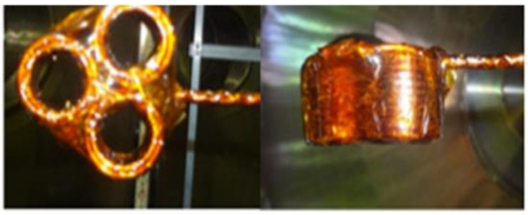

Fig. 1. Top and Side views of the developed Multi-Coil Magnetic Sail.

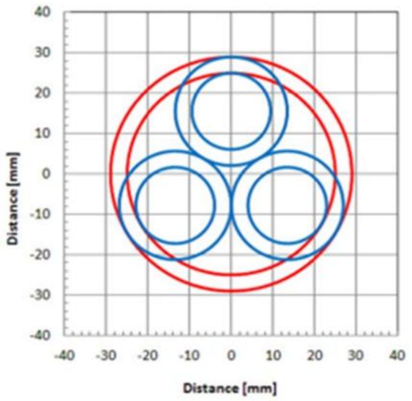

Fig. 2. Comparison view of the difference between conventional single-coil Magnetic Sail (red line) and Multi-Coil Magnetic Sail (blue line).

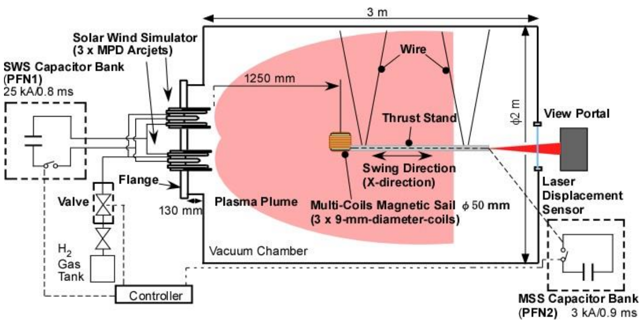

Fig. 3. Experimental configuration of Multi-Coil Magnetic Sail.

Table 1. Specification of the experimental setup for Multi-Coil Magnetic Sail simulations.

Multi-Coil Magnetic Sail Simulator	
Outer diameter, mm	25
Number of coils	3
Coil radius, mm	11
Wire diameter, mm	2
Number of turns	20
Coil area perpendicular to the flow, mm^2	1263
Operating condition	
Maximum coil current, A	1800
Solar Wind Simulator (MPD arcjets)	
Number of MPD arcjets	3
Inner diameter of a MPD arcjet, mm	50
Injection gas	Hydrogen
Operating condition	
Total gas flow rate, g/s	0.72
Plasma number density, m^{-3}	7.9×10^{17}
Plasma velocity, km/s	29
Diameter of test section, mm	511

conditions are adopted on the Multi-Coil Magnetic Sail experiments. A comparison view of these coils is shown in Fig. 2 and top/side views of developed Multi-Coil Magnetic Sail are shown in Fig. 1.

3. Experimental Setup

3.1. Facility for Multi-Coil Magnetic Sail Experiment

The experimental setup for a Multi-Coil Magnetic Sail is shown in Fig. 3. It consisted of two simulators, a solar wind simulator and a Multi-Coil Magnetic Sail simulator, both of which were developed in ISAS/JAXA[10,11].

Three MagnetoPlasmaDynamic (MPD) arcjets, which can easily produce a high-velocity and high-density plasma jet, were used as the solar wind simulator and it was mounted on the wall of the chamber. A multiple coil, simulating the coil of Magnetic Sail, was also installed inside the chamber, and it was immersed in the plasma flow. The details and operating conditions of these simulators are summarized in Table 1. These simulators were operated in a quasi-steady mode of about 0.5-1.0 ms duration using pulse forming networks.

3.2. Thrust Measurement of Pure Magnetic Sail

Thrust measurements were carried out by the parallelogram-pendulum method. The coil simulating a Pure Magnetic Sail was mounted on a thrust stand suspended by four steel wires (Fig. 3). For each shot of the MPD arcjets and coil combination, the impulse was measured from the maximum swing of the pendulum. The displacement of the pendulum in the X-direction was measured with a laser displacement sensor. For calibration of the pendulum and position sensor combination, impulses of known magnitude were applied to the coil using a simple pendulum consisting of a steel ball and string in an atmospheric pressure environment. The impulses of the ball were calculated from its mass and the striking velocity evaluated from energy conservation for the calibration pendulum.

The impulse of a Magnetic Sail is calculated by the following equation:

$$(F\Delta t)_{Magsail} = (F\Delta t)_{total} - (F\Delta t)_{SWS} \qquad (1)$$

When only the solar wind simulator is operated, the pressure on the coil surface produces thrust; this impulse corresponds to $(F\Delta t)_{SWS}$ in Eq. (1). If the coil current is initiated during the solar wind operation, the impulse, $(F\Delta t)_{total}$, becomes larger than $(F\Delta t)_{SWS}$. The thrust of a Magnetic Sail is defined as the difference between the two impulses divided by the SWS operation duration (Δt = 0.5 ms):

$$F_{Magsail} = \frac{(F\Delta t)_{Magsail}}{\Delta t} \qquad (2)$$

To derive Eq. (2), a rectangular waveform against time is assumed for the impulse, which seems a reasonable approximation based on the discharge current profiles in Fig. 4.

4. Experimental Results and Discussion

All the experiments were operated for the same simulated solar wind conditions (u_{sw} = 29 km/s, n = 7.9×10^{17} m^{-3}) and the same coil position (1250 mm away from the Solar wind simulator exit).

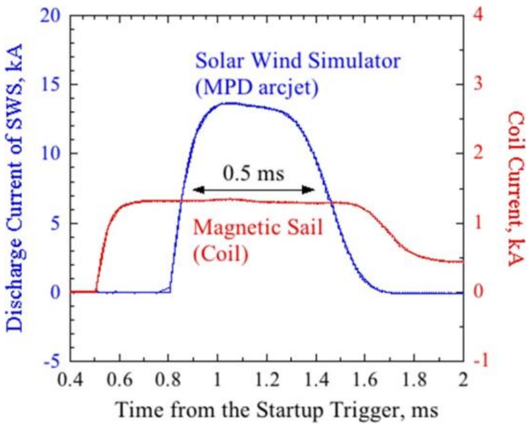

Fig. 4. Profiles of the current of SWS (charging voltage = 2.7 kV) and the coil current (charging voltage = 1.5 kV).

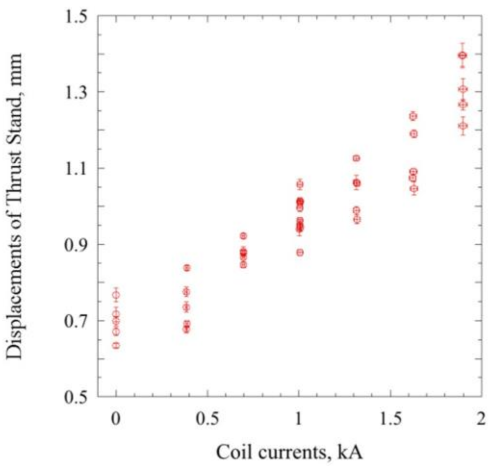

Fig. 5. Measured displacements of thrust stand for various coil currents (SWS charging voltage = 2.7 kV).

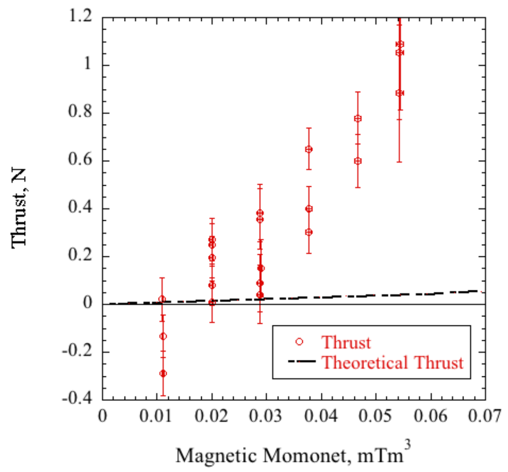

Fig. 6. Thrusts of multi-coil magnetic sail for various magnetic moments (SWS charging voltage = 2.7 kV).

4.1. Displacement of Multi-Coil Magnetic Sail

The measured displacements with the laser sensor for various coil currents are plotted in Fig. 5. The coil current was set in total 7 stages from 0 A to1.9 kA at an interval of 0.35 kA. In the case of 0 A-coil-current, magnetosphere was not existed because a magnetic field was not generated and the displacement of about 0.7 mm was mainly caused by neutral particles colliding with the coil. In the other cases, the displacement increase from 0.8 mm to 1.3 mm with increasing of coil current from 0.35 kA to 1.9 kA. These differences from the displacement of 0 kA indicates that the force exerted on the coil depending on the coil current.

4.2. Thrust of Multi-Coil Magnetic Sail

The impulse is estimated using the first peak of the swing of the thrust stand. The thrust of Multi-Coil Magnetic Sail is calculated using Eq. (1), (2). Thrust data for Magnetic Sail with various magnetic moments are shown in Fig. 6. We can find the thrust increases as the magnetic moments increases. The magnetic moment is calculated by the following equation;

$$M = 3 \times \mu_0 N I n r_{coiS}^2 \tag{3}$$

Assuming multi coils as a single hoop coil, theoretical thrust is predicted by the following equation;

$$F = C_d \frac{1}{4}\left\{\frac{n}{\mu_0}(n_{cw} N_i u_{cw}^2)\right\}^{\frac{1}{3}} M^{\frac{2}{3}} \tag{4}$$

Theoretical thrust of Multi-coil Magnetic Sail is calculated from Eq.(4) . For example, F= 0.04 N is for u_{sw} = 27 km/s, n = 7.9×10^{17} m^{-3}, M= 0.05 mTm^3 (1.8kA-coil-current), Cd= 0.8 (from Ref. 12). At this stage, we see that the measured thrust is much larger than the theoretical prediction. However, we can conclude that the interaction between the plasma flow and the magnetic field produced with the multi-coil is produced and the thrust was observed.

7. Conclusion and Future work

Thrust measurements of a Multi-coil Magnetic Sail were conducted in the laboratory. The experimental setup consists of a solar wind simulator and 25-mm-outer-radius coil simulating a Multi-Coil Magnetic Sail spacecraft placed inside a large vacuum chamber. Multi-Coil consists of three-small coils (20-turns, 11-mm-radius). The thrust of the Multi-coil Magnetic Sail was observed and increased as the magnetic moment increased.

Acknowledgments

We would like to thank the space plasma laboratory of ISAS/JAXA, and the members of the MPS research group for their valuable advice and support in conducting our experiment. A part of this research is supported by The Chukyo University Research Fund.

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