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Technical Notes

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Thrust Measurement of a Pure Magnetic Sail Using the Parallelogram-Pendulum Method

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Nomenclature

B = magnetic flux density, T
B_m = magnetic flux density at the magnetospheric boundary, T
C = coefficient
C_d = thrust coefficient
F = thrust, N
L = standoff distance of the magnetic cavity, m
M = magnetic moment, Tm^3
M_a = ion Mach number
m_i = mass of the proton (1.67×10^{-27} kg)
n = number density, m^{-3}
R_L = ratio of the ion Larmor radius r_{Li} to magnetic cavity size L, m
r_{Li} = ion Larmor radius at the magnetospheric boundary, m
S = representative area of the magnetic cavity (πL^2), m^2
u = velocity of solar wind, m/s
Δt = operation duration, s
μ_0 = permeability in vacuum (1.26×10^{-6} H/m)
ρ = density of solar wind, kg/m^3

Subscripts

i = ion
m = magnetopause
magsail = when a magnetic sail is operated
SWS = when a solar wind simulator is operated
total = when a magnetic sail and a solar wind simulator are operated

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I. Introduction

A MAGNETIC sail (magsail) is a deep space propulsion system that uses the energy of the solar wind. Magsails were first proposed by Zubrin [1] in 1991. He conceptually designed a spacecraft with a large hoop coil, shown in Fig. 1, that could produce an artificial magnetic cavity (magnetosphere) to reflect the solar wind particles approaching the coil. Because of this interaction, the solar wind flow will lose its momentum, and the corresponding repulsive force would exert on the coil to accelerate magsail spacecraft in the solar wind direction. Because various magnetic sails have recently been studied, a magsail spacecraft consisting of only a coil is called a *pure magsail* in this Note to distinguish it from other electromagnetic sails such as the minimagnetospheric plasma propulsion (M2P2) [2] or the plasma magnet [3].

One can easily imagine that a large magnetosphere enhances the solar-wind-to-magnetosphere interaction. Zubrin [1] theoretically estimated that a 20-N-class pure magsail is possible by making a 100-km-diam blocking area [2]. Numerical simulations [4,5] also support Zubrin's [1] estimation, but the thrust of a pure magsail was never obtained experimentally. To demonstrate a pure magsail in the laboratory, thrust measurement of a pure magsail scale model was conducted using our test facility for magnetic sails [6]. Some preliminary results are reported in this Note.

II. Experimental Setup

A magnetoplasmadynamic (MPD) arcjet was selected as a solar wind simulator (SWS) to produce a plasma flow simulating the solar wind [6,7]. The discharge chamber of the MPD arcjet is 50 mm in inner diameter and 100 mm in length, which consists of a molybdenum anode and a 20-mm-diam cathode. When the MPD arcjet is operated by a protracted current pulse in Fig. 2, a plasma accelerates into a steady diffuse phase of 0.8 ms duration. This quasi-steady operation is realized by precise synchronization of a hydrogen mass injection as well as a current pulse. For each pulse of the MPD arcjet, a fast-acting valve is used to quickly raise an injected hydrogen mass flow rate to a steady-state value (0.4 g/s); then the current pulse is initiated and reaches a steady value (11 kA) by a bank of 10×200 μF capacitors arranged in an LC ladder network. The mass flow rate remained until the current pulse was completed. The pressure in a vacuum chamber was 10^{-5} Pa before firing the MPD arcjet and 10^{-2} Pa just after firing.

In our experiment, the MPD arcjet (chamber pressure) was attached to a 2.5-m-diam vacuum chamber, as in Fig. 3, and a solenoidal coil was located at a distance 600 mm away from the solar wind simulator. The coil operation was synchronized with the MPD arcjet operation (Fig. 2). At the coil position, as a result of an interaction between a 0.5-m-diam solar wind flow ($u = 47$ km/s and $n = 1.8 \times 10^{19}$ m^{-3}) and a magnetic field of the solenoidal coil, a magnetosphere was formed around the coil. In the laboratory

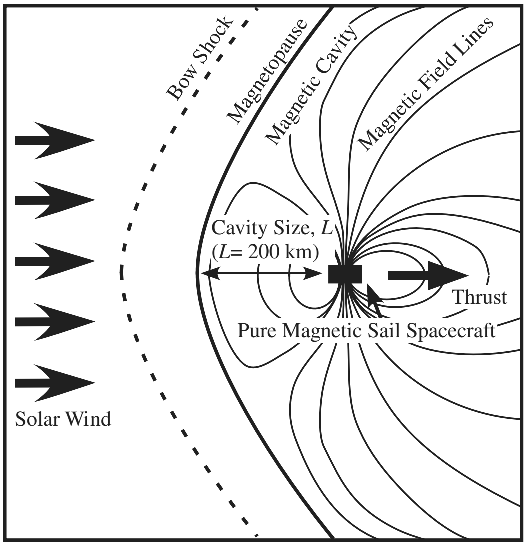

Fig. 1 Illustration of a pure magnetic sail.

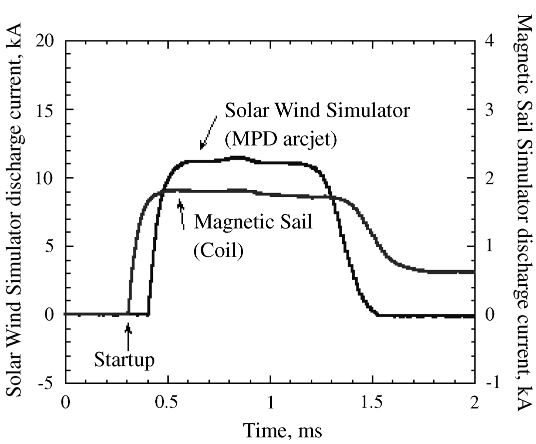

Fig. 2 Profiles of the current of the MPD arcjet (charging voltage is 4.0 kV) and coil current (charging voltage is 1.5 kV).

experiment, the size of the magnetosphere (L) was typically 0.1 m, and the ion gyration radius at the magnetospheric boundary (r_{Li}) was 0.047 m. To obtain $r_{\mathrm{Li}} = m_i u/(eB_m)$ in the laboratory, the magnetic flux density ($B_m = 10.5$ mT) was calculated from a pressure balance at the magnetospheric boundary, $B_m^2/(2\mu_0) = \rho u^2$. Among nondimensional parameters, r_{Li}/L is the most important similarity parameter for a pure magsail [6], and $r_{\mathrm{Li}}/L = 0.1$ in the laboratory experiment corresponds to a magnetosphere with $L = 720$ km and $B_m = 58$ nT if a pure magsail is in an orbit near the Earth.

Thrust measurements were carried out by the parallelogram-pendulum method. The coil simulating a pure magsail was mounted on a thrust stand suspended with four steel wires (Fig. 3). For each shot of the MPD arcjet and coil combination, an impulse was measured from the maximum swing of the pendulum. The displacement of the pendulum in the X direction was measured with a laser position sensor. For the calibration of the pendulum and position sensor combination, impulses of known magnitude were applied to the coil, simulating a pure magsail. A simple pendulum consisting of a steel ball and a string was used in an atmospheric pressure environment, and the impulses of the ball were calculated from its mass and striking velocity evaluated from the energy conservation for the calibration pendulum. Calibration using six different masses showed that the impulse was proportional to the maximum displacement of the pendulum, and the scatter of the data points about the line indicated that a standard deviation of no more than 9% of the impulse was achievable. Furthermore, a comparison of calibrations at an atmospheric pressure and in the vacuum chamber showed that the calibration at an atmospheric pressure was accurate within 2%. Major errors in thrust come from electromagnetic noise while starting up the discharge of the coil; that is, the pendulum was found to swing only if the coil current was introduced. This noise was, however, less than 20% of the averaged impulse. Shot-to-shot deviations were also found; they might be caused by the aforementioned electromagnetic noise or the shot-to-shot fluctuations of the simulated solar wind. The shot-to-shot variations were found to be less than 10% of the averaged value that was obtained from five data points for each condition.

The impulse of a pure magsail is evaluated by the following equation:

$$(F\Delta t)_{\mathrm{magsail}} = (F\Delta t)_{\mathrm{total}} - (F\Delta t)_{\mathrm{SWS}} \tag{1}$$

When only the solar wind simulator is operated, the pressure on the coil surface produces thrust; this impulse corresponds to $(F\Delta t)_{\mathrm{SWS}}$ in

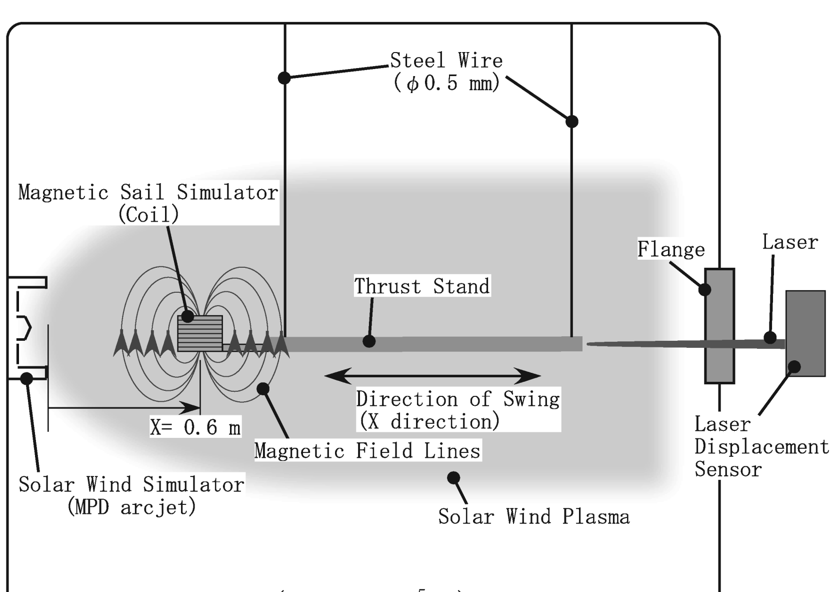

Fig. 3 Schematics of thrust measurement of a pure magsail scale model.

Table 1 Details of coils for a pure magsail

	Coil 1	Coil 2	Coil 3
Coil radius, mm	25	25	35
Wire radius, mm	1	0.5	1
Number of turns	20	20	10
Coil area perpendicular to flow, mm^2	1263	591	929
Magnetic moment, mTm^3	0.12, 0.22, 0.35	0.11, 0.22, 0.32	0.12, 0.23, 0.35

Eq. (1). If the coil current is initiated during the solar wind operation, the impulse $(F\Delta t)_{\mathrm{total}}$ becomes larger than $(F\Delta t)_{\mathrm{SWS}}$. The thrust of a pure magsail is defined as the difference between the two impulses divided by the SWS operation duration ($\Delta t = 0.8$ ms):

$$F_{\mathrm{magsail}} = \frac{(F\Delta t)_{\mathrm{magsail}}}{\Delta t} \tag{2}$$

To derive Eq. (2), a rectangular waveform against time is assumed for the impulse, which seems to be a reasonable approximation (see the discharge current profile in Fig. 2).

III. Results and Discussion

To evaluate the effect of coil size on a pure magsail's thrust, three coils with nearly the same magnetic moment are used. The dimensions of the coils are listed in Table 1, in which the magnetic moments were derived from the coil geometry and the coil current. Displacement waveforms of the thrust stand were observed in Fig. 4 when coil 1 was immersed into the plasma flow ($u = 47$ km/s, $n = 1.8 \times 10^{19}$ m^{-3}, and $M_a = 3$). It was found that the maximum displacement for $M = 0.35$ mTm^3 was about 2 times larger than that without a coil current. The impulse of a pure magsail, $(F\Delta t)_{\mathrm{magsail}}$, is then evaluated from the difference between the maximum displacements with or without coil current. Figure 5 shows the thrust data of a pure magsail for various magnetic moments. Thrust is increased when the magnetic moment is increased from 0.1 to 0.2 mTm^3, but for the largest magnetic moment ($M = 0.35$ mTm^3), the thrust values scatter around 1.2 N due to large electromagnetic noises at the highest coil current.

To discuss the thrust characteristics, the thrust formula of a magsail is briefly discussed. When the cavity size of the laboratory magnetosphere is

$$L = \left(\frac{M^2}{8\mu_0 \pi^2 \rho u^2}\right)^{1/6} \tag{3}$$

the thrust of a pure magsail is expressed as [6]

$$F = C_d \frac{1}{2}\rho u^2 S = C_d \frac{1}{2}\rho u^2 \pi L^2 = \left(C_d \frac{1}{4}\left(\frac{\rho^2 u^4 \pi}{\mu_0}\right)^{1/3}\right) M^{2/3} \tag{4}$$

If the velocity and the density of the simulated solar wind are given, the magnetic cavity size L depends only on the magnetic moment of the coil from Eq. (3). This is why the coil configurations in Table 1 did not affect the thrust characteristics. In spite of the limited accuracy of the thrust measurement, the theoretical curve $F \sim CM^{2/3}$ fits the experimental data well; it is hence possible to say that the preceding formula is suitable to show the thrust characteristics of a pure magsail.

Next, let us compare the experimental data in the laboratory with that of numerical predictions. For $M = 0.35$ mTm^3 using coil 1 ($F = 0.92$ N, $\rho = nm_i = 2.1 \times 10^{-8}$ kg/m^3, and $u = 47$ km/s), we find $C_d = 0.92$. An approximate formula of the thrust coefficient of a magsail in space, C_d, was calculated on collisionless plasma and proposed by Fujita [4] as follows:

$$C_d = \begin{cases} 3.6\exp\{-0.8R_L^2\} & \text{for } R_L < 1 \\ \frac{3.4}{R_L}\exp(-\frac{0.22}{R_L^2}) & \text{for } R_L \geq 1 \end{cases} \tag{5}$$

In Fig. 6, thrust coefficients obtained from the Fujita's [4] formula

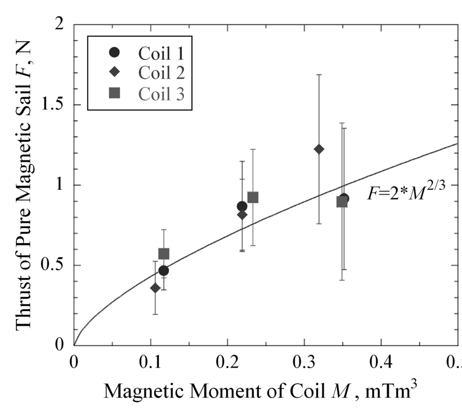

Fig. 5 Thrust vs magnetic moments of coils (solar wind simulator was operated for H_2 mass flow rate of 0.4 g/s, and 3 types of coils (radius = 25 or 35 mm) are positioned at $X = 0.6$ m). Dashed line corresponds to $F = 2M^{2/3}$.

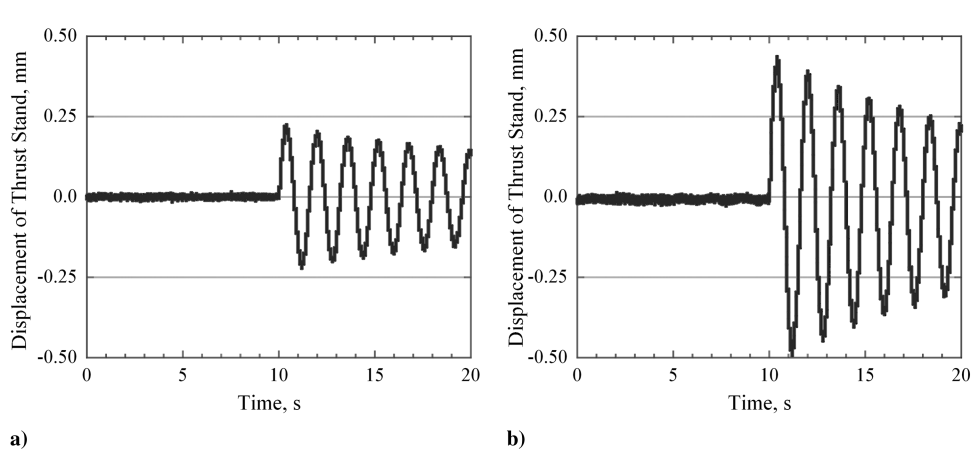

Fig. 4 Thrust stand's swing when coil 1 was immersed into the H_2 plasma flow ($u = 47$ km/s and $n = 1.8 \times 10^{19}$ m^{-3}): a) without coil current and b) with 11 kA coil current ($M = 0.35$ mTm^3).

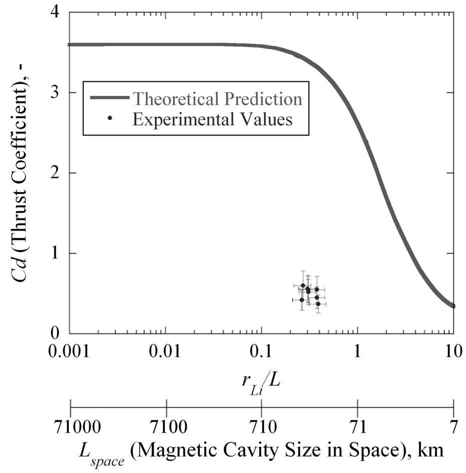

Fig. 6 Nondimensional thrust characteristics of a pure magnetic sail (solar wind simulator was operated for H_2 mass flow rate of $0.4\ g/s$ and 14 kA. Coils ($radius = 25$ or 35 mm) are positioned at $X = 0.6$ m; theoretical plot is from [4]).

and the experimental results are plotted. Judging from some data points that are available at this stage, we see that the measured thrust is much smaller than the theoretical predictions. Although theoretical prediction in space was conducted in collisionless conditions, collisions of charged particles with neutral particles cannot be neglected in the laboratory experiment, because the MPD arcjet produced a partially ionized plasma. The motion of charged particles is different between a collisionless plasma and a collisional plasma. Accordingly, the structure of the laboratory magnetopause might be different from that in space. The collisional effect may cause the discrepancy between the theoretical and the experimental thrust value.

IV. Conclusions

Direct thrust measurement of a pure magsail was conducted by the parallelogram-pendulum method. When a high-density plasma jet ($\sim 10^{19}\ m^{-3}$) was supplied from a hydrogen MPD arcjet with a high velocity ($47\ km/s$), a thrust level of 1 N was detected for a magnetic moment of 0.2 mTm^3 (which corresponds to a 25-mm-radius coil with 20 turns). It is found that thrust is increased when increasing the magnetic moment of the coil simulating a pure magsail.

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