Laboratory Simulation of Magnetic Sails: Preliminary Results

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A magnetic sail is a unique propulsion system, which travels interplanetary space by capturing the energy of the solar wind. In order to simulate the interaction between the artificial magnetic field produced around a spacecraft and the solar wind, a scaled-down laboratory experiment was conducted in a space chamber. Preliminary results showed some strong interactions between the high-density and high-velocity plasma flow and an artificial magnetic field, hence the possibility of the magnetic sail simulator is provided; however, further improvement is required to realize a collision-less solar wind plasma flow in the laboratory.

1. Introduction

For the case of the Earth, a large-scale interaction between the Geomagnetic field and the solar wind occurs. It is intensively discussed that, as a result of such interactions, what amount of the momentum of the solar wind will transfer to the Earth. A magnetic sail realizes analogous interactions between the solar wind and an artificial magnetic field produced around a spacecraft, to obtain a drag force in the direction of the solar wind. In order to demonstrate the momentum transfer process of the magnetic sail, we design an experimental simulator of the magnetic sails that operates in a space chamber.

2. Scaling of magnetic sail

Figure 1 shows the schematics of interactions between the magnetic field around a spacecraft and the solar wind. Owing to very low-density solar wind plasma flow, the plasma behaves as collision-less particles, whose movement separates the region between the plasma and the magnetic field. This boundary is referred to as a magnetospheric boundary or a magnetic sheath because charge separation between the ions and electrons occurs there. In addition, the magnetic field is always denoted as the magnetic cavity. The thickness of the magnetic sheath, \( \delta \), and the size of the magnetic cavity, \( L \), are important parameters to describe the scaling of the magnetic sail. Here, \( \delta \) and \( L \) are expressed as,

\[
\delta = \frac{c}{\omega_p} \quad (1)
\]

\[
L = \frac{B_0^2}{2\mu_0 n m u} \quad (2)
\]

where \( c \) is the light velocity, \( \omega_p \) plasma frequency, \( \mu_0 \) the permeability in vacuum, \( n \) number density, \( B_0 \) the magnetic flux density at \( a \), \( m \) mass of ions, and \( u \) velocity [1]. In the laboratory experiment, diffusive effect, with collision frequency \( v_{\text{coll}} \), enlarges the magnetic sheath thickness \( \delta \) to \( \delta_D \).

\[
\delta_D = \frac{v_{\text{coll}}}{\omega_p} u = \sqrt{\frac{u}{\omega_p}} \quad (3)
\]

In Fig.2, thrust of the magnetic sail, \( F \), is plotted following the formulation below.

\[
F = C_d \frac{1}{2} \rho u^2 S \quad (4)
\]

where \( S = \pi L^2 \) is the characteristic area, and \( C_d \) is drag coefficient. The values of \( C_d \) are only numerically estimated for various cases, and \( C_d \) ranges from 0.5 to 3.0[2][3] corresponding to MIN and MAX in Fig.2. To achieve thrust around 1 N, one has to identify \( C_d \) characteristics for \( r_L > L \), where \( r_L \) is ion Larmor radius at the magnetospheric boundary.

3. Experimental apparatus and preliminary results

In our preliminary experiment, a coil of 20 mm in diameter was used to produce 1 T magnetic field at the center of the coil. Into the magnetic field, a plasma jet from an MPD arcjet was introduced to observe possible interactions using the Langmuir probes and Mach probes. Requirements for the plasma flow in
the laboratory experiment are summarized in Fig. 3 in comparison with experimental data.

To establish the conditions $r_{1,2}<L$ and $\delta_D/L << 1$, both $h_{\text{high}}$-density and high-velocity plasma flow is required, however, until now, only moderate $\delta_D/L$ values are realized. So far, as is shown in Fig. 4, due to this diffusive interaction between the plasma jet and the magnetic field, the magnetic field cannot prevent the fast ions into the cavity. The simulator is currently improved to achieve smaller $\delta_D/L$, which is necessary to form a clear magnetospheric boundary.

**References**


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