Magnetic Topology to Stabilize Ionization Oscillation in Anode-layer-type Hall Thruster

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Ionization oscillation of a Hall thruster is one of the most serious problems. In order to suppress the ionization oscillation of an anode-layer-type Hall thruster, we tried to reduce the magnetic field in the anode hollow using a magnetic shield. Firstly, we validated the effectiveness of a magnetic shield with numerical simulation which was developed for the UT anode-layer-type Hall thruster (power: 1.7 kW, thrust: 93 mN, I_{sp} : 1900 s). Secondly, we developed a new anode-layer-type Hall thruster in which anode hollow magnetic flux density is reduced using a magnetic shield and measured its oscillation amplitude and thrust efficiency. As a result, the oscillation amplitude was drastically reduced by the magnetic shield; the oscillation amplitude was less than 0.4 in the whole operation range. Moreover, the thrust efficiency is also improved by more than 10 percent by the magnetic shield.

Key Words: Electric Propulsion, Hall Thruster, Ionization Oscillation

Nomenclature

B_0	: magnetic flux density
e	: elementary electric charge
I_d	: discharge current
$\dot{m}$	: mass flow rate
M	: mass
r	: r coordinate
T	: temperature
V_d	: discharge voltage
z	: z coordinate

Subscripts

Bohm	: Bohm diffusion
e	: electron
ela	: elastic scattering
exc	: excitation collision
i	: ion
ion	: ionization collision
n	: neutral particle
p	: primary electron
p0	: primary electron, initial state
s	: secondary electron
w	: wall

1. Introduction

A Hall thruster is one of the most promising electric propulsion systems for a satellite station keeping and orbit transfer maneuvering because it produces high thrust efficiency with a specific impulse range of 1,000 ~ 3,000 s. Especially, an anode-layer-type Hall thruster¹⁾ has the higher thrust density than the other type, the magnetic-layer-type Hall

thruster. However, the anode-layer-type Hall thruster has never been loaded on a satellite in practical use because of its discharge current oscillation.²⁾

In particular, the ionization oscillation in the frequency range of 10-100 kHz has large amplitude and causes harmful effects on the operation. Operation in unstable range has the fear that the oscillation grows up and the operation is stopped. In addition, this oscillation enlarges the current capacity margin of power supply and increases its weight. Thus, unstable operation leads to low reliability and increase in bus system mass.

The oscillation amplitude is defined as

$$\Delta \equiv \frac{1}{\bar{I}_d} \sqrt{\frac{\int_0^\tau (I_d - \bar{I}_d) d\tau}{\tau}} \left(\bar{I}_d \equiv \frac{\int_0^\tau I_d d\tau}{\tau} \right). \quad (1)$$

In general, the oscillation amplitude of Hall thrusters which is practically used, such as PPS-1350, is less than 0.2.³⁾ Therefore, we use “small oscillation” when the oscillation amplitude is less than 0.2 in this paper.

In our previous research⁴⁾, we found that the ionization oscillation occurs when the anode cannot absorb electrons efficiently. In this case, many electrons stay in the acceleration channel and ionize the propellant drastically. As a result, the propellant is starved and ionization rate decreases.

In order that the anode absorbs electrons efficiently, it is likely that the magnetic flux density in the anode hollow should be low because electrons can contact with the anode in wide area. In this study, first, we verified this assumption using numerical simulation. After that, we developed a new anode-layer-type Hall thruster in which anode hollow magnetic flux density is reduced using a magnetic shield.

2. Numerical Simulation

2.1. Brief overview of the numerical model

The intended Hall thruster is UT-anode-layer-type Hall thruster (Fig. 1). It has two guard rings made of stainless steel kept at the cathode potential. The inner and outer diameters of the rings are 48 mm and 62 mm, respectively. Magnetic flux density is variable by changing the current of a solenoid coil set at the center of the thruster. Xenon is used as a propellant.

The calculation domain is shown in Fig. 2. To analyze the plasma, fully-kinetic 2D3V Particle-in-Cell Direct Simulation Monte Carlo (PIC DSMC) method is used. In the code, one macro-particle contains 10^6 - 10^9 of real particles. For simplicity, only singly charged ionization is considered. A mass ratio M_e/M_n is increased from 4×10^{-6} to 1×10^{-2} artificially to speed up the calculation. Electron temperature, collision cross sections, and B which act only on electrons are adjusted by mass ratio in order that collision frequency, the Debye length, and the Larmor radius return “real” values.

A cylindrical coordinate system (r, θ, z) is used. Particles' positions are expressed in two-dimensional space whereas velocity in three-dimensional velocity space. Figure 2 shows the computation grid used in this calculation. The radial cell length is getting smaller toward the anode surface and smaller than the Debye length near the anode surface in to capture the sheath structure in the hollow anode case. Plasma potential distributions are solved using Poisson's equation

$$\frac{\partial^2 \phi}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) = -\frac{e}{\epsilon_0} (n_i - n_e) \quad (2)$$

which is solved using the Successive Over-Relaxation (SOR) method. Inter particle collisions are solved using DSMC method. The three primary collisions, Xe-e⁻ elastic scattering, Xe-e⁻ ionization collision, and Xe-e⁻ excitation collision are included in this code. The other collisions are neglected because their collision frequencies are much smaller than that of these three collision frequencies. These frequencies are found from σ which is calculated using polynomial fitting of measurement data.⁵⁾

In addition, it is known that anomalous diffusion is dominant in the channel in the high B case.⁶⁾ To consider this effect, Bohm diffusion coefficient is implemented in terms of the virtual collision frequency as

$$\nu_{\text{Bohm}} = \frac{1}{16} \frac{eB}{m_e} \quad (3)$$

Then, total collision frequency is defined as

$$\nu_{\text{total}} = \nu_{\text{ela}} + \nu_{\text{ion}} + \nu_{\text{exc}} + \nu_{\text{Bohm}} \quad (4)$$

The energy conservation before and after ionization collisions of the primary and secondary electrons is expressed as

$$\epsilon_{p0} = \epsilon_p + \epsilon_s + \epsilon_{\text{ion}} \quad (5)$$

ϵ_s is taken from the experimental equation.⁷⁾

Mersenne Twister random number⁸⁾ is used in this DSMC code. The occurrences period of this random number is

$2^{19937}-1$ (about 106000), which is much larger than the number of occurrences of random number during one period of the discharge current oscillation (about 10^{18} times in 10^{-4} s in the calculation).

Boundary conditions in this calculation are shown in the Fig.3. Neutral particles are fed from the base of the anode hollow with a room temperature $T_n=300$ K half-Maxwellian velocity distribution, while electrons are injected or withheld from the acceleration channel exit with a $T_e=10$ eV half-Maxwellian distribution. Electron number density equals to ion number density on the acceleration channel exit plane. Ions are not fed from anywhere.

On the anode surface, neutral particles are reflected with the wall temperature $T_n=T_w=500$ K, electrons are lost, and ions become neutral particles. On the upper and lower boundary in the acceleration channel, neutral particles are lost, whereas electrons and ions are reflected specularly, because this boundary is not the channel wall but that of calculation region. On the acceleration exit plane, all particles are lost.

In solving the Poisson's equation (Equation (2)), the Dirichlet condition is given on the anode surface and channel exit and the Neumann condition on the other boundaries.

Figure 4 shows the computed r component of magnetic flux density distribution in the Hall thruster, which is normalized by the peak maximum of the distribution B_0 . In this study, two magnetic topology cases were calculated. Case 1 represents the ordinary magnetic flux density distribution. On the other hand, case 2 represents the magnetic flux density in the case that the magnetic shield is used. In this case, the magnetic flux density in the anode hollow is almost zero.

Fig. 1. Schematic of UT-anode-layer-type Hall thruster.

Fig. 2. Calculation domain.

Fig. 3. Boundary conditions.

Fig. 4. Magnetic flux density distribution in the axial direction (Case 1: without magnetic shield, Case 2: with magnetic shield).

2.2. Calculation result

Figure 5 shows the oscillation amplitude as a function of B_0 . In case 1, the oscillation is large when the magnetic flux density is larger than 15 mT. In this magnetic flux density range, the anode cannot efficiently absorb electrons trapped by the strong magnetic field. The trapped electrons easily cause the ionization oscillation. In the range of $B_0 > 20$ mT, the ionization oscillation is still observed, however, the oscillation amplitude is smaller than that in the B_0 is about 18 mT. In this range, anomalous diffusion is dominant, which helps electron move to the anode. Therefore, the ionization oscillation is relatively small. This tendency represents the experimental result⁴⁾.

On the other hand, the oscillation amplitude is less than the criterion value ($A=0.2$) in whole magnetic flux density range in case 2. This result indicates that the high magnetic flux density in the anode hollow causes the ionization oscillation.

Figure 6 shows the electron number density distributions and potential distribution at $B_0=20$ mT. In the case that the magnetic flux density in the anode hollow is high (case 1), electrons cannot penetrate the hollow. In this case the potential drop appears near the anode tip ($z=15$ mm). This potential shape causes the ionization oscillation as discussed in our former work.⁴⁾

On the other hand, in the case that the magnetic flux density in the anode hollow is low (case 2), the electron penetrates the anode hollow and contacts with the anode surface in wide area.

As a result, the potential slope appears at the thruster exit; this is typical potential shape when the ionization oscillation does not occur.

Fig. 5. Calculated oscillation amplitude as a function of the magnetic flux density (Case 1: without magnetic shield, Case 2; with magnetic shield, $V_d=250$ V, $\dot{m}=1.36$ mg/s, Previous model thruster head).

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(a) case 1

7

(c) case 2

Fig. 6. Calculated electron number density distribution and potential distribution ($B_0=20$ mT, $V_d=250$ V, $\dot{m}=1.36$ mg/s, Previous model thruster head).

3. Experimental Verification

3.1. Anode-layer-type Hall thruster with magnetic shield

As mentioned above, to deduce the magnetic flux density is hopeful to stabilize the oscillation. Therefore, we developed a new anode-layer-type Hall thruster.

The developed Hall thruster is shown in Fig. 7. The inner and outer diameters of the acceleration channel are 31 and 45 mm, respectively. The channel length is 3 mm. The magnetic field in the acceleration channel is applied by a solenoid coil. In order to reduce the magnetic flux density in the anode hollow, the magnetic shield can be set around the hollow anode.

Figure 8 shows the magnetic flux density distribution in the thruster. The red solid line and the blue broken line show the thruster without and with the magnetic shield, respectively.

Fig. 7. Newly developed anode-layer-type Hall thruster.

Fig. 8. Magnetic flux density distribution in the axial direction in the new Hall thruster.

3.2. Experimental setup

Figure 9 shows a schematic diagram of the measurement system. The vacuum chamber whose diameter and length are 2.0 and 3.0 m was used. The pumping system comprises four

pumps: a diffusion pump (37000 l/s), a mechanical booster pump (10000 m³/h) and two rotary pumps (15000 l/min). Throughout this experiment, the background pressure was kept under 5.0×10^{-3} Pa.

In order to measure I_d , the voltage between the both ends of 0.5Ω metal-film resistor, which was inserted between the anode and discharge power supply, was measured by an oscilloscope with a differential probe. In this experiment, 5 ms data of I_d was collected at the sampling rate of 10 MHz.

For thrust measurement, a two-axis dual pendulum thrust stand (Fig. 10) was used.⁹⁾ This thrust stand has two pendulums and four arms per pendulum. All joints between any two components consist of knife-edges and supporting point of each arm consists of two orthogonal knife-edges. Pendulums can move in the two directions: axial and transverse direction of a thruster. A thruster and sensor targets are mounted on the inner pendulum and two displacement sensors are set on the outer pendulum. The thermal influence from a Hall thruster is cancelled out by those pendulums. Because this thrust stand is the type put on the chamber, it is hardly affected by the chamber vibration. In this experiment, this thrust stand was used to measure only the axial thrust.

Fig. 9. Schematic diagram of the measurement system.

Fig. 10. Thrust stand.

3.3. Result and discussion

Figure 11 shows the oscillation amplitude as a function of the magnetic flux density. The red line and blue line show

Fig. 11. Experimentally measured oscillation amplitude as a function of the magnetic flux density ($V_d=250$ V, $\dot{m}=2.72$ mg/s, New thruster head).

Fig. 12. Experimentally measured thrust efficiency as a function of the magnetic flux density ($V_d=250$ V, $\dot{m}=2.72$ mg/s, New thruster head).

without and with magnetic shield case, respectively. As shown in this figure, the magnetic shield suppresses the oscillation amplitude. This is the result that is expected by the numerical simulation result.

Figure 12 shows the thrust efficiencies as a function of the magnetic flux density. As shown in this figure, the maximum thrust efficiency is 41% in the operation with magnetic shield, while 30% in the operation without magnetic shield. This result indicates that the magnetic shield is useful not only for discharge stabilization but also for higher efficiency. This is probably because the potential slop appears at the thruster exit as shown in Fig. 5(b); in this case, ions are produced in the high potential region, therefore, the energy efficiency is larger than that in the case that potential slop appears on the anode

tip (w/o magnetic shield case).

4. Conclusion

In order to suppress the ionization oscillation of an anode-layer-type Hall thruster, we tried to reduce the magnetic field in the anode hollow using a magnetic shield.

Firstly, we validate the effectiveness of magnetic shield with numerical simulation. Secondly, we developed a new anode-layer-type Hall thruster in which anode hollow magnetic flux density is reduced using a magnetic shield and measured its oscillation amplitude and thrust efficiency. As a result, using a magnetic shield, the oscillation amplitude was drastically reduced by the magnetic shield; the oscillation amplitude was less than 0.4 in the whole parameter range. Moreover, the thrust efficiency is also improved by more than 10 percent.

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