Thrust Performance in Hall Thruster with Pulsating Operation

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An innovative engine, designated “Volterra,” has been developed and the thrust performance, thrust, beam divergence angle, and ion energy distribution function were investigated using a 1 kW class magnetic-layer-type Hall thruster developed at Kyushu University. The thrust of this engine is superior to that of the thruster with 150 V constant voltage operation, but the ion energy distribution function is wider. Plume divergence is almost the same as for the thruster with 150 V constant voltage operation.

Key Words: Electric Propulsion, Hall Thruster, Pulsating Operation, Diagnostics

Nomenclature

- \(C\) : capacitance values of capacitor
- \(E_b\) : ion energy
- \(F\) : thrust
- \(g\) : acceleration of gravity
- \(I_d\) : discharge current
- \(i\) : time index during navigation
- \(L\) : induction of coil
- \(\dot{m}\) : anode mass flow rate
- \(T\) : constant time (longer than oscillation period)
- \(V_d\) : discharge voltage

1. Introduction

Due to the capacity limits of a satellite payload, satellite propulsion systems should be as small as possible. These propulsion systems consist primarily of the thruster head, propellant tank, propellant feed system, and power processing unit (PPU); the PPU in particular should be as small as possible, with low power loss. The “harmonized PPU with Hall thrusters” is an effective candidate for small PPU with low power loss.

In the Hall thruster, the discharge current naturally oscillates, with the largest oscillation being prey-predator (ionization) oscillation.1-5) These oscillations are characteristic of and intrinsic to Hall thrusters, and it was rather than attempt to suppress oscillation we accept it, unless it inhibits operation. That is, we have defined “stability” as “discharge maintained.” In this context, we have developed a “harmonized PPU with oscillating Hall thrusters” named the “Volterra Engine,”6,7) to honor the work of Vito Volterra.8) The harmonized PPU provides fluctuating voltage in accordance with the fluctuating impedance of the Hall thrusters. Our previous study showed that the discharge current of the Hall thruster synchronized with discharge voltage provided from the harmonized PPU (pulsating boost chopper circuit).6,7)

The aim of the present study is to evaluate the effect of the pulsating operation on thrust performance, thrust, discharge current, power consumption, beam divergence angle, and ion energy distribution function.

2. Experimental Setup

Figure 1 shows a cross-section of the 1 kW class magnetic layer type Hall thruster used in the current experiments. The inner and outer diameters of the acceleration channel are 50 mm and 70 mm, respectively. The acceleration channel material is pure boron nitride. There are one inner solenoid coil and four outer solenoid coils for applying a radial magnetic field in the acceleration channel. The magnetic field on the inner wall is stronger than that on the outer wall, since the magnetic flux is constant.

Xenon gas (99.995% pure) was used as the working gas and the mass flow rate was controlled using thermal mass flow controllers. As an electron source, we use a hollow cathode (Vecco, HC252). Thrust performance tests were conducted in the space science plasma chamber at ISAS/JAXA, which is 2.5 m diameter by 5.0 m length. The pumping system consists of two cryogenic pumps (22,000 l/s in nitrogen) and a turbo molecular pump (air pumping speed 3400 l/s in nitrogen). The chamber baseline pressure was below 1×10^-7 Pa and the
background pressure was maintained below $2 \times 10^{-3}$ Pa at a xenon mass flow rate of 2.2 mg/s (anode 2.0 mg/s and cathode 0.2 mg/s).

Figure 3 shows a conceptual diagram of the circuit that provides harmonized discharge voltage as the Volterra engine power processing unit. It works as a current source if the Hall thruster needs current, and it works as voltage source if the impedance of the Hall thruster is high and the Hall thruster requires high discharge voltage to maintain the discharge. The circuit parameters, including chopping frequency, duty ratio, primary supplied voltage (base voltage), capacitance of capacitor, and inductance of the coil, can be changed. In this study, the capacitance was changed from $0.22 \mu F$ to $2.2 \mu F$, and inductance was changed from 0.5 mH to 0.9 mH. There is a minimum acceptable chopping frequency, which depends on the thruster operating condition. If we operate below the minimum chopping frequency, the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET, 2SK4207,) is braked down. The reason why the MOSFE is braked down will be discussed in our future work.

A pendulum-type thrust stand was used for the thrust measurements. Thrust stand calibration is conducted with a set of known weights in a pulley system assembly. The overall uncertainty in thrust is conservatively estimated at ±5%.

An ion collector (9 mm diameter circle) is set at 1500 mm downstream of the thruster for the measurement of the ion beam current, as shown in Fig. 4(a). Outside the collector, there is a rectangular electrode, with a circular 10mm diameter hole, as shown in Fig. 4(a).

The same potential is applied to the electrode and collector, in order not to overestimate the ion beam current density. The retarding potential analyzer (RPA) is set 1500 mm downstream of the thruster for the measurement of the ion beam profile and ion energy distribution function. The ion collector and RPA can
be moved along the line perpendicular to the thruster axis. The cross section of the RPA, with four meshes, is shown in Fig. 4(b). The four grids are the floating grid (FG), to shield out electric potentials that are applied to the other grids, electron retarding grid (ERG), ion retarding grid (IRG), and secondary electron suppression grid (SERG). We applied -40 V to the SERG and -30 V to the ERG and the collector.

3. Results and Discussion

The thrust performance of Hall thrusters, in terms of specific impulse, $I_{sp}$, and thrust efficiency, $\eta_t$, is defined as follows.

$$ I_{sp} = \frac{F}{m g} $$

$$ \eta_t = \frac{F^2}{2m \int_0^T V dI / T} $$

Figure 5 shows the history of the discharge voltage and the discharge current for four chopping frequencies: 12 kHz, 16 kHz, 20 kHz and 30 kHz, with the capacitance of the capacitor fixed at 0.47 μF, the inductance of the coil fixed at 0.5 mH, and the duty ratio of chopping in the pulsating boost chopper circuit at 0.33.

We do not observe a distinct dependency of the phase angle between the discharge current and the discharge voltage on the chopping frequency, though if the discharge voltage is a sine function, a strong dependency of the phase angle on the chopping frequency is observed. As in our previous study, the amplitude of the discharge voltage decreases with an increase in chopping frequency, and at 30 kHz it is about 50 V (peak to peak). With an increase in the chopping frequency, the voltage fluctuation becomes smaller and the history of the discharge voltage approaches constant voltage operation, that is, the discharge voltage is close to the base voltage, in this case, 150 V.

Figure 6 shows the dependence of the thrust and power consumption on the chopping frequency of the pulsating boost chopping circuit. The thrust decreases with an increase in chopping frequency. Beyond a critical frequency, in this case 18 kHz, the thrust increases with an increase in chopping frequency. On the other hand, the power consumption decreases with chopping frequency, as a result, the thrust efficiency has a maximum value of 0.17 at a chopping frequency of 30 kHz. The thrust, and power consumption of the Volterra engine at 30 kHz are 14.3 mN and 294 W, respectively. This is superior to performance under DC operation, which produces thrust and power consumption of 13.6 mN, 336 W, respectively. The power consumption of the Volterra engine is less than that of DC operation due to the phase angle difference between the discharge voltage and the discharge current, as shown in Fig. 5. The increase in thrust is due to the improvement in beam energy efficiency, as described below.
Figure 7 shows the ion beam profile ($E_b > 100 \text{ eV}$) as measured by RPA for three chopping frequencies (16 kHz, 24 kHz, and 32 kHz) and DC operation. With the increase in chopping frequency, the ion beam current increases, that is, the propellant unitization improves. The beam profile of the Volterra engine is almost the same as that of DC operation; the full width of half maximum is 18.6 to 19.6 degrees. This result may show that the lifetime of the Volterra engine is almost the same as that of DC operation. That is, the Volterra operation has little effect on the beam divergence and thus on the ion bombardment on the acceleration channel wall.

The average ion energy decreases with the increase in chopping frequency, as shown in Fig. 8. This is due to the maximum discharge voltage decrease with the increase in the chopping frequency. The ion energy distribution function becomes narrower with the increase in chopping frequency and approaches that of DC operation. The tradeoff between propellant unitization and average ion energy causes the dependency of the thrust on the chopping frequency, as shown in Fig. 6. Volterra operation leads to improvement of the beam energy efficiency, though the ion energy distribution function of the Volterra engine is wider than that under DC operation. This degrades the total thrust efficiency, though the degradation is negligible compared to other factors, since the thrust is almost the same as that under DC operation, or even a little larger.

The effect of pulsating operation on thrust performance, thrust, thrust efficiency, and beam divergence in a Hall thruster was investigated using a 1 kW class magnetic layer type Hall thruster. Thrust and thrust efficiency with pulsating operation are 14.3 mN and 0.17, respectively, which is superior to DC operation. The effect on plasma divergence is negligible. The ion energy distribution function with pulsating operation is wider than that with DC operation.

4. Conclusion

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References