Evaluation of Quasi-Steady Operation of Applied Field 2D-MPD Thruster using Electric Double-Layer Capacitors

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Abstract: In order to achieve quasi-steady operation of MPD thruster, we developed a power supply replaces PFN. This was used to obtain propulsive performances for each operation time. First we reports the output characteristics of the power supply showing the discharge waveforms obtained by the operation times, 0.3 to 3.0 ms. Secondly, we discuss the dependence of the propulsive performances for each operation time, which are thrust, thrust efficiency and thrust to power.

Nomenclature

I	=	impulse, N·m
F	=	thrust, N
t_{on}	=	turn-on timing, ms
t_{off}	=	turn-off timing, ms
η	=	thrust efficiency, -
$\dot{m}$	=	mass flow rate, mg/s
P	=	input power, kW
I_d	=	discharge current, A
V_d	=	discharge voltage, V

I. Introduction

ELECTRIC propulsion tends to increase input power because it is applied to large-scale missions. Asteroid explorer Hayabusa returned in 2010 used 300 W-class microwave discharge ion thruster[1]. At present, some 10 kW-class Hall thrusters have been developed[2,3]. For the future, we focus on the 100 kW-class thruster. Magneto-Plasma-Dynamic (MPD) thruster is a favorite candidate.

In the ground experiment of MPD thrusters, it is difficult to input a large amount of power for a long time because the back pressure of the vacuum chamber is deteriorated. Therefore a pulsive operation by Pulse Forming Network (PFN) is common for performance evaluation[4,5,6]. In the pulse operation, the section in which the discharge current is stable is called a quasi-steady state, and its propulsion performance is evaluated as a steady operation performance. However, the quasi-steady section is very short as 0.5 ms[7] or less, and there are many unsteady sections which come from the erroras shown Fig. 1. In fact, pulsive performance evaluation by PFN is controversial.

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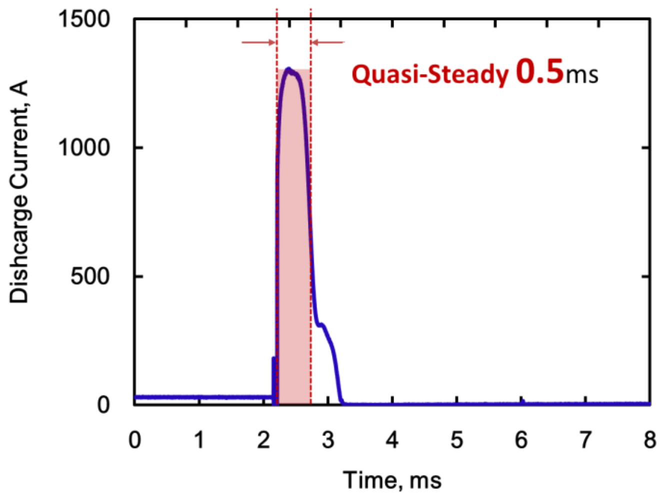

Figure 1: Quasi-steady section in discharge waveform by PFN[7]

II. Contents

In order to perform precise performance evaluation in pulse operation of MPD, sufficient quasi-steady environment is required. Therefore, it is necessary to expand the stable discharge section and reduce the instability of the discharge start and end. That is, ideally, the discharge waveform may be a rectangular wave.

A. The Previous Research

We have developed a power supply capable of outputting an ideal rectangular waveform in order to prepare a discharge environment with high quasi-steady[8].

In the power supply, compared to the discharge waveform of PFN as shown Fig. 2, the quasi-steady section where the discharge current is stable is greatly enlarged, an output close to a rectangular wave with less extra discharge is obtained. This is because Electric Double-Layer Capacitors (EDLCs) with large capacities are used as power sources, and Insulated Gate Bipolar Transistor (IGBT) switches on/off at high speed. In addition, the start timing and the discharging time can be arbitrarily set by the IGBT.

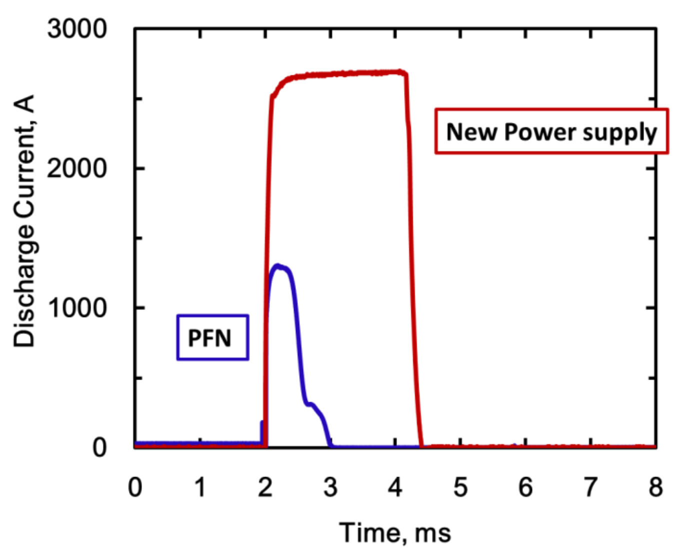

Figure 2: Comparison of Discharge Waveform by PFN[7] and developed new power supply[8]

B. Purpose and Method

In this research, we confirm that discharge with high quasi-steady can be performed by the developed power supply. The operation time is varied from 0.3 to 3.0 ms to obtain the operation time characteristic of the propulsion performance. In the ideal quasi-steady state, the propulsion performance should show a constant value independent of the operation time.

C. Experimental Instrument

Fig. 3 shows the schematic of the experimental setup. We adopted an applied-field 2D-MPD thruster with coils wound on both sides of a rectangular thruster head, and a Th-W rod is used for each anode and cathode. The power source developed in the previous research is used for discharge between electrodes and the external coil respectively. Furthermore, Fast Acting Valve (FAV) that generates gas pulse of about 5ms at arbitrary timing is disposed behind the thruster and an igniter for ignition start to discharge is disposed on the inner wall of the discharge chamber. These sets are mounted on a gravitational pendulum type thrust stand, and the vibration displacement at thrust is read with a laser displacement meter. This is converted to an impulse by the calibration result. Considering the influence on the vibration of the thrust stand, plain flexible cables is used from the power supply system as shown Fig. 4.

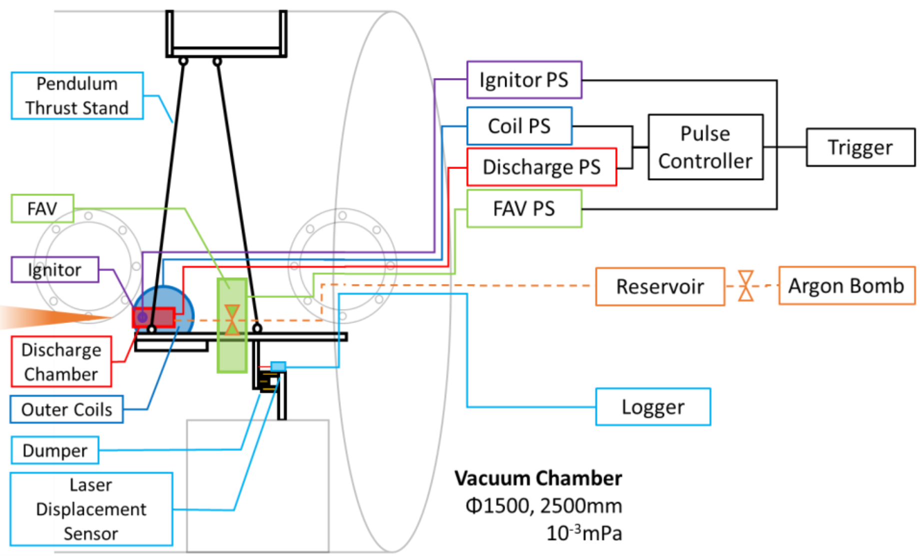

Figure 3: Schematic of Experimental Instruments

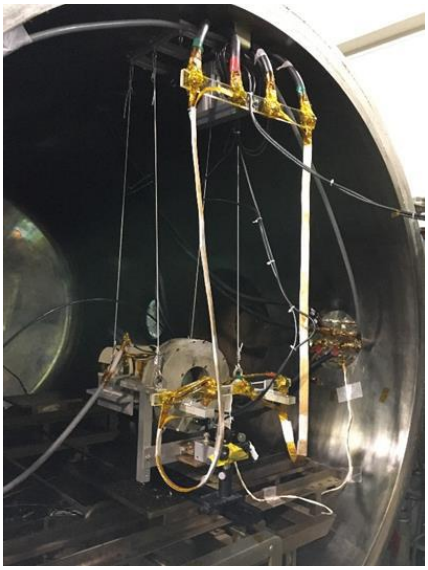

Figure 4: Test Facility

D. Experimental Condition

The operation sequence of each module is shown in Fig. 5. Considering the time when the gas reaches the discharge chamber, the discharge is started by the igniter 4ms after FAV is opened.

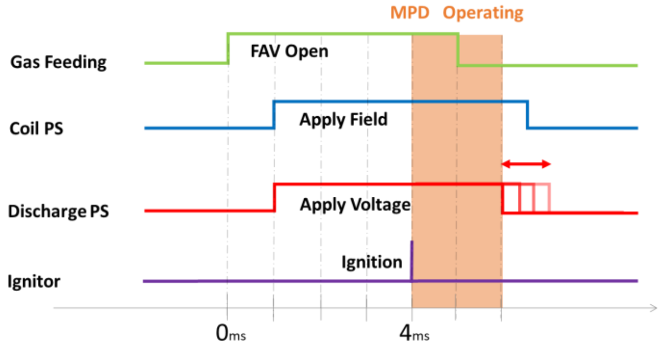

Figure 5: Operation sequence

The operation time was adjusted by changing the turn-off time by IGBT. The discharge current is adjusted to 1000 A-class by adjusting the charging voltage for each condition. Mass flow rate of propellant argon was fixed, and two patterns of magnetic field strength were tried.

Operation time	0.3 – 3.0ms
Discharge current	1000A-class
Mass flow rate	Ar 130mg/s
Magnetic field	90 / 140mT

E. Experimental Result

Fig. 6 shows discharge current waveforms at each discharge time at external magnetic field 90 and 140 mT.

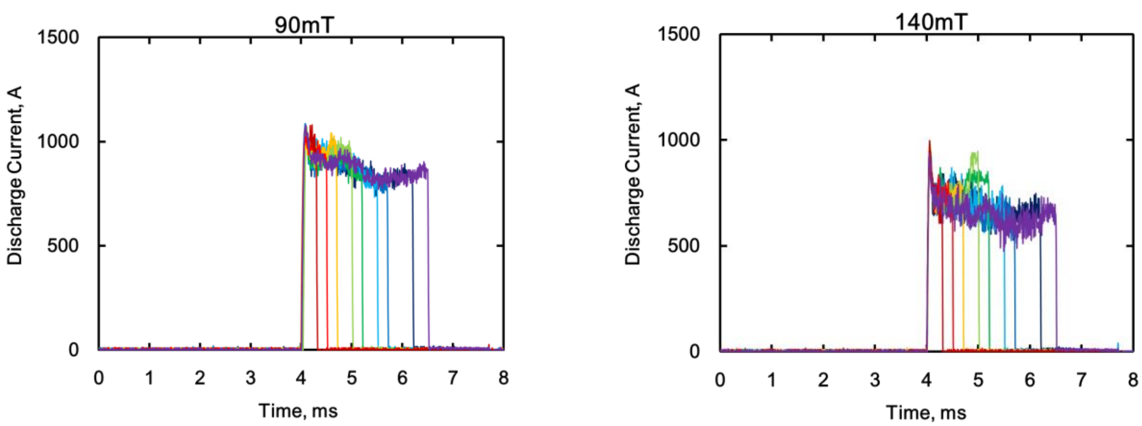

Figure 6: Discharge waveform with magnetic field 90 mT (left) and 140 mT (right)

As evaluation of thrust performance, thrust from Eq. 1, thrust efficiency from Eq. 3, and thrust per input power P derived from Eq. 2 were calculated as the thrust to power. Fig. 7 was plotted against the operation time to evaluate the operation time characteristics of propulsion performance.

$$F = \frac{I}{t_{off} - t_{on}} \quad (1)$$

$$P = \frac{\int_{t_{on}}^{t_{off}} I_d(t) \cdot V_d(t) dt}{t_{off} - t_{on}} \tag{2}$$

$$\eta = \frac{F^2}{2\dot{m}P} \tag{3}$$

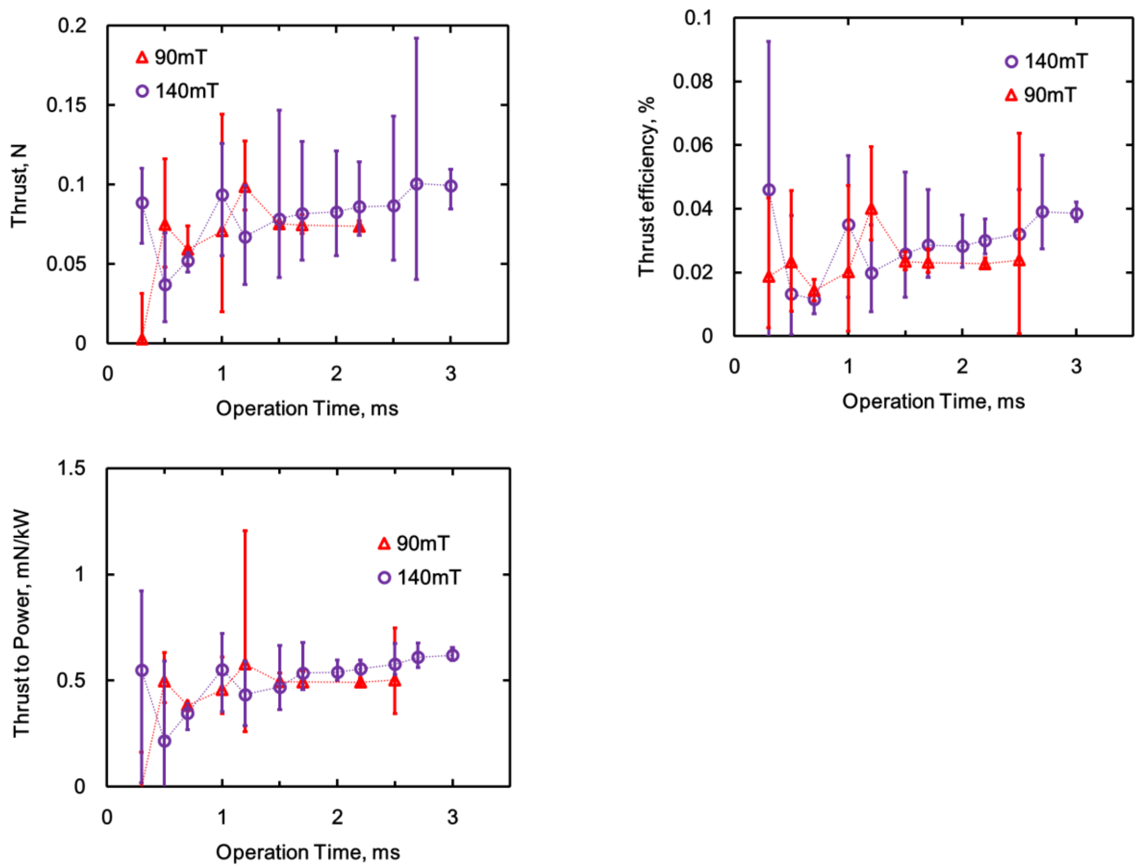

Figure 7: Operation time characteristics of propulsion performance

F. Discussion

In the discharge waveforms of Fig. 6, some noise is given by an external magnetic field, and its amplitude also increases due to the increase of the magnetic field. In addition, the rectangle waves collapses as compared with Fig. 2 in which no magnetic field is applied, and the discharge is a little bit unstable.

In Fig. 7, the variation in performance is small at operation time 1 ms and after. However, because the performance value is low and the performance improvement due to the increase of the magnetic field is not noticeable, there is a possibility that the magnetic field does not work well.

According the thrust to power, since the thrust for each input power is evaluated, the influence due to the dispersion error of the discharge waveform is small. In fact, the error bars representing the standard error are smaller than those in the thrust and the thrust efficiency, and independence to the operation time after 1 ms is remarkable. The reason why the performance slightly increases with operation time is thought to be attributable to thrust due to extra gas due to electrode erosion.

III. Conclusion

In this research, in order to confirm the quasi-steady state in the operation of MPD thruster, the propulsion performance per discharging time was acquired using the power supply developed in the previous research. As a result, time independence was observed after the discharge time of 1 ms and operation with high quasi-steady was confirmed. In the discharge waveform under each condition, some noise and collapse occurred due to applying the magnetic field.

For propulsion performance, the value is generally low and improvement due to the magnetic field is not much noticeable. But the error decreased with the thrust to power considering the input power. Future work are improvement of the performance value and discussion on quasi-steady state of PFN based on this research.

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