

A New Magnetic Flux Density Control Method to Improve Power Consumption of Hall Thruster

IEPC-2011-182

*Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011*

Hiroyuki Osuga¹

Mitsubishi Electric Corporation, Kamakura Works, Kamakura, Kanagawa, 247-8520, Japan

Fujio Kurokawa²

Nagasaki University, Nagasaki, Nagasaki, 852-8521, Japan

Naoji Yamamoto³

Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

and

Taichiro Tamida⁴

Mitsubishi Electric Corporation, Advanced Technology R&D Center, Amagasaki, Hyogo, 661-8661, Japan

Abstract: The wall surface of the plasma generation and acceleration domain is worn out by the colliding ions and this causes the channel wall to deteriorate and change shape. Over time, this results in lower efficiency of the Hall thruster, which shortens the lifespan of the propellant, thus reducing the lifespan of the satellite itself. In view of this, it is necessary to develop technology that limits the deterioration of the channel, while maintaining high thrust efficiency of the Hall thruster. In this paper, we propose algorithm of a new power supply control method that take into account channel abrasion deterioration as well as the details of the experiment result. This power supply control technique requires that we control magnetic flux density under the constant acceleration voltage as the principal objective, assuming the condition where we use constant propellant flow quantity control to plan the reduction of the system. We show the new control algorithm of the power supply which found the operating point where the optimal thrust efficiency is provided from these empirical formulas automatically.

Nomenclature

F	= Thrust, [N]
I_a	= anode current, amperes, [A]
I_c	= coil current, amperes, [A]
I_{ci}	= inner coil current, amperes, [A]

¹Senior engineer, Space system Department, Osuga.Hiroyuki@bx.MitsubishiElectric.co.jp

²Professor, Graduate School of Engineering, fkurokaw@nagasaki-u.ac.jp

³Assistant Professor, Graduate School of Engineering Sciences, yamamoto@aees.kyushu-u.ac.jp

⁴Senior Researcher, Power electronics Department Center, Tamida.Taichiro@aj.MitsubishiElectric.co.jp

I_{ciopt}	= optimal inner coil current of the thrust efficiency, amperes, [A]
I_{co}	= outer coil current, amperes, [A]
K_e	= thrust efficiency map parameter
K_F	= thrust map parameter
M	= ion mass, [kg/s], (Xe = 2.25×10^{-25} kg)
e	= electron density number, $1.602176487 \times 10^{-19}$, [C]
Q	= gas flux, [kg/s]
V_a	= anode voltage, [V]
η_u	= propellant efficiency
η_E	= energy efficiency
σ	= standard deviation, which represents the current oscillation strength
τ	= period of current measurement

I. Introduction

A number of different electrical propulsion systems have been developed for space vehicles with a focus on path control for satellites and probes for space exploration. One such type of electrical propulsion, the Hall thruster¹, is characterized by high thrust density and relatively simple structure. This has led to Hall thrusters being noted among the various electrical propulsion methods as particularly suited for the next generation of satellites; in recent years several Hall thrusters have been developed with outputs of over 250mN².

Since Hall thrusters are discharge devices that produce thrust through generating plasma, their electrical properties are highly non-linear and difficult to control. The stability of discharge is clearly affected by the characteristics of the power source. Particularly when starting up and maneuvering, control specific to the power source is needed³. While this is a concern, the changing stability of the electric discharge as the operating time lengthens is also a problem. The wall surface of the plasma generation and acceleration domain is worn out by the colliding ions and this causes the channel wall to deteriorate and change shape. Over time, this results in lower efficiency of the Hall thruster, which shortens the lifespan of the propellant, thus reducing the lifespan of the satellite itself. In view of this, it is necessary to develop technology that limits the deterioration of the channel, while maintaining high thrust efficiency of the Hall thruster.

In this paper, we propose algorithm of a new power supply control method that took into account channel abrasion deterioration as well as the details of the experiment result. This power supply control technique requires that we control magnetic flux density under the constant acceleration voltage as the principal objective, assuming the condition where we use constant propellant flow quantity control to plan the reduction of the system.

Firstly we produced a Hall thruster with two different channels, one in brand-new condition and the other with acceleration domain wall surface deterioration caused by colliding ions in plasma. We measured the characteristic data of each the Hall thrusters. Secondly we arranged a power supply parameter in the examination conditions and made a performance characteristic map. We examined the thrust efficiency data to find the most suitable control point for the anode current and thrust efficiency. It is not dependent on propellant flow quantity Q . Finally, we show the new control algorithm of the power supply which found the operating point where the optimal thrust efficiency was provided from these empirical formulas automatically.

The operating point that power consumption is small after channel deterioration when an appropriate magnetic flux density is chosen, is able to save energy.

II. Experimental Set-up

A. Test configuration

The experiment setup consists of a Hall thruster, five kinds of power supplies and two xenon-flow-controllers. This Laboratory model (LM) Hall thruster was developed at Kyushu University. Figure 1 shows the axial cross section of the Hall thruster, the block diagram of power supplies and the mass flow controller for propellant gas. The LM Hall thruster we developed is a magnetic layer type, which is typified by a stationary plasma thruster (SPT). A hollow cathode is fitted externally because the Hall thruster requires an external electron source.

The power supplies (It is called a power processing unit (PPU).) are fitted for an anode electrode, two magnet electrodes, a keeper electrode and a cathode heater electrode. The mass flow controller (MFC) is used to supply xenon gas to the hollow cathode. As long as the hollow cathode operates stably, it rarely affects the oscillation phenomenon. Therefore, we did not consider the operation conditions of the hollow cathode in this study. Xenon gas is also supplied to the anode electrode through a MFC.

Here, Q indicates the gas flux of the Hall thruster and does not include the gas flux of the hollow cathode. The Hall thruster is equipped with power supplies for an anode electrode, an inner magnetic coil and outer magnetic coils. The PPU for the next generation satellite was set to work under an input voltage range of between 32.5V and 50 V so as to match various low earth orbit satellites bus. The currents of the inner and outer magnetic coils can be individually regulated. The operation conditions are determined by four parameters: the anode voltage V_a , propellant gas flux Q , inner magnetic coil currents I_{ci} and outer magnetic coil currents I_{co} . The oscillation is detected by measuring the anode current I_a . Tests were conducted in a vacuum chamber of 1.0 m diameter by 1.2 m length. A hollow cathode was used as the electron source.

Table 1 shows output characteristic requirements of the PPU and also the output power characteristics required from the Hall thruster for an experiment.

Table 1 Output characteristic requirement of the PPU.

Name	Voltage Range (V)	Current Range (A)	Maximum Power (W)	Regulation Type*1
Anode PS	200 -350	0.5-3.0	1050	C.V
Keeper PS	25	0.2-1.0	25	C.C
	500	0.01	5	C.V
Heater PS	40	2.0-4.0	160	C.C
Inner magnet PS	7	0.2-3.0	21	C.C
Outer magnet PS	12	0.2-3.0	36	C.C
Mass flow PS	15	0.1-0.8	12	C.C

Type*1: C.V, Constant voltage, C.C, Constant current

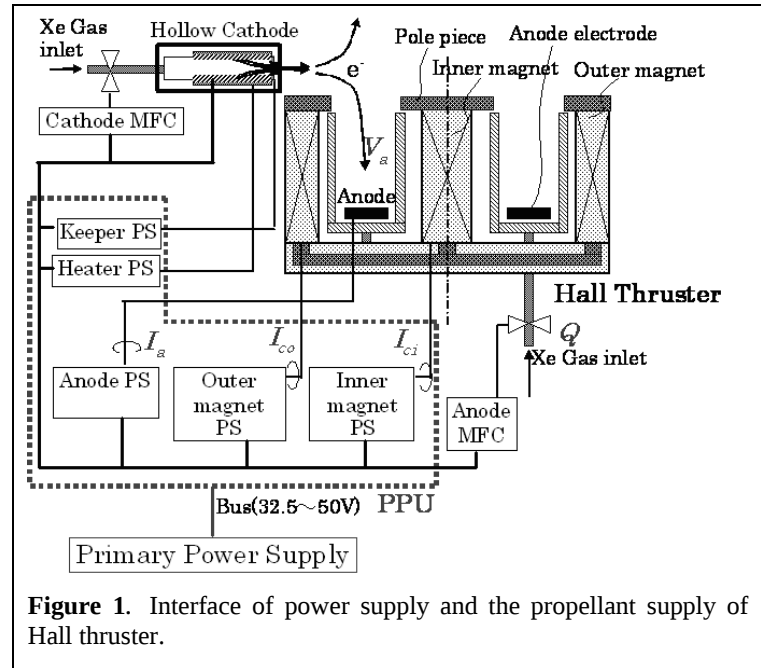


Figure 1. Interface of power supply and the propellant supply of Hall thruster.

B. Hall thruster

The life time is the very important problem of Hall Thruster. It is one of our important subjects to control the Hall Thruster stably even at the End of Life (EOL). At the EOL of the thruster, the exit of the channel is subjected by erosion. To simulate the erosion effect, we compare the characteristics of two thrusters with the different shape of channel exit. The photographs of the LM Hall thruster are shown in Fig. 2 and Fig. 3. Figure 2 shows the Beginning of Life (BOL) channel. Figure 3 shows the EOL channel model. The BOL channel is 10 mm. To simulate the wear and tear of use, the EOL channel model has a 12.8-degree angle cut at the channel exit and the channel itself is widened by 2.5mm so that the channel becomes 12.5mm wide. Comparing the characteristics of these thrusters, we think that the thruster characteristics at the EOL can be simulated. These channel materials are BN. A hollow cathode is fitted externally because the Hall thruster requires an external electron source.

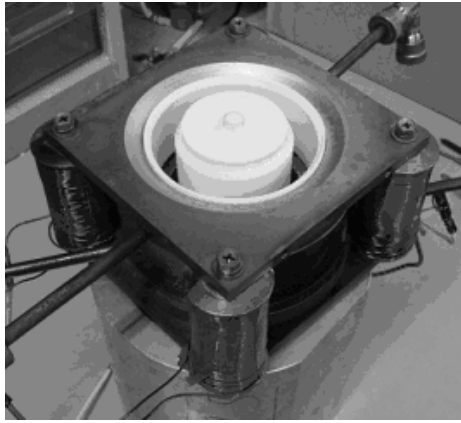


Figure 2. Photograph of LM Hall thruster (BOL).

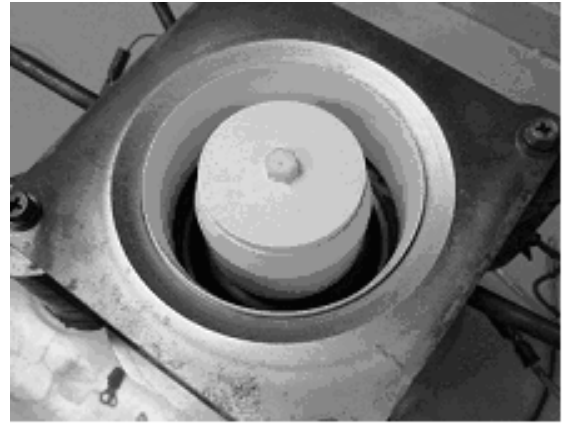


Figure 3. Photograph of LM Hall thruster (EOL).

III. Power Control Method for Hall Thruster

A. Thrust control method

In this measurement, we fixed both the inner magnet coil current I_{Ci} and outer magnet coil current I_{Co} to I_C . The measured oscillation strength is estimated by the following equation using the standard deviation,

$$\sigma = \sqrt{\frac{1}{\tau} \int_0^{\tau} (I_a - \overline{I_a})^2 \cdot d\tau} \quad (1)$$

where $\overline{I_a}$ is the average of anode current.

We performed a theoretical and experimental study of low frequency oscillation in this Hall thruster, and found that the oscillation level could be clearly indicated by the external operation parameters, that is, anode voltage V_a , gas flux Q and coil current I_C ⁴.

Similarly, we found that the thrust condition could be clearly indicated by the external operation parameters, that is, anode voltage V_a , gas flux Q and coil current I_C ³. Figure 4 shows the relationship between the parameters and the thrust, and we call it “Thrust Control Map”. The thrust contour is plotted with the anode voltage V_a on the ordinate, and the magnetic flux density (or coil current) on the abscissa. The thrust control method is especially important when the operation or thruster conditions change temporally. When the operation conditions such as the anode voltage, V_a , or coil current, I_C , change transiently, the set of external control parameters may pass the region in which the current oscillation becomes very severe, and the momentary strong oscillation could have a fatal effect on the satellite system.

B. Constant flow rate control method for controlling of the thrust

The conventional control method needs to change the xenon mass flow rate. Then, Hall thruster system uses two xenon mass flow controllers and these power supplies. Therefore, the PPU weight and power consumption increases. We know the thrust control method keeps constant flow rate by thrust-control-map, as show in Fig. 5. We propose the constant flow rate control method for controlling of the thrust for the next generation satellites. The benefits are light weight and low cost. This control method is maximum thrust control for a Hall thruster system. The inner coil current and the outer coil current are synchronous according to the V_a .

The thrust of Hall thruster is estimated by the following equation,

$$F = \eta_u \times Q \times \sqrt{2 \times \eta_E \times e \times V_a / M} \quad (2)$$

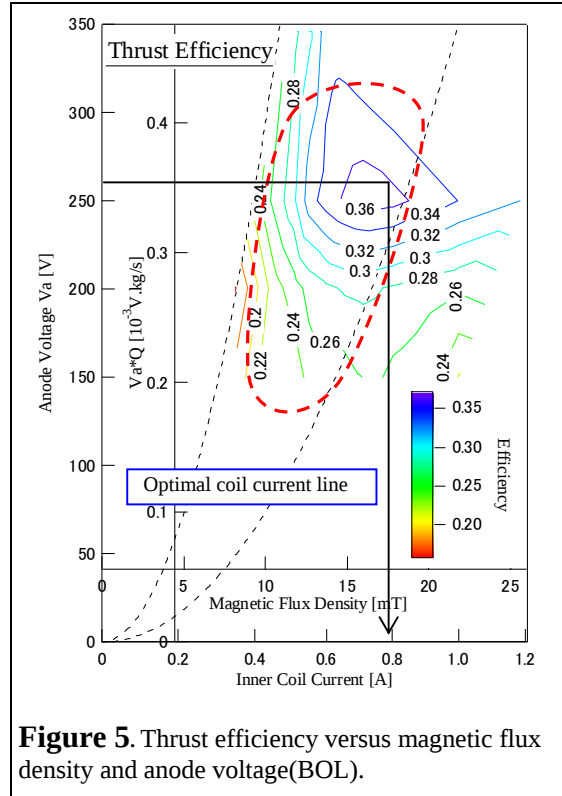
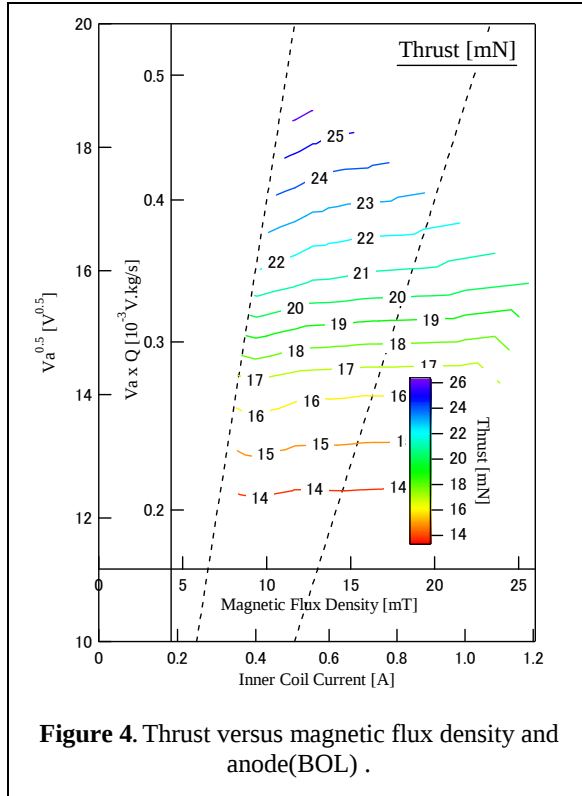
Assuming that η_u and η_E do not change, when we keep the gas flux Q constant, we derive;

$$F = k_F \times \sqrt{V_a} \quad (3)$$

The k_F is calculated by the following equation using the thrust map.

$$F = 1.25 \times \sqrt{V_a} \quad (4)$$

Then, xenon mass flow rate is 1.36×10^{-6} [kg/s].



The thrust value increases in proportion to the square root of the anode voltage. As it has been proved, the theory will be of practical importance. The synchronous Power supplies control is a very important factor for the stable control of Hall thrusters. For example autonomic operation will be possible for the Hall thruster system, including the power supply, to automatically find the stable operational conditions for an externally given target thrust value. Because the current oscillation can be essentially suppressed, it is possible to take EMC measures for the other equipment installed in the satellite. Also the optimization of the power supply design is possible, such as the reduction of power supply capacity. We think that this study will be an essential technology for the stable control of Hall thrusters.

C. Thrust efficiency control method

Figure 5 shows the relationship between the parameters and the thrust efficiency, called “Thrust Efficiency Map”. The thrust efficiency is plotted with the anode voltage V_a on the ordinate, and the magnetic flux density (or coil current) on the abscissa. The thrust efficiency control method is especially important when the operation or thruster conditions change temporarily. When the operation conditions such as the anode voltage, V_a , or coil current, I_c , change transiently, the set of external control parameters may pass the region in which the current oscillation becomes very severe. For thrust efficiency control, the anode power supply is controlled by anode voltage with the magnetic flux density. The stable operation region is the red dotted line area. The maximum thrust efficiency base line is the right side line, as is $1 \times B \text{ (T)}^2$

It shows that when the anode voltage or gas flux changes transiently, the coil current must be controlled synchronously according to the V_a or Q . When the flow rate is constant, the V_a and the coil currents control the thrust efficiency. In the red dotted area, amplitude is less than 1 ampere of the discharge oscillation current.

D. The power consumption control method with the thrust control map

Figure 6 shows the test results the anode voltage valuable parameters and the thrust efficiency for five-discharge voltage. The thrust efficiency is plotted with the magnetic flux density (or coil current) on the abscissa. The Hall thruster system has an optimum operating point, which extracts maximum available thrust power from constant gas flow rate. Moreover, the thrust efficiency sensitively varies with magnetic flux density. This fact proves clearly that thrust efficiency can be improved more than 22% by I_c . Therefore, we propose that it is the best system control for synchronizing a coil current and an anode voltage when changing a thrust. Then, the Hall thruster system requires the maximum thrust efficiency point tracking control of power supplies to obtain as large as possible thrust efficiency. It shows that when the anode voltage changes transiently, the coil current must be controlled synchronously according to the V_a . It is the optimal control method for thrust efficiency. The thrust efficiency control method is especially important when the operation or thruster conditions change temporarily.

Now that we have become familiar with optimal value of the utilization of the mapping, we will be able to discuss the value of the optimal thrust efficiency on the BOL. We keep the gas flux Q constant. The optimal coil current of Hall thruster is estimated by the following equation,

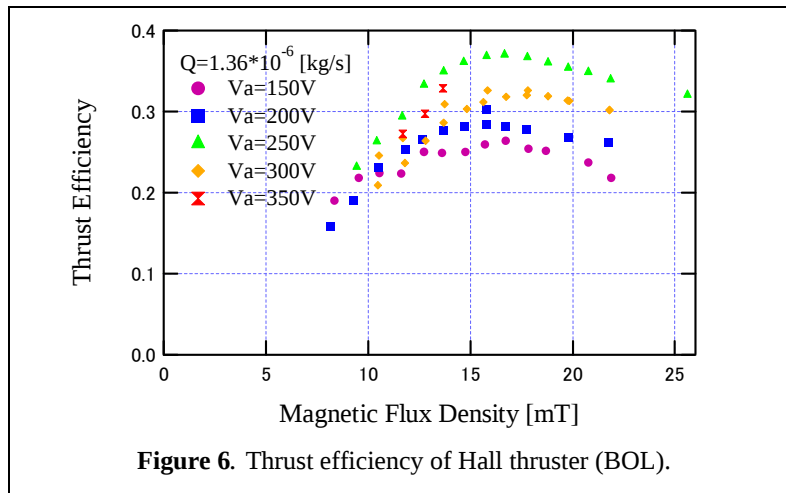
$$I_{cipt} = k_e \times \sqrt{V_a} \quad (5)$$

The k_e is calculated by the following equation using the thrust efficiency map.

$$I_{cipt} = 0.052 \times \sqrt{V_a} \quad (6)$$

V_a : anode voltage, [V]

For example, the target point of the red dotted area has optimal control thruster efficiency at 250 V. The I_{cipt} value is calculated from an anode voltage. This optimal control value is equal to the right side dotted line on the oscillation mode map. As the result, thrust efficiency is over 36 %.



E. Comparison of BOL channel model and EOL channel model

The BOL channel model thrust achievements compare favorably with EOL channel thrust model. The thrust of EOL channel model is equal to or less than 6 %, and it works on an operating domain that is stable. The thrust is in proportion to the square root of anode voltage. The EOL thrust can be written as follows:

$$F(EOL) = 0.937 \times \sqrt{V_a} \times 0.94 \quad (7)$$

Then, xenon mass flow rate is 1.02×10^{-6} [kg/s].

The optimal coil current of the EOL channel model Hall thruster is estimated by the following equation,

$$I_{ciopt}(EOL) = 0.052 \times \sqrt{V_a} \times 1.21 \quad (8)$$

The BOL channel model test results are shown in Fig. 7. The EOL channel model test results are shown in Fig. 8. The xenon mass flow rate is 1.02 mg/s. This fact proves clearly that a new thrust control method applies to BOL

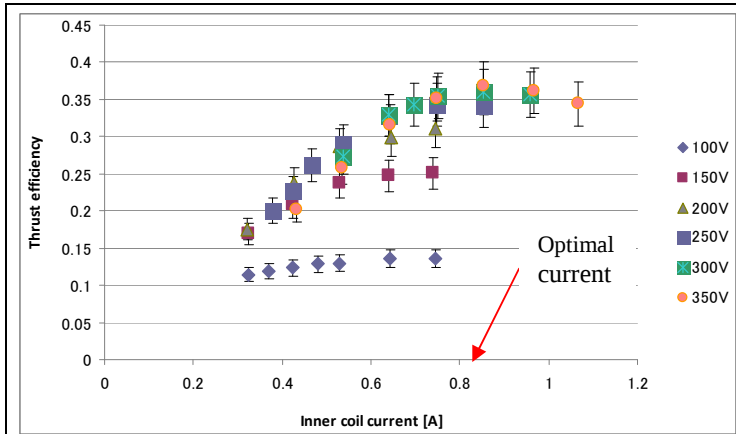


Figure 7. BOL channel model thrust efficiency versus inner coil current. (Xenon mass flow rate = 1.02×10^{-6} [kg/s]).

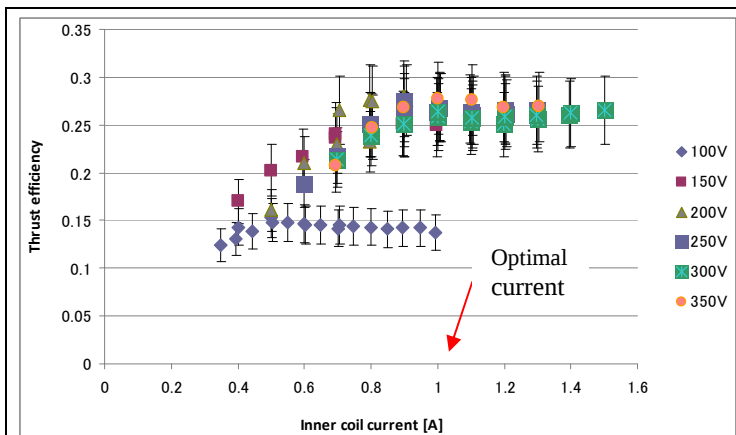


Figure 8. EOL channel model thrust efficiency versus inner coil current. (Xenon mass flow rate = 1.02×10^{-6} [kg/s]).

channel model and EOL channel model. Figure 8 and Fig. 9 show the relationship between the I_{ci} parameters and the thrust efficiency. Then, the xenon mass flow rate is constant. As a result of maximum performance experiments for 20mN-class Hall thruster, over 36 % thrust efficiency of the Hall thruster was found to be sensitive to the anode voltage and applied magnetic flux density. The next generation super low altitude satellites using Hall thrusters require high thrust efficiency that will be over 25 %. The value of this is low power consumption in small electrical propulsion systems. The EOL channel model thrust efficiency achievements compare favorably with the BOL channel thrust efficiency model. The thrust efficiency of EOL channel model is equal to or less than 6 %, and it works on a stable operating.

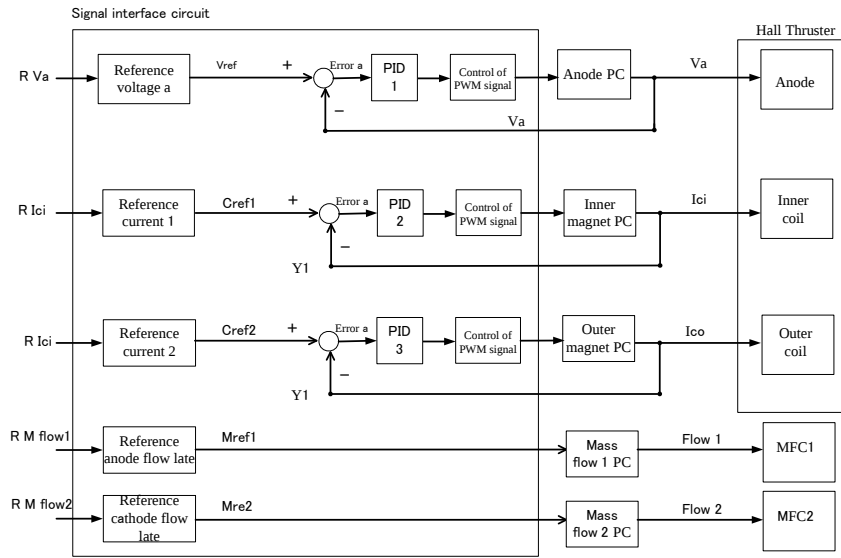
IV. Control Method of Magnetic Flux Density

A. Outline of a control method of the magnetic flux density

The conventional control method needs to change the xenon mass flow rate. Then, Hall thruster system uses two xenon mass flow controllers and these power supplies. Therefore, the PPU weight and power consumption increases. We know the thrust control method keeps constant flow rate by thrust-control-map, as show in Fig. 4. Figure 9 shows a general control system of the Hall thruster. The thrust control method of the conventional system for the Hall thruster was on-off

control only, as like a chemical propulsion thruster.

We propose the constant flow rate control method for controlling of the thrust. The benefits are light weight and low cost. Figure 10 shows a new control method of the Hall thruster. This control method gives maximum thrust efficiency control for a Hall thruster system. The inner coil current and the outer coil current are synchronous according to the V_a . In addition, an anode current is sensing to control the stable conditions. The optimal coil current value is calculated by an anode current within oscillation-mode-map. The Hall thruster control system does not have a mass flow rate controller. The system consists of the fixed flow control devices. The system keeps constant flow rate.



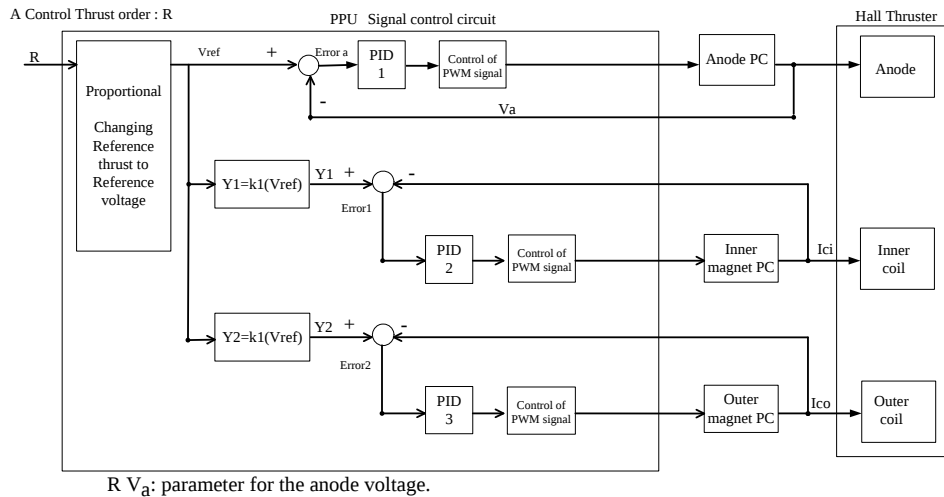
$R V_a$: parameter for the anode voltage.

$R I_{Ci}$: parameter for the inner magnetic current.

$R I_{Co}$: parameter for the outer magnetic current. $R M_{flow1}$: parameter for the mass flow control of the anode.

$R M_{flow2}$: parameter for the mass flow control of the cathode.

Fig. 9. A general control system for thrust efficiency of Hall thruster.



$R V_a$: parameter for the anode voltage.

Fig. 10. Control method for high thrust efficiency of Hall thruster.

B. Optimal control Method for thrust efficiency

The Hall thruster system has an optimum operating point, which extracts maximum available thrust power from constant gas flow rate. Moreover, the thrust efficiency varies with magnetic flux density and is sensitive. When we require over 25 % thrust efficiency, one possibility is to assume that I_{Ci} is over 0.5 amperes. Another possibility is that it derives from an anode voltage. This fact proves clearly that a new power control method applies to the BOL channel model and the EOL channel model. Therefore, the Hall thruster system requires the maximum thrust efficiency point tracking control of power supplies to obtain as large as possible thrust efficiency. It shows that as times goes by the coil current must be controlled synchronously for each V_a . It is the optimal control method for thrust efficiency.

C. Control algorithm to improve the power consumption

We show the new control algorithm of the power supply which found the operating point where the optimal thrust efficiency is provided from these empirical formulas automatically. The automatic magnetic flux density control flowchart to improve power consumption control algorithm shown in figure 11. It becomes the essential condition for low power consumption to get high thrust efficiency.

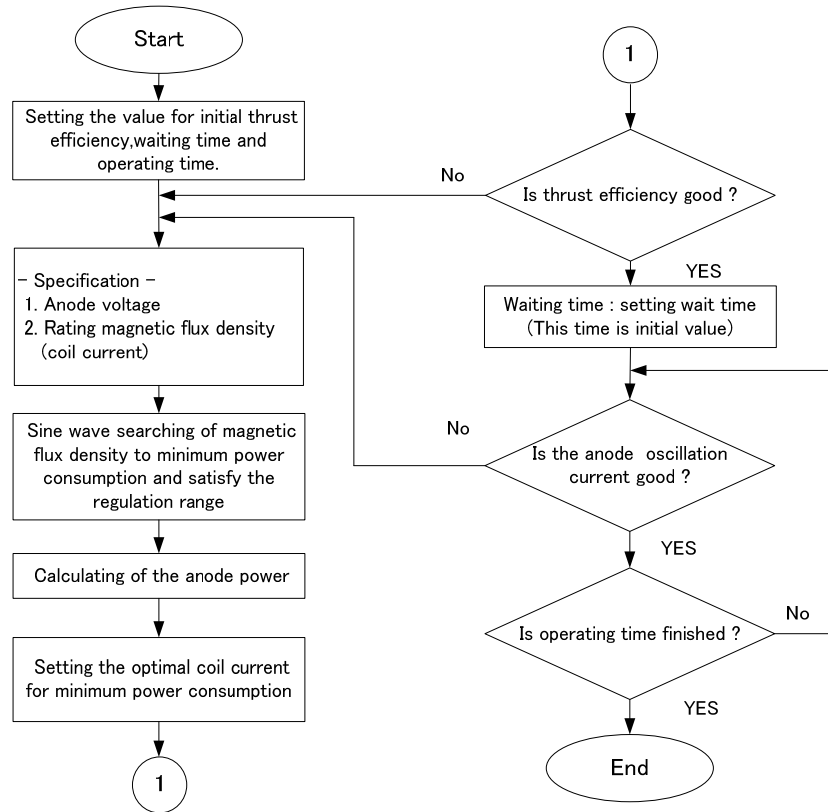


Figure 11. Automatic Magnetic Flux Density Control Flowchart to Improve Power Consumption.

V. Test Results and Discuses

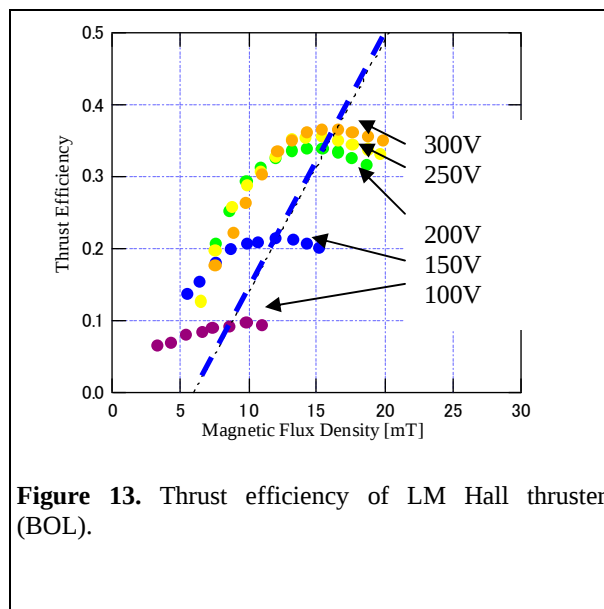
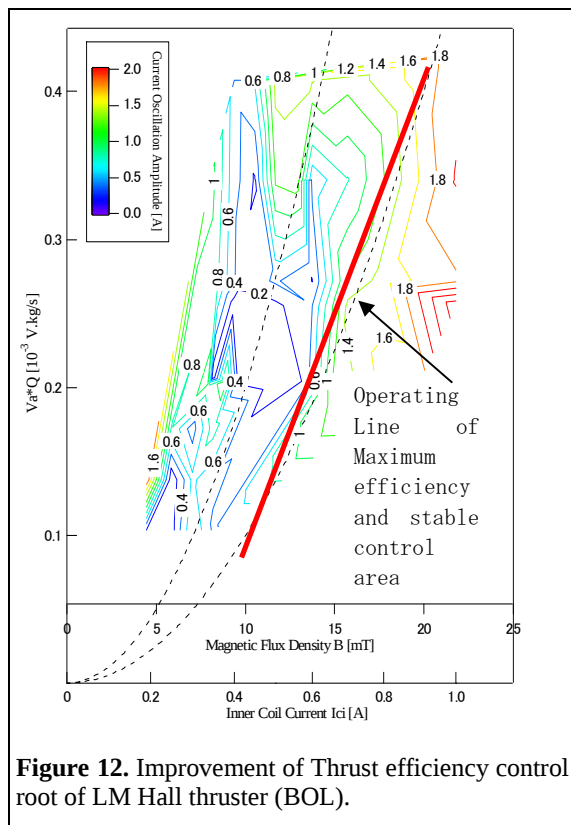
We arranged a power supply parameter in the examination conditions and made a performance characteristic map. The improvement of thrust efficiency control root of LM Hall thruster (BOL) is shown in Fig. 12. The thrust efficiency of LM Hall thruster (BOL) is shown in Fig. 13. Then, xenon mass flow rate is 1.02×10^{-6} [kg/s]. We examined the thrust efficiency data to find the most suitable control point for the anode current and thrust efficiency.

It is not dependent on propellant flow quantity Q . The result of the experiment, magnetic induction B_{effmax} of the promotion efficiency maximum point of the magnetic flux density of the Hall thruster which simulated BOL is given in an expression (8). It shows a red line.

$$B_{effmax} [mT] = (2 \times (V_a - 80V))^{0.5} \quad (8)$$

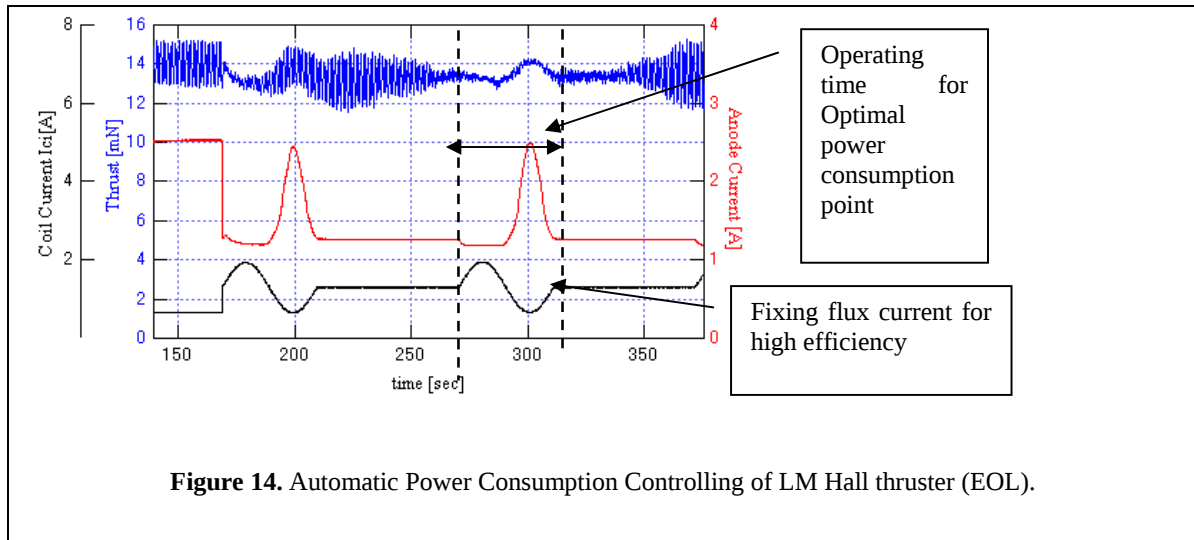
$$T_{effmax} = (B_{effmax} - 6) \times 0.035 \quad (9)$$

Therefore, the operating point to give the greatest efficiency can be decided on a red line for stable operating domains. The optimal point gives a small electric discharge vibration. This operating point changes by propellant flow quantity Q , but it can be derived uniquely as demonstrated with the red line of figure 12. The magnetic flux density for the high thrust efficiency point to get the maximum efficiency for the EOL thruster is stronger than the BOL thruster.



Regarding the control algorithm, we tested an operating experiment in the Hall thruster with simulated deterioration. It simulated EOL because of difficulty with stable control in the channel that we deteriorated.

As a result of the experiment, a new power supply control algorithm found that the optimal point for thrust efficiency work adequately, shown in figure 14. The magnetic flux density control method improves thrust efficiency more than 10%. The operating point that power consumption is small after channel deterioration when an appropriate magnetic flux density is chosen, was able to save energy.



VI. Conclusion

We propose algorithm of a new power supply control method that take into account channel abrasion deterioration as well as the details of the experiment result. This power supply control technique requires that we control magnetic flux density under the constant acceleration voltage as the principal objective, assuming the condition where we use constant propellant flow quantity control to plan the reduction of the system. We show the new control algorithm of the power supply which found the operating point where the optimal thrust efficiency is provided from these empirical formulas automatically.

As a result of the experiment, a new power supply control algorithm found that the optimal point for thrust efficiency work adequately. The magnetic flux density control method improves the thrust efficiency more than 10%. The operating point that power consumption is small after channel deterioration when an appropriate magnetic flux density is chosen, is able to save energy. The ability to improve 10% of efficiency leads to an extension of the lifespan of satellites by 10%. We will use this automatic magnetic flux density control method to improve power consumption for the future satellites.

Acknowledgments

We acknowledge Professor N. Nakashima Kyushu University for the Vacuum chamber facility available to us during the visiting collaboration. The authors acknowledge the technical contributions of T. Ezaki of Kyushu University.

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