Magnetic Responsiveness of Magnetic Circuit composed of Electrical Steel for Hall Thruster

IEPC-2017-355

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

Yusuke Oka[1]
The University of Tokyo, Tokyo, Tokyo, 113-8656, Japan

Satoshi Hosoda[2], Ryudo Tsukizaki[3], Kazutaka Nishiyama[4] and Hitoshi Kuninaka[5]
Japan Aerospace eXploration Agency (JAXA), Sagamihara, Kanagawa, 252-5210, Japan

Abstract: Hall thruster is an electric propulsion device and appropriate for satellite station keeping and mass transport of a future manned space mission. One of the main problems of a Hall thruster is the discharge current oscillation, especially at the frequency range of around 10 kHz. This phenomenon causes damage to Power Processing Units (PPU) and makes the thruster operation unstable. The objective of this research is suppression of unstable thruster operation and discharge current oscillation by using the Electrical steel sheets for a Hall thruster's magnetic circuit and fluctuating the magnetic field strength. The Electrical steel core has a low eddy current loss and higher magnetic responsiveness to alternating current, especially compared to the Pure Iron which is normally used for a Hall thruster. This enables us to alter the magnetic field strength easily. For the first step, three kinds of magnetic circuits (Pure Iron Cross-shaped type, Electrical Steel Cross-shaped type, and Electrical steel Radiating-shaped type) are composed and tested their magnetic responsiveness and the fluctuation of the magnetic field strength. As a result, at the target range of 10 kHz, the Electrical Steel Cross-shaped type shows the highest responsiveness and as high amplitude of magnetic field strength as the Radiating-shaped type.

1. Introduction

1.1 Suppression of Discharge Current Oscillation

Hall thruster is an electric propulsion device which has over 50 % thrust efficiency and high specific impulse (1000 ~ 3000 sec). It also has higher thrust density than Ion engine and is suitable for satellite station keeping and mass transport of a future manned space mission[1-3]. One of the main tasks of a Hall thruster is suppression of the "Discharge Current Oscillation", which causes damage to the PPU (Power Processing Unit), unstable thruster operation and lower thrust efficiency. Some studies showed this phenomenon is caused by ionization rate change[4-7]. The main objective of this research is suppression of the discharge current oscillation by applying electrical steel to the magnetic circuit of a Hall thruster. Specifically, by sending alternating current to each solenoidal coil, magnetic field strength or magnetic flux density changes periodically and this suppresses the oscillation. This operation needs the core material which has higher magnetic responsiveness. At the same time, it can restrain the unstable operation when each coil and

[1] Graduate Student, Department of Aeronautics & Astronautics, oka@ep.isas.jaxa.jp
[2] Engineer, JAXA Space exploration center, hosoda@ep.isas.jaxa.jp
[3] Assistant Professor, JAXA Space exploration center, ryudo@ep.isas.jaxa.jp
[4] Associate Professor, JAXA Space exploration center, nishiyama@ep.isas.jaxa.jp
[5] Professor, JAXA Space exploration center, kuninaka@isas.jaxa.jp

discharge circuit are connected in series. As a previous step for these, it is necessary that the magnetic responsiveness of magnetic circuits composed of the Electrical steel for a Hall thruster is investigated.

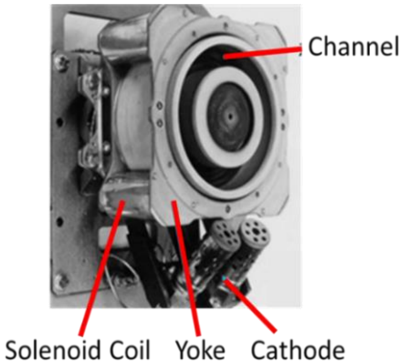

Figure 1: Example of a Hall Thruster (Fakel SPT-100)

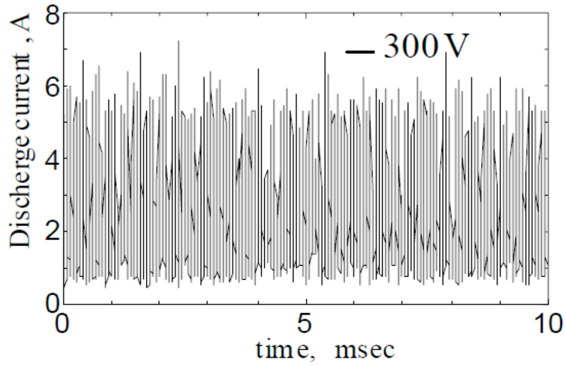

Figure 2: Example of Discharge Current Oscillation[2)]

1-2: Electrical Steel

The Electrical steel sheet is an iron core material with high electric-magnetic energy conversion efficiency, and it has a feature that energy loss (eddy current loss) due to iron loss and an eddy current is small. By using core material formed by stacking electrical steel sheets, it is possible to produce a highly efficient solenoid coil with suppressed core loss and eddy current loss. Since the influence of the eddy current is small, it is considered that the magnetic field fluctuates rapidly in response to the current fluctuation of the coil (Magnetic responsiveness). There are two kinds of electrical steel sheets. One is “Grain-Oriented Steel” which has high magnetic characteristics in only one direction and mainly used for transformer cores. The other is "Non-Oriented Steel" which has uniform magnetic characteristics in each direction and used for motors. [8,9)]

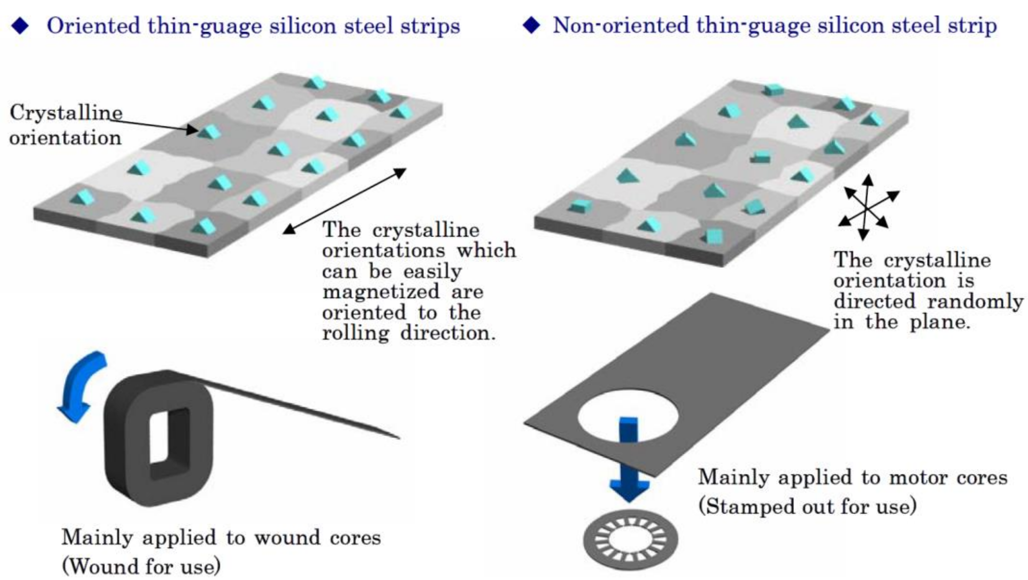

Figure 3: Example of Electrical Steel (Silicon Steel Strips composed by Nikkin Denji Kogyo) [9)]

2. Experimental Setup

2.1 Purpose of this Experiment

(1) Design magnetic circuit for a Hall thruster
(2) Investigate the responsiveness of composed magnetic circuit
(3) Optimize the shape of magnetic circuit

2.2 Detail of Magnetic Circuits

Three kinds of the magnetic circuits are composed, “Pure Iron Cross-shaped”, “Electrical Steel Cross-shaped”, and “Electrical Steel Radiating-shaped” respectively. Figure 4 shows the “Electrical Steel Cross-shaped” circuit and Figure 5 shows the “Electrical Steel Radiating-shaped” circuit.

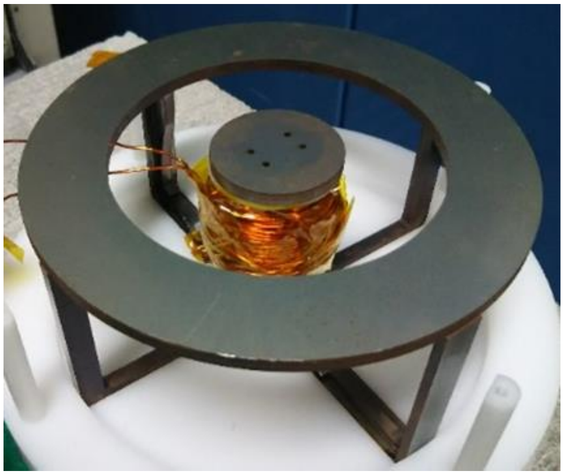

Figure 4: Cross-shaped Magnetic Circuit (Composed of 0.050mm Grain-Oriented Electrical Steel Sheets & 0.50mm Non-Oriented Steel Sheets)

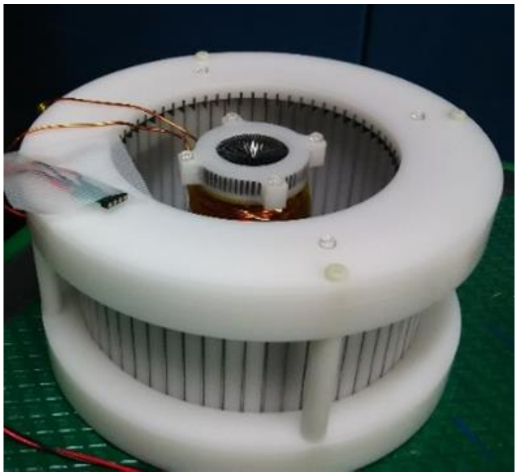

Figure 5: Radiating-Shaped Magnetic Circuit (Composed of 0.50mm Non-Oriented Electrical Steel Sheets)

2.3 Experiment Setup

One solenoidal coil (Inner coil) is mounted on each magnetic circuit which has 300 turns and 0.7 ~ 1.3 Ampere current during each experiment (DC: 1.0 A, AC : ±0.30A, Frequency: 10 Hz ~ 10 kHz). Magnetic flux density is measured with a hall sensor. Figure 6 shows the electrical circuit around the solenoidal coil. Figure 7 shows the electrical circuit around the solenoidal coil which has three resistance: 1.0 Ω for measurement of coil current, 10 kΩ and 390 kΩ for the measurement of the power supply voltage. Since we utilize the AC current at the range of 10 kHz, an oscilloscope is used for these measurements.

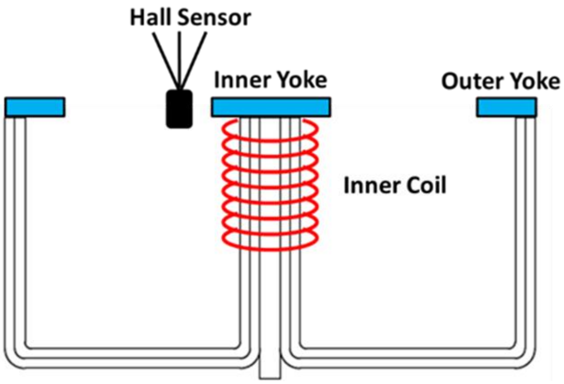

Figure 6: Experimental Setup of Solenoidal Coil & Magnetic Circuit (Cross-shaped Magnetic Circuit)

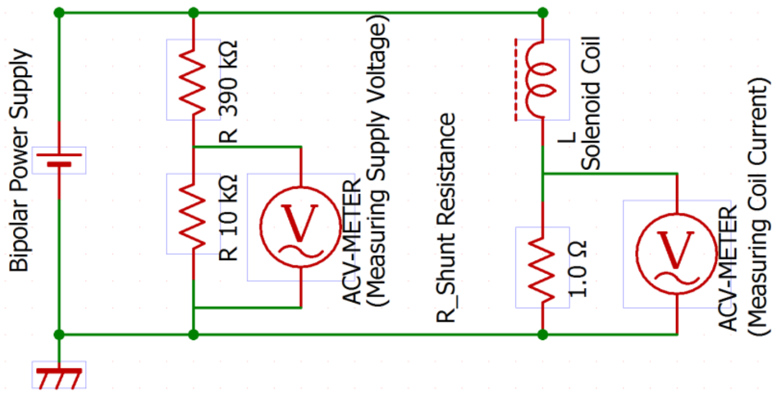

Figure 7: Electrical Circuit around Solenoidal Coil

3. Result, Discussion & Future Plan

3.1 Result

Figure 8 and Figure 9 show the phase difference (between coil current and magnetic flux density) and the amplitude of alternating magnetic flux density at the frequency of 10 Hz, 100 Hz, 1 kHz, 5 kHz and 10 kHz. Blue points ● show the result of "Pure Iron Cross-shaped", red points ● show "Electrical Steel Cross-shaped" and orange points ● "Electrical Steel Radiating-shaped". Figure 10 shows the Q value estimated from the coil voltage and current. Figure 11 ~ 13 show waveforms of coil current and magnetic field, measured with Pure Iron Cross-shaped, Electrical Steel Cross-shaped, and Electrical Steel Radiating-shaped respectively. Q value is a quality factor of solenoid coil at the high frequency and calculated by the next equation.

$$Q = 2\pi f L/R$$
$$(f\text{: frequency(Hz)}, L\text{: Inductance(H)}, R\text{: Resistance}(\Omega))$$

According to Figure 8, from 10 Hz to 5 kHz, the Radiating-shaped has the smallest phase difference. However, at the frequency of 10 kHz, the result of Cross-shaped Electrical steel is the smallest. From Figure 9, Radiating-shaped Electrical Steel shows the highest amplitude overall. Figure 10 also shows that, at the frequency of 10 kHz, Q value of the "Radiating-shaped" is smaller than that of the "Cross-shaped Electrical Steel".

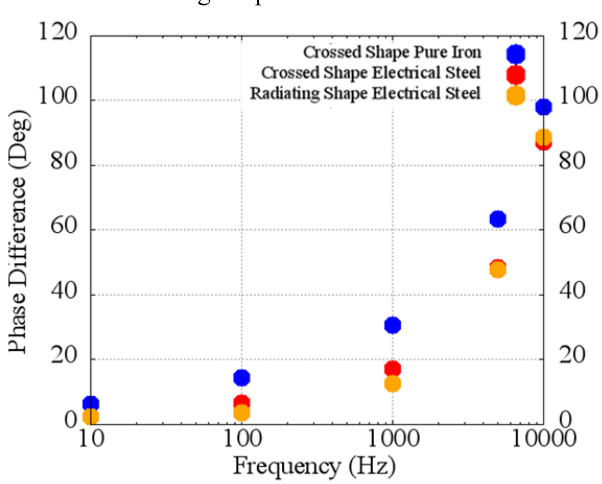

Figure 8: Phase Difference between Coil Current and Magnetic Flux Density

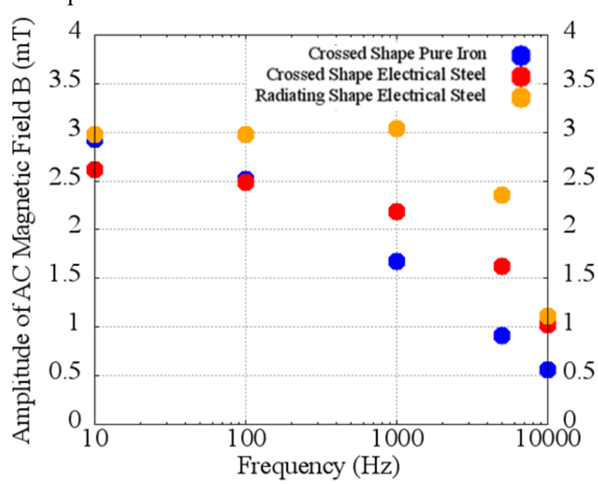

Figure 9: Amplitude of Alternating Magnetic Flux Density

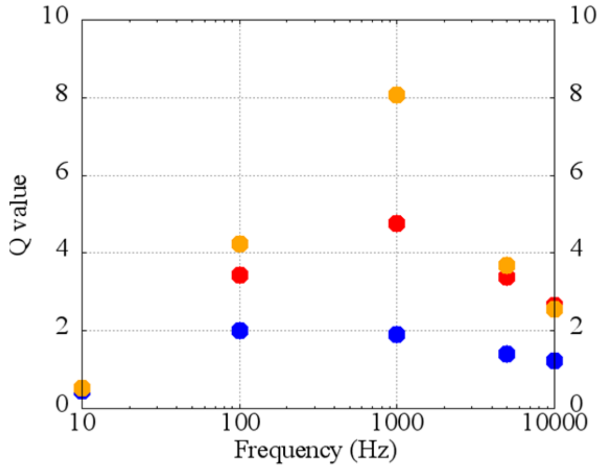

Figure 30: Q value estimated from Coil Voltage and Current

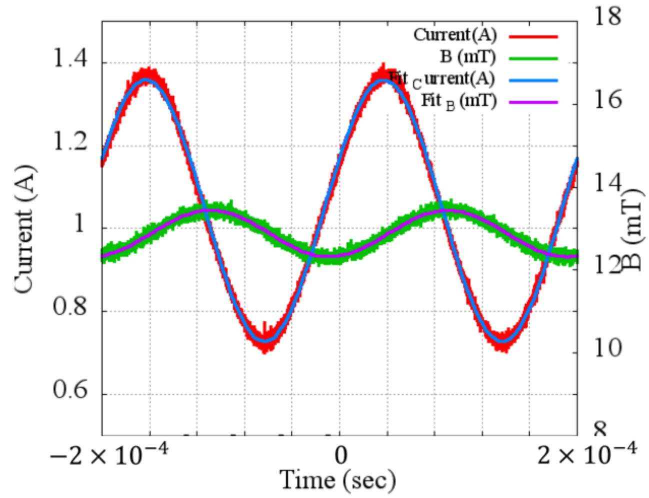

Figure 11: Coil Current & Magnetic Flux Density (Pure Iron Cross-Shaped Magnetic Circuit)

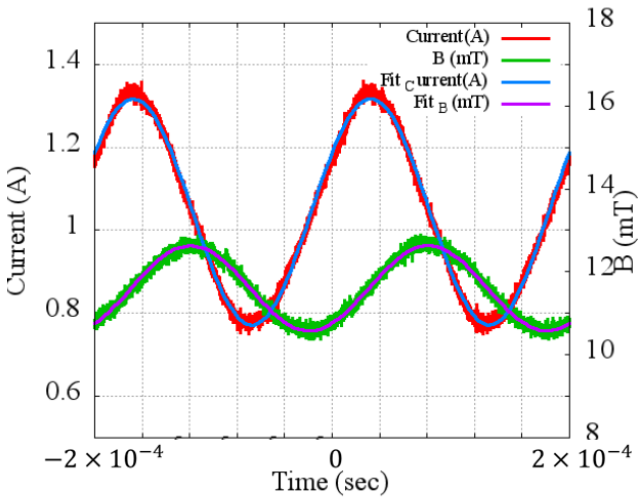

Figure 12: Coil Current & Magnetic Flux Density (Electrical Steel Cross-Shaped Magnetic Circuit)

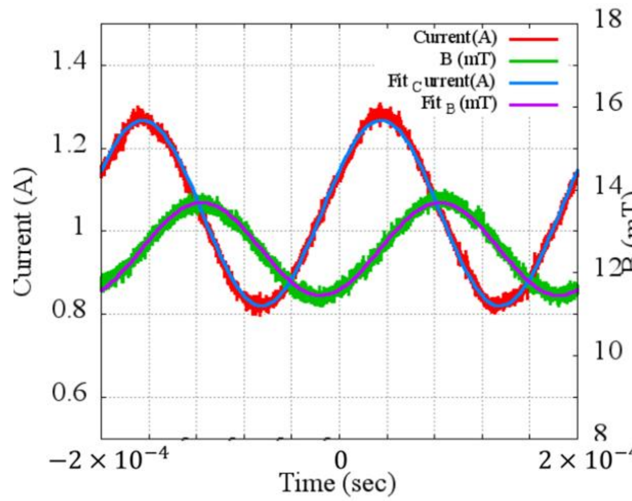

Figure 11: Coil Current & Magnetic Flux Density (Electrical Steel Radiating-Shaped Magnetic Circuit)

3.2 Discussion

From Figure 8, 9, & 10, Radiating-shaped magnetic circuit has relatively higher magnetic responsiveness than each Cross-shaped circuit overall. But at the frequency of 10 kHz, it is not so different from the Cross-shaped magnetic circuit. It is probably because of the thickness of the Electrical steel sheets. Electrical Steel Radiating-shaped type is composed of thicker electrical steel sheets (Thickness: 0.50 mm) and the Electrical Steel Cross-shaped type is composed of thinner sheets (Thickness: 0.050 mm). Typically the thinner this sheet thickness is, the more appropriate for the high-frequency alternating magnetic field.

The Cross-shaped circuit is designed with simple transformer cores and yokes for simplicity, and it is assumed to have unnecessary eddy current loss at the surface of each yoke. The Radiating-shaped circuit is designed for reducing this unnecessary eddy current loss at contact surfaces, so it shows high responsiveness at the range of 10Hz ~ 5 kHz. But it is composed of 0.50 mm electrical steel sheets for simplicity, it shows less responsiveness at 10 kHz.

3.3 Future Plan

Our final goal is to compose the prototype thruster with electrical steel and prove whether it is effective for the suppression of Discharge Current Oscillation. When composing a Hall thruster, it is an easier choice to utilize the

"Electrical Steel Cross-shaped" magnetic circuit, because it is simple and easy to attach some tubes for propellant. As a future work, a prototype of a Hall thruster will be composed with the "Cross-shaped electrical steel" circuit and test whether it can restrain the discharge current oscillations.

4. Summary

It is proposed that, as a way of suppressing discharge current oscillation, applying electrical steel for the magnetic circuit of a Hall thruster. In this paper, as a preliminary step, three kinds of magnetic circuits are composed and investigated the each circuit's magnetic responsiveness. As a result of applying the alternating current, the amplitude of the magnetic field fluctuation increased in the magnetic circuit of Electrical steel, and the phase difference of the current-flux density waveform became small. This experiment also shows, at the frequency range of over 10 kHz, the "Cross-shaped" magnetic circuit responds to the magnetic field rapidly. Moreover, when composing a Hall thruster, lots of equipment (such as tubes for propellant, anode and BN channel) needs to be attached, the simple shape like the "Cross-shaped" type is the best choice. So the "Cross-shaped electrical steel" circuit is chosen for a prototype of a Hall thruster.

Appendix

An appendix, if needed, should appear before the acknowledgement.

References

The following pages are intended to provide examples of the different reference types. You are not required to indicate the type of reference; different types are shown here for illustrative purposes only.

[1)] K.Kuriki, Y.Arakawa: 電気推進ロケット入門 (東京大学出版, 2003)
[2)] H.Tahara, T.Fujita and Y.Shimizu, "Performance Prediction in Long Operation for Magnetic-Layer-type Hall Thrusters", IEPC 2009 -140
[3)] Boeuf, J.P. and Garritues, L., "Low Frequency Oscillation in a Stationary Plasma Thruster", J. Appl. Phys., 84(1998), pp.3541-3554
[4)] Baranov V. I., Nazarenko Yu. S., Petrosov V. A., Vasin A. I., and Yashonov Yu. M. "Theory of oscillations and Conductivity For Hall Thruster" AIAA 96-3192, 32nd AIAA/ASME/SAE/ASEE joint Propulsion Conference, Lake Buena Vista, FL, July 1996
[5)] Fife, J. M., Martinez-Sanchez, Manuel, and Azabo, James "A numerical study of low-frequency discharge oscillations in Hall thrusters" AIAA96-3052, 33rd AIAA/ASME/SAE/ASEE joint
Propulsion Conference. Seattle, WA, July, 1997
[6)] Darnon F., Kadlec-Philippe C., Bouchoule A., and Lyszuk M. "Dynamic Plasma & Plume Behavior of SPT thrusters" AIAA98-3644, 34th AIAA/ASME/SAE/ASEE joint Propulsion Conference. July 1998, OH.
[7)] N. Yamamoto, N. Yasui, K.Kourasaki and Y. Arakawa: "Suppression of the discharge vibration of a Hall thruster" STEP-2003-04, 2003, pg.229-232
[8)] NIPPON STEEL & SUMITOMO METAL, "ELECTRICAL STEEL SHEETS", D003jec_05_201509f, 2012
[9)] NIKKIN DENJI KOGYO Co., Ltd., "Thin-gauge silicon steel strips and Applied products", 2008