Performance Evaluation of Surface Arc Thruster and Development Air Bearing Thrust Measurement System

IEPC-2019-556

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Kotaro Hiraka[1], Hiroaki Murakami[2], Senior Shimhanda[3], Kazuhiro Toyoda[4], Mengu Cho[5]
Kyushu Institute of Technology, Kitakyushu, Fukuoka, 804-8550, Japan

Abstract: Surface Arc Thruster (SAT) is a small thruster under development at Kyushu Institute of Technology and aims to be mounted on Cubesats. This thruster is similar to Pulsed Plasma Thruster, but it is different in that discharge current is controlled to a constant low current and is maintained for about several milliseconds to several tens milliseconds. It is aimed for efficient propellant consumption and reduction of noise due to discharge. In this thesis, about SAT prototype, the thruster internal pressure was measured and evaluated when discharging was generated. And, Paraffin wax was investigated as a propellant to replace Teflon and its performance was evaluated. Furthermore, thrust measurement system using air bearing was prototyped and tested its functions.

Nomenclature

A_e	=	nozzle exit area, m^2
A_t	=	nozzle throat area, m^2
F	=	thrust, N
I	=	moment of inertia, kgm^2
L	=	angular momentum, Nms
$\dot{m}$	=	mass flow rate, kg/s
N	=	force moment, N
n	=	number of injection
p_a	=	vacuum chamber pressure, Pa
p_c	=	plenum chamber pressure, Pa
p_e	=	nozzle exit pressure, Pa
T	=	Dynamic friction torque
v_e	=	waypoint index
γ	=	specific heat ratio
ω	=	angular velocity, rad/s

[1] Graduate student, Department of Electrical Space Engineering, LaSEINE, p108094k@mail.kyutech.jp
[2] Alumni, Department of Electrical Space Engineering, LaSEINE, n108110h@mail.kyutech.jp
[3] Graduate student, Department of Electrical Space Engineering, LaSEINE, s350937s@mail.kyutech.jp
[4] Associate Professor, Department of Electrical Space Engineering, LaSEINE, toyoda@ele.kyutech.ac.jp
[5] Professor, Department of Electrical Space Engineering, LaSEINE, cho@ele.kyutech.ac.jp

I.Introduction

SINCE 2017 there has been a sharp increase in the launch of Nano-satellites, which are less than 50 kg, are low in cost, and can be developed quickly.[1] However, even Nano-satellites may require propulsion in these two cases: (1) for attitude/orbit control, and (2) for de-orbiting (debris mitigation). In Kyushu Institute of Technology(Kyutech), Surface Arc Thruster (SAT) are being developed as an electric propulsion for mounting a small satellite.[2] The operating principle of SAT is similar to the pulsed plasma thruster (PPT), but differs largely in that discharge current is limited to about several A and is maintained for several milliseconds to several tens milliseconds. So, reduction of noise due to discharge and improvement of propulsion efficiency can be expected. SAT gets thrust by injecting a propellant vaporized by discharge from a nozzle, so it is classified as an electro thermal acceleration type propulsion.

In order to design an appropriate nozzle for SAT, the pressure change inside the thruster by injection was measured using a pressure sensor, and the thrust of the SAT was calculated by measuring pressure change. And as a new propellant to replace Teflon, Paraffin wax is devised and evaluated the performance. Furthermore, in order to measure the thrust of the SAT directly, the thrust measurement system was examined with the air bearing and developed.

II.Surface Arc Thruster

A. Principle

Figure 1 shows the principle of SAT operation. A capacitor and a current regulative circuit are connected to SAT. First, capacitor is charged fully, and in order to induce surface arc discharge, a high voltage is caused by the igniter (Fig. 1(a)). A discharge current due to surface arc discharge flows from the anode to the cathode, the discharge current is sustained to several A by the current regulative circuit and lasts for several milliseconds to several tens milliseconds (Fig. 1(b)). The propellant gas is injected from nozzle, and thrust is obtained (Fig. 1(c)).

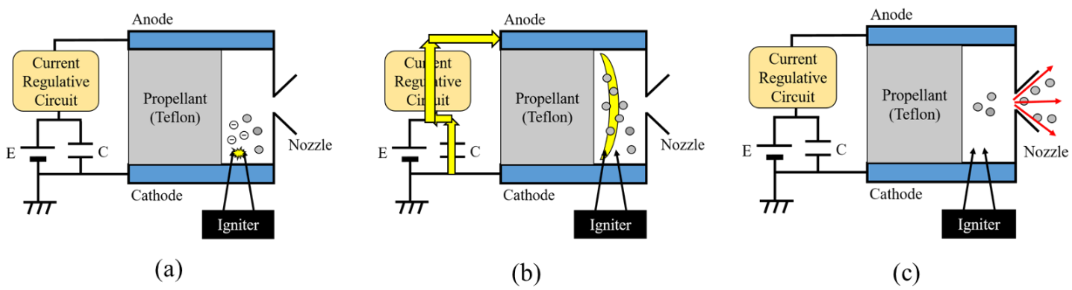

Figure 1. Principle of Surface Arc Thruster[3]

B. Current Regulative Circuit

The current regulative circuit to maintain constant discharge current is important to Surface Arc Thruster. There are two types of current regulative circuits. The first circuit is using only current regulative diodes(CRD) (Fig. 2). In this circuit, more than one hundred CRDs are connected in parallel and it is possible to control the current from 1A to 5A per 1A. However, the size of the circuit is too large to install on Nano-satellites.

Next circuit (Fig. 3) is combined CRD and transistor. By making the base current a constant small current using CRD, it can be amplified to a constant current of several A. Furthermore, this circuit size is much smaller than only CRD circuit.

The circuit of Fig. 2 is used to experiments in chapter III, IV, and the circuit of Fig. 3 is used in chapter VI, VII.

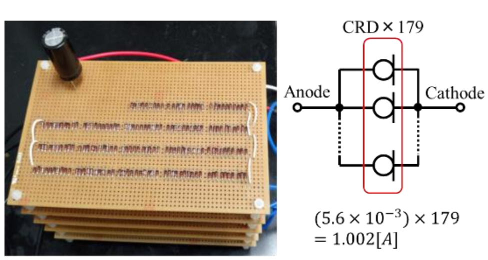

Figure 2. current regulative circuit (CRD)[2]

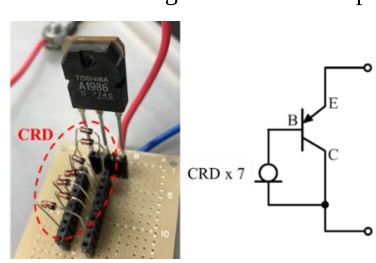

Figure 3. current regulative circuit (CRD+transister)

C. SAT-ver.2

SAT-ver.2 is a prototype of SAT and is used in all experiments described in this paper. The design of SAT-ver.2 is shown in Fig. 4. A size of SAT-ver.2 is $\phi 26 \times D42mm$, and a size of plenum chamber from which propellant gas is generated is $\phi 6 \times 1mm$. Aluminum is used for anode and cathode materials, an alumina insulation pipe is inserted in a center of cathode, and an igniter is inserted therefrom. In addition, O-rings are inserted between a propellant and anode/cathode, and they prevent leakage of gas from other than a nozzle.

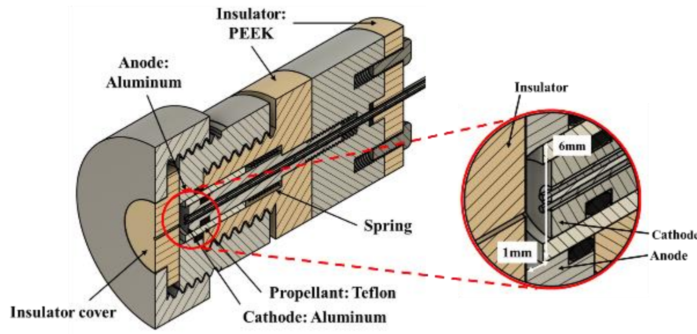

Figure. 4 Design of SAT-ver.2

III. Pressure Measurement

SAT obtains thrust by aerodynamic acceleration of gas vaporized propellant at discharge. Therefore, unless a nozzle opening ratio is appropriate, thrust cannot be maximized. Thus, it is very important to know how the pressure of a plenum chamber changed during discharge. We attempted to directly measure the pressure inside the plenum chamber. If it can be measured, it is possible to calculate thrust and impulse bit generated at the time of discharge.

An experimental system is shown in Fig. 5. In this experiment, a differential pressure sensor was used. The output voltage corresponding to the pressure difference between the vacuum chamber and the plenum chamber was measured with an oscilloscope. The pressure sensor and SAT are connected by a stainless pipe of 1.5mm in diameter (Fig. 6). For the nozzle cover of SAT-ver.2, MACOR® was employed. It is highly heat-tolerant ceramic. In each experiment, a power supply voltage was set to 100V, a capacitor was set to 2mF, and the constant current was set to 5A.

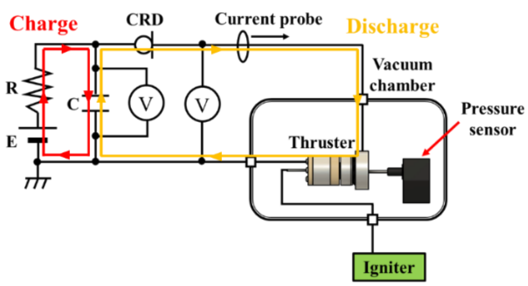

Figure 5. Experimental system of pressure measurement

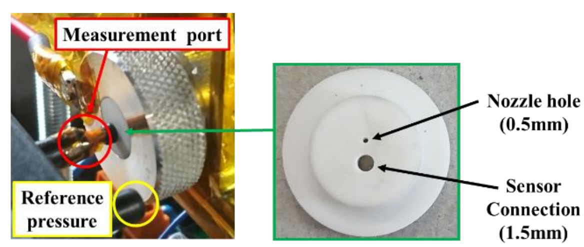

Figure 6. Connection between pressure sensor and thruster

The results are shown in Fig. 7. From Fig. 7, it was confirmed that the pressure in a plenum chamber rose to about 1000Pa at the maximum when discharge occurred. Therefore, it can be considered that vaporized gas is always generated during discharge, and a pressure in the plenum chamber is maintained although there is an increase or decrease, and the thrust is generated.

Next, the thrust of SAT-ver.2 is calculated using the result. The thrust of propulsion can be expressed by Eq. (1) from an injection speed and a math flow rate.

$$F = v_e \dot{m} + (p_e - p_a) A_e \qquad (1)$$

The injection velocity and mass flow rate can be expressed by Eqs. (2) and (3).

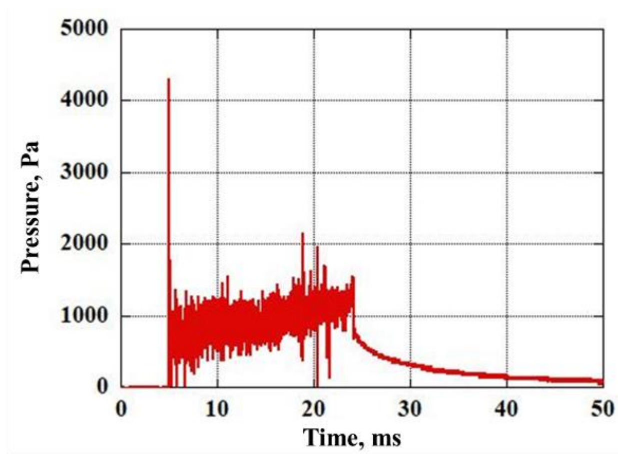

Figure 7. Pressure of Plenum Chamber

$$v_e = \sqrt{\frac{2\gamma RT_c}{\gamma-1}\left\{1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right\}} \qquad (2)$$

$$\dot{m} = \frac{p_c A_t}{\sqrt{RT_c}}\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (3)$$

By substituting Eqs. (2) and (3) into Eq. (1), thrust can be expressed by a following equation.

$$F = p_c A_t \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left\{1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right\}} + \left(p_e - p_a\right)A_e \quad (4)$$

From Eq. (4), thrust can be calculated from plenum chamber pressure and nozzle exit pressure, area of nozzle throat and nozzle exit. Also, the ratio between the plenum chamber pressure and the nozzle exit pressure can be obtained from a following Eq. (5).

$$\frac{A_e}{A_t} = \sqrt{\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \Bigg/ \left\{\left(\frac{p_e}{p_c}\right)^{\frac{2}{\gamma}} - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma+1}{\gamma}}\right\}} \quad (5)$$

From Eq. (5), the nozzle exit pressure can be calculated if the nozzle opening ratio and the plenum chamber pressure are known. Since the plenum chamber pressure has already been measured, the thrust of SAT-ver.2 can be calculated using Eqs. (4) and (5).

Next, a thrust during discharge is calculated using Eq. (4). In the case of four nozzle opening ratios A_e/A_t of 1, 10, 30, 100, thrust was calculated and compared. A throat diameter of SAT-ver.2 used in experiment is 0.5mm, a throat area is 0.196mm^2, and specific heat ratio of Teflon used as a propellant is $\gamma = 1.3$. Fig. 8 shows the thrust calculation result.

As shown in Fig. 8, when a nozzle opening ratio becomes 10 or more, it does not change much, but when $A_e/A_t = 100$, the thrust became the largest and it was found that the maximum thrust increased to about 600μN during discharge. It can also be confirmed that the thrust is constantly changing during the discharge, this indicates that the amount of the propellant gas is not constant, even if the discharge current is constant. Next, Table. 1 shows calculation results of impulse bits obtained during discharge. As shown in Table. 1, when A_e/A_t is 100, the impulse bit becomes 11.5μNs, which is the maximum.

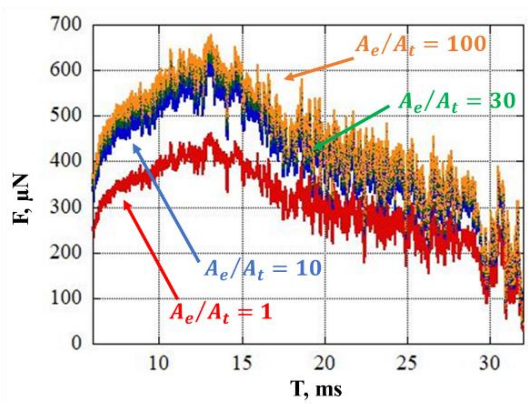

Figure 8. Calculated Thrust from pressure

Table 1. Impulse bit

Case	Ibit, μNs
Ae/At=1	7.86
Ae/At=10	10.6
Ae/At=30	11.1
Ae/At=100	**11.5**

IV. Case of different propellant shape

We examine the effect of propellant shape on SAT thrust. The shape to be compared is shown in Fig. 9.

In Case 1, thrust is compared when changing the propellant depth to 2mm or 4mm. In Case 2, thrust is compared when changing the inner diameter of the propellant to 2mm or 4mm. In these cases, not only a plenum chamber pressure but also a vacuum chamber pressure is measured at the same time.

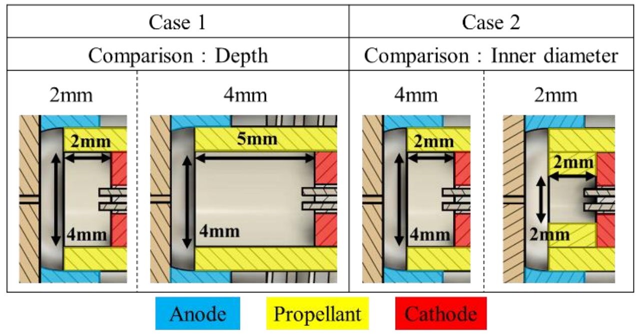

Figure 9. Comparative case of propellant shape

First, the vacuum chamber pressure and plenum chamber pressure at Case 1 are shown in Fig. 10 and Fig. 11. Comparing the vacuum chamber pressure, when the propellant depth is 2mm, the change amount is $\Delta p = 0.38 \times 10^{-3} Pa$, and when the propellant depth is 4mm, it becomes $\Delta p = 2.95 \times 10^{-3} Pa$, which is 8 times or larger. In addition, comparing the plenum chamber pressure, the pressure increases to about 1kPa at the maximum when the propellant depth is 2mm, and at 4mm, a pressure reached to 5kPa. Therefore, it is considered that the longer propellant depth is, the larger the amount of vaporized propellant will be and the plenum chamber pressure will also increase.

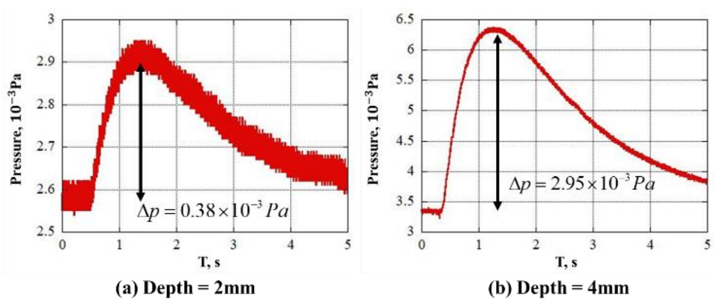

Figure 10. Pressure of vacuum chamber in case 1

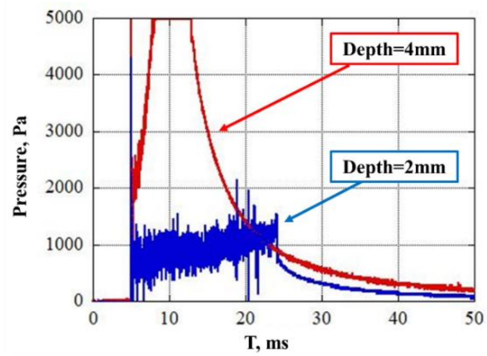

Figure 11. Pressure of plenum chamber of case 1

Next, the vacuum chamber pressure and the plenum chamber pressure in Case 2 are shown in Fig. 12 and Fig. 13. The measurement result of Case 2 that propellant inner diameter is 4mm was used result of propellant depth=2mm because conditions of propellant are same.

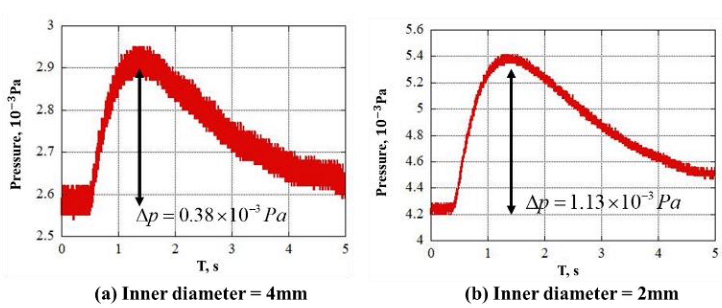

Figure 12. Pressure of vacuum chamber in case 2

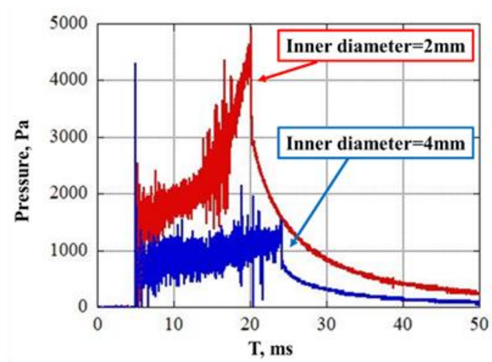

Figure 13. Pressure of plenum chamber of case 2

When comparing the vacuum chamber pressure, when 4mm, the amount of change is $\Delta p = 0.38 \times 10^{-3} Pa$, when 2mm, it is $\Delta p = 1.13 \times 10^{-3} Pa$, which is about three times larger. In comparison with the plenum chamber pressure, when the inner diameter of the propellant is 2mm, the pressure rises up to about 4kPa at the maximum, which is about

4 times as large as the case of 2mm. From the above, it is considered that the smaller the propellant inner diameter, the larger amount of vaporized propellant and the larger the plenum chamber pressure.

V. Investigation about charring problems

Figure. 14 is a result of measuring the vacuum chamber pressure when SAT is injected 10 times. As shown in Fig. 15, when the surface of propellant is charred, Teflon is not exposed on the surface, and it becomes difficult to give energy to the propellant even if discharge occurs next time. As a result, the amount of vaporized propellant decreases, so the pressure in the vacuum chamber will not rise as well. In this state, the pressure of the plenum chamber of SAT also doesn't rise, so that thrust cannot be obtained either. As the SAT acquires thrust by dynamic gas acceleration, it is a serious problem when the pressure fails to rise; it is necessary to understand why charring occurs.

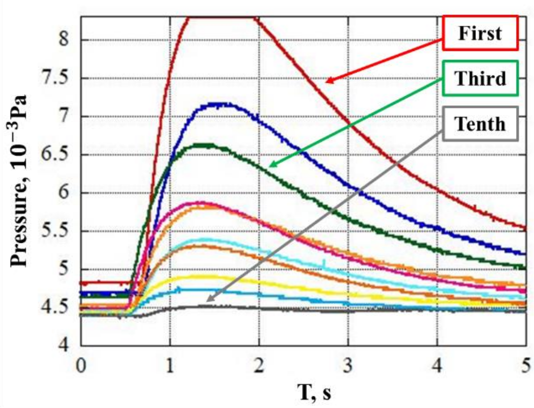

Figure 14. Pressure of vacuum chamber for ten times

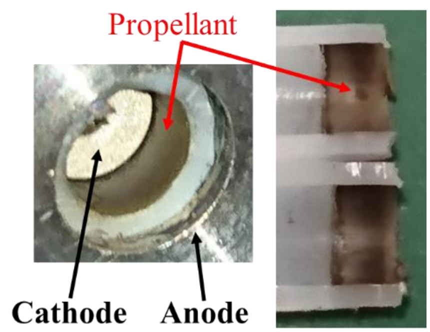

Figure 15. Charring after experiment

One of the reasons for the occurrence of charring is that the carbonized low temperature propellant may cool after discharge and adhere to the propellant surface. Since a discharge current of SAT is limited, it is considered that some of the generated gas also contains propellants in a low temperature state. In addition, although the vaporized propellant is injected from the nozzle, since the flow rate is determined by a throat area. So, all of the gas is not injected during discharge, and the gas remains even after a discharge. Therefore, it is thought that the low temperature gas remaining after discharge cold to carbonize and adhere to the surface of the propellant so that charring occurred. Thus, as shown in Fig. 16, injection was done only once with a nozzle cover removed, and it was checked the state of the propellant after that. The experimental circuit is basically the same as in Fig. 5.

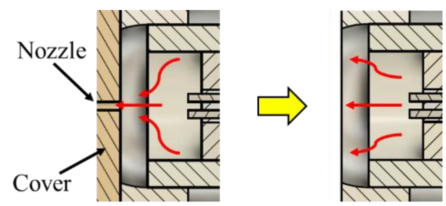

Figure 16. SAT-ver.2 without nozzle

If the above process occurs, propellant vaporized in the absence of the nozzle cover is instantly injected outside the propulsion, so it is considered that charring hardly occurs. Figs. 17 and 18 show a measured vacuum chamber pressure and propellant state after discharge. As shown in Fig. 17, even when the discharge occurred with the nozzle cover removed, a pressure of vacuum chamber increased, so it is considered that the propellant was vaporized. However, as shown in Fig. 18, since charring was observed on the propellant surface even with a single discharge, even if the nozzle cover was removed, the problem couldn't be solved. Therefore, as long as Teflon is used as propellant for SAT, this problem is considered to occur. So, it is necessary to find an alternative propellant for Teflon.

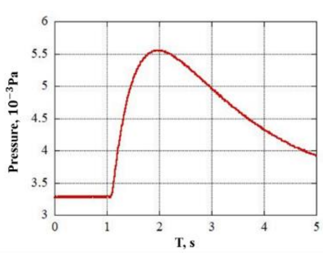

Figure 17. Pressure of vacuum chamber in case of SAT without nozzle

Figure 18. Propellant after discharge

VI. Paraffin Propellant

We examined whether the performance improves when Paraffin wax is used as an alternative propellant. The Paraffin has a melting point of 45 ° C to 75 ° C, which is much smaller than that of Teflon.

As a performance evaluation, first, it was injected 50 shots with the nozzle removed, and the pressure change in the vacuum chamber was measured. Propellant depth was set to 2mm, and diameter was 4mm. The measurement results are shown in the Fig. 19. As can be seen from the Fig. 19 unlike the case of Teflon, there was no decrease in pressure change. The relationship between discharge time and pressure change is shown in the Fig. 20. It was found that the pressure change increased in proportion to the discharge time.

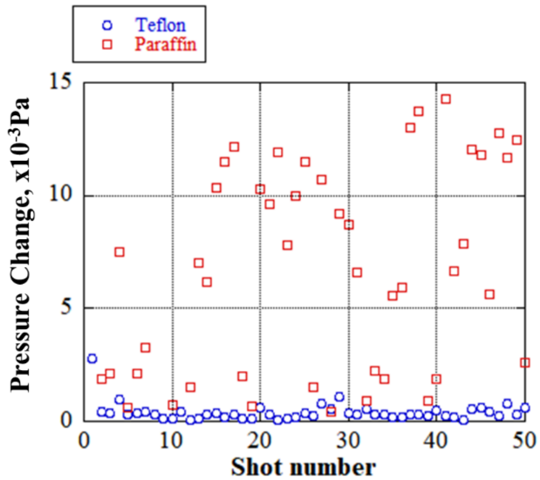

Figure 19. Compare Pressure change (Paraffin, Teflon)

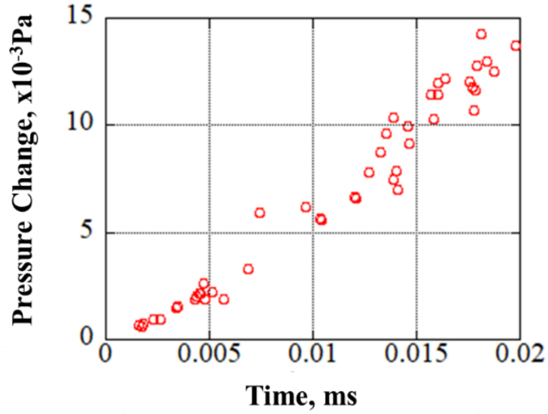

Figure 20. Duration time vs Pressure change(Paraffin)

Subsequently, as in the case of Teflon, the change in pressure in the plenum chamber during discharge was also measured for Paraffin. The test conditions are the same as in fig. 5, and injection was performed 200 times. The measurement results are shown in the Fig 21. In addition, the impulse bits calculated from the pressure change of each injection are shown in the Fig. 22. Calculation method is same as at Teflon. The change in pressure tended to be larger than in the case of Teflon, but the discharge time was much less through 200 injections. On the other hand, as shown in Fig. 23, there was a slight correlation between discharge time and thrust. The cause of the decrease in discharge time when covered is not known, so it is needed to be verified.

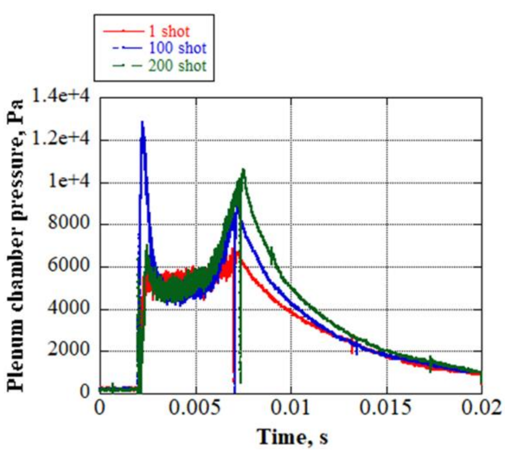

Figure 21. Plenum chamber pressure(Paraffin)

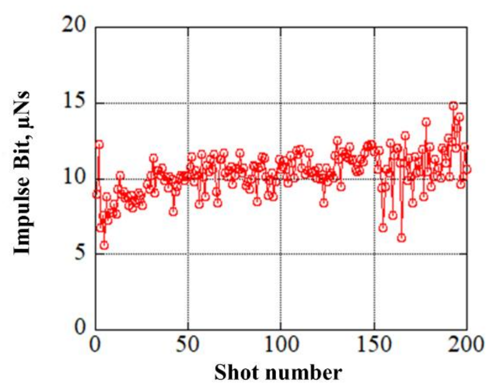

Figure 22. Calculated impulse bit(Paraffin)

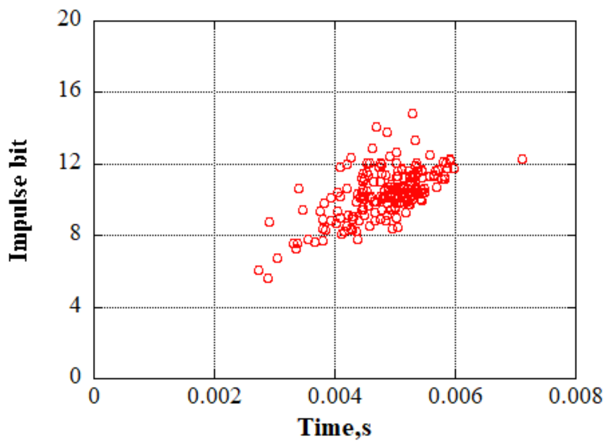

Figure 23. Duration time vs Impulse bit(Paraffin)

Figure 24. Surface of propellant(Paraffin)

The images of the propellant surface before and after the experiment are shown in the Fig. 24. Charring was seen as with Teflon, but the performance became much better than Teflon. In the future, we plan to measure temperature of the propellant surface during discharge and consider charring and model internal phenomena.

VII. Air Bearing Thrust Measurement System

In our laboratory, thrust measurement using spherical air bearing is carried out in previous research. A schematic diagram of a spherical air bearing is shown in Fig. 25. By forcing air from the bottom, the spherical bearing floats on this air and creates a micro friction state. As shown in Fig. 26, the table is fixed to the spherical bearing, and SAT and circuit are installed on it. The impulse bit of the propulsion unit is obtained by measuring rotation of the table by the injection of the propulsion unit with the gyro sensor.

In the previous study, it was not possible to calculate the correct impulse bit because it was not calibrated, but it was confirmed that the table was rotated by the injection of the SAT. Figure. 27 shows a change in the angular velocity of the table when 155 injections of the propulsion device are performed.

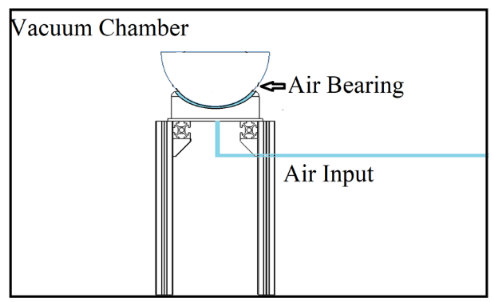

Figure 25. Spherical air bearing overview[4]

Based on this result, we are considering thrust measurement using spherical air bearing also in SAT. Advantages of using spherical air bearings can be applied to attitude control testing. However, in the previous study, since the charging voltage and the discharging current could not be measured, it is necessary to develop a system capable of simultaneously measuring them.

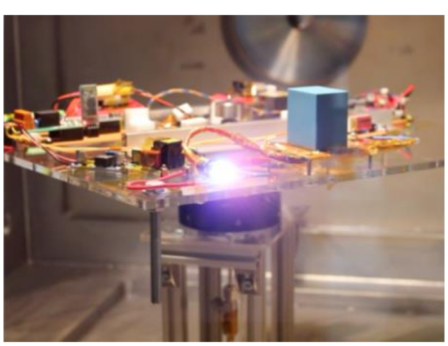

Figure 26. State of thrust measurement using spherical air bearing[5]

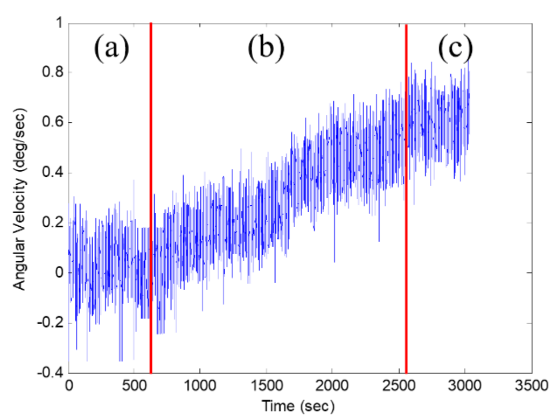

Figure 27. Changes in the angular velocity of the table due to the 155 injection of the propulsion unit[5]
((a) before injection, (b) during injection, (c) after injection)

The outline of the measurement system under development is shown in Fig. 28, and the circuit that is being fabricated is shown in Fig. 29. The inputs of the igniter and the high-voltage DCDC converter are switched by the relay that is controlled by MPU. The microcomputer can communicate with the PC by the communication module of the 2.4 GHz band (Bluetooth). Current Regulative Circuit (CRC) is made up of a transistor and a CRD to achieve downsizing. Capacitor voltage and discharge current are measured by a USB oscilloscope (OPENSCOPE MZ) with a

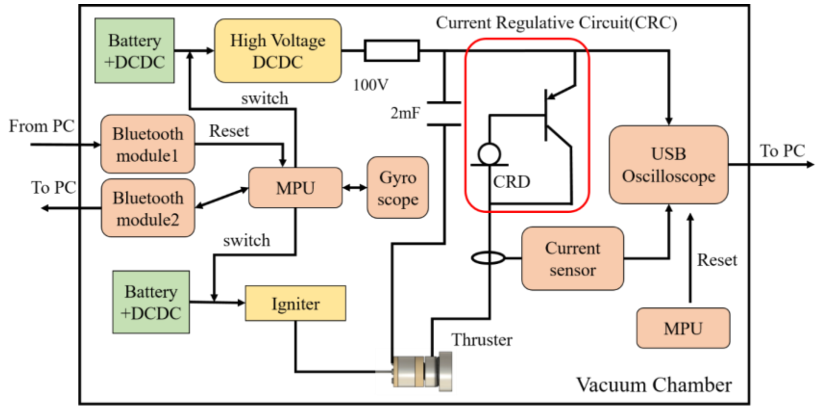

Figure 28. Measurement system overview

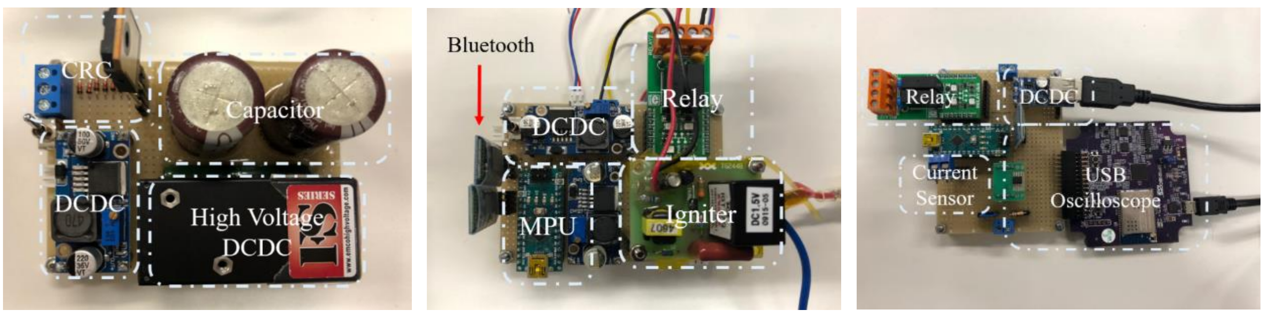

Figure 29. Circuit Overview

Wi-Fi module and the data send to PC. MPU and USB oscilloscopes can be reset from the PC as measures against freeze.

Also, from the thrust calculated by pressure measurement, the minimum resolution of the impulse bit required for this measurement system was set to 0.1μNs. To derive the impulse bit from the angular velocity of the table, the equation of motion of rotation is applied.

$$n\frac{dL}{dt} = I\Delta\omega + T \qquad \frac{dL}{dt} = N = I_{bit} \times r \tag{6}$$

In order to check the system operation, we connected a miniaturized circuit to the propulsion unit and placed it on a table, measured the discharge current and capacitor voltage correctly, and confirmed whether the data could be acquired by the PC and whether the table rotated.

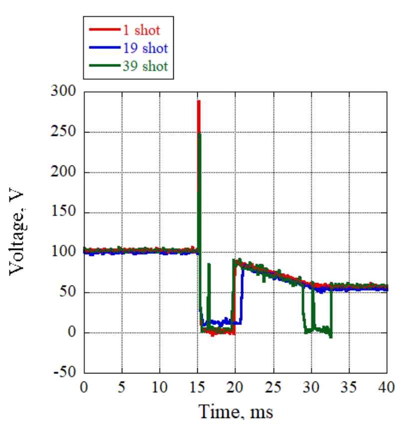

Figure 30. Voltage waveform

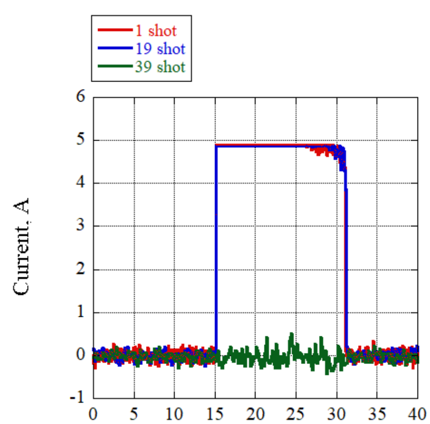

Figure 31. Current waveform

Figures 30 and 31 show the waveforms of the measured discharge current and capacitor voltage. In this experiment, 39 shots were successful, but communication was frequently interrupted. Although it was confirmed that the angular velocity of the table has changed, it was not certain whether the rotation was caused by injection, but it is also considered that the rotation was caused by the frictional force of the incoming air, and both the mechanism and the circuit need to be improved.

VIII.Conclusion

In this paper, we discussed the measurement of internal pressure change by SAT injection and development of thrust measurement system of SAT using air bearing.

From the pressure measurement of the plenum chamber, it was confirmed that the propellant was vaporized by discharge and the pressure increased. Furthermore, the thrust of SAT and appropriate nozzle opening ratio could be calculated from pressure change. By changing the shape of the propellant, it was confirmed that the pressure in the plenum chamber was improved.

From the measurement of the pressure in the vacuum chamber, it was confirmed that each time of discharge was repeated, a decrease in the degree of pressure change and a charring of the surface of the propellant were observed. On the other hand, it was confirmed that the performance is improved when the propellant was changed to Paraffin wax.

For the thrust measurement system using air bearing, it was possible to miniaturize the circuit and to perform the operation test in the vacuum chamber.

In the future, we continue evaluating Paraffin wax propellant and consider the optimized parameter of SAT. For the thrust measurement system using air bearings, we will improve the whole system.

References

[1]Space Works , "Nano/Microsatellite Market Forecast, 8th Edition", pp.7(2018), URL:http://www.spaceworkscommercial.com/wp-content/uploads/2018/04/Nano-Microsatellite-Market-Forecast-8th Edition-2018.pdf

[2]Murakami, H., Sakurai, M., Toyoda, K., and Cho, M., "Preliminary Experimental Results of Surface Arc Thruster", 35th International Electric Propulsion Conference, IEPC-2017-491, Georgia, USA,2017.

[3]Hiraka, K., Murakami, H., Toyoda, K., and Cho, M., "Performance Evaluation and Development of Thrust Measurement System of Surface Arc Thruster", 32nd ISTS, Fukui, Japan, 2019.

[4]Marcos, H, H., and Cho, M., "Lean Satellite Attitude Testing Platform in Vacuum Environment", Kyushu Institute of Technology, Japan, 2018, Master Thesis

[5]Phongsakorn, M., and Cho, M., "Attitude Determination and Control System Using Vacuum Arc Thruster for Nano-satellite", Kyushu Institute of Technology, Japan, 2018, Master thesis