Research and Development on Coaxial Pulsed Plasma Thruster with Feed Mechanism

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Abstract: Research and development on pulsed plasma thruster (PPT) for small satellites have been conducting in Tokyo Metropolitan University (TMU). In this study, improvement of total impulse on coaxial PPT was conducted in order to apply it to propulsion systems for small satellites. In previous study, total impulse was improved from 3.5Ns to 17.5Ns by single thruster head. Now, a PPT with propellant feed mechanism named Disk Feed PPT, which changes a used cylindrical propellant for a new one, was developed. As a result, Disk Feed PPT achieved total impulse of 160Ns.

Nomenclature

d	=	cavity inner diameter
l	=	cavity length
d_c	=	cathode inner diameter
E_0	=	stored energy
C	=	capacitance
V	=	charged voltage
g	=	gravity acceleration
I_b	=	impulse bit
I_{tot}	=	total impulse

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I. Introduction

SMALL satellites are developed in the resent space exploration because of its good cost performance, short development period and utilization of advanced technologies. Along with that, compact, lightweight and highly functional propulsion devices are required for them. Pulsed Plasma Thruster (PPT) is one of the electric propulsion devices, which is expected to be applied for small satellites, because of the following features[1,2]:

1) Simplicity; PPT system has a simple and lightweight structure, and high durability because it does not need any tanks, seals and mechanical valves by using a solid propellant such as poly-tetrafluoroethylene (PTFE).
2) Precise total impulse; PPT can control total impulse easily because it generate accurate and small pulse-thrust at optional time interval.
3) Low power consumption; PPT can operate at several watts.

In Tokyo Metropolitan University (TMU), research and development on two types of PPT for small satellites have been conducted. One is rectangular PPT; the other is coaxial PPT.

PPT-B20[3,4] is a typical rectangular PPT that has parallel plate electrodes and a breech-fed propellant. The photograph and the thrust performances are shown in Fig. 1 and Table 1. It has achieved the small impulse bit of 22 μ Ns with the high specific impulse of 960 s. The power consumption of its all system is only 4.2W at 0.75Hz operation frequency and it has achieved a million shot operations continuously. Recently, the missions for small satellites have been required widely. PPT-B20 is appropriate to the missions that demand a precise total impulse with a long lifetime, such as attitude control and vibration control. However, its impulse bit is too small to comply with the missions that demand a high ΔV such as station keeping and an orbit transfer.

On the other hand, coaxial PPT with PTFE cylindrical cavity has achieved larger impulse bit and lower specific impulse compared with rectangular PPT such as PPT-B20 at the same stored energy.[5,6] It will be required to comply the missions that demand a high ΔV in time. The thrust performance ranges of rectangular PPT and coaxial PPT in TMU are shown in Fig. 2. The combination of rectangular PPT and coaxial PPT will enable to achieve various missions. Then, research and development on the coaxial PPT system have been conducted .

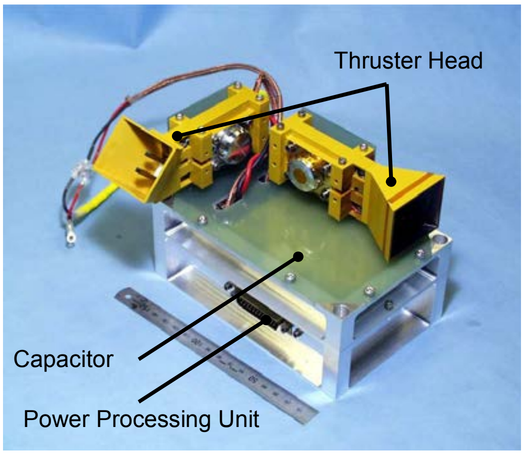


Figure 1. Photograph of PPT-B20 system.

Table 1. Thrust performances of PPT-B20 system.

Items	Value
Capacitance, μF	3
Charged Voltage, kV	1.5 (Nominal)
Stored Energy, J	3.3 (Nominal)
Power Consumption, W	4.2 (Nominal)
Impulse Bit, μNs	22
Mass Shot, μg	2.3
Specific Impulse, s	960
Thrust Efficiency, %	3.1
Specific Thrust, μN/W	6.5

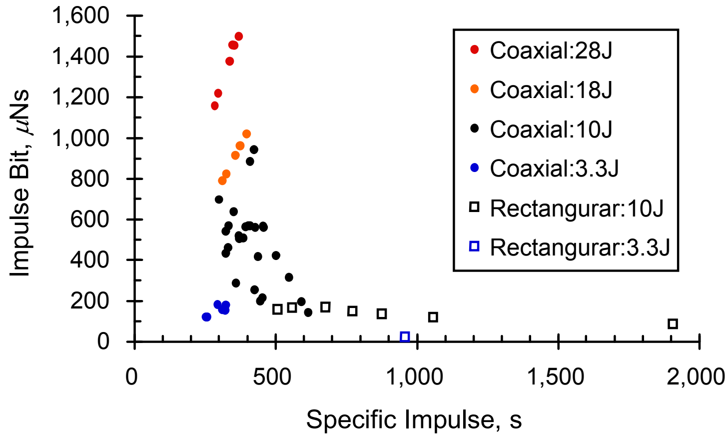


Figure 2. Thrust performance range of rectangular PPT and coaxial PPT in TMU.

II. Coaxial PPT

A. Coaxial PPT[5-8]

Coaxial PPT consists of four parts as shown in Fig. 3: cylindrical anode, cylindrical cathode with orifice, ignitor, and hollow propellant. The electrodes and the propellant are coaxially arranged, and ignitor is mounted on the cathode. Main discharge current passes and evaporates the cylindrical cavity of the propellant and neutral propellant /plasma are ejected from an orifice of the cathode by electrothermal force mainly. In TMU, the characteristics, the problems, and the approach to total impulse improvement by single thruster head had been studied and described as follows.

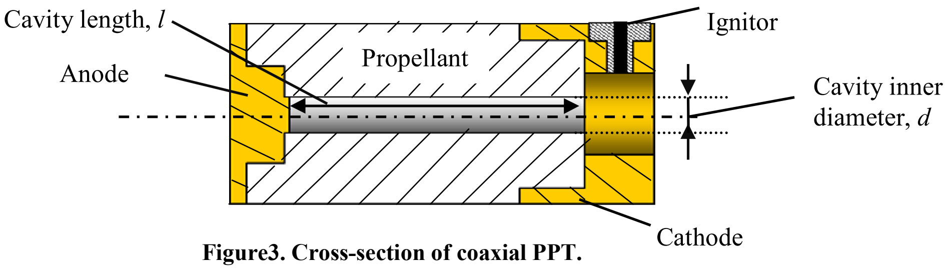


Figure3. Cross-section of coaxial PPT.

B. Single Thruster Head[5-8]

PPT is required the long time operation as the small impulse bit propulsion device in the satellites mission. In order to estimate the lifetime of coaxial PPT, repetitive operation test has been conducted. The result of the test by single PPT was shown in Fig.4. Thrust performances are decrease because of the cavity inner diameter become increase while PPT running. Shot number of 60,000shots was decided as maximum shot number in these experimental dimensions, because miss shots occurred frequently over 60,000 shots at this thruster form. PPT with the cavity length of 30mm achieved the maximum total impulse of 17.5Ns from 3.5Ns by a single propellant at previous study

Table 2 shows total impulse requirements for some small satellite missions. Total impulse of 17.5Ns, obtained in previous study, is too small to apply to satellite mission. Therefore, coaxial PPT must be improved to achieve larger total impulse. In order to overcome this problem, it is considered that propellant feed mechanism is the most effective.

Table 2. Small satellite (50kg) missions and required performances.

Mission	Total Impulse, Ns
Attitude Control (1 year)	150-200
Drag Free (1year, 400km)	3,000-4,000
De-orbit (800-200km)	10,000-20,000

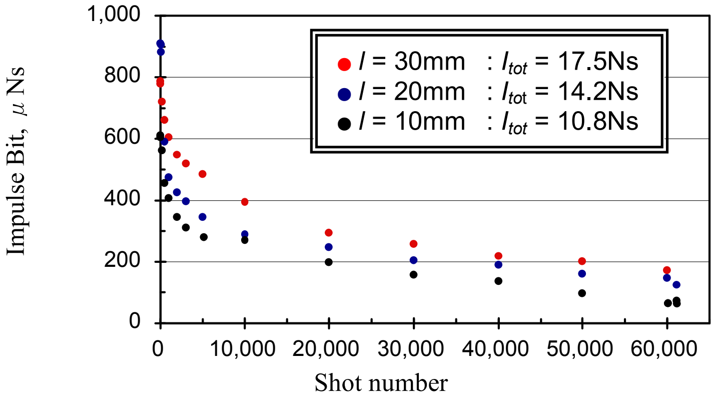
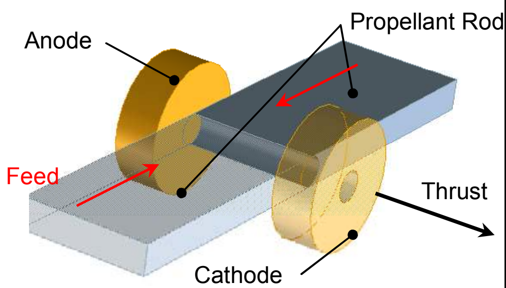
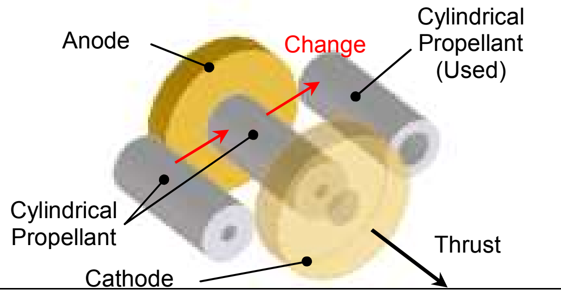


Figure 4. The result of repetitive operation test by single PPT.

C. Feed Mechanism[9]

As described above, propellant feed was very important to obtain practical total impulse. Two of propellant feed has been considered as shown in Table 3. One is the method to feed the propellant rods, which makes the cavity as a discharge chamber with several rods; the other is the method to change the cylindrical propellants many times. In the former case, since propellant rods are only pushed into the discharge chamber when a part of the propellant is consumed, feed action is very easy. Initial cavity configuration will be kept conceptually and constant thrust performances will be achieved. However, it was actually difficult to maintain the cavity configuration and to provide constant thrust performances. On the other hand, in the latter case, when the single propellant rod was consumed until the end of its lifetime, the used propellant is changed to the new propellant. “Changing” is a little bit difficult as feed action compared with “Feeding” of some rods. Moreover, the propellant will recover to its original fresh condition by changing the propellant. And then, as a matter of course, thrust performances will get back to initial performances. Since the propellants have a seamless cavity, destruction of the feed mechanism by plasma leakage never occurs. In addition, if a propellant has some issues, refreshing the propellant makes possible to continue repetitive operation. Therefore, the latter way; changing cylindrical propellants was adopted in TMU.

Table 3. Type of the propellant feed mechanism and the characteristics.

Items	Feeding Propellant Rods	Changing Cylindrical Propellants
Concept Figure		
Merit	● Thrust performances are steady conceptually. ● Feed action is easy such as follow springs.	● Discharge chamber can be refreshed with propellant. ● Discharge chamber does not have any seam.
Demerit	● Leaked plasma from the seam of discharge chamber destroys this mechanism.	● Thrust performances are deteriorated gradually. ● Change action is complicated such as motor drive.

III. Objective

For various mission of small satellite, the objective of this study is to improve total impulse of the coaxial PPT by propellant feed mechanism.

IV. Experimental Apparatus and Procedure

A. Disk Feed PPT-1

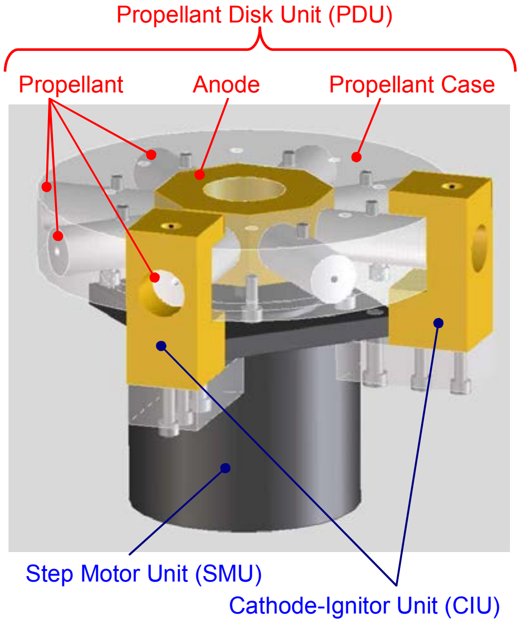
Disk Feed PPT-1 (DF-1) is the prototype coaxial PPT with propellant change mechanism. Conceptual schematic and photograph of DF-1 are shown in Fig. 5. DF-1 consists of the three units: Propellant Disk Unit (PDU), Cathode-Ignitor Unit (CIU) and Step Motor Unit (SMU) as shown in Fig.5 (a). PDU contains several propellants, an anode, and a propellant case. This part was fixed on the axis of the step motor through the holding fixture, and was rotated by the motor. CIU, which contains cathode and ignitor, was fixed on the baseplate. This part has no contact with PDU. Main electrical discharge occurs between the cathode and the anode through the cavity of the propellant. Used propellant was replaced with the new one by rotation of PDU.

As the anode rotates with the propellants, the anode face will be refreshed. Moreover, multidirectional thrust is achieved by addition of CIU at the optional direction, because the propellants are placed radially. It is an advantage for the small satellite to achieve required attitude with limited thruster system.

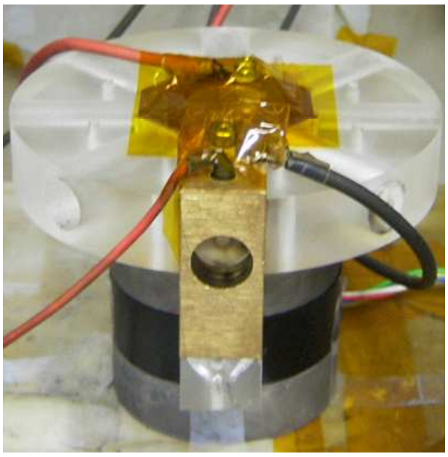
Repetitive operation test using DF−1 has conducted as well as that of single thruster head. Experimental condition was shown in Table 4. Before this test, it was checked whether each propellant was placed in front of the cathode and DF-1 operated in every case in the vacuum facility.

Table 4. Experimental condition of repetitive operation test by Disk Feed PPT-1.

Items	Value
Cavity Diameter, *d*, mm	2.0
Cavity Length, *l* ,mm	30
Cathode Inner Diameter, d_c ,mm	12
Propellant Number	8
Capacitance, *C* , μF	6
Charged Voltage, *V* ,kV	1.8
Stored Energy, E_0 ,J	10



(a) Conceptual schematic of Disk Feed PPT-1.



(b) Photograph of Disk Feed PPT-1 for experiments.

Figure 5. Photograph and basic concept of Disk Feed PPT-1.

B. Disk Feed PPT-2

Disk feed PPT-2 （DF-2）is the second model for the feed mechanism. Conceptual schematic and photograph of DF-2 are shown in Fig. 6. DF-2 consists of the three units: PDU, CIU, SMU same as DF-1. DF-2 is the experiment model that solve the trouble at DF-1. Improvements at DF-2 are follows.

1. In order to enhance adhesion of propellant and anode, both propellant and anode were designed screw cutting and the anode was screwed into the propellant. Cross-section of diagram was shown Fig.7.

2. At DF-1, CIU has no contact with PDU. So, there is the gap between propellant and cathode. Because of the gap between propellant and cathode may affect operation and thrust performance, DF-2 can be changed the gap of between cathode and propellant. Then, the investigation of the influence of the gap had conducted to find the optimum gap at DF-2.The experimental condition was same as repetitive operation test at DF-1.The gap in this test was changed into 0mm,0.3mm,0.5mm, and 1.0mm.

3. For the satellite deployment, DF-2 has attained light weight. Table 5 shows mass breakdown at DF-1 and DF-2.

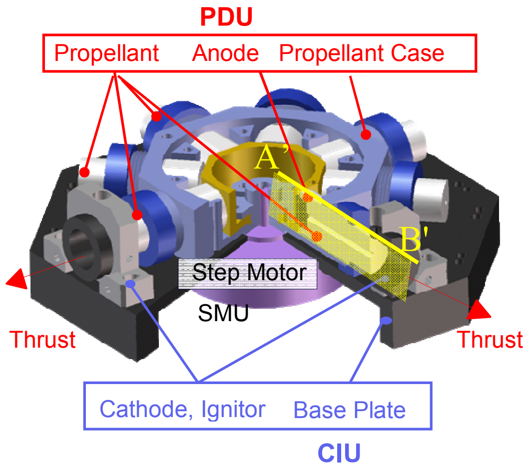
Repetitive operation test using DF-2 has conducted as well as that of DF-1. Experimental condition was same as DF-1 shown in Table 6.

Table 5. Mass breakdown at DF-1 and DF-2

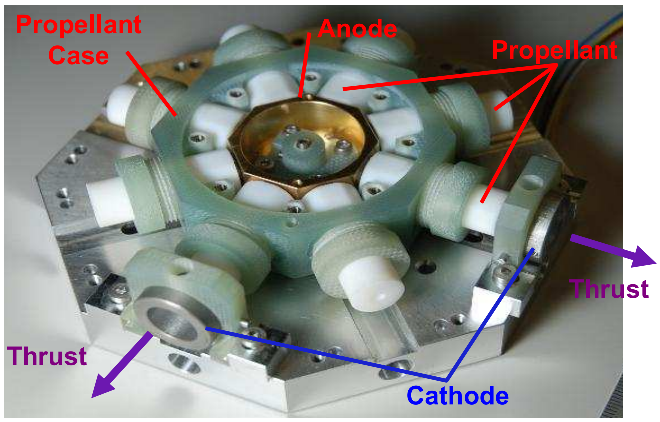
	Disk Feed PPT-1	Disk Feed PPT-2
	mass, g	
CIU	87	88
PDU	300	165
SMU	450	268
Total	837	521

Table 6. Experimental condition of repetitive operation test by Disk Feed PPT-2.

Items	Value
Cavity Diameter, d, mm	2.0
Cavity Length, l ,mm	30
Cathode Inner Diameter, d_c ,mm	12
Propellant Number	8
Capacitance, C , μF	6
Charged Voltage, V ,kV	1.8
Stored Energy, E_0 ,J	10



(a) **Conceptual schematic of Disk Feed PPT-2.**



(b) Photograph of Disk Feed PPT-2 for experiments.

Figure 6. Photograph and basic concept of Disk Feed PPT-2.

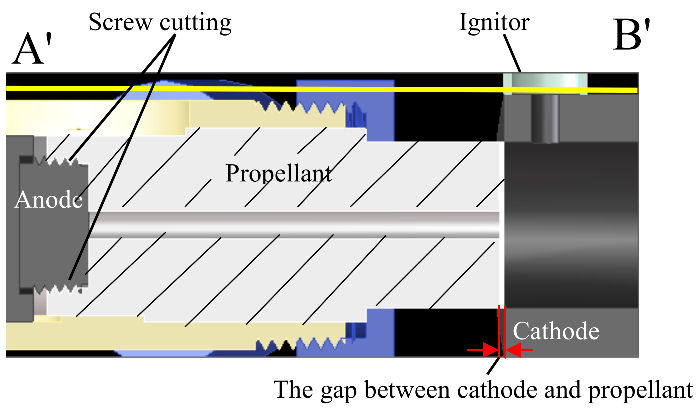


Figure7. Cross-section diagram of DF-2.

C. Vacuum Facility

All experiments were conducted in a vacuum chamber, and its diameter and length are approximately 1m and 2m, respectively. Through a PPT operation, a pressure in the vacuum chamber was kept at approximately 6×10^{-3}Pa.

D. Thrust Performances

In this study, the impulse bit I_b, was obtain in the measurements of thrust performances. And the impulse bit history and the total impulse I_{tot} were obtained in the repetitive operation tests. The impulse bit was measured by target method[10].

Total impulse was estimated by impulse bit history of repetitive operation. The plots were connected with straight line, which recorded the value of impulse bit and shot number. Total impulse was estimated by the integration from the area surrounded by impulse bit history.

V. Results and Discussions

A. Disk Feed PPT-1 (DF-1)

Repetitive operation of approximately 150,000shots was achieved with DF-1. Impulse bit history of this test was shown in Fig. 8, and total impulse of 54.6Ns was obtained. DF-1 operated approximately 25,000shots per one propellant rod and propellant was changed. On the other hand, operation of 60,000shots was achieved previous study. If these achievements are combined, DF-1 has possibilities to achieve further shot number of 480,000shots and total impulse of 140Ns.

This result is only 32％of target which is 480,000shots. Following two reasons were confirmed as trouble to obstruct accomplishment and investigated cause of malfunction.

1. At single thruster head, the anode has two steps to enhance adhesion of propellant and anode. However, since an anode is flat at DF-1, the sublimated propellant begins to leak from that anode side. Then, energy density decrease and it may be cause of miss shot.
2. As mentioned above, CIU has no contact with PDU. For the reason, there is gap between propellant and cathode. Main discharge between the anode and cathode may have not occurred because of the influence of the gap.

B. Disk Feed PPT-2 (DF-2)

The result of the investigation of the influence of the gap was shown in Table 6. As the result, the performance was better when the gap is smaller. Rotary disk unit was able to drive without problems except when the gap was 0mm. However, the operation had been terminated about 50,000shots at 0.5mm and 1.0mm. Total impulse is same in 50,000 shots at all conditions. Therefore, the gap of 0.3mm was adopted at DF-2. In addition, 80,000 shots operation per one propellant rod was confirmed at DF-2. However, as miss shots occurred frequently after 60,000 shots in all conditions, and the unstable operation continued, we decided that 60,000 shots were maximum shot number at DF-2. As total impulse, DF-2 achieved 20Ns by 60,000 shots per one propellant. And then, DF-2 is possible to achieve 160Ns.

Repetitive operation of approximately 480,000shots was achieved with DF-2. Impulse bit history of this test was shown in Fig. 9, and total impulse of 160Ns was obtained. DF-2 operated approximately 60,000shots per one propellant and all propellants were able to replace in this test. DF-2 achieved 150-200Ns level total impulse which is required for attitude control in 50kg class small satellite. Moreover, if Disk Feed PPT mounts more propellants, more total impulse will be achieved.

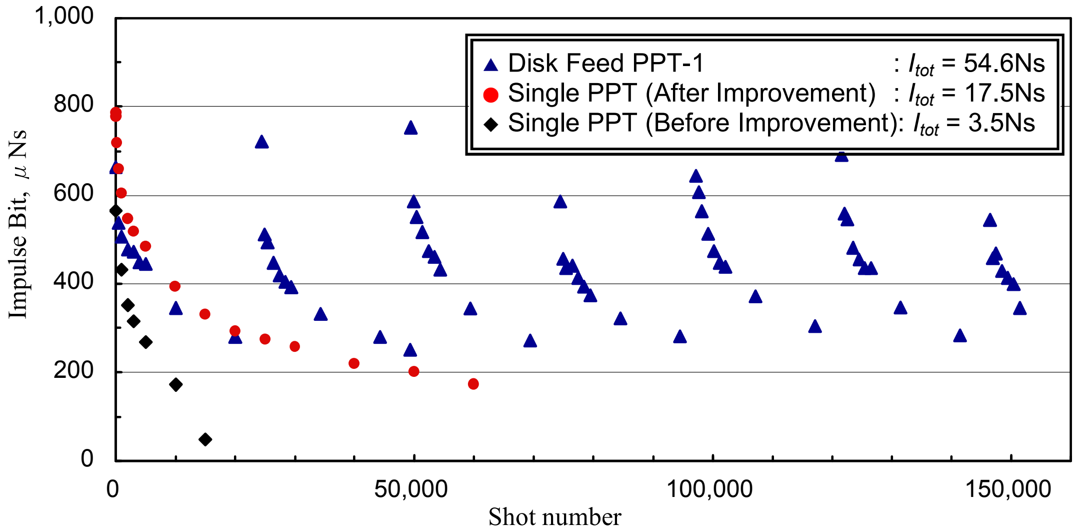


Figure 8. Impulse bit history of repetitive operation test at Disk Feed PPT-1.

Table6. Result of investigation influence of the gap.

C/P Distance	0 mm	0.3 mm	0.5 mm	1 mm
Rotary Drive	N/A	Good	Good	Good
Total Impulse (~ 50,000shot)	18.8 Ns	18.3 Ns	19.0 Ns	18.7 Ns
Total Shot Count	80,000	80,000	55,000	50,000
Total Impulse (~ operation stop)	25.9 Ns	23.9 Ns	20.2 Ns	18.7 Ns
Cause of operation stop	Run out of propellant		Miss Shot	

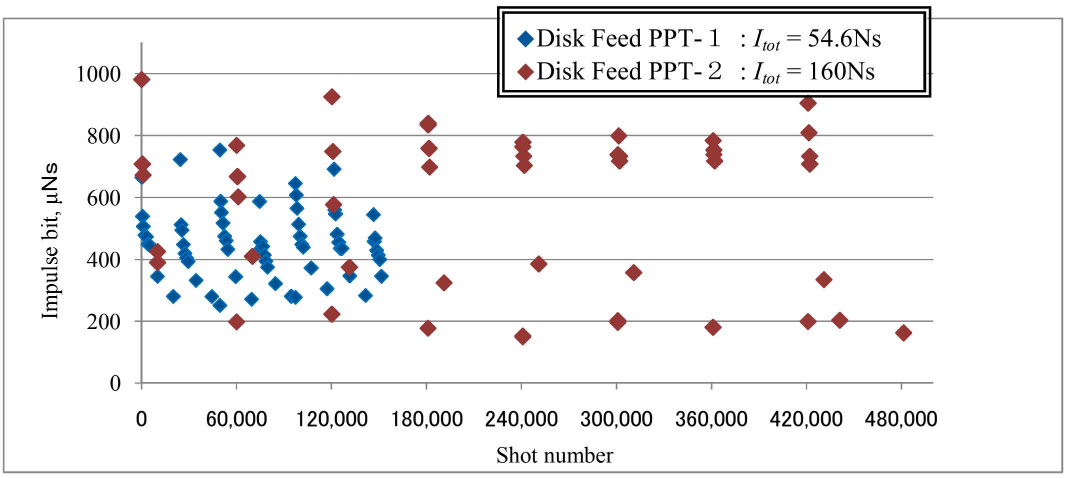


Figure 9. Impulse bit history of repetitive operation test at Disk Feed PPT-2.

VI. Conclusions

Conclusions of this study were as follows:

Development of Propellant Feed Mechanism.

・Disk Feed PPT-1

1) DF-1 was developed as the PPT with propellant change mechanism.
2) DF-1 achieved shot number of 150,000shot and total impulse of 54.6Ns in repetitive operation test at the stored energy of 10J.

・Disk Feed PPT-2

3) DF-2 was developed as next model of DF-1
4) The optimum gap between cathode and propellant at DF-2 is 0.3mm.
5) DF-2 achieved shot number of 480,000shots and total impulse of 160Ns in repetitive operation test at the stored energy of 10J. This result is the great achievement enough to apply small satellite mission like attitude control.

Acknowledgments

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