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Verification of the Electrical Thrust Control Valve in the Small LOX/Methane Engine Firing Tests

Yutaro Ota[*†], *Hiroya Asakawa*[*], *Ryohei Ishikawa*[**], *and Tatsuya Hashizume*[***]
**IHI Corporation*
229, Mizuho-machi tonogaya, Nishitama-gun, Tokyo, 190-1297 Japan
***TOKO VALEX CO.,LTD.*
4-2-17, Matsushima, Edogawa-ku, Tokyo 132-0031 Japan
****JAXA*
2-1-1 Sengen, Tsukuba-shi, Ibaraki-ken, 305-8505 Japan
ota2065@ihi-g.com – *asakawa1840@ihi-g.com*

Abstract

This study reports on the development status and test results of electrically actuated cryogenic propellant valves in LOX/Methane engine firing test. These electrically actuated valves allow for engine throttling during operation. During the LOX/Methane engine firing tests, the response characteristics of valve performance to engine combustion behavior were properly confirmed using actual propellant. The stable operation of the electrically actuated valve under required high pressure conditions at cryogenic temperatures was demonstrated and the expected results were obtained.

1. Introduction

Methane is attracting attention as a fuel for rocket engines due to the following advantages; superior propulsion per unit density, less soot generation, or evaporation and less risk of leakage, and common use of parts with oxidizer due to the similar temperature and quantity required in engine operation. In recent years, the development of rocket engines using LOX/methane as propellant, such as Prometheus, M-10, Raptor and BE-4, has been progressing worldwide [1-3]. In Japan, research and development to improve the performance of regeneratively-cooled LOX/methane rocket engines for application to future space transportation systems was started in 2013, and after open-cycle engine tests in 2018, closed-cycle engine demonstration tests were conducted starting in 2020 [4-6].

The electrically actuated cryogenic propellant valves developed are planned for use in current research and development programs and future engine systems. Electric operation eliminates pneumatic gas and its supply system including gas accumulator, and is expected to simplify and lighten the engine system, as well as cost reduction. Meanwhile, engine thrust throttling is a function required for future transportation systems, including deep space exploration. Therefore, this valve is equipped with propellant flow control function in addition to Open-Close function, so that the engine thrust level can be easily varied without replacing the trimming orifice as conventionally. With continuous throttling of the valve achieved electrically, the engine operating point (mixture ratio and combustion pressure) can be varied during engine combustion.

Asakawa et al. reported that they have been developing this motorized valve by improving with various elemental tests [5-6]. Since the development of the valve itself, including the controller, was completed, this paper reports on the operational test results of the electrically actuated valve under actual propellant and control conditions in LOX/Methane engine firing tests.

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2. Experiment

2.1 Requirements

The research program was undertaken to investigate the feasibility of a high-performance methane engine as part of a 30 kN-class LOX/methane full-expander cycle engine study. The vacuum Isp of the engine is projected to reach 370s with a nozzle expansion ratio of 210. It is also envisaged to be employed in future transport systems such as lunar landers and has a continuous throttling function. Engine characteristics are shown in Table 1.

Table 1 30 kN-class LOX/methane full-expander cycle engine specification.

Item	Value
Thrust, vacuum	30 kN
Isp,vacuum	370 sec (Expansion Ratio = 210)
Propellant	LOX/methane
Throttling	50 to 100 % (Continuous)

In addition to shutoff valves in the main oxidizer line and main fuel line, the engine requires flow control valves in the turbine bypass line, regenerative cooling outlet and main oxidizer line. However, it is undesirable to install flow control valves and shutoff valves in the same line, as this leads to an increase in engine mass and engine system complexity. As such, the development of the valve with two functions, flow control and shutoff, was essential. For chilldown valves, electrically operated flow control is also desired. The advantage is that the valve throttling allows for efficient cooling of the engine and ground facility systems, thus saving chilldown time and propellant. The development of four valves was planned: the main propellant valves (MOV and MFV) and the chilldown valves (OCV and FCV).

2.2 Valve design

For efficient development, all valves are based on the same common design except for the Cv value. The valve configuration is shown in Figure 1.

The main features of the valve design are as follows:

- A poppet design for easy mass flow control.
- A bellows sealing element to ensure fluid sealing and non-leakage.
- A unique high thrust, stepping motor system with a Harmonic Drive® reducer and 3D toggle [7-8].
- A 3D toggle structure (Figure 2), generating a large sealing force at shutdown for extremely low leakage volume even at extremely low temperatures.

The mechanical principle of the valve design is as follows:

- The stepping motor generates and transmits the torque to the HarmonicDrive®.
- The HarmonicDrive® amplifies and transmits torque to the 3D toggle.
- 3D toggle converts the torque into axial thrust and adjusts the throttling by moving the poppet.

The IHI-TDM method, based on Total Design Management (TDM) method, a combination of Set Based Design (SBD) and Model Based Risk management (MBR) (Figure 3) [9], was used for design optimization. SBD is a design method in which the desired design solution is selected by filtering from a whole set of design solutions with both design variables and evaluation indicators as attribute values, according to the will of the designer and the customer. Deriving the optimum solution from filtering is efficient because it eliminates the need for calculations each time there is a change in requirements. Another feature is that the design can also take robustness into account, taking into account error factors rather than champion data. MBR is a risk management method that identifies poor technical understanding of the equations, coefficients and input values of the mathematical models used by the designer as a risk, assesses the magnitude of the risk defined by the level of technical understanding and impact, and implements risk reduction

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measures. In combination, these enable a rapid development process with fewer setbacks. The details of the development process are reported by Asakawa et al and shown in the references [5-6].

The specifications of the valve designed based on the previously noted functional requirements and engine targets are shown in Table 2. The representative appearance of the electrically actuated valve is also shown in Figure 4.

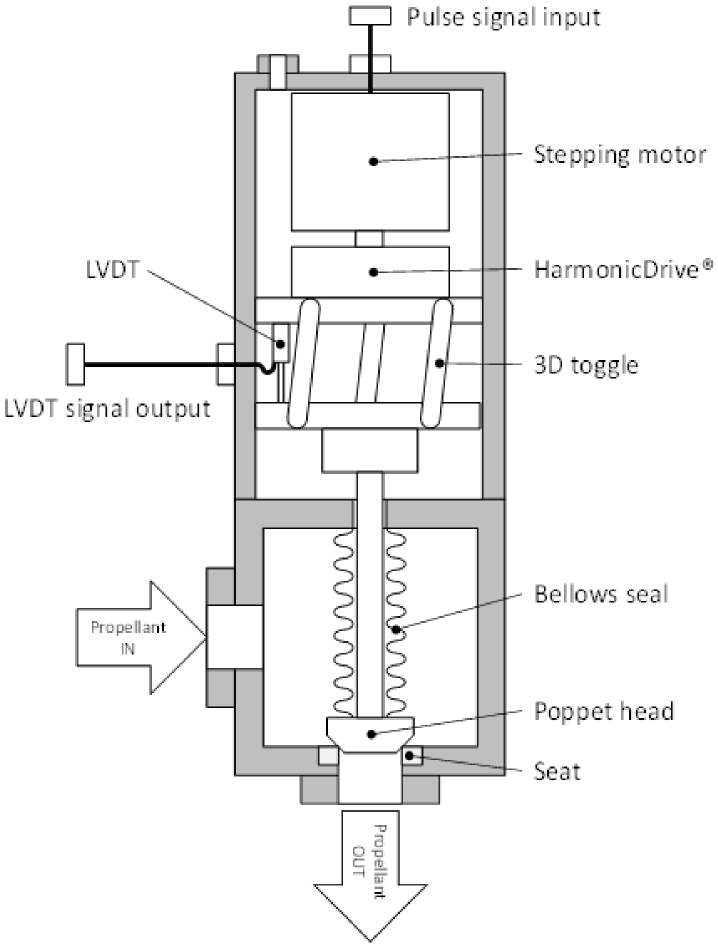

Figure 1 Valve configuration.

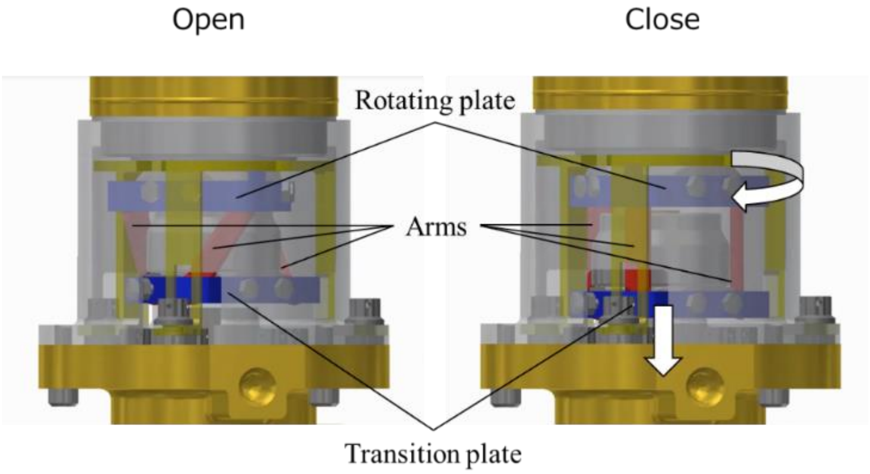

Figure 2 3D toggle configuration.

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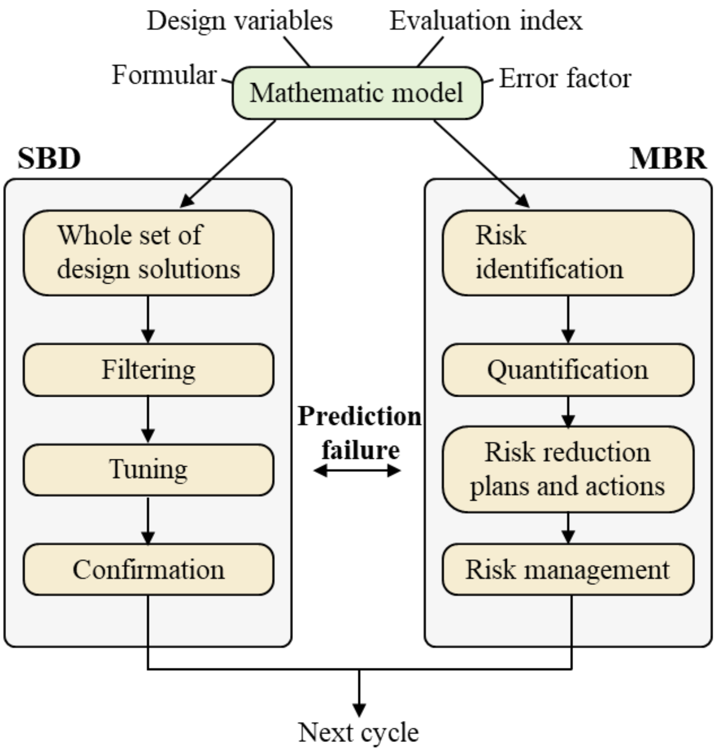

Figure 3 The conceptual drawing of IHI-TDM method.

Table 2 Design requirements for electrically actuated valves.

Item	MOV/MFV	OCV/FCV
Operating pressure	13 MPa	13MPa
Leakage	Ambient : less than 1 sccm Cryogenic : less than 60 sccm	Ambient : less than 1 sccm Cryogenic : less than 60 sccm
Operating temperature	77 to 333 K	77 to 333 K
Proof pressure	Operating pressure×1.5	Operating pressure×1.5
Burst pressure	Operating pressure×2.5	Operating pressure×2.5
Cv (Flow capacity)	>17.9 (Water: 4.3 L/s @288.75 K, ΔP: 0.1 MPa)	>2.45 (Water: 0.6 L/s @288.75 K, ΔP: 0.1 MPa)
Operating cycle	Ambient: More than 500 times Cryogenic: More than 500 times	Ambient: More than 500 times Cryogenic: More than 500 times
Size	ϕ90 x 327.5 mm	ϕ77 x 261.5 mm
Mass	Less than 3.2 kg	Less than 2.1 kg
LVDT (Position detection)	DC15 V	DC15 V
Motor	DC24 V (nominal)	DC24 V (nominal)

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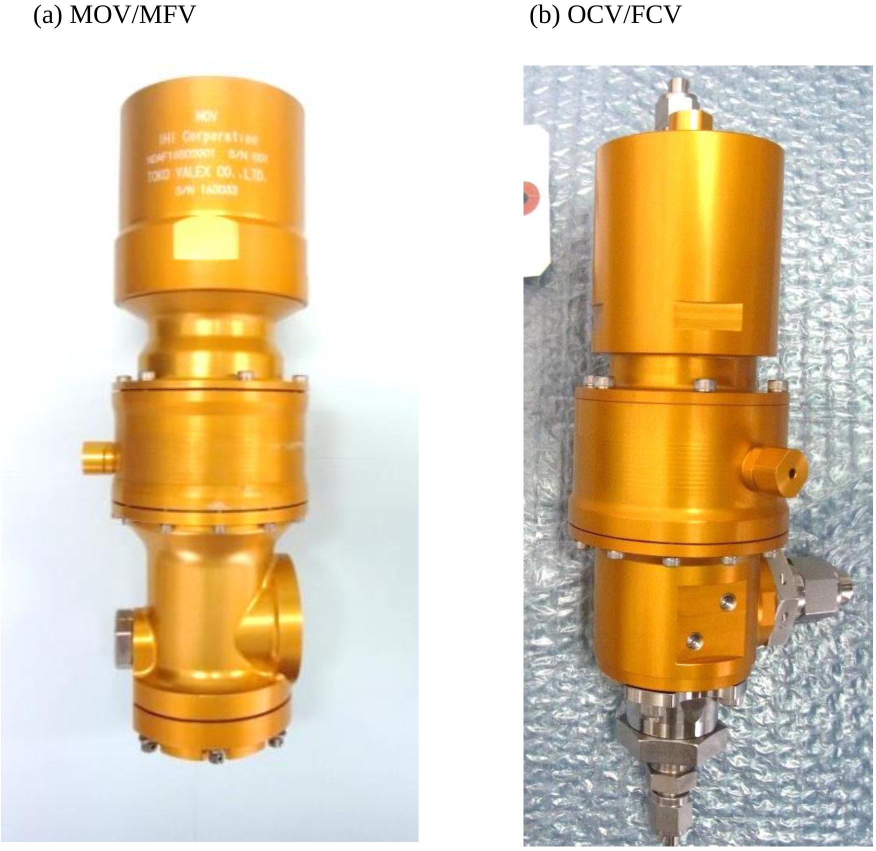
(a) MOV/MFV

(b) OCV/FCV

Figure 4 The outer appearance of the electrically actuated valves.

2.3 Firing test

Firing tests were carried out with the valve configuration shown in Figure 5. The LOX/methane engine used for the firing tests is a full-expander cycle system. The MOV and MFV were attached to the main oxidiser line and fuel line respectively, while the OCV and FCV were attached to the chilldown line. During chilldown, the throttling of the OCV and FCV were adjusted each time by manual operation. The MOV and MFV were fully closed and the OCV and FCV were fully open immediately before the test. After the start of the test, the throttling was controlled fully automatically by sequence control and changed according to the indicated timing. Due to control constraints, the cycle time for checking the throttling and signal transmission was 10 Hz. The program outline of the sequence control is as follows. First, the OCV and FCV are shifted to the fully closed state immediately after the start of the test. Afterwards, stable start-up and steady-state operation were targeted by adjusting the propellant amount while adjusting the MOV and MFV throttling in accordance with an appropriately set sequence. At the end of the test or in the event of an emergency stop, all valves were set to automatically shift to the closed state. For the chilldown valve of the turbo pump bearing, the cryogenic pneumatic valve developed by IHI in the past was applied to this demonstration engine firing test [10].

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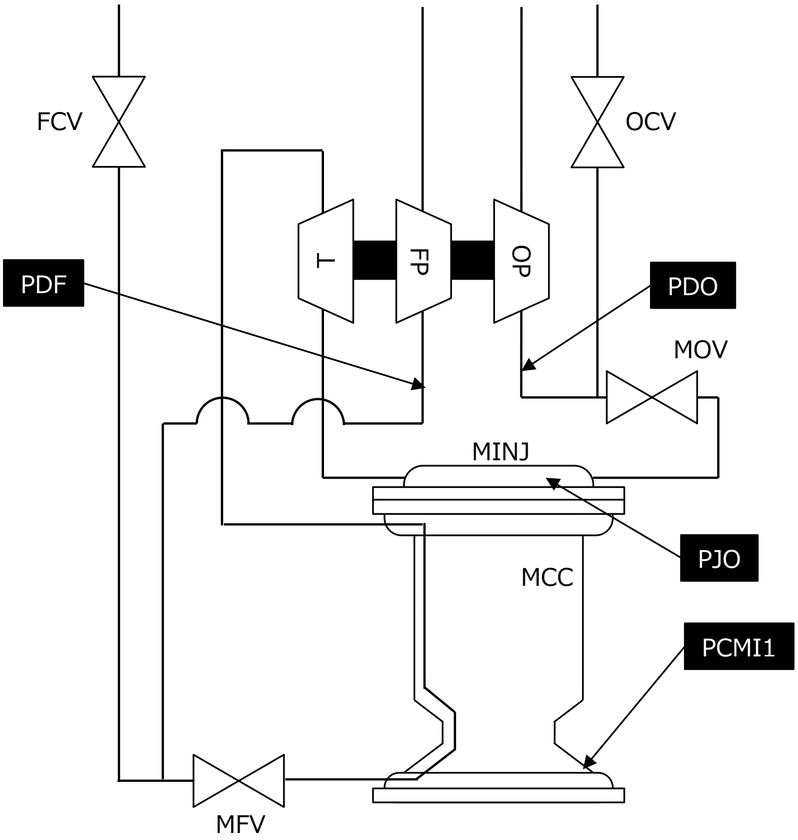

Figure 5 Firing test configuration.

3. Results

Figure 6 shows the valve throttling states during chilldown. The OCV and FCV in the chilldown line were manually operated, and their throttlings were changed as needed depending on the situation. By throttling, the chilldown time was reduced as effective cooling of targeted areas in an engine as compared to the fully open valve condition. In particular, the FCV showed stable operation even after reaching cryogenic temperatures, even though minor throttling adjustments were conducted to fine-tune areas to be cooled. These results indicate that there is no problem in manual control of the electrically actuated valve under cryogenic conditions.

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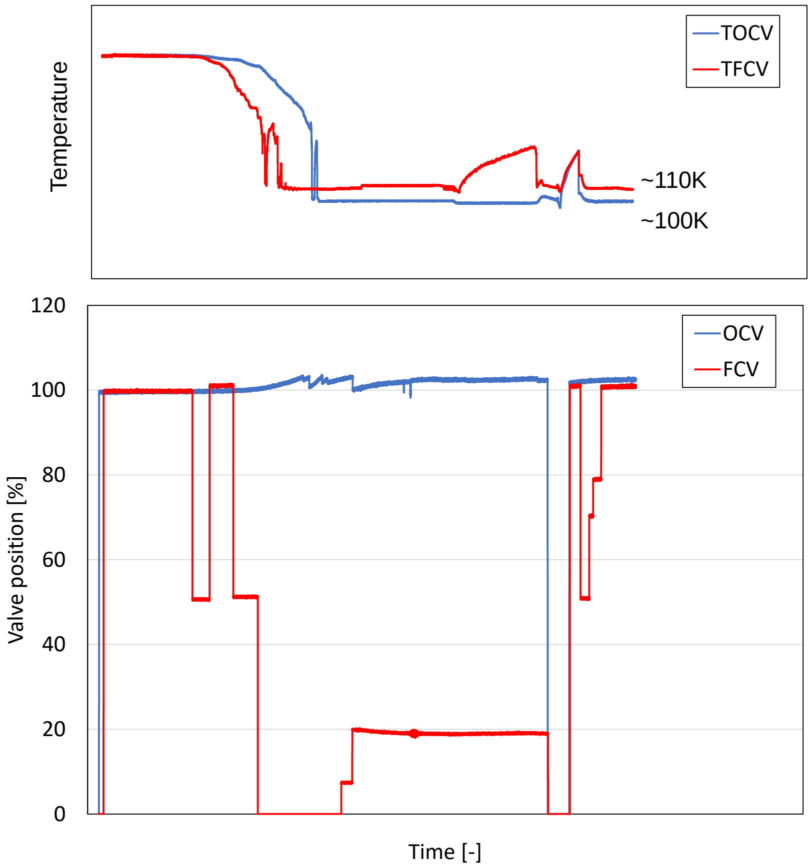
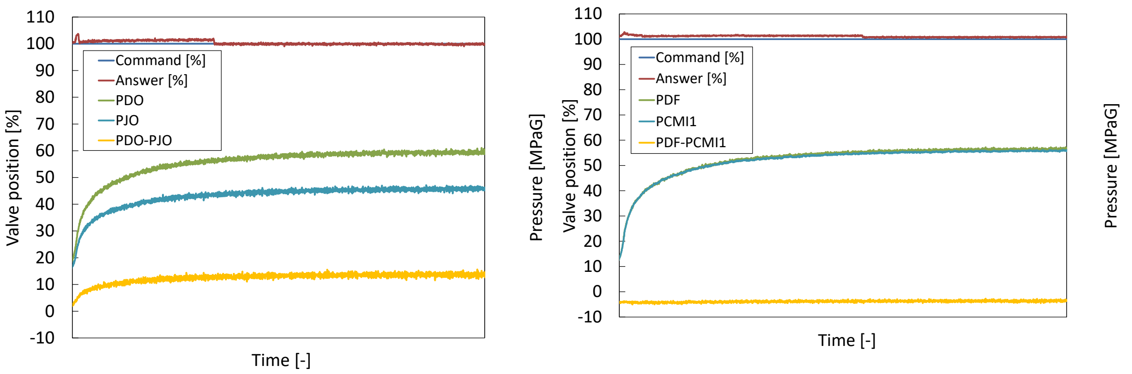


Figure 6 Valve throttling during chilldown.

The throttling command and execution histories of each valve during the firing test (steady-state operation) are shown in Figure 7. Both the MOV and MFV were fully opened by adjusting the throttling as programmed. Slightly greater than 100% opening occurred immediately after full opening due to a sudden pressure increase, but the feedback control function automatically adjusted the throttling to normal immediately. The throttling hardly fluctuated during steady-state operation and the performance was stable even when the propellant was flowing at cryogenic temperatures and high pressures. The OCV and FCV were fully closed immediately after the start of the sequence as programmed. The throttling of these valves did not change at all even in the event of pressure fluctuations during the firing test, and they were able to maintain their fully closed state reliably. These results indicate that there is no problem in sequence control of electrically actuated valves under cryogenic and high-pressure conditions. While the stability of operation was confirmed, it took more than 1 s to operate from fully-closed to fully-open or from fully-open to fully-closed, so further improvement of the speed should be aimed for in the future. Although thrust control during steady-state operation was not conducted in this test series, the results of these firing tests and the results of the throttling adjustment sub-component test [6] suggest that it is also considered sufficient, and we would like to verify this in future tests.

Reproducibility was also checked. Multiple tests were conducted and a detailed comparison of the rise and fall profiles showed that the variation in actuation speed from test to test was small, with a maximum of 0.1 s. It is assumed that this variation is due to errors in the timing of signal transmission and reception, which depend on the control cycle. These test series were controlled at 10 Hz due to control system limitations, but these valves can also be controlled at 100 Hz. Therefore, in principle, the control error can be reduced to about 0.01s.

Finally, an image of the engine firing test is shown in Figure 8. As mentioned earlier, the valve throttling did not fluctuate during the test and stable combustion could be maintained. It was also confirmed that not only the electrically actuated valve but also the pneumatic valve operated stably under cryogenic conditions. The measured motor casing temperatures of both the electric and pneumatic valves showed that no abnormal temperature rises or drops occurred. Therefore, it can be concluded that there was no leakage of cryogenic fluid or heating due to overload.



(a) MOV

(b) MFV

(c) OCV

(d) FCV

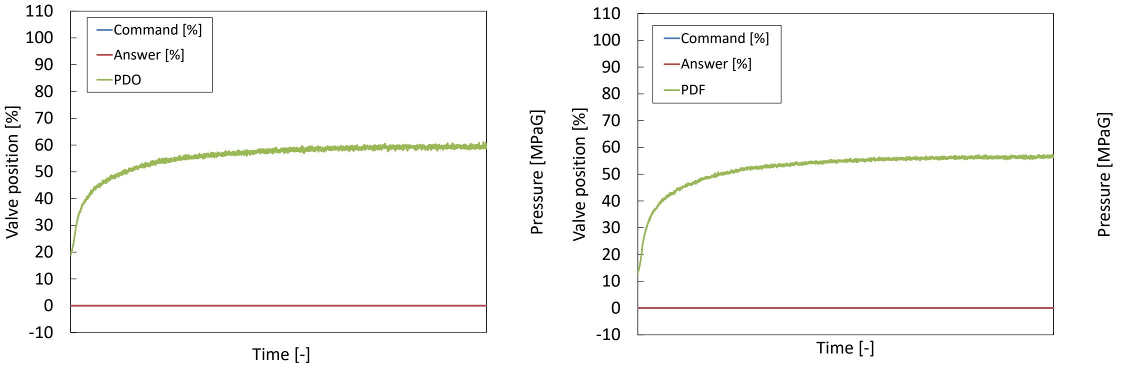


Figure 7 The throttling command and execution history of each valve during the firing test.

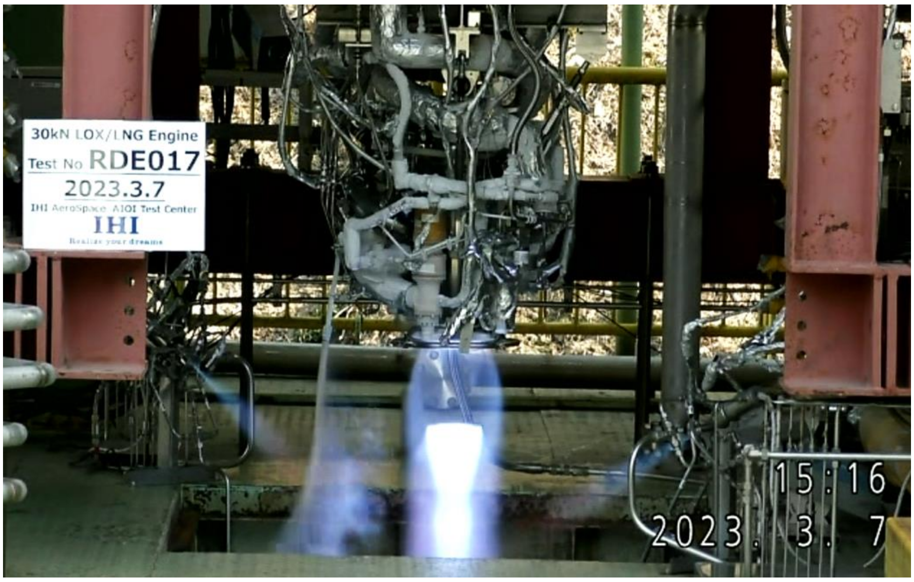


Figure 8 The image of the firing test.

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4. Future work

In this test series, only the chilldown valve was adjusted for throttling, but in sub-component testing, the throttling adjustment of the MOV and MFV was also checked [6]. The test results show that the developed electrically actuated valve has been verified to work in a LOX/Methane rocket engine under operational conditions, and thrust control will be verified in the future when it is installed in a future transportation system. Using the knowledge gained from the development of this model, we will begin development of a new type of electrically actuated valve that is more compact, lower cost, and has a faster response time.

5. Conclusion

The electrically actuated valves developed for current research programs and future transportation systems were tested in firing tests of a LOX/Methane rocket engine under operational conditions. The results demonstrated that the electrically actuated valves developed for the main propellant valve and chilldown valve operated stably under high pressure conditions at cryogenic temperature. This marks the completion of a significant tollgate in the development of electrically actuated valves for future engines and makes them ready for preparation for actual operation. In addition, integration of the valve to future transportation systems is also promising. Development aiming at further downsizing, cost reduction, and faster response time will be continued in parallel.

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