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Research and Development Result of Cryogenic Propellant Valve for Small Thrust LOX/methane Rocket Engine

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Abstract
For small thrust LOX/methane rocket engine, new cryogenic propellant valves which are actuated by an electric motor were developed. The valves have the functions not only for the shut-off valves, but also the control of the propellant flow rate. Since the valves are actuated by the electric motor, the engine system does not need any pneumatic system for them, which mean the engine system can become much simplified. This paper describes the development and test of the prototype cryogenic propellant valves which are actuated by the electric motor for both controlling the propellant mass flow and functioning open and close.

1. Introduction

In Japan, research and development have been conducted on a regenerative cooling LOX/methane rocket engine to achieve higher performance than so far demonstrated [1].
In 2016, based on a system study, many types of LOX/methane shear co-axial injectors for the main combustor were designed and then the firing tests of single injector element were performed under high pressure condition [2]. The test results showed that several promising candidates of injector element design have such high performance.
Now, multi-element firing tests are planned with the selected element designs for the purpose of confirming the performance [3].
The concept of this firing test configuration is to test the multi-element injector installed on the test bench assembly of a regenerative-cooled combustion chamber, a turbopump and propellant valves, similar to the expander cycle engine configuration of 30kN-class thrust.
During test firing, the operating conditions will be varied for acquiring the performance sensitivity to the mixture ratio and the combustion pressure, or the operating characteristics for engine throttling. In order to realize those operations, cryogenic propellant valves which are actuated by electric motors were newly developed.
The valves have the function of propellant flow control as well as open/close function.
As a result, by equipping such valves, the engine can change the operating point easily during firing operation without replacing conventional trimming orifices.
In addition, since the valves are actuated by the electric motor, the engine system does not need any pneumatic system for them, that mean the engine system can become much simplified.
This paper describes the development and test of the prototype cryogenic propellant valves which are actuated by the electric motor for both controlling the propellant mass flow and functioning open and close.

2. Requirements for Valves

2.1 Target Engine

In order to demonstrate the high performance of the engine, this research and development targets the expander cycle engine which has 30kN-class thrust, capability for throttling and capability for both high Isp and simple engine system. Determined engine requirements are as shown in Table 1.

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Table 1: Engine performance target.

Item	Value
Thrust, vacuum	30 kN
Isp,vacuum	370(eps=210)
Propellant	LOX/methane
Pc	4.7MPa
MR	3.3
Throttling	50 to 100 % (Continuous)

The vacuum Isp of the engine will be reached 370s with nozzle extension, nozzle expansion ratio of which is 210. Since the firing test planned in 2017 is the sea level test, the engine will be performed without nozzle extension. The expansion ratio of thrust chamber is 4.6.
Fig.1 shows engine system diagram of with nozzle extension and Fig.2 shows engine system diagram without nozzle extension.

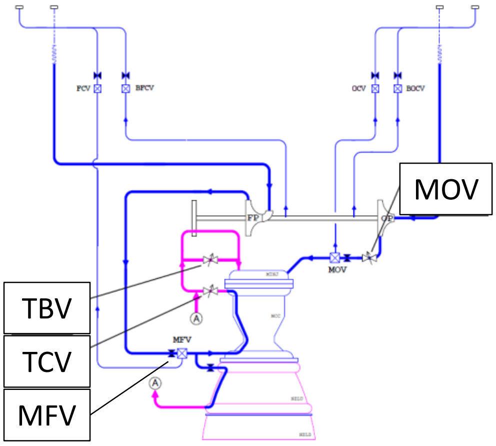

Figure 1: Engine system diagram with nozzle extension.

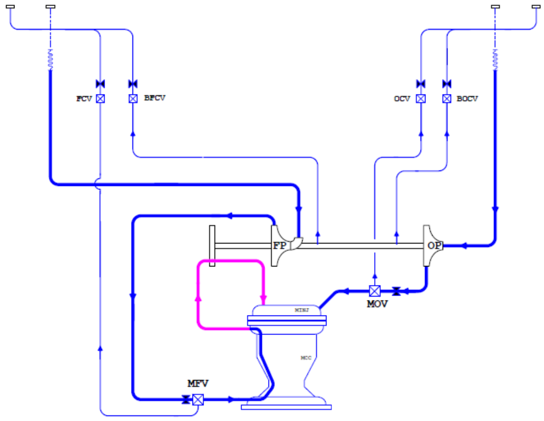

Figure 2: Engine system diagram without nozzle extension.

2.2 Requirements for Valves

As mentioned above, propellant valves are required functions of propellant supply start/stop and propellant mass flow control. However, if shutoff valves and flow control valves were respectively installed in propellant supply line, the system is complicated and engine mass get heavier.
Then, the goal of the research and development of propellant valve is to develop the valve which have the function of propellant mass flow control as well as open/close function. In addition, electrical motor is selected for valve actuation. By adopting electrical motor, the engine system does not need any pneumatic system, which means the engine system can become much simplified.
The engine system has four different valves, main fuel valve (MFV), main oxidizer valve (MOV), thrust control valve (TCV) and turbine bypass valve (TBV).
MOV and MFV require open/close functions, since they are used for the shutoff of oxidizer and fuel. In addition, MOV needs flow control function for managing the engine mixture ratio. TCV installed at outlet of chamber regenerative cooling needs flow control function, which is used for keeping pressure of coolant (methane) higher than critical pressure during engine throttling. TBV needs flow control function, controlling turbine bypass mass flow for mainly thrust control when engine throttling.
In accordance with aforementioned functional requirements and engine target, Performance requirements of valves are as shown in Table 2. To develop the valves efficiently, common design was applied to MOV, MFV, and TCV, except Cv value. TBV was designed separately, since TBV can be downsized than other valves due to smaller Cv requirement.

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Table 2: Valve requirements.

	MEOP[MPa]	Cv[-]	Remarks
MOV	6.8	17.9	For flow control & shut off
MFV	13	17.9	For shut off
TCV	13	24	For flow control
TBV	13	2.5	For flow control

3. Design result

3.1 Overview of valve structure

Valve configuration is shown in Fig.3. Poppet type was selected, which can control mass flow rate easily. Bellows was adopted for sealing the fluid. The valve is rotationally actuated by stepping motor and HarmonicDrive® speed reducer, and the rotation is transduced to axial movement by the toggle structure.

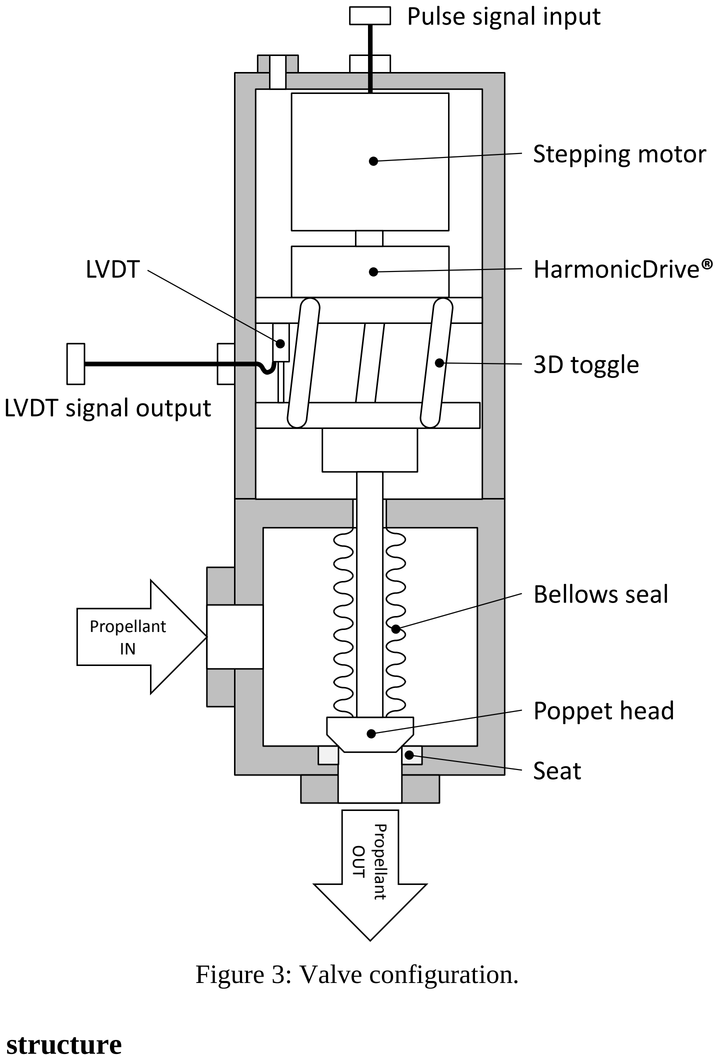

Figure 3: Valve configuration.

3.1 Overview of valve structure

Stepping motor

The stepping motor is adopted for actuation. Stepping motor is simple structure motor which is consisting of coil and permanent magnet. It is not required brush for rectification of current such as used for DC motor, and also it does not need hole sensor which is used for brushless DC motor. Therefore, the motor could actuate the valve with robustness in the operation since the motor does not have the component functionally sensitive to cryogenic condition.

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HarmonicDrive® speed reducer

HarmonicDrive® was used for the valves as a speed reducer. HarmonicDrive® has backlash free and high accuracy positioning control characteristics, therefore it is appropriate for flow control valves. In addition, it can realize high reduction ratios with small sized and light weight, then the total valve size including motor can be downsizing.

Toggle

To transduce motor torque to thrust, 3D toggle was selected [4-5].

The actuator size for shutoff valve depends on shutoff power, which becomes rather large. To avoid that, the valve actuator can generate bigger power at shutoff phase by adopting 3D toggle which consists of the toggle structure as shown in Fig.4.

As shown in Fig.5, by adopting 3D toggle, the velocity of axial displacement is getting to zero, when the toggle arm is moving upright, and the motor torque can be transduced to thrust totally. Hence, axial thrust at valve close can be increased without increasing motor torque. For this, motor can be downsized and also electric power can be reduced.

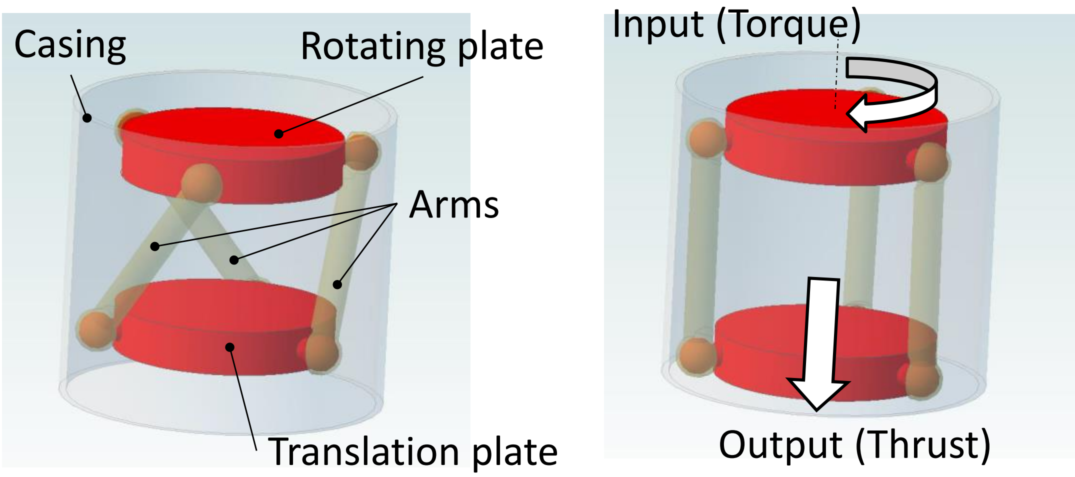

Figure 4: 3D toggle configuration.

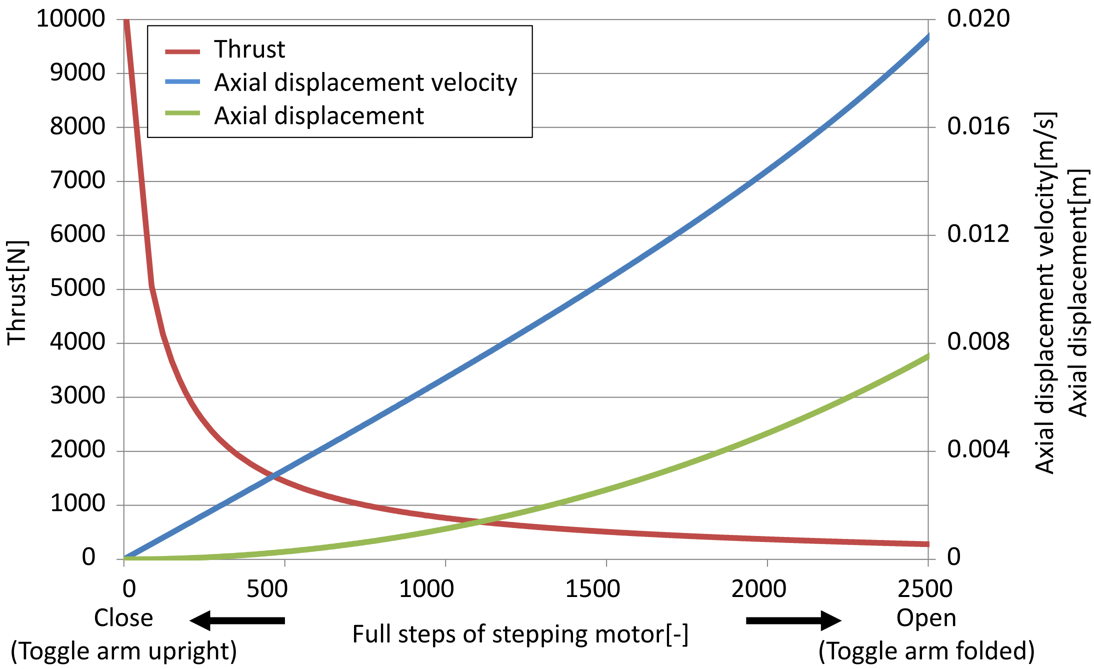

Figure 5: Thrust profile of 3D toggle (example).

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Latch function
The valve has latching mechanism. When the 3D toggle arm pass over the upright state of toggle arm, the valve is in latch condition, which makes the valve keep close condition by latch mechanism in case without electric power.

Positioning sensor
To detect poppet head position, linear variable differential transformer (LVDT) is installed to actuator. In general, stepping motor uses the encoder as positioning sensor, measuring the rotation of the motor. However, by using LVDT, poppet head position can be detected directly.

The design summary is shown in Table 3 and 4. The design optimization was done with IHI Total Design Management (IHI-TDM) [6]. IHI-TDM is an optimal design method including robustness.

Table 3: Design summary of MOV/MFV/TCV.

Item	MOV/MFV/TCV design result
MEOP	13[MPaG]
Leakage	Ambient : less than 1[sccm] Cryogenic : less than 60[sccm]
Actuator	Stepping motor
Operating temperature	MOV/MFV : 77 to 333[K] TCV : 77 to 450[K]
Proof pressure	MEOP×1.5
Burst pressure	MEOP×2.5
Cv	MOV/MFV : 17.9 TCV : 24
Life time	Ambient : More than 2000 times Cryogenic : More than 2000 times
Responsiveness	Less than 1.7[sec]
Mass	Less than 4.0[kg]

Table 4: Design summary of TBV.

Item	TBV design result
MEOP	13[MPaG]
Leakage	Ambient : less than 1[sccm] Cryogenic : less than 60[sccm]
Actuator	Stepping motor
Operating temperature	77 to 450[K]
Proof pressure	MEOP×1.5
Burst pressure	MEOP×2.5
Cv	2.5
Life time	Ambient : More than 2000 times Cryogenic : More than 2000 times
Responsiveness	Less than 1.7[sec]
Mass	Less than 2.0[kg]

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4. Manufacturing and element test

The pictures of the valve assemblies are shown in Fig.6.

Figure 6: Pictures of MOV and TBV.

For verification of valve function, the following tests were performed. In this section, test results for MOV/MFV/TCV have been described, since at the time of this paper writing, tests for MOV/MFV/TCV have been done.

<u>Hydrostatic proof pressure test</u>
To verify robustness of the valves, the valves were subject to the hydrostatic proof pressure test up to MEOP × 1.5 and were kept a specified time. After that, visual inspection and disassembly inspection were performed. As a result, any harmful damage was not observed.

<u>Leakage test</u>
To confirm shutoff function of the valves, leakage test was performed under ambient and cryogenic temperature. Close-positioned valves were pressurized up to MEOP by gaseous helium, and internal leakage was measured by soap film flowmeter. It could be confirmed that all valves leakage level was less than specified value.

<u>Valve actuation test</u>
To confirm flow control function of the valves, the valves were tested open-close actuation operation under the specified operating temperature and pressure. Test configuration is shown in Fig.7. All valves could actuate without motor step out under ambient and cryogenic condition. For this, it is confirmed that the valves can function as flow control valves. However, the test result shows that modification of the control logic will be needed to realize faster responsiveness.

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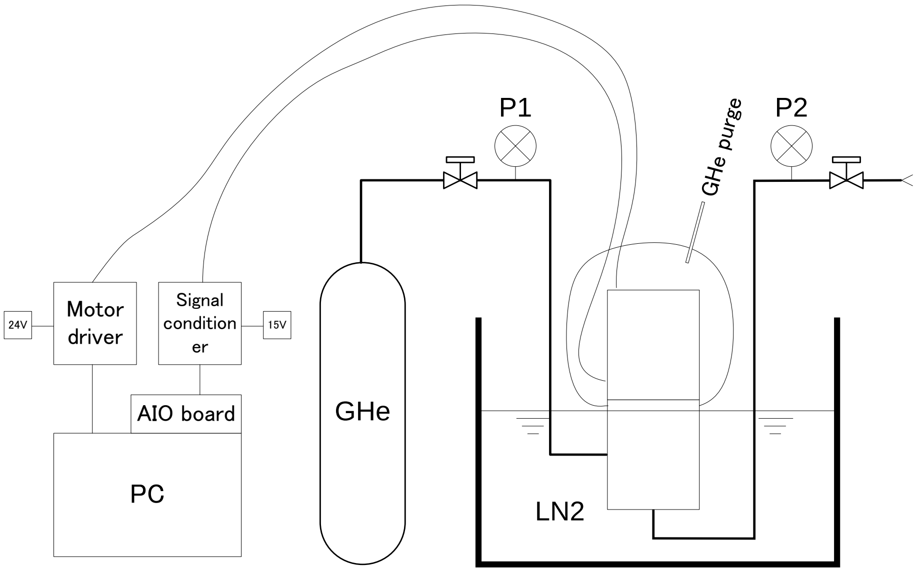

Figure 7: Valve actuation test configuration.

5. Conclusion

The valves for the small thrust LOX/methane rocket engine was designed, manufactured, and assembled. The verification tests were performed and the uncertainties in design were mitigated. The test result shows the modification of the control logic of the valves is necessary to obtain faster responsiveness.

To obtain valve characteristics with actual propellant, valve test will be conducted at IHI Aioi test site in the autumn of 2017. After that, the valves will be utilized for the firing test of small thrust LOX/methane rocket engine. Set-up of the firing test will be as shown in Fig. 8.

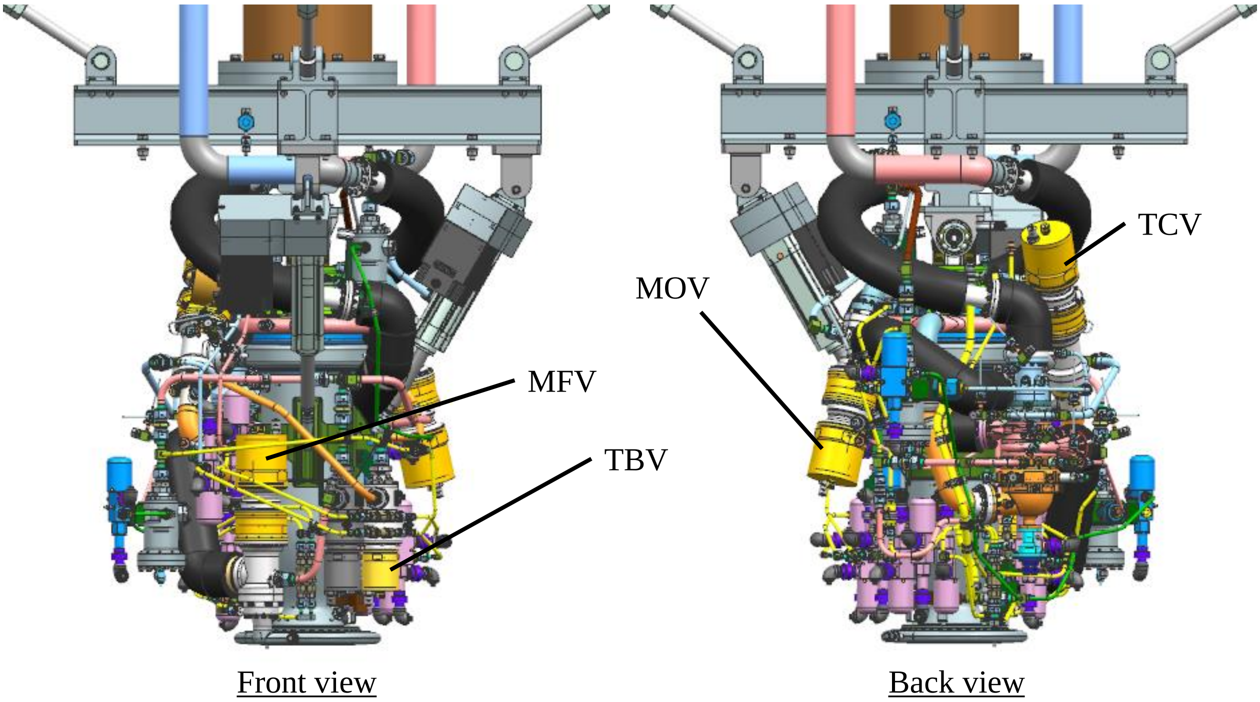

Figure 8: The firing test configuration.

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