DOI: 10.13009/EUCASS2023-312
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Demonstration plan of fault diagnosis in propulsion system during HTV-X experiment mission for future technologies

Kaname Kawatsu[*†], Kohji Tominaga*, Taiichi Nagata*, Go Fujii**, Yoshinori Kondoh**, and Kazutoshi Ombe***
** JAXA Research and Development Directorate*
2-1-1 Sengen Tsukuba, Japan
*** JAXA Human Spaceflight Technology Directorate*
2-1-1 Sengen Tsukuba, Japan
[†] *kawatsu.kaname@jaxa.jp*

Abstract

A liquid propulsion system is one of the key systems to space transportation. In addition, autonomous decision-making, without earth-based control or astronauts, will become important for space exploration of the lunar orbit and beyond. One solution for quick and accurate fault diagnosis of fluidic components is to focus on the dynamic pressure response in the piping system. This solution is realized by model-based approach to obtain a prior dataset under fault conditions. This paper covers the results of consideration and preliminary analysis to develop a demonstration plan on orbit utilizing the HTV-X as an experimental platform for future technologies.

1. Introduction

NASA has proposed the Artemis program to return astronauts to the Moon and pave the way for a manned mission to Mars [1]. The concept of a gateway in cis-lunar space as an outpost for future deep space exploration is discussed worldwide [2]. In December 2020, the Japanese government signed an agreement with the United States regarding Gateway and formally agreed to participate in the Artemis program. In July 2020, MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology) and NASA also issued a joint declaration, agreeing to cooperate in lunar exploration [3].

JAXA plans to support the Gateway program by providing a transport service based on the technology heritage through the ISS (International Space Station) missions by the HTV (H-II Transfer Vehicle) and its successor the HTV-X under developing [4-5]. When activities in deep space (the Moon and beyond) expand in the future, it will be essential for Japan to enlarge its space transportation capability [6]. In addition, autonomous decision-making without earth-based control or support by astronauts will become important for space exploration of the lunar orbit and beyond, as shown in Figure 1.

The spacecraft propulsion system for attitude and dynamics control, the primary actuator of spacecraft Guidance, Navigation, and Control (GN&C), is among the most critical systems for achieving mission success and safety. Therefore, its reliability and robustness must be maximized to ensure high mission availability. The pressure-fed, bi-propellant liquid propulsion system is a major spacecraft and satellite propulsion system architecture. This propulsion system provides thrust for attitude and dynamics control. However, several undesirable phenomena and component faults can arise, leading to the loss of performance or safety.

Conventional independent redundant architectures for spacecraft propulsion systems are based on cold backup such as the HTV. This architecture is wasteful for spacecraft with limited resources because the backup system is only used if a fault occurs in a primary system. Therefore, a new propulsion system architecture based on resilient engineering was applied for the HTV-X [5], where all resources are utilized during normal system operation. The HTV-X is designed to manage impaired performance due to a fault, as shown in Figure 2.

The HTV-X propulsion system configuration based on the new resilient architecture is more efficient than the conventional design. However, there is another issue regarding this new architecture. The conventional architecture makes detecting propulsion system failures simply, as the disturbing force or torque due to the failure is easily observed as an abnormal spacecraft attitude from nominal system status. The resilient architecture has an intrinsic recovery due to its functionally redundant nature for faults in liquid propulsion components, such as valves and the filter. The decrease in thrust due to a fault is normally compensated by other thruster control, so it is difficult to identify the component under failure condition from a spacecraft's attitude.

DOI: 10.13009/EUCASS2023-312

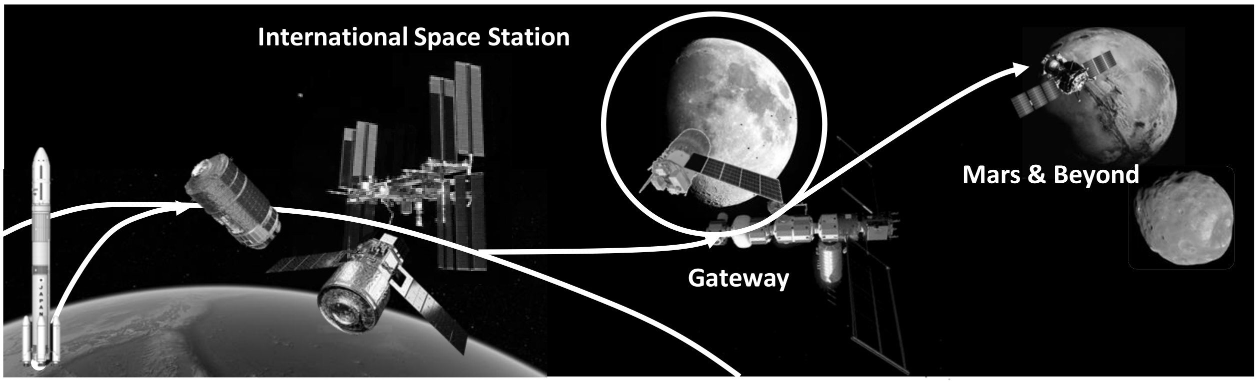


Figure 1: Space exploration from the Earth to lunar orbit and beyond.

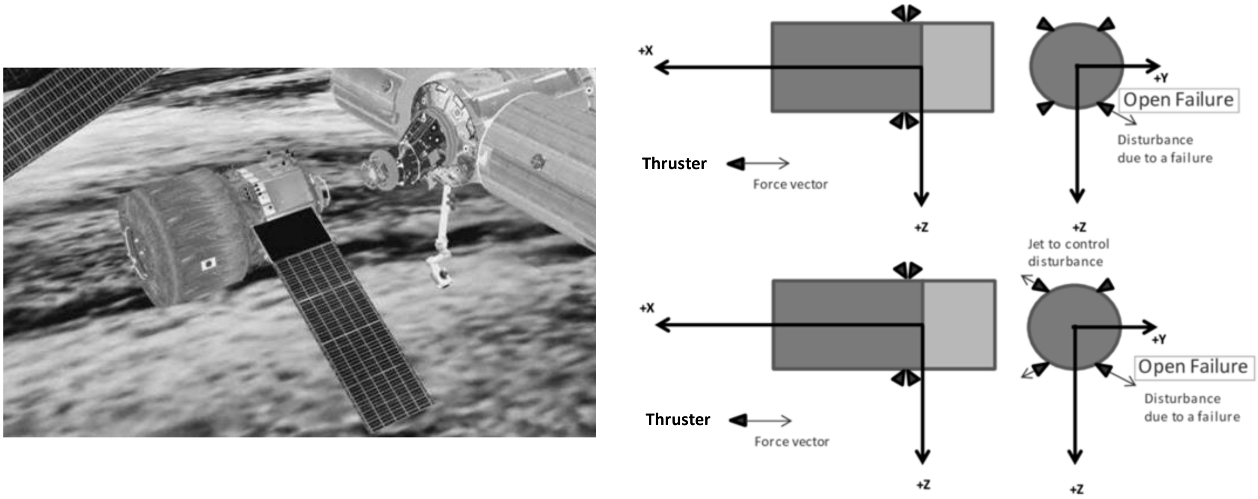


Figure 2: Resilient redundant architecture of propulsion system of the HTV-X [5].

This research aimed to resolve these difficulties by putting forth a novel concept to identify branches with a fault by focusing on the dynamic behavior of fluid inside the propulsion system. A pressure surge due to a water hammer is caused by a sudden change in the fluid flow velocity in the piping system after a fast-acting valve opens or closes. A pressure surge is usually undesirable regarding risk of structure damage. On the other hand, its propagation through the system piping can provide useful information for monitoring the state of the propulsion system.

The fluid flow rate and length of the pipes determine the amplitude and frequency of the surge pressure. Based on that, fault detection and diagnostics can focus on the dynamic response of surge pressure in the frequency domain. They were implemented by propulsion system modeling and simulation techniques and demonstrated with a fundamental experiment in a past study [7-8].

A model-based strategy to realize fault detection and diagnosis is an important feature of the proposed method, given the difficulty of creating a dataset by testing only the hardware for each fault condition (e.g., component location and status under a fault) due to the huge number of fault scenarios. Using a model for the target propulsion system to create a useful dataset is time-effective and can cover various off-nominal scenarios.

The proposed model can also update and validate the model step-by-step through the system's life cycle [9]. Models used for critical decision-making, such as fault detection and diagnosis, require a high degree of validation of their validity and quantitativeness. In addition to the previous verification at the element level and in ground tests, this study focuses on data obtain on orbit with the HTV-X. The data acquisition is important to confirm the method's feasibility and validate the model focusing on the speed of sound in the propellant, which is dominant in the dynamic response of pressure in the piping system.

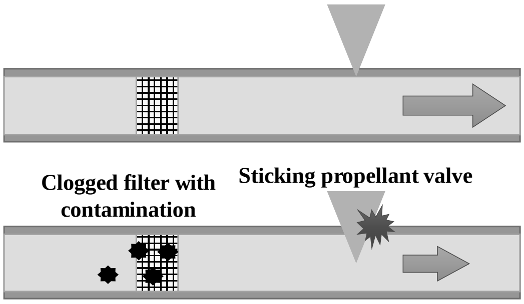
DOI: 10.13009/EUCASS2023-312

2. Approach

The fault detection and diagnosis approach that considers faults of fluidic components, such as propellant valves and filters, was proposed by focusing on the dynamic change in pressure in the piping system under thruster pulse operation [7]. This approach does not need additional sensors, such as a flowmeter, only pressure sensors that can be found in a liquid propulsion system.

A spacecraft's liquid propulsion system poses the potential risk of several failure modes. These failure modes are categorized at the system level and component level. In a component-level failure mode, several are due to accidents, so reducing the risk of these failures in the design phase is difficult. Consequently, this study focused on component-level failure modes as fault detection and diagnosis targets.

The most common component faults are a sticking propellant valve and a clogged filter, which lower the propellant flow rate, as shown in Figure 3. This study's fault detection and diagnosis focus on a reduced propellant flow rate because of these two faults.



Component	Failure mode	Effect
Filter	Clogged fault	Lower flowrate causes thrust decrease
Prop. valve	Sticking fault	Lower flowrate causes thrust decrease
	Closed fault	Missed valve operation causes thruster inoperative

Figure 3: Target failure modes in the propulsion system.

A change in the propellant flow rate due to a component fault affects the pressure amplitude of a water hammer's surge pressure generated when a valve opens or closes. This is because the momentum of the fluid dominates the magnitude of water hammer surge pressure when the valve is closed, as expressed in Eq. (1) [10]. The pressure magnitude (P_{wh}) can be determined based on the conservative assumption of instantaneous stoppage of flow in a pipe using the liquid density (ρ), speed of sound in fluid (c), and difference in fluid velocity before and after a valve actuation (ΔV).

$$P_{wh} = \rho \cdot c \cdot \Delta V \qquad (1)$$

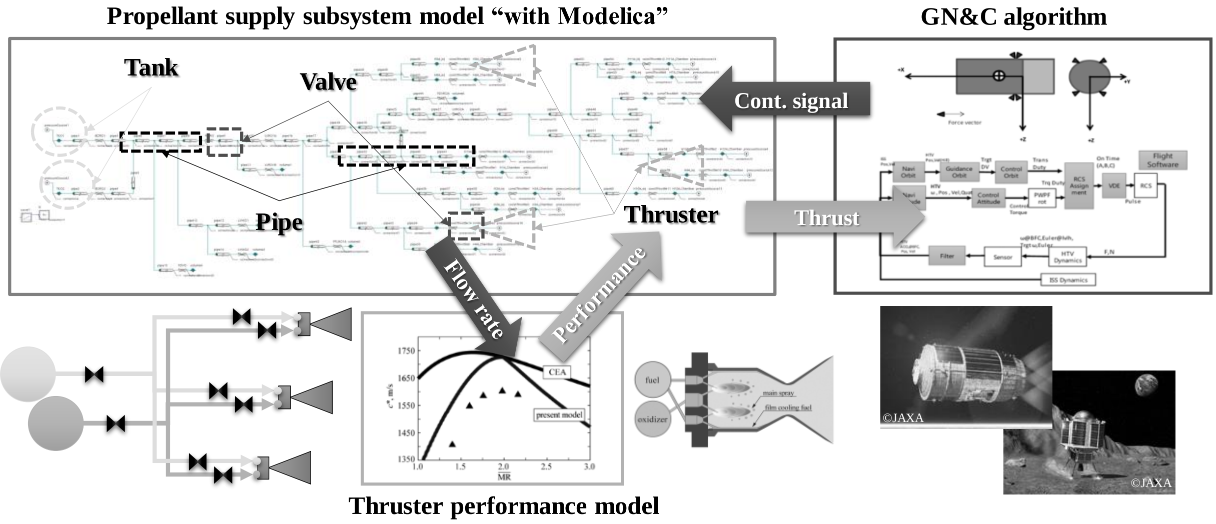
Moreover, since the fundamental frequency of the first harmonic with a water hammer (f_{wh}) is determined by the speed of sound in fluid (c), and the propagation path length (L) for a single constant-diameter pipe with one open and one closed boundary (non-paired boundaries) as expressed in Eq. (2) [11], the proposed approach focuses on the propagation frequency. As a result, the branch where the failure occurred can be determined.

$$f_{wh} = c/4L \qquad (2)$$

The problem with fault detection and diagnosis by focusing on the dynamic response of the propulsion system piping pressure under normal and abnormal conditions lies in the need for a dataset. Preparing a dataset for system-level fault detection and diagnosis testing under normal and abnormal conditions is difficult because of cost and time constraints. One solution utilizes a physical model verified by test results with a feasible case and scale. A model-based strategy to realize fault detection and diagnosis is also an important feature of our proposal, given the difficulty of creating a dataset under each fault condition (e.g., component location and status under a fault) due to the huge number of fault scenarios by testing only the hardware.

Using a model for the target propulsion system to create useful data is time-effective and can cover various fault scenarios. This model-based approach utilizes multi-physic /system-level modeling and simulation using Modelica, an equation-based, object-oriented language that allows the acausal modeling of complex cyber-physical systems [12]. In realizing this approach, our study utilizes a Modelica-based space propulsion system-level integrated model (shown in Figure 4) developed by JAXA [13]. This modeling and simulation technique is already used for risk evaluation on the spacecraft propulsion system for new spacecraft, such as the SLIM (Smart Lander for Investigating Moon) [14], JAXA's new lunar lander mission being developed.

DOI: 10.13009/EUCASS2023-312


Propellant supply subsystem model "with Modelica"

GN&C algorithm

Thruster performance model

Figure 4: Integrated propulsion system model [13].

The ability of the integrated propulsion system model to consider pressure loss, mass flow rate, and fluid inertia in the pipe element allows an evaluation of the dynamic behavior of fluid in the piping system, such as pressure wave propagation and dynamic response propellant flow rate. The frequency characteristic of pressure wave propagation is common to the effects of a water hammer and crosstalk in terms of fluidic component damage and unstable operation.

This Modelica-based model can model various dynamic systems, such as valve operation, fluid dynamic behavior, and pressure wave propagation in the piping system. The variation of dynamic response between fault scenarios can be evaluated by dynamic simulation using SimulationX® [15], which supports Modelica-based modeling and simulation. This variation between fault scenarios is caused by the effect of the pipeline length upstream of the thruster. This approach can detect and diagnose faults in a propulsion system consisting of several pipes of different lengths.

Moreover, the space propulsion system-level integrated model incorporates a bi-propellant thruster performance model [16, 17]. This thruster performance model has successfully clarified the dominant factors governing the spray structure of unlike impinging jets inside the combustion chamber, thereby deducing a new mixing model and achieving a straightforward formulation of thruster performance. This fusion of Modelica-based propellant supply subsystem modeling and a bi-propellant thruster performance model allows an evaluation of the performance of an integrated propulsion system.

Figure 5 shows the simplified model of the propulsion system and failure scenario for the trial study to confirm the potential of the proposed system-level integrated model-based approach as a fault detection and diagnosis procedure for liquid propulsion systems of spacecraft. In this trial, valve operation failure due to insufficient opening caused by a mechanical fault (sticking) was modeled as a decreased valve open area with each propellant control valve targeting a thrust level of 50% of normal condition.

Figure 6 shows the dynamic simulation results using the model and failure scenario shown in Figure 5 as a dynamic pressure response in the piping system with a pressure sensor installed at the junction of the piping branches. The variation of dynamic response between scenarios can be seen in the time-series pressure data at the junction. However, it is difficult to identify the difference between thruster faults from this time-series data. In other words, it is difficult for fault diagnosis to identify the branch faulting data in the time domain. Figure 6(b) shows the transformation results from the time domain (shown in Figure 6(a)) to the frequency domain with surge pressure data after the valve closing.

Conversely, data in the frequency domain can be confirmed to illustrate the difference between normal and abnormal conditions and the location of the branch where the propellant valve fault occurred from the results, as shown in Figure 6(b). These different patterns in the frequency domain are caused by the effect of the pipeline length upstream of the thruster. This length is a factor of surge pressure propagation speed due to a water hammer caused by a valve closing. Therefore, this concept has the potential for an approach that can detect and identify faults in a propulsion system with several pipes of different lengths, focusing on surge pressure response in the frequency domain.

DOI: 10.13009/EUCASS2023-312

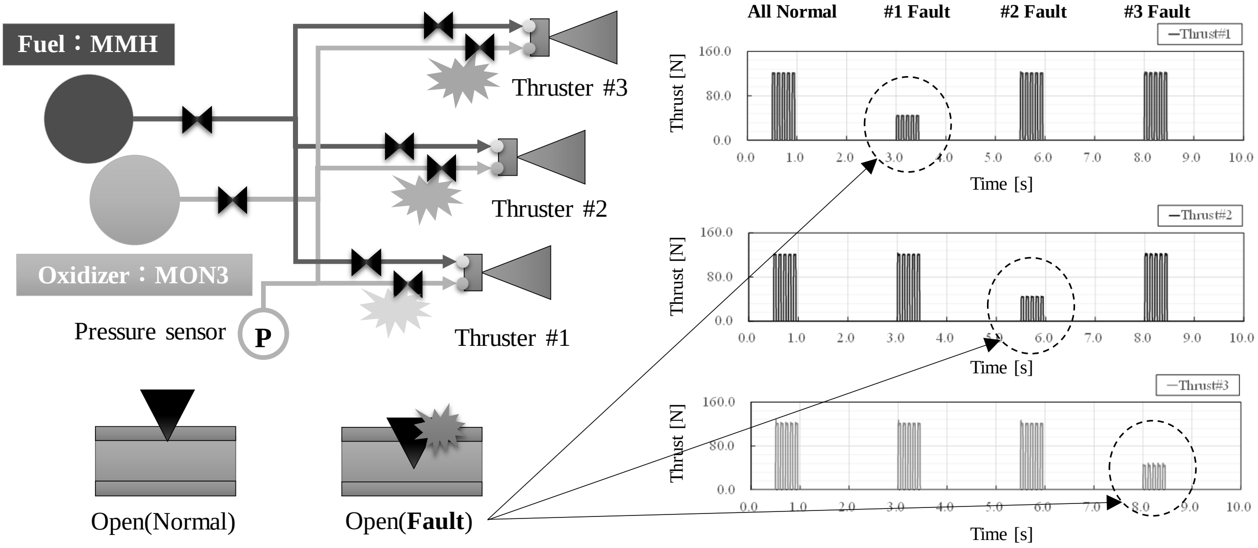


Figure 5: Trial study model and failure scenario [7].

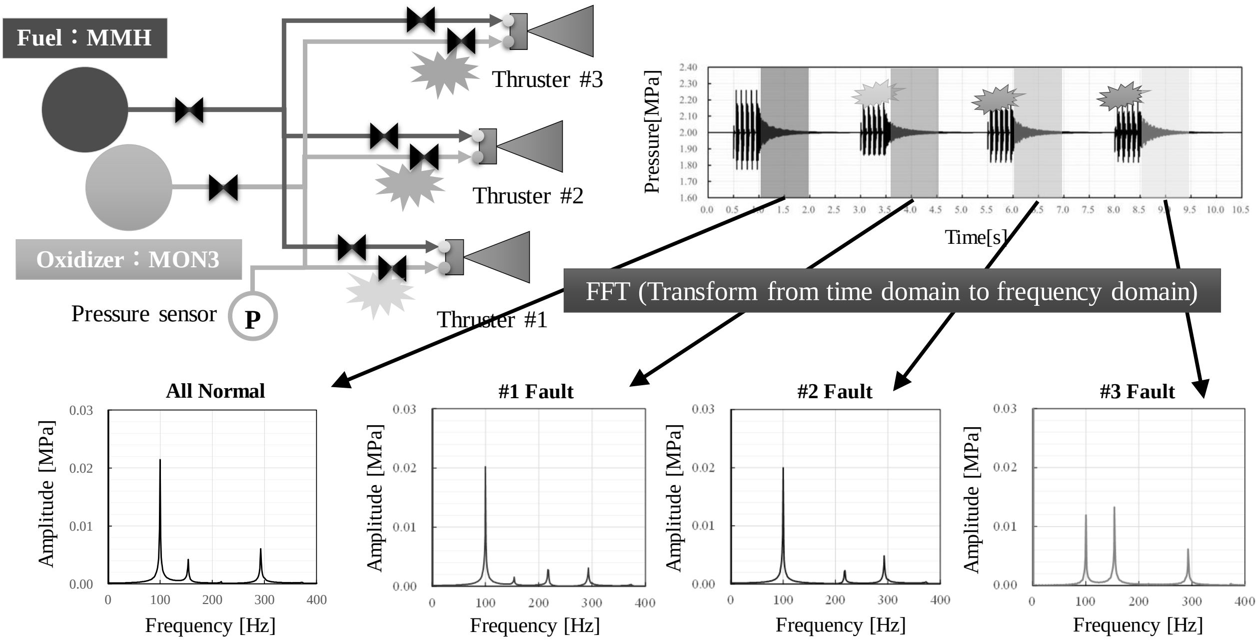


Figure 6: Dynamic pressure response at the junction under normal/abnormal conditions [7].

3. Demonstration Plan

This chapter shows a demonstration plan of fault diagnosis in a propulsion system to confirm the feasibility of the proposed approach and obtain data to increase the validity of the dynamic response analysis model providing a preliminary dataset for fault diagnosis on orbit with the HTV-X as an experiment platform for exploitation of future space technologies. The HTV-X will be operated to transfer essential cargo for the ISS missions and life support goods for astronauts. Furthermore, the HTV-X has an important feature for flying experiment platforms to exploit future space technology. After transporting cargo and leaving the ISS, the HTV-X can be used as a platform for technical demonstration up to 1.5 years during the Technology Demonstration Mission Phase, as shown in Figure 7.

In this demonstration, data with pressure sensors already installed HTV-X propulsion system will be obtained to validate the dynamic response model, especially regarding the speed of sound in the propellant, which is one of the important parameters representing pressure propagation and water hammer. The capability of long-term operation on

DOI: 10.13009/EUCASS2023-312

orbit with HTV-X enables us to understand change with the speed of sound in propellant during a mission. On the other hand, it has limitations regarding fault diagnosis due to the difficulty of install faults in actual propulsion components. That is why abnormal conditions with healthy components to simulate faults are considered. Furthermore, preliminary analysis has been carried out by using dynamic response model for the HTV-X under normal and abnormal conditions ensures that useful validation data can be obtained for the features of interest in fault diagnosis, even if only for healthy components.

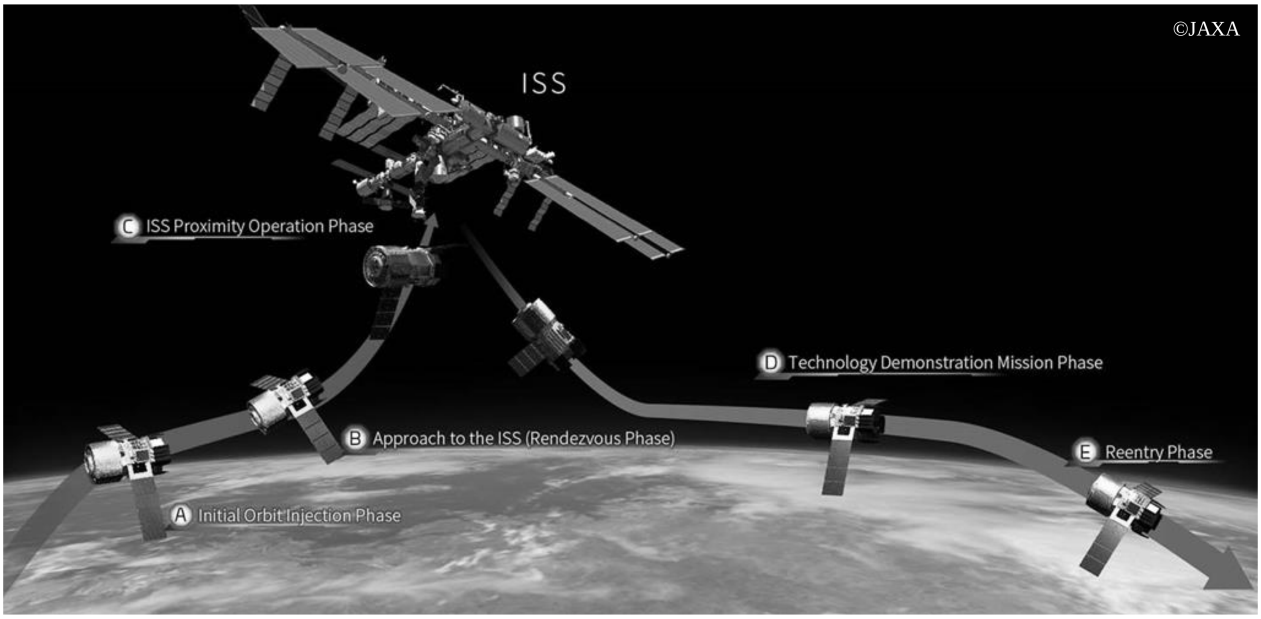


Figure 7: Overview of mission profile with HTV-X (planned) [4].

3.1 Purpose and target of demonstration

The speed of sound in a propellant is the key parameter of the frequency response of pressure fluctuation in the propellant supply piping system, which is the focus of the proposed failure diagnosis method. However, there are uncertainties in the sound velocity due to the presence of pressurized tank gases (He, for example) in the propellant and local bubbles. These are difficult to verify in ground tests because they are assumed to be affected by the gravity environment [18-19]. This is strong motivation and purpose to obtain data on orbit with HTV-X.

In this study, a parametric study with the speed of sound using a dynamic response analysis model for the HTV-X propulsion system is carried out to confirm the effect of the uncertainties on the sound velocity. This analysis model is based on the Modelica language to simulate dynamic response due to a water hammer caused when a solenoid valve opens or closes during actuation, based on the hydraulic model library implemented in SimulationX®, as shown in Figure 8.This model consists of propellant tanks, pipes, junction of pipe branches, valves, and pressure sensors. The pipe element of this model considers the steady-state and dynamic pressure loss in straight lines. The complex flow behavior in the pipe is simplified and considered only by a single flow resistance and flow inertia. Furthermore, the frictional behavior determines pressure drop (ΔP) through the pipe element. Simulation is conducted using the backward differentiation formula (BDF) solver, also suited to SimulationX®.

Figure 9 shows the results of numerically simulating the pressure at a junction within each branch (A, B, and C) in the time domain (Figure 9(a)) and frequency domain (Figure 9(b)) when the propellant flow control valve (thruster A-1, B-1 and C-1) opens and closes. The speed of sound in the propellant changes 5 or 10% in the range for this parametric analysis. The results of the analysis confirm that the natural frequency of the entire system (about 10Hz) and their amplitudes are affected by the sound velocity and that the effect is also significant in the high-frequency region (over 20Hz) that is the focus of the fault diagnosis.

Unfortunately, in the past HTV operations, data on the dynamic response of pressure in the propulsion system has been obtained only at low sampling rate (around 1Hz order). Not enough data have been obtained to validate the model, especially focusing on sound velocity. The same data acquisition cycle is planned for the HTV-X as for the HTV for constant monitoring. Therefore, additional data acquisition in a higher cycle is proposed to obtain verification data with the existing function (DWELL mode). Although this DWELL mode can acquire data at a high frequency (256 Hz), it temporarily accumulates data and down link to the ground system. That is why it is necessary to make targeted settings for the data acquisition timing and the thruster injection pattern for the demonstration.

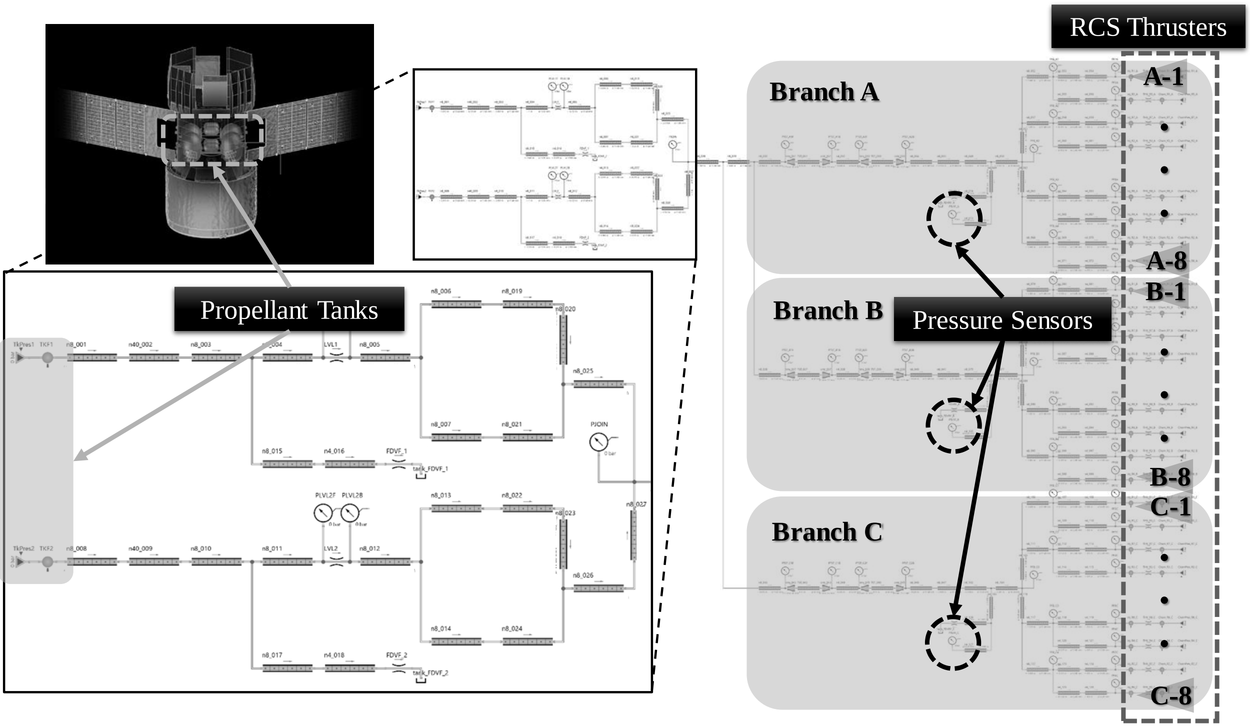
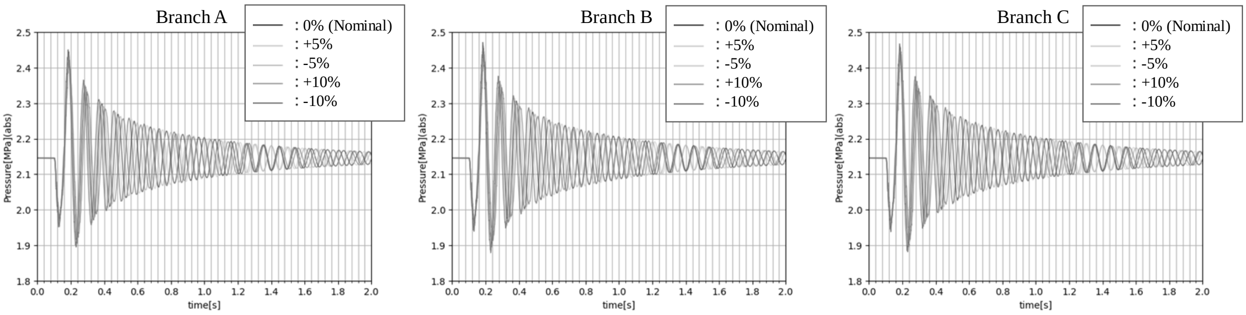
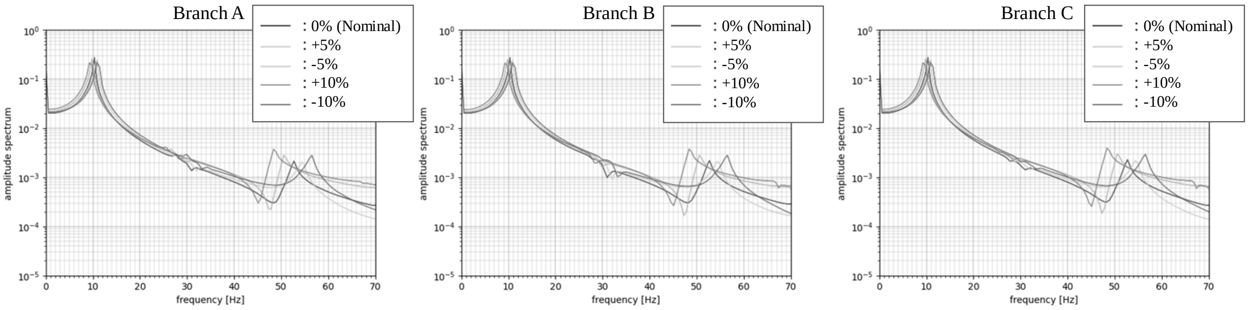


Figure 8: Dynamic response analysis model for the HTV-X propulsion system.



(a) Dynamic response in the time domain



(b) Dynamic response in the frequency domain

Figure 9: Dynamic response analysis results with the HTV-X propulsion system model.

3.2 Plan for demonstration on orbit with HTV-X

While data acquisition on orbit with the HTV-X is a useful opportunity for model validation, it is a real mission with some limitations. One of them is that only two of the three implemented redundant propulsion branches (Branch A, B, and C) are operated on orbit, and the remaining one is a backup for switching branches to perform conventional FDIR (Fault Detection, Isolation, and Recovery) based on the HTV-X vehicle attitude. The waste of redundant configuration and additional operation for the conventional FDIR motivates this study. A further limitation in demonstrating fault diagnosis is that it is difficult to implement fault injection in the propulsion system components, such as the propellant flow control valve, and it is necessary to simulate a fault in a healthy component.

In this proposal, valve open and closed failure are targeted as major failure modes and simulated by intentionally delaying the valve close actuation timing or not opening the valve, respectively. These operations do not fully simulate actual fault conditions. However, it enables us to obtain data to confirm the effect of flow rate change caused by failure as dynamic response pressure fluctuation and amplitude focused on the proposed fault diagnosis method.

Figure 10 shows a proposed operation simulating open failure condition with healthy components. The intent of this operation is to intentionally delay the timing of valve close command for a particular valve (e.g. Branch A or C) in order to reproduce a fault condition where the valve remains open. The duration to keep the valve open under normal conditions is 125 [ms], but for reproduction of abnormal conditions, the time is set to 250 [ms], which is twice as long.

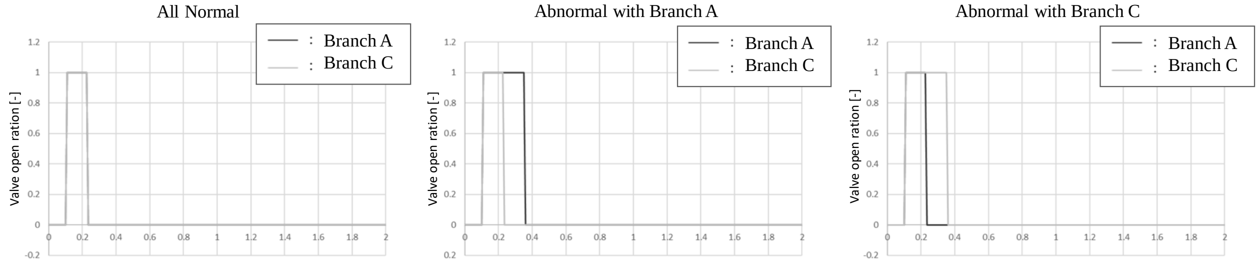
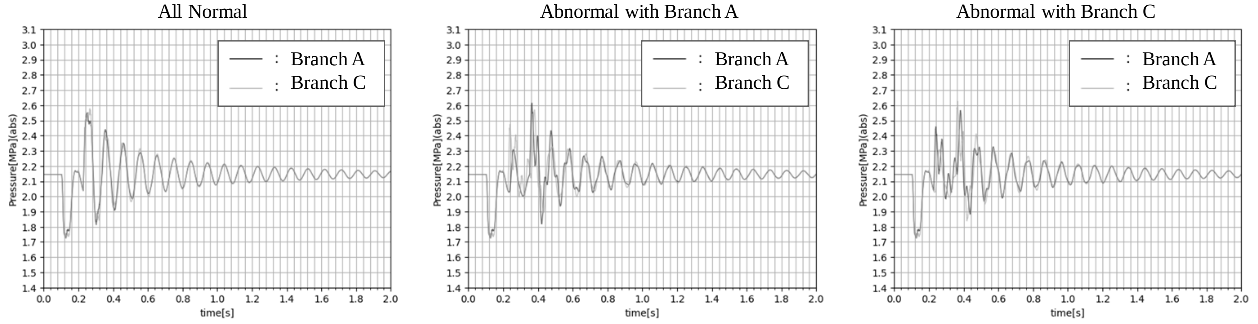


Figure 10: Proposed operation pattern for thruster data acquisition on orbit with the HTV-X.

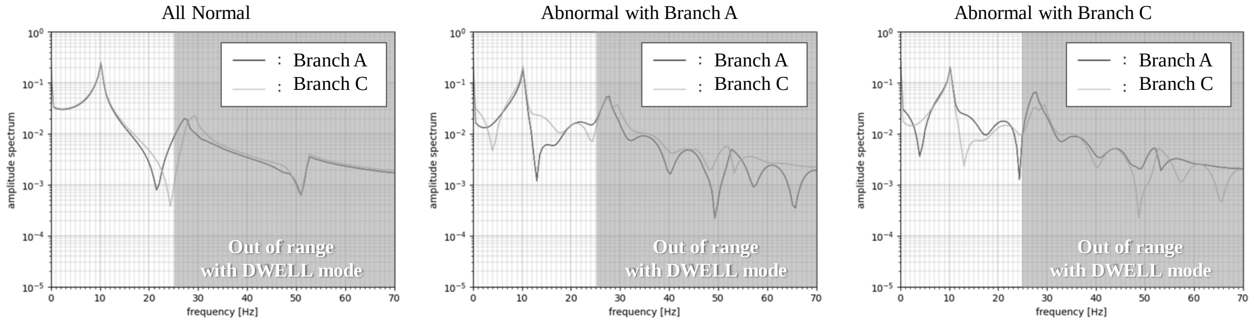
Figure 11 shows the results of dynamic response analysis with the HTV-X propulsion system model (in Figure 9) under the operation pattern proposed for the data acquisition on orbit (Figure 10). This analysis is carried out simulating propellant flow control valve (Thruster 1, 2, 7, and 8) operation pattern for “All are normal” (Valves installed in Branch A and C are normal condition), “Abnormal with Branch A” (Reproduce abnormal only for valves installed in the Branch A), and “Abnormal with Branch C” (Reproduce abnormal only for valves installed in the Branch C).

In these results, pressure responses are different not only between normal and abnormal but also different branches (A and C) in the frequency domain in 10-25Hz, the range of data in the DWELL mode. These results suggest that this data acquisition enables an increase in both the validity of the dynamic response analysis model and the feasibility of the fault detection method, even if it is not the same as an actual failure.



(a) Dynamic response in the time domain

DOI: 10.13009/EUCASS2023-312


All Normal

Abnormal with Branch A

Abnormal with Branch C

(b) Dynamic response in the frequency domain

Figure 11: Dynamic response analysis results under the proposed operation pattern with the HTV-X model.

4. Conclusion

This study aimed to obtain fault detection and diagnosis solutions for spacecraft liquid propulsion systems to realize quick and accurate autonomous decision-making without earth-based control or astronauts. This will become increasingly important for space exploration of lunar orbit and beyond. In pursuit of this goal, a novel fault detection and diagnosis approach was proposed for propulsion systems focusing on the frequency domain dynamic response of pressure propagation due to water hammers in the piping system.

However, for the model to accurately predict the response in the frequency domain in advance, it is necessary to correctly determine the speed of sound in the propellant fluid, a dominant parameter determining propagation frequency. In the past, sufficient data with speed could not be obtained in actual operation of spacecraft to validate the model due to low resources and limited frequency for data accumulation. This issue for model validation for fault diagnosis remains.

This study constructed a dynamic response analysis model targeting the HTV-X propulsion system to evaluate frequency domain response under normal conditions (without faults) and abnormal conditions with healthy components to simulate faults under several constraints possible in an HTV-X mission. The analysis results confirm the feasibility and effectiveness of the proposed data acquisition plan. The data will be obtained on orbit during the HTV-X mission based on the proposed plan is also useful to improve model validity on our future work.

Realizing this approach is expected to improve the reliability and robustness of spacecraft and propulsion systems. In addition, from the perspective of fault detection and diagnosis, the propulsion systems configuration (including piping and thruster arrangement) can be determined in the upstream design phase. We believe that our approach will optimize the performance, availability, and robustness of future spacecraft.

References

[1] National Aeronautics and Space Administration (NASA), “NASA’s Lunar Exploration Program Overview,” https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf (accessed June 14, 2023).
[2] Edwards, C. M. and Cichan, T., “From the Moon to Mars Base Camp: An Updated Architecture that Builds on Artemis,” ASCEND 2021, AIAA 2021-4137, 2021.
[3] Japan Aerospace Exploration Agency (JAXA) Research and Development Directorate, “Research on space exploration,” https://www.kenkai.jaxa.jp/eng/research/exploration/exploration.html (accessed June 14, 2023)
[4] Japan Aerospace Exploration Agency (JAXA), “HTV-X Project,” https://humans-in-space.jaxa.jp/en/htv-x/ (accessed June 14, 2023)
[5] Noumi, A., Ujiie, R., Ueda, S., Someya, K., Ishihama, N., and Kondoh, Y., “Verification of HTV-X resilient design by simulation environment with model-based technology,” 2018 AIAA Modeling and Simulation Technologies Conference, AIAA SciTech Forum, AIAA 2018-1926, 2018.
[6] Japan Aerospace Exploration Agency (JAXA) Research and Development Directorate, “Innovative Space Transportation,” https://www.kenkai.jaxa.jp/eng/research/kakushinyusou/kakushinyusou.html (accessed June 14, 2023)
[7] Kawatsu, K., Noumi, A., Ishihama, N., Nagata, T., Inoue, C., Fujii, G., Tani, H., and Daimon, Y., “Resilient Redundant Spacecraft GN&C System Fault Detection and Diagnostics,” 1st Edition of the Aerospace Europe Conference, AEC2020-467, 2020.

DOI: 10.13009/EUCASS2023-312

[8] Kawatsu, K., Fujii, G., Nagata, T., Yamamoto, H., and Daimon, Y., "Preliminary Demonstration of Concept for Fault Diagnosis in Resilient Redundant Spacecraft Propulsion," AIAA SciTech 2023 Forum, AIAA 2023-1259, 2023.

[9] Kawatsu, K., Izato, Y., and Miyake, A., "Framework for Model-Based Approach of Life Cycle Risk Management for Spacecraft Liquid Propulsion System," 33rd International Symposium on Space Technology and Science, 2021.

[10] Brindle, B., Gilbert, J., Moore, J. D., and Risha, A. G., "Effects of Water Hammer on Propulsion Systems," 52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA-2016-4981, 2016.

[11] Wylie, E. B., Streeter E. B., Fluid transients in systems, Prentice-Hall, 1993.

[12] Modelica Association, Modelica Language Specification, https://www.modelica.org/documents.

[13] Kawatsu, K., Inoue, C., Terauchi, Y., Daimon, Y., Fujii, G., and Noumi, A., "System-level Integrated Modeling and Simulation Targeting Space Propulsion System for Design Evaluation and Risk Assessment," 32nd International Symposium on Space Technology and Science, 2019.

[14] Fujii, G., Kawatsu, K., Daimon, Y., Michigami, K., Kushiki, K., Sawai S., and Sakai, S., "Verification of the Transient Behavior of the SLIM Propulsion System (Smart Lander for Investigating Moon)," AIAA Propulsion and Energy 2021 Forum, AIAA 2021-3582, 2021.

[15] ESI-ITI GmbH, SimulationX website, https://www.simulationx.com/simulation-software.html.

[16] Inoue, C., Oishi, Y., Daimon, Y., Fujii, G., and Kawatsu, K., "Direct Formulation of Bipropellant Thruster Performance for Quantitative Cold-Flow Diagnostic," *Journal of Propulsion and Power*, vol. 37(6), pp. 842-849, 2021.

[17] Oishi, Y., Tauchi, S., and Inoue, C., "Unsteady Stream-Tube Model for Pulse Performance of Bipropellant Thrusters," *Journal of Propulsion and Power*, vol. 39(1), pp. 3-10, 2023.

[18] Kurishita, Y., Noritake, S., Matsuyama, K., Masuda, K., Miyanaga, M., Himeno, T., and Takata, S., "HTV Numerical Simulation Model of the Helium Solubility in the Propellant," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2014-3567, 2014.

[19] Yamamoto, H., Kawatsu, K., Daimon, Y., and Fujii, G., "Development of a Dynamic Response Model Considering Trapped Gas Effect for Spacecraft Liquid Propulsion Systems," *Journal of Evolving Space Activities*, vol. 1(34), 2023.