

Coupled Simulation of Propulsion System and Guidance and Control System

Yu Daimon^{†}, Takahiro Ito[‡], Kaname Kawatsu^{*}, Himeko Yamamoto^{*}, and Hideyo Negishi^{*}*

^{}Research and Development Directorate, Japan Aerospace Exploration Agency (JAXA), Tsukuba, Japan*

[†]Department of Engineering Mechanics and Energy, University of Tsukuba, Tsukuba, Japan

[‡]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA), Sagami-hara Japan

daimon.yu@jaxa.jp – ito.takahiro@jaxa.jp – kawatsu.kaname@jaxa.jp – yamamoto.himeko@jaxa.jp
– negishi.hideyo@jaxa.jp

[†] Corresponding Author

Abstract

Precise thrust control is critical in modern space missions, particularly for planetary landings and on-orbit servicing operations. We proposed and tested two types of coupled simulation approaches for propulsion systems and guidance and control systems: One-way Coupling and Two-way Coupling. The One-way Coupling method accounts for ignition delays and valve actuation lags, offering shorter computation times for early design stage simulations. The Two-way Coupling method enhances simulation fidelity by incorporating valve-induced flow fluctuations and thruster cross-talk effects. Our results indicate superior accuracy in predicting thrust variations and system responses, contributing to more reliable thrust management.

1. Introduction

Precise thrust control is becoming increasingly critical in modern space missions, particularly for planetary landings and on-orbit servicing operations such as docking. Traditionally, propulsion system development has relied heavily on ground-based firing tests, which are both costly and time-consuming. However, existing simulation approaches often lack sufficient fidelity for transient thrust behavior, making it challenging to accurately predict performance in landing and docking scenarios. To address these limitations, we at the Japan Aerospace Exploration Agency (JAXA) Research Unit III have developed a one-dimensional simulation tool to predict the dynamic response of propulsion systems, enabling more efficient system evaluations while reducing reliance on physical testing.

Recent research by NASA has demonstrated the effectiveness of transient propulsion system simulations using Numerical Propulsion System Simulation (NPSS) to improve thrust variation predictions [1]. This approach employs fuel flow scheduling through interpolation tables to capture ignition delays and transient thrust fluctuations, allowing for more precise system response assessments. However, NPSS-based transient analyses primarily focus on predefined fuel supply schedules, and do not account for valve-induced flow fluctuations or cross-talk effects between thrusters, which can be critical for precision maneuvers.

To address this gap, our simulation tool introduces three key advancements over previous models. First, it incorporates a performance prediction model [2] that accurately reflects thruster geometry information, allowing for realistic propulsion assessments. Second, it employs a trapped gas model [3, 4] to reproduce phase shifts caused by residual gases, such as purge gas introduced at pipe ends. Third, it features a high-fidelity ignition delay model [5], which captures the delay between valve opening and combustion initiation, significantly improving transient thrust predictions. These enhancements contribute to higher accuracy in propulsion system simulations, supporting more refined mission feasibility assessments and precision guidance strategies.

By integrating this simulation tool from the conceptual design phase, we establish a promising framework for optimizing thrust management strategies in future space missions. A particularly effective application is its coupling with guidance and control system analysis, enabling preemptive evaluations of landing and docking maneuvers. Unlike NPSS-based transient simulations, which primarily rely on predefined fuel scheduling, our approach incorporates valve-induced flow fluctuations and thruster cross-talk effects into the transient simulation framework. By coupling propulsion system dynamics with real-time control algorithms, we aim to improve thrust management reliability and reduce uncertainties during critical mission phases. This methodology bridges existing gaps in transient modeling and contributes to the advancement of autonomous precision guidance technologies.

2. Numerical Setup and Modelling

The basic tool for the propulsion system simulation is Simulation X, a Modelica-compatible multi-physics system-level modeling language. In the guidance and control program, MATLAB is used. There are two ways to couple these two programs. First, the thrust required by the MATLAB program is defined as a function of the value previously determined in Simulation X. This represents a one-way coupling from the propulsion system to the control system. In this case, the thrust is expressed as a function of time from valve opening, incorporating the effects of ignition delays and flow rate fluctuations associated with the valve's opening and closing. We will refer to this as the MATLAB-Based Coupling Method. The second method involves calling the valve open/close signals in Simulation X from the FMU (Functional-Mockup Unit) of the MATLAB program. This represents a two-way coupling between the propulsion system and the control system. This approach accounts for flow fluctuations induced by prior valve operations and crosstalk with other thrusters, in addition to ignition delays and flow variations caused by its own valve operations, thereby yielding more accurate results. We will refer to this as the SimulationX-Based Coupling Method. In this study, we use a test case involving a spacecraft equipped with two main thrusters (OME) and twelve reaction control system (RCS) thrusters. The simulation specifically targets the final stage of the moon landing sequence, where precise thrust control is essential. The main thrusters provide high thrust for landing operations, while the RCS thrusters are arranged for attitude control. Based on this system configuration, simulations were conducted using two types of coupled simulation approaches with Simulation X and MATLAB.

2.1 Guidance, Navigation, and Controls Simulation (MATLAB)

The guidance, navigation, and control method developed by JAXA utilizes a Pulse-Width Pulse-Frequency (PWWF) modulator to control the spacecraft's attitude. The PWWF modulator generates on-off control signals, offering advantages such as reduced energy consumption and ease of adjustment. Figure 1 shows the block diagram of the guidance system. In Fig. 1(a), based on the initial altitude, velocity, and final target altitude and velocity, a reference trajectory (altitude and velocity) and guidance commands, i.e., target thrust acceleration and thrust direction vector (used in the controller for attitude guidance calculation), are generated. The terminal powered descent guidance for the Smart Lander for Investigating Moon (SLIM) [6] is used for the guidance algorithm. In Fig. 1(b), the thrust direction vector from the left block diagram is smoothed to achieve better tracking performance.

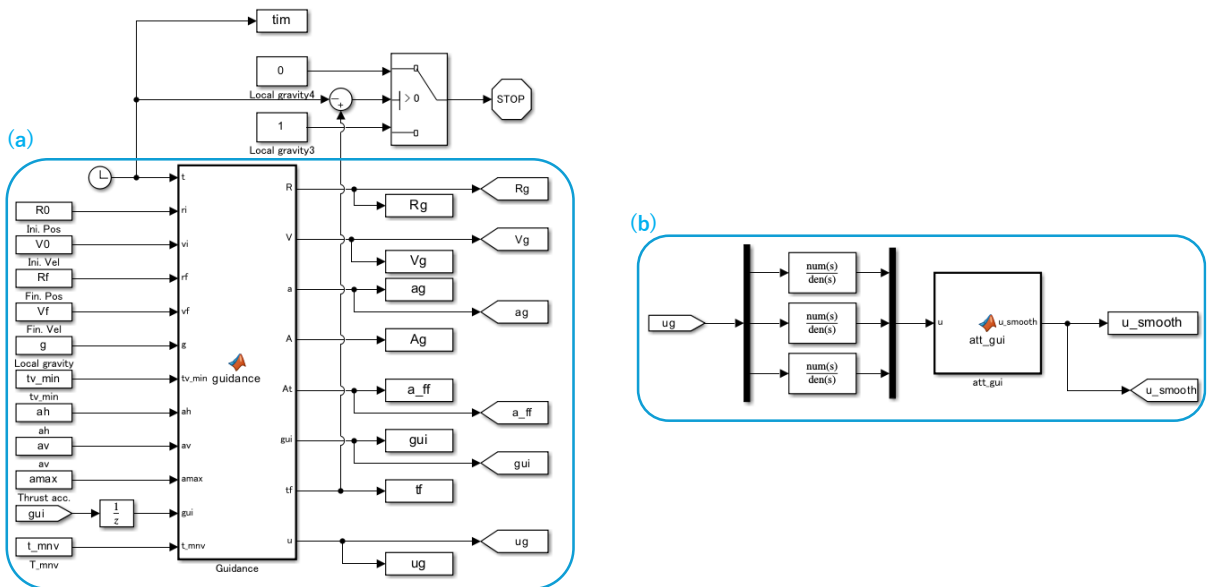
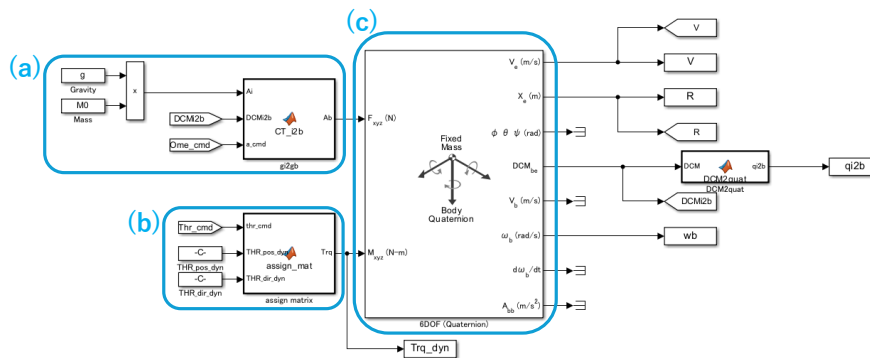


Figure 1: Block diagram of the guidance system.

Figure 2 shows the block diagram of the control system. In Fig. 2(a), translational control is applied based on the tracking errors of position and velocity. From the control signals generated in Fig. 2(a), OME ON/OFF commands are

Figure 3 shows the block diagram of the dynamics system. In Fig. 3(a), the force is calculated from the OME thrust and gravity, incorporating elements such as gravity and mass. Moving to Fig. 3(b), the torque is derived from the RCS thruster thrust. Finally, in Fig. 3(c), the 6DOF Dynamics section computes the body position, velocity, and attitude from the force and torque.



2.2 Liquid Propulsion System Simulation (Simulation X)

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for real gases. A water flow test was conducted to validate this model, evaluating the impact by varying gas quantity and position as parameters. As a result, the thrust fluctuation frequency in actual systems can now be reproduced more accurately. Finally, we describe the ignition delay model [5], which is the most unique feature of this technology. By visualizing the ignition phenomenon through experimental tests, we understand and model the phenomenon, demonstrating that ignition delays at various flow rates can be represented in one-dimensional system analysis.

3. Results and discussion

In this section, we present the results of our coupled simulation approaches and discuss their implications for precise thrust control in spacecraft missions. We compare the MATLAB-Based Coupling Method and the SimulationX-Based Coupling Method to highlight their respective advantages and limitations..

3.1 Results of MATLAB-Based Coupling Method (One-way Coupling Method)

In this section, we demonstrate the effectiveness of the MATLAB-Based Coupling Method by comparing its results with those obtained using only MATLAB without coupling. Figure 4 shows (a) the thrust of the main thruster (b) the thrust of RCS 1, (c) the position of the spacecraft, and (d) the velocity of the spacecraft. In the uncoupled MATLAB-only case, the main thruster thrust is modeled as a step function based on valve opening and closing, as shown in Fig. 4(a). In contrast, the MATLAB-Based Coupling method models the main thruster thrust as a time-dependent function, incorporating the ignition delay following valve activation, the pressure rise prior to ignition due to pre-ignition reactions, and the pressure peak at ignition. Because the MATLAB-Based Coupling method accounts for ignition delay, the spacecraft altitude decreases during the delay period, resulting in a longer main thruster firing duration. Although the simulation results are presented only up to 6 seconds, the thrust timing continues to shift during the landing sequence. In Fig. 4(b), the thrust of RCS1 is selectively presented as a representative case. The first firing occurs at nearly the same timing in both the uncoupled and the MATLAB-Based Coupling methods. However, in the MATLAB-Based Coupling method, the thrust profile more accurately reflects ignition delay and valve actuation lag. As a result, subsequent firing timings are shifted. These differences can potentially affect the precision and timing of attitude control, which is particularly critical in missions requiring high-accuracy maneuvering. Fig. 4(c) and 4(d) present the spacecraft's position and velocity profiles, respectively. The MATLAB-Based Coupling method introduces more realistic thrust dynamics, but the differences in position and velocity between the coupled and uncoupled simulations are not significant. However, as shown in the enlarged view of the Z-direction velocity in Fig. 4(d), the thrust timing shift observed in Fig. 4(a) is reflected in the Z-direction velocity. Still, the overall deviation remains small, and the impact on translational motion is limited. Even so, slight differences in velocity can become critical in precision maneuvers such as final descent or docking.

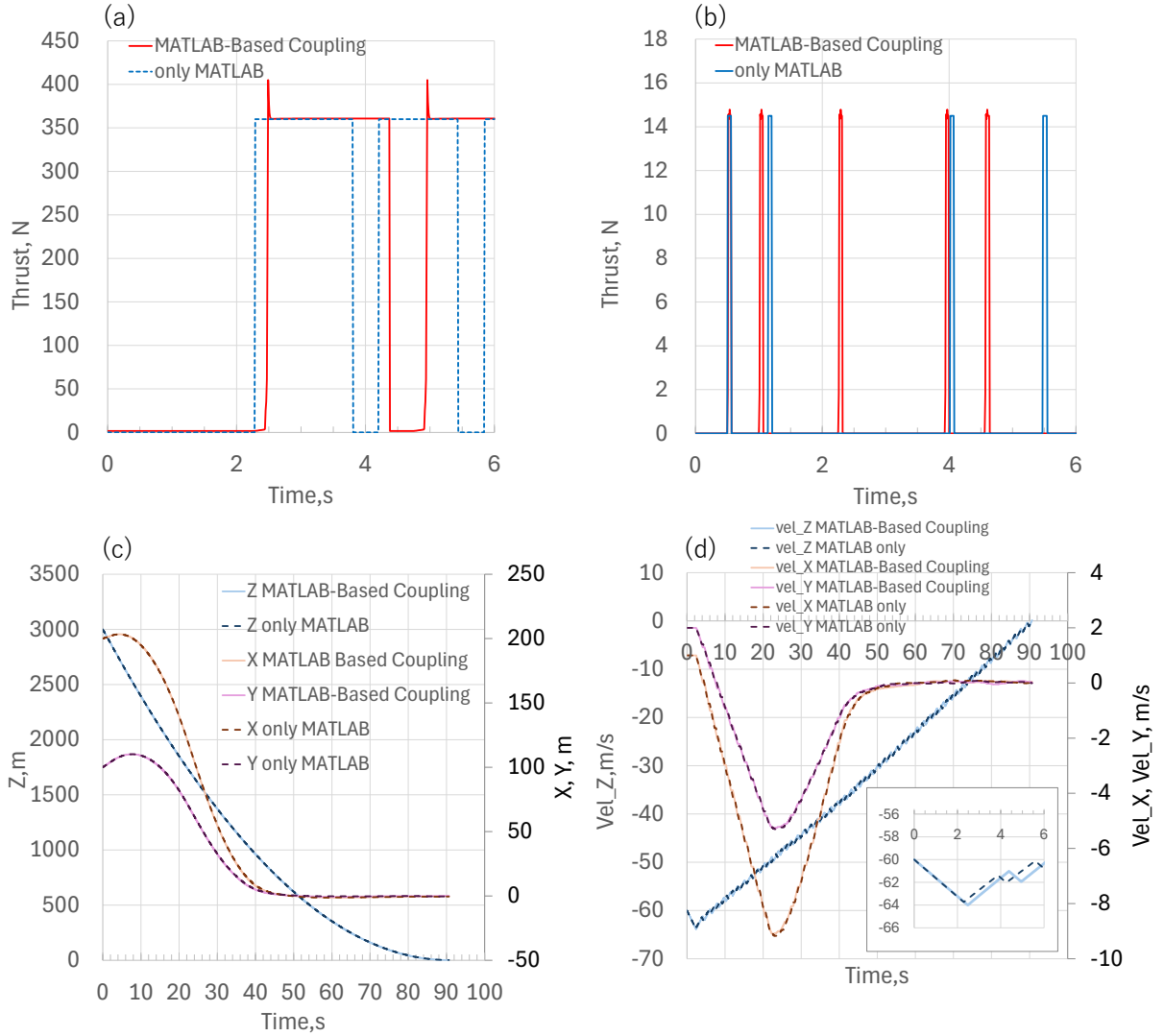


Figure 4: Thrust and Dynamics Histories Using MATLAB-Based Coupling. (a) Main thruster thrust. (b) RCS1 thrust. (c) Spacecraft position. (d) Spacecraft velocity.

3.2 Results of SimulationX-Based Coupling Method (Two-way Coupling Method)

Figure 5 shows the simulation results obtained using the SimulationX-based coupling method, in comparison with those from the uncoupled MATLAB-only approach. This method integrates valve signal handling via FMU and accounts for flow fluctuations due to prior valve operations and crosstalk between thrusters, providing a more physically accurate thrust profile. Compared to the MATLAB-based coupling method, the SimulationX-based approach captures subtle variations in thrust timing and magnitude, particularly in scenarios involving multiple thruster interactions. Figure 5(a) shows the thrust history of two main thrusters. In the SimulationX-based coupling method, the pipe lengths between the main thrusters and the RCS (Reaction Control System) thrusters are taken into account. This allows the two main thrusters to be evaluated individually, as disturbances caused by RCS operations propagate through the propulsion system with different delays and attenuations. As a result, time-dependent and asymmetric effects on the thrust behavior of each main engine are observed while the main engine valves remain open. Figure 5(b) shows the thrust history of RCS 1. Similar to Figure 4(b), the timing of the first pulse matches that of the MATLAB-only result. However, in the SimulationX-based coupling result, the thrust values are more physically representative, which leads to a gradual shift in the timing of subsequent pulses. Furthermore, since crosstalk effects are taken into account, it can be observed that when the RCS thruster is fired at the moment the main engine valve is closed (as shown

in Figure 2(a)), the resulting thrust is approximately 40 % higher. Figures 5(c) and 5(d) show the spacecraft's position and velocity, respectively. As discussed in Figures 4(c) and 4(d), the differences in position and velocity remain minimal between the coupled and uncoupled simulations.

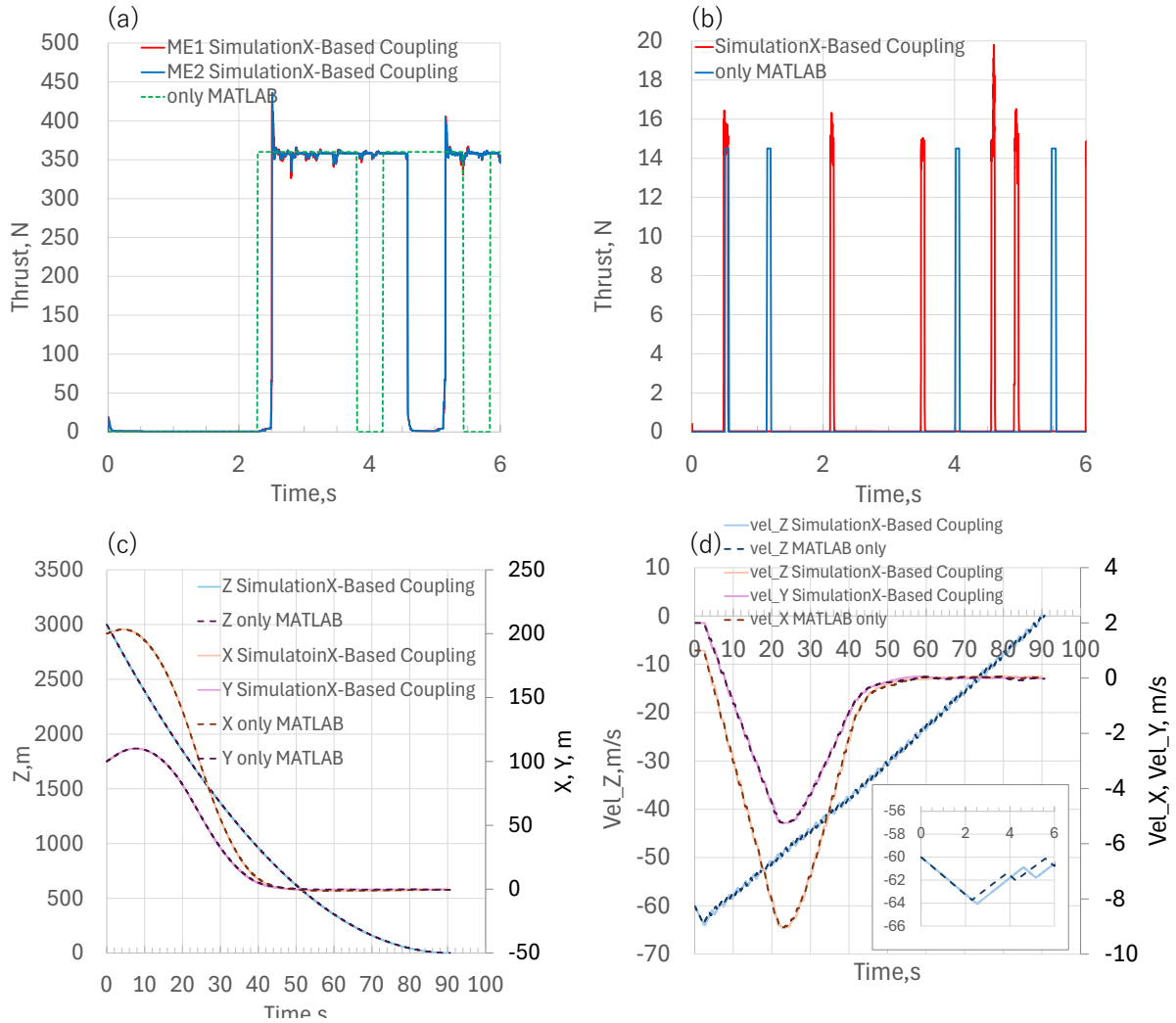


Figure 5: Thrust and Dynamics Histories Using SimulationX-Based Coupling. (a) Main thruster thrusts. (b) RCS1 thrust. (c) Spacecraft position. (d) Spacecraft velocity.

As shown in Fig.5, the most important feature of SimulationX-Based Coupling method is the evaluation of cross-talk. Figure 6 shows representative examples of cross-talk using the SimulationX-Based Coupling Method. (a) illustrates the thrust history of the two main thrusters, and (b) shows the thrust history of the twelve RCS thrusters. As already shown in Figure 5(a), thrust fluctuations can be observed in Figure 6(a) while the main thruster valves are open. This is due to the flow fluctuations caused by the opening and closing of the RCS thruster valves, as shown in Figure 3(b), which are transmitted to the main thrusters. Under the given conditions in Figure 6(b), the RCS thrusters are expected to generate approximately 14N of thrust. However, the water hammer effect occurring immediately after the main engine valves close causes pressure fluctuations that propagate throughout the system, resulting in substantial variations in the thrust of the RCS thrusters. When the main engine valve closes around 21.6 seconds, pressure fluctuations propagate through the piping, reaching each RCS thruster and inducing flow variations and corresponding thrust fluctuations. Observing the thrust of the RCS thrusters, we can see that from approximately 21.8 seconds to 22.4 seconds, there is an amplitude that gradually attenuates. When the main engine valve closes around 23.6 seconds, the RCS thrusters fire immediately afterward, resulting in significant thrust fluctuations, with variations up to 40% observed.

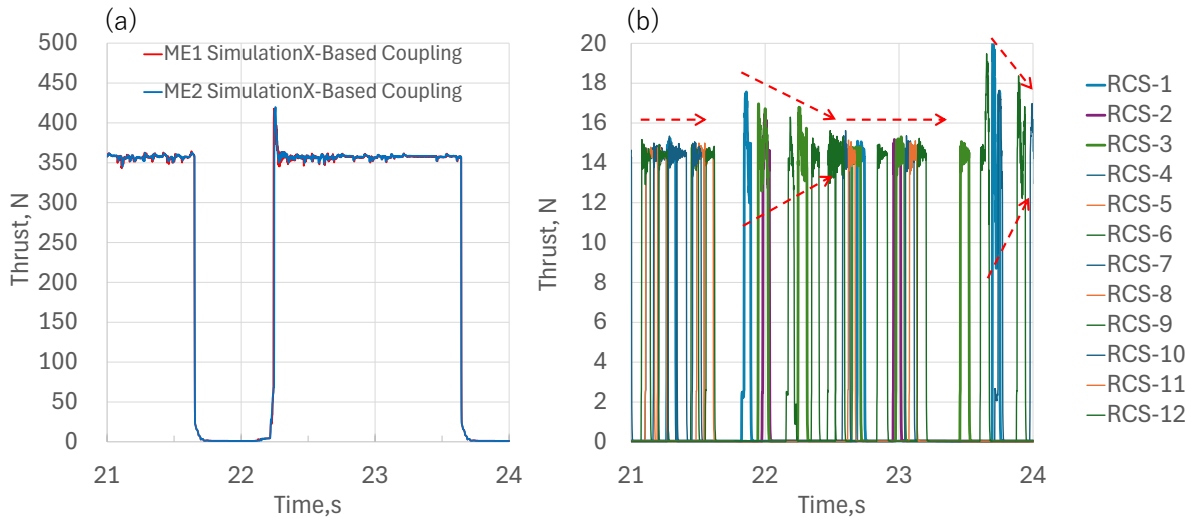


Figure 6: Typical Results of Cross-talk Effects. (a) Main thruster thrusts. (b) RCS thruster thrusts.

4. Conclusions

In this study, we proposed and tested two types of coupled simulation approaches for propulsion systems and guidance and control systems, utilizing both MATLAB and SimulationX. The MATLAB-Based Coupling Method (One-way Coupling) demonstrated the importance of accounting for ignition delays and valve actuation lags in thrust modeling, which significantly impacts the precision of attitude control during critical mission phases. Additionally, the MATLAB-Based method has the advantage of shorter computation times, making it suitable for Monte Carlo simulations in the early design stages. The SimulationX-Based Coupling Method (Two-way Coupling) further enhanced the simulation fidelity by incorporating valve-induced flow fluctuations and thruster cross-talk effects, providing a more accurate representation of thrust dynamics.

Our results indicate that the SimulationX-Based Coupling Method offers superior accuracy in predicting thrust variations and system responses, particularly in scenarios involving multiple thruster interactions. This method's ability to evaluate cross-talk effects and flow fluctuations contributes to more reliable thrust management and reduced uncertainties during landing and docking maneuvers.

By integrating these advanced simulation tools from the early design stages, we establish a robust framework for optimizing thrust management strategies in future space missions. The coupling of propulsion system dynamics with real-time control algorithms paves the way for the advancement of autonomous precision guidance technologies, supporting more refined mission feasibility assessments and precision guidance strategies.

As future work, we aim to enhance the accuracy of this tool by incorporating the effects of propellant sloshing during landing and estimating the center of gravity shifts due to propellant consumption. This will enable the development of a highly accurate virtual landing tool.

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