Investigation and development of the multi-disciplinary model-based system-level simulation for launch and re-entry vehicles

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Abstract

Reentry safety evaluation (risk assessment of residual debris) of rocket upper stages and spacecraft is an important theme to ensure the sustainability of space development, and establishment of comprehensive system design and model-based design/development methods that can handle complex systems such as innovative future space transportation systems is also important. In this project, the common issue of these two important themes, "development of efficient integrated simulation technology for system behavior," is being adressed. Research and development are conducted on methods that large-scale analyses such as parametric studies and probabilistic evaluations allow large-scale analyses such as parametric studies and probabilistic evaluations to be carried out efficiently on a JSS, using the re-entry safety analysis code LS-DARC and the space transportation system launch and re-entry integrated analysis tool LS-LUCA for the study of new space transportation systems such as next-generation flagship launch vehicles and for safety design in manned space transportation.

Reasons and benefits of using JAXA Supercomputer System

- The system can be used quickly by JAXA employees without complicated and time-consuming procedures.
- Since JSS is a JAXA internal system, it can be connected within the same JAXA intranet, and there is little risk of information leakage.
- The system can securely handle sensitive information, such as highly confidential rocket upper stage and spacecraft design information, in a closed environment within JAXA.
- Immediate support for system usage is available.

Achievements of the Year

Result 1: Improvement of model accuracy in re-entry melting analysis of the upper stage of a launch vehicle

- In order to improve the accuracy of the re-entry melting analysis of the upper stage of a flagship launch vehicle and to realize a design improvement that enhances the demisability of debris (accelerated melting design), we have improved LS-DARC functions that can consider aerodynamic characteristics and heat flux distribution for real complex shapes, 3D heat transfer analysis, shape and heat capacity changes due to melting. The JSS3's computing power enabled us to efficiently perform a number of validation analyses associated with the LS-DARC functionality and to perform melting analyses of the actual upper stage of the rocket using the LS-DARC function. LS-DARC, which can handle real complex shapes and shape changes, can evaluate physical phenomena that cause objects to melt easily that cannot be handled by conventional analysis techniques, such as increased heat flux at small radius of curvature and decreased heat capacity due to melting (Figs. 1 and 2).

- The analysis was able to obtain a large amount of data necessary to determine debris melting, such as the behavior of the six-degree-of-freedom during re-entry, a basic understanding of the time variation of altitude and velocity that determines the heat flux level profile, the time variation of heat flux to the components of the vehicle at different entry angles, and the total amount of heat input.

- In order to achieve the final goal of the project, which is to increase the accuracy of the analysis of the upper stage of the rocket and reduce EC, it is necessary to perform a parametric analysis of the entire vehicle configuration, which consists of more than 100 components, by shaking the entry angle and attitude rate at the start of re-entry. This was not possible with commercially available computers, but by utilizing JSS3, it was found to be possible to perform the analysis in 20 hours per case, giving us the prospect of achieving the goal in a short period of time.

Result 2: Improvement of Reentry Melting Analysis Model Formulation for Rocket Upper Stage and Spacecraft Basic Geometry

- The current re-entry melting analysis tool, ORSAT-J, is an object-oriented model that treats the geometry of complex objects as a combination of basic shapes such as cylinders, spheres, boxes, etc. Debris motion is assumed to be three degrees of freedom, and aerodynamic and heat flux modeling is performed using semiempirical formulations. In this theme, first of all, probabilistic evaluations of six cases of cylinders with three attitude rate components were efficiently performed by utilizing the computational power of JSS3, which is based on the component shapes and masses of the upper stage rocket and satellite.

- The effect of shape and mass characteristics on the drag coefficient, total heat input, and the pace of debris deceleration were systematically understood through the melt analysis for the actual vehicle.

- formulation of the re-entry melting analysis model, Monte Carlo analysis of more than 1000 times per case was necessary for more than several dozen combinations of shape and mass properties, which was not possible using commercial computers. However, by using JSS3, it was found that a Monte Carlo analysis of 1,000 times per case could be performed in 5 hours, which gave us the prospect of achieving the goal in a short period of time.

Result 3: Improvement of efficiency of system feasibility evaluation for launch and re-entry of space transportation systems

- In order to study future space transportation systems, it is necessary to conduct coupled analysis of multiple physics fields for many system design options to evaluate the feasibility of systems including reentry and return for reuse, and to evaluate the feasibility of crew life saving by launch and abort systems to ensure expandability

to manned space transportation. The computing power of JSS3 enables efficient system feasibility evaluations and numerous design study iterations.

- The sensitivity of key design parameters could be evaluated by performing structural feasibility evaluation in addition to aerodynamic stability and orbit feasibility during launch and re-entry for the reference design of the flagship launch vehicle.

- To achieve the final goal of this project, which is to evaluate the system feasibility of the next-generation flagship launch vehicle, it is necessary to evaluate multi-disciplinary system feasibility such as aerodynamics, orbit, heat resistance, and structure for more than several dozen combinations of airframe shape and mass characteristics. It was confirmed that JSS3 can evaluate the feasibility of a large number of design options by utilizing its computing power. At the present stage, the analysis time can be reduced to about 10 minutes for one option. In the future, it will be necessary to conduct high-load CFD analysis for evaluation of aerodynamic characteristics at sub-supersonic and supersonic speeds, which require even higher analysis accuracy, and FEM analysis for evaluation of heat resistance and structural feasibility of detailed geometry in a short period of time.

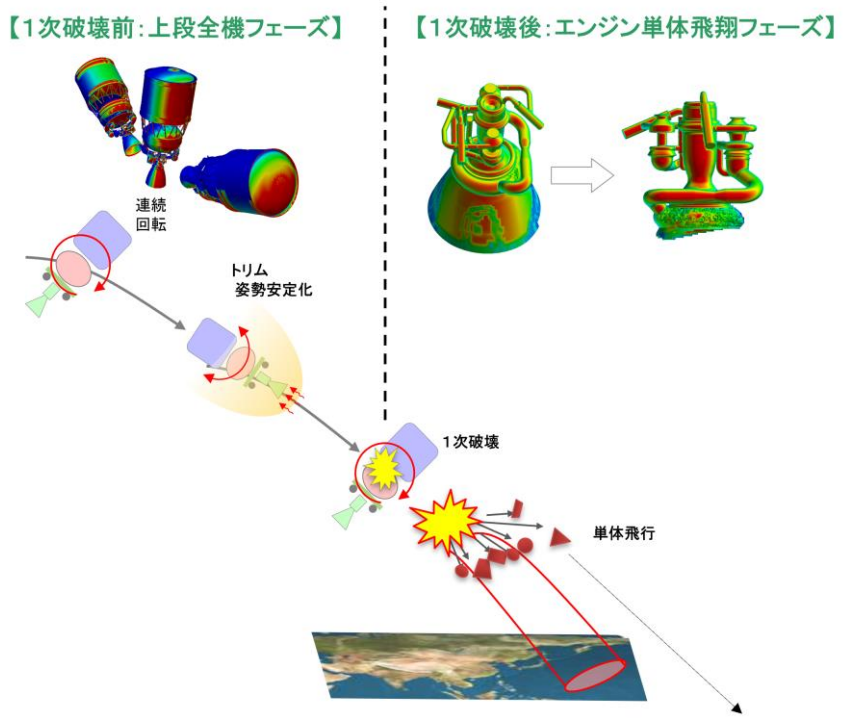

Fig. 1: Example of melting analysis results considering actual complex geometry and shape change due to melting (rocket upper stage)

Publications

- Non peer-reviewed papers

1)Keiichiro Fujimoto, Hideyo Negishi, Shinjiro Tsuji, Kenichi Sato, Tsutomu Matsumoto, Takayuki Itoh, Shohei Kawahara, "COMPARISON OF RE-ENTRY SAFETY ANALYSIS TOOL LS-DARC AND ORSAT-J FOR MODEL UPDATE," 13th IAASS Conference, 2024.

2)Keiichiro Fujimoto, "DEVELOPMENT OF QUANTITATIVE CREW SAFETY ASSESSMENT METHOD BASED ON MULTI-PHYSICS SIMULATION CODE LS-LUCA," 13th IAASS Conference, 2024.

- Oral Presentations

3)Shinjiro Tsuji, Keiichiro Fujimoto, Hideyo Negishi, "Validation of heat flux and aerodynamic model of Multi-physics coupled simulation tool LS-DARC/LUCA for Rockets and Reentry vehicles -1st Report," 4O11, 68th Space Sciences and Technology Conference, 2024

4)Keiichiro Fujimoto, Kaname Kawatsu, Yuuki Tomita, Yuri Hachiya and Takashi Uchiyama, "Development of Quantitative Crew Safety Analysis Model for Launch Abort System of Human Space Flight –2nd report," 1G18, 68th Space Sciences and Technology Conference, 2024

5)Takanobu Kamiya, Keiichiro Fujimoto, Hideyo Negishi, "Debris Mitigation Status for Rocket Upper Stage in Japan," the 11th Space Debris Workshop, 2024

Usage of JSS

Computational Information

Process Parallelization Methods	MPI
Thread Parallelization Methods	OpenMP
Number of Processes	1 - 216
Elapsed Time per Case	16 Hour(s)

JSS3 Resources Used

Fraction of Usage in Total Resources[*1](%): 0.08

Details

Computational Resources		
System Name	CPU Resources Used (core x hours)	Fraction of Usage[*2](%)
TOKI-SORA	0.00	0.00
TOKI-ST	684,791.89	0.70
TOKI-GP	9.58	0.00
TOKI-XM	0.00	0.00
TOKI-LM	0.00	0.00
TOKI-TST	0.00	0.00
TOKI-TGP	0.00	0.00
TOKI-TLM	0.00	0.00

File System Resources		
File System Name	Storage Assigned (GiB)	Fraction of Usage*2 (%)
/home	500.06	0.34
/data and /data2	500.00	0.00
/ssd	36,576.67	1.96

Archiver Resources		
Archiver Name	Storage Used (TiB)	Fraction of Usage*2 (%)
J-SPACE	4.77	0.02

*1: Fraction of Usage in Total Resources: Weighted average of three resource types (Computing, File System, and Archiver).

*2: Fraction of Usage：Percentage of usage relative to each resource used in one year.

- **ISV Software Licenses Used**

ISV Software Licenses Resources		
	ISV Software Licenses Used (Hours)	Fraction of Usage*2 (%)
ISV Software Licenses (Total)	0.11	0.00

*2: Fraction of Usage：Percentage of usage relative to each resource used in one year.