JASMAC Conference of the Japan Society of Microgravity Application

OR2-2

微小重力天体着陸時の探査機の推進剤のスロッシングのメカニカルモデルの提案と検証

Mechanical Model of Spacecraft Propellant Sloshing during Decent Operation on Microgravity Celestial Body

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1. Background

JAXA plans to explore a Martian satellite, which is a microgravity object in the Martian atmosphere, based on its experience in microgravity object exploration, as represented by the Hayabusa project[1)]. This plan is referred to as Mars Moons Exploration (MMX; Martian Moons eXploration)[2)]. One of the challenges in landing is that the spacecraft has a large amount of liquid propellant and oxidizer, and there are concerns regarding the effects of sloshing [3)]. Additionally, landing on a slope needs to be considered, and the effects of sloshing must be investigated. Computational Fluid Dynamics (CFD) fluid analysis is required to reproduce sloshing accurately; however, it is computationally time-consuming. Therefore, if there are multiple possible landing scenarios, it is necessary to propose a reduced model that can accurately reproduce sloshing with a smaller computational load than that of CFD.

Because three landing scenarios are assumed in MMX, the proposed model should be able to accommodate changes in the sloshing phenomenon owing to the different amounts of propellant and oxidizer remaining.

This study proposes a mechanical model that can reproduce the sloshing phenomenon of a propellant onboard a spacecraft while landing on a microgravity object. The values of the model parameters were determined according to the operational scenario using a genetic algorithm. Numerical calculations were performed and compared with the CFD analysis to validate the model with the obtained parameters.

2. Degenerate model of propellant

2.1. The results of CFD analysis

The CFD results for each evaluation item of the axisymmetric sloshing of the propellant for the input acceleration during landing are shown in **Figures 1 and 2**. Focusing on the shape transition of a propellant with a nominal liquid level as an example, the following observations were made.

① At approximately 16–17 s, a Z-positive reaction force is generated owing to the downward movement of the liquid surface.

② At approximately 17–19 s, a Z-negative reaction force was generated owing to the upward movement of the liquid surface.

③ At approximately 20 s, the load peak occurred owing to the collision of the upper end of the liquid column.

④ At approximately 20–24 s, the upward movement of the liquid through the liquid column and the Z-positive load due to the collision continued.

⑤ After approximately 23 s, part of the colliding liquid returns and hits the liquid surface.

⑥ After 24 s, the load decreased while the wave propagated across the interface.

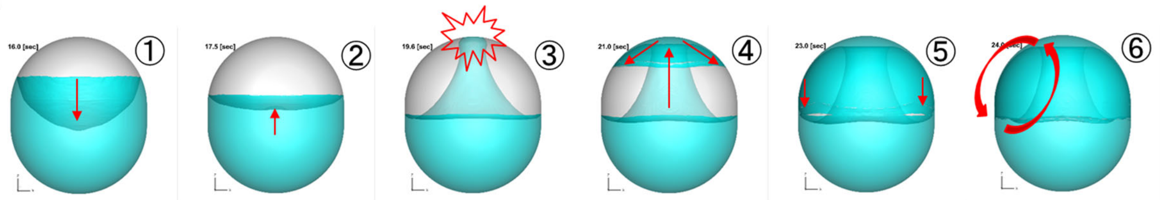
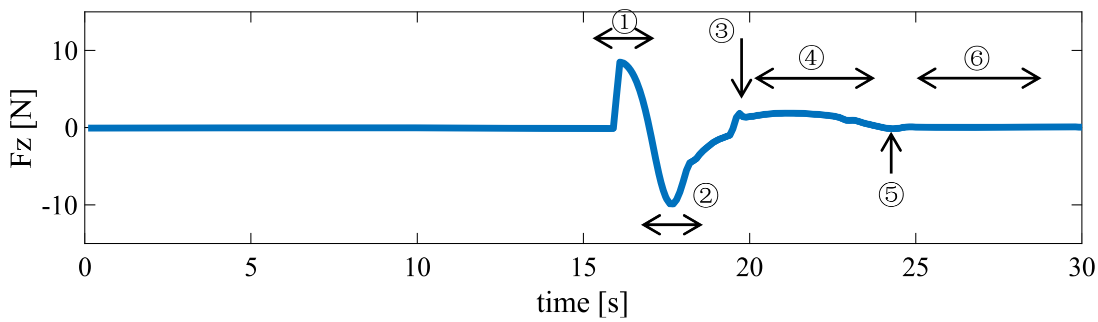
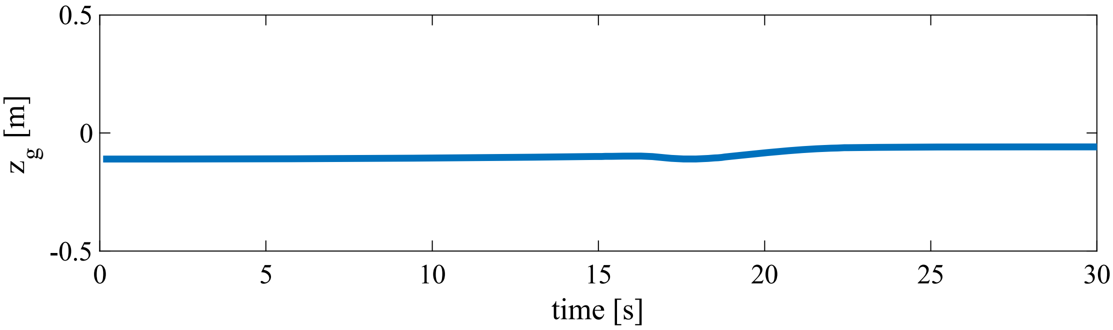


Figure 1. Animation of CFD results in nominal scenario.

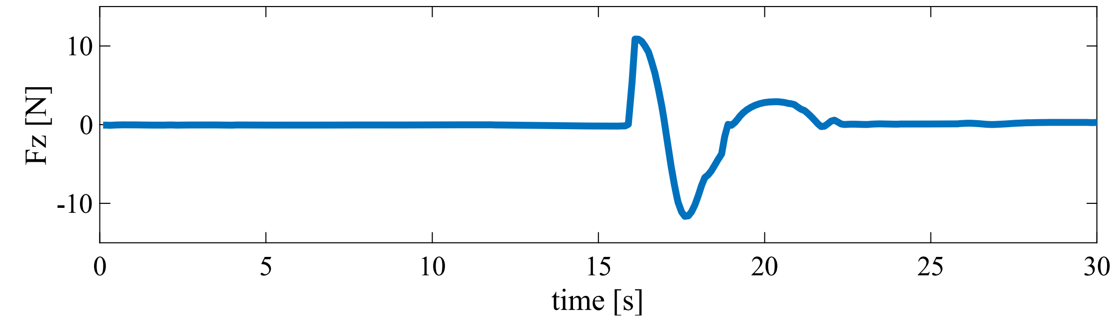


(a) Tank reaction force.

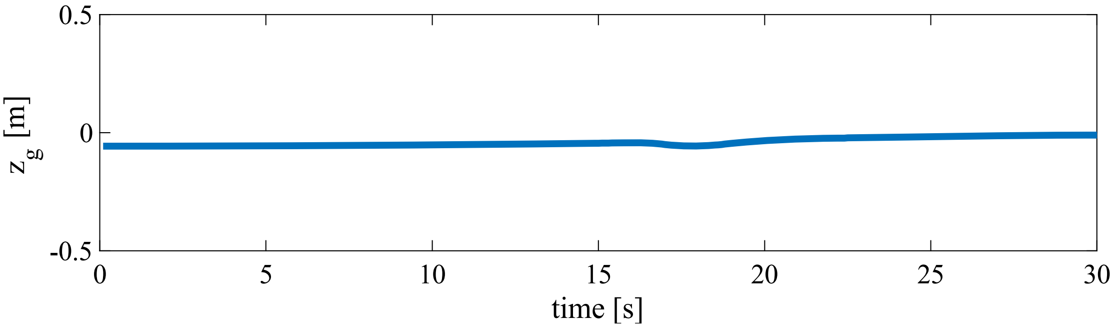


(b) Center of gravity

Figure 2. CFD results during 1st decent operation on microgravity celestial body.

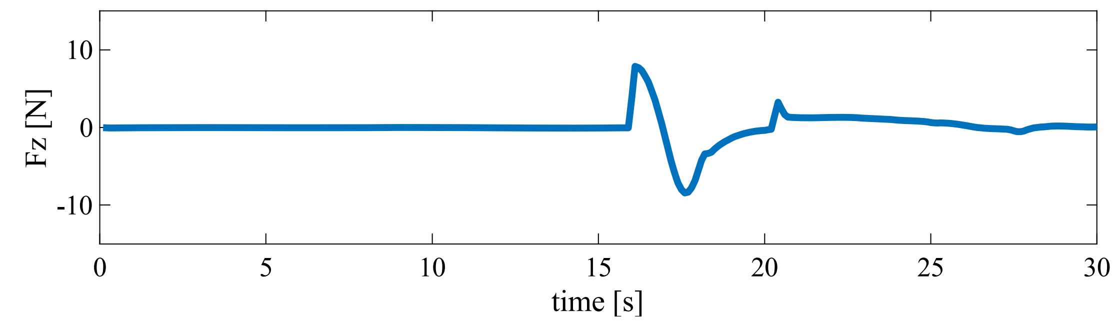


(a) Tank reaction force.

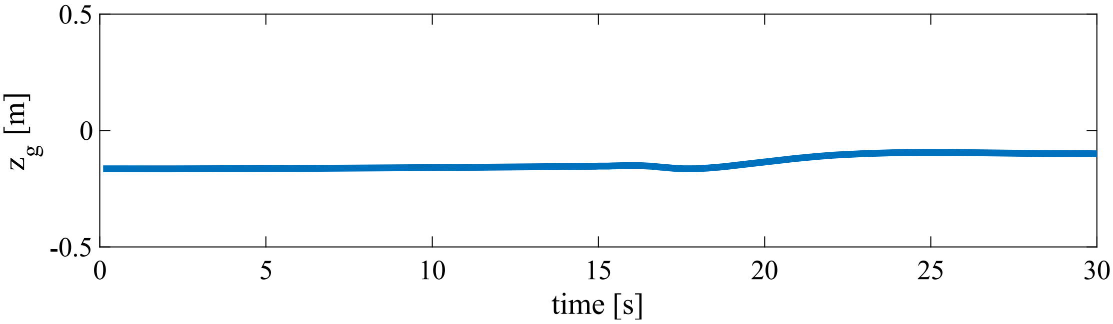


(b) Center of gravity

Figure 3. CFD results during 2nd decent operation (nominal scenario) on microgravity celestial body.

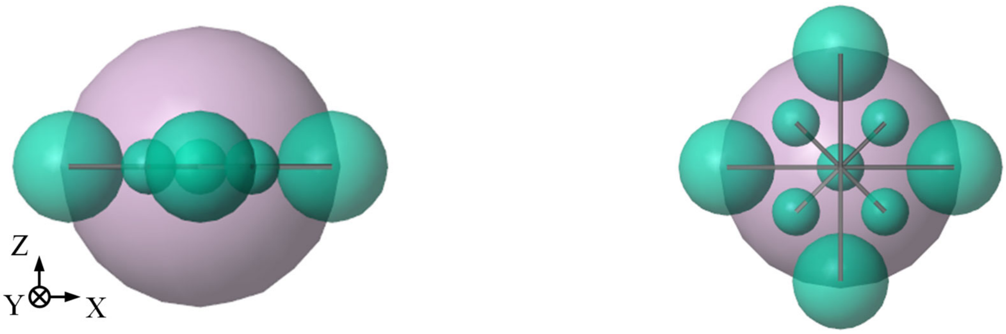


(a) Tank reaction force.



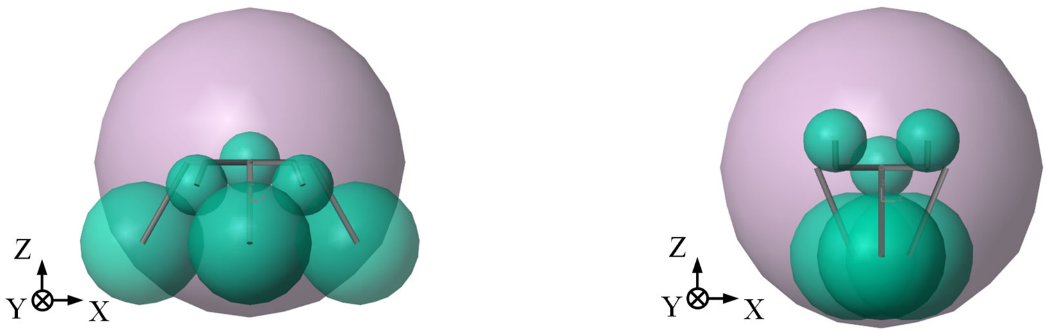
(b) Center of gravity

Figure 4. CFD results during 3rd decent operation on microgravity celestial body.



(a) Front side (b) Top side

Figure 5. Proposal model



(a) Front side (b) Top side

Figure 6. Axisymmetric sloshing of the proposed model

2.2. Evaluation item to tune parameters of degenerate model

We propose a propellant degeneracy model that can accurately analyze propellant sloshing by comparing and examining CFD results. The following three evaluation items were compared with the CFD results:

① Reaction force exerted on the tank by propellant sloshing

② The point of reaction force exerted by the propellant sloshing on the tank should be specifically adjusted.

③ The center of gravity of the propellant

Figures 2 to 4 show the CFD results for each evaluation item of axisymmetric propellant sloshing for the input acceleration during the first, second, and third landings, respectively.

3. Degenerate model

3.1. Definition of model

The proposed model was constructed using the Simscape Multibody in MATLAB. The proposed model and its principles of operation are illustrated in **Figures 5 and 6**, respectively. Axisymmetric sloshing is represented by the rotation around the axis of the link joints, and pendulums with different masses and link lengths are attached to represent the oscillations of axisymmetric sloshing, especially at points that need to be adjusted.

3.2. Parameters of degenerate model

As shown in **Figure 7** and **Table 1**, there are many parameter variables in the proposed model, such as the

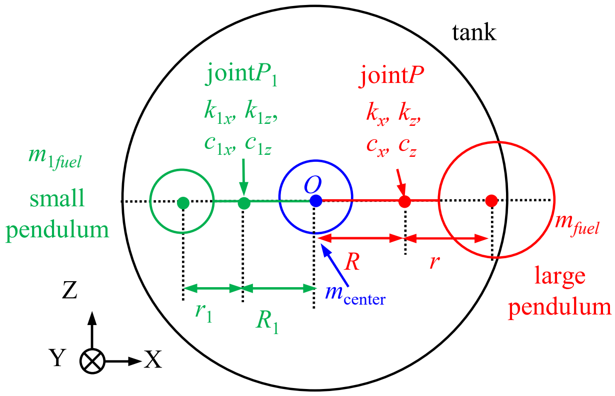


Figure 7. Parameters of the proposed model

mass of the pendulum, link length, and damping coefficient of the joints, and it is difficult to determine the optimal parameters through trial and error.

Therefore, we introduce a genetic algorithm that can derive an optimal or sub-optimal solution in a relatively short time.

3.3. Genetic Algorithm

In this study, the parameters were determined using a genetic algorithm. The degree of adaptation is expressed by the following equation:

$$f = f_{force} + f_{com}, \tag{1}$$

$$f_{force} = \frac{1}{\sum_{i=0}^{t_s}(f_{sim} - f_{CFD})^2}, \tag{2}$$

$$f_{com} = \frac{1}{\sum_{i=0}^{t_s}\left(x_{g,sim} - x_{g,CFD}\right)^2}, \tag{3}$$

where f_{force} is the fitness value of the reaction force of the propellant sloshing and f_{com} is the fitness value for the center of gravity of the spacecraft with the propellant. f_{sim} is the reaction force of the propellant sloshing derived from the simulation, and f_{CFD} is the reaction force of the propellant sloshing derived from the CFD. $x_{g,sim}$ and $x_{g,CFD}$ are the centers of gravity of the spacecraft with the propellant derived from the simulation and CFD, respectively.

where N is the total number of samples, N1 is the number of samples at the point where the transverse sloshing should be aligned, N2 is the number of samples at the point where the axisymmetric sloshing should be aligned, n1 is the sample start point at the point where the transverse sloshing should be especially aligned, and n2 is the sample starting point at the point where the axisymmetric sloshing should be especially aligned. n2 denotes the sample starting point of the axisymmetric sloshing, which is particularly aligned. The simulation time was 40 s, and the data sampling interval was 0.01 s. The number of generations was set to 100, the crossover rate to 0.8, and the mutation rate to 0.03. The crossover method was a one-point crossover with random crossover points, and the crossover individuals were determined using a tournament strategy.

4. Simulation Results

In this section, the proposed degenerate model and CFD results are compared. **Table 2** shows the analytical conditions, and **Table 3** shows the values of the model parameters obtained by the genetic algorithm. **Figures 8–10** show the results of the numerical analysis using the model parameters listed in **Table 3**. It can be seen that the proposed model is more consistent with the CFD results, with smaller errors in the center of gravity position, tank reaction force, and especially in all the points that need to be aligned. In addition, the conventional model is characterized by the fact that adaptability 3, which is the point to be especially adjusted, is small in all cases, making it difficult to adjust adaptability 3. However, the proposed model has much larger adaptivity, which enables highly consistent matching. As we were able to verify the effectiveness of the proposed model, we constructed a coupled analytical model incorporating the degenerate model proposed in section 3-2 in section 3-3.

Table 1. Model parameters

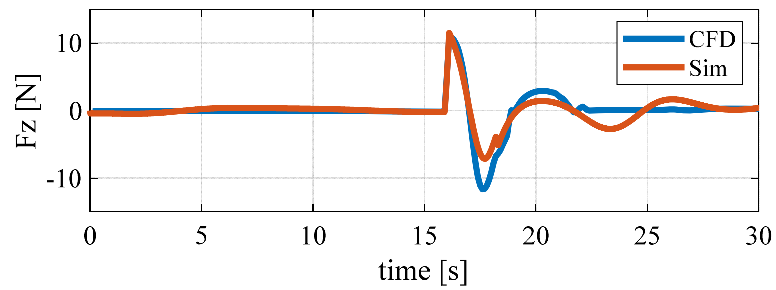
Symbol	Parameter	Unit
m_{center}	Fixed mass	kg
m_{fuel}	Large pendulum slosh mass	kg
$m_{1\mathrm{fuel}}$	Small pendulum slosh mass	kg
R	Large pendulum cross link length	m
R_1	Small pendulum cross link length	m
r	Large pendulum tip link length	m
r_1	Small pendulum tip link length	m
k_x	Large pendulum lateral sloshing link spring coefficient	Nm/rad
k_z	Large pendulum axisymmetric sloshing link spring coefficient	Nm/rad
k_{1x}	Small pendulum lateral sloshing link spring coefficient	Nm/rad
k_z	Small pendulum axisymmetric sloshing link spring coefficient	Nm/rad
k_{1x}	Large pendulum lateral sloshing link damping coefficient	Nms/rad
k_{1z}	Large pendulum axisymmetric sloshing link damping coefficient	Nms/rad
c_x	Small pendulum lateral sloshing link damping coefficient	Nms/rad
c_z	Small pendulum axisymmetric sloshing link damping coefficient	Nms/rad

Table 2. Weight of propellant and oxidizer in operational phase.

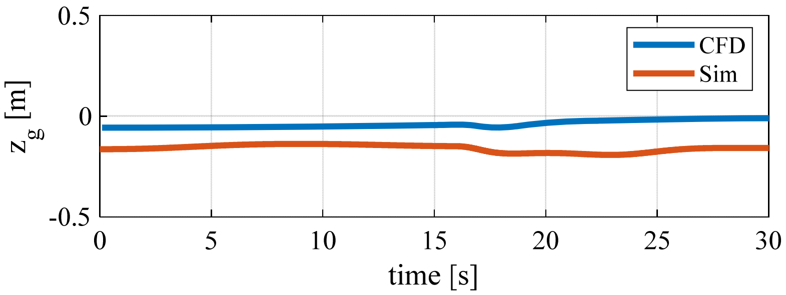
Liquid type	**1st Landing**	**Nominal**	**3rd Landing**
propellant	488 kg	404.5 kg	321 kg
oxidizer	214.5 kg	180.5 kg	146.5 kg

Table 3. Weight of propellant and oxidizer in operational phase.

Parameters	**Unit**	**Range**	**1st Landing**	**Nominal**	**3rd Landing**
m_{center}	kg	100 - 250	191	138	101
m_{fuel}	kg	20 – 60	45	54	57
r	m	0.20 – 0.30	0.28	0.25	0.25
r_1	m	0.020 – 0.30	0.045	0.056	0.023
k_x	Nm/deg	0.000050 – 0.0010	0.00083	0.00067	0.00022
k_z	Nm/deg	0.000050 – 0.0010	0.00016	0.000094	0.00006
k_{1x}	Nm/deg	0.000050 – 0.0010	0.00037	0.00018	0.00095
k_{z1}	Nm/deg	0.000050 – 0.0010	0.00041	0.00013	0.00028
c_x	Nms/deg	0.0030 – 0.050	0.012	0.0040	0.0181
c_z	Nms/deg	0.0030 – 0.050	0.050	0.0047	0.0317
c_{1x}	Nms/deg	0.000010 – 0.0010	0.00090	0.00060	0.00069
c_{1z}	Nms/deg	0.000010 – 0.0010	0.00042	0.00054	0.00081

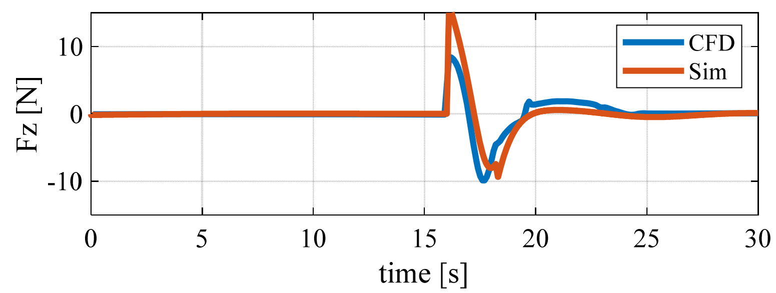


(a) Tank reaction force.

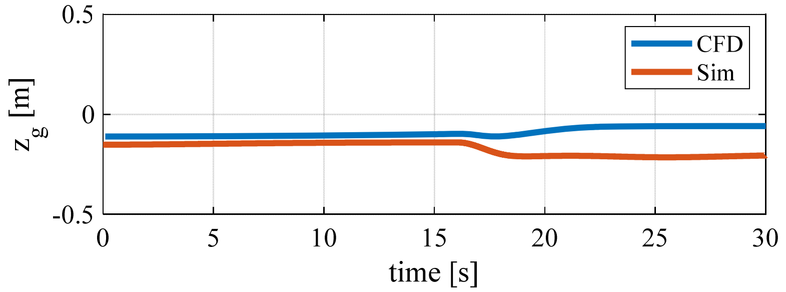


(b) Center of gravity

Figure 8. Comparison results of the proposed model during 1st decent operation on microgravity celestial body.

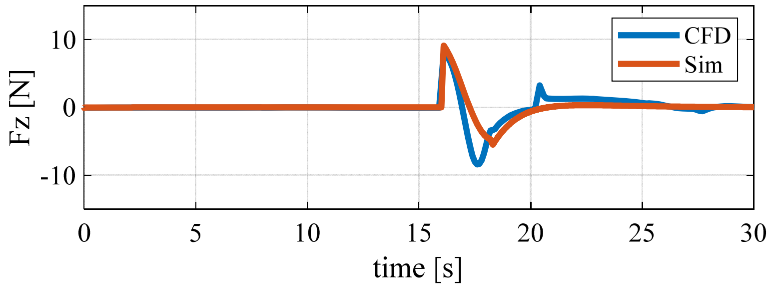


(a) Tank reaction force.

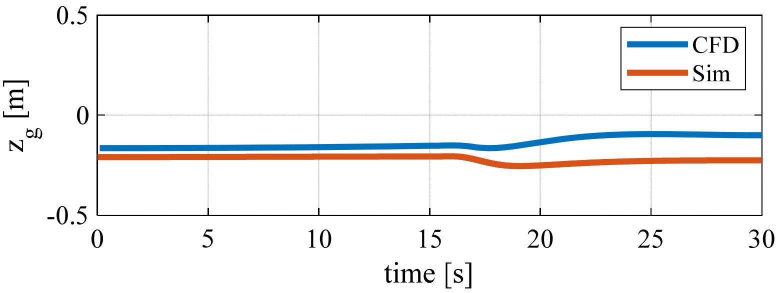


(b) Center of gravity

Figure 9. Comparison results of the proposed model during 2nd decent operation on microgravity celestial body.



(a) Tank reaction force.



(b) Center of gravity

Figure 10. Comparison results of the proposed model during 3rd decent operation on microgravity celestial body.

4. Conclusions

In this paper, we propose a mechanical model that can reproduce the sloshing phenomenon of a propellant onboard a spacecraft during landing on a microgravity object. The values of the model parameters were obtained using a genetic algorithm based on an operational scenario. A numerical analysis was performed using the model with the determined parameters, and the validity of the model was verified by comparison with the results of CFD analysis.

References

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2) JAXA, Martian Moons eXploration (MMX), https://www.isas.jaxa.jp/missions/spacecraft/developing/mmx.html (as of 2023/9/6).

3) Romero Calvo, A., García Salcedo, A. J., Garrone, F., Rivoalen, I., Cano Gómez, G., Castro Hernández E., and Maggi, F. StELIUM: A student experiment to investigate the sloshing of magnetic liquids in microgravity. Acta Astronautica, 173 (2020)., 344 355, https://doi.org/10.1016/j.actaastro.2020.04.013.