A Study on the Micro Gravity Sloshing Modeling of Propellant Quantity Variation

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ABSTRACT

In this study, the sloshing phenomenon is analyzed for the internal fluid mass change. And the change of the sloshing modeling design variables according to the fluid mass change is also analyzed. First, the sloshing phenomenon for each case is analyzed by CFD when the internal fluid mass is fixed. An appropriate sloshing modeling structure is proposed based on the analyzed results. The PSO method, which is one of the parameter optimization methods, is used as a method for appropriately selecting design variables of proposed sloshing modeling. In the same way, assuming a situation where the internal fluid mass changes in several levels, the sloshing modeling design variables for each internal fluid mass are calculated. The internal fluid varies from 10% to 90% in 10% increments so it is divided into 9 levels. By understanding the relationship between the optimized modeling design variables and the internal fluid mass, a sloshing model can be proposed to respond to the internal fluid mass change.

KEYWORDS : Sloshing Modeling, second-order system, Parameter Optimization, Parametric Study

NOMENCLATURE

a – Acceleration input
d – Magnitude of the input
f – Frequency of the input
L – second-order system for sloshing modeling
ζ - Damping coefficient of the system
ω_n - Natural frequency of the system
V – Fluid volume ratio to the storage tank volume
J – cost function for the optimization algorithm
C_1 - Weighting for previous velocity of each particles
C_2 - Weighting for difference between local optimum and current position of each particles
C_3 - Weighting for difference between global optimum and current position of each particles
$\vec{p}_i$ - Local optimum of each particles
$\vec{p}_g$ - Global optimum of entire group
$\vec{x}_i$ - Current position of each particles
$\vec{v}_i^{'}$ - Velocity of each particles in the previous generation
$\vec{v}_i$ - Updated velocity of each particles for the present generation

1 INTRODUCTION

Recently, various missions using spacecraft are increasing globally [1]. Various types of spacecraft are being created and launched, ranging from low Earth orbit to deep space exploration. For low Earth orbits, transports for space station maintenance and satellites to explore the Earth surface and for commercial purposes are being launched. In the case of deep space exploration, preliminary exploration is underway to build a base on the moon and Mars, and spacecraft is being launched or planned [2] for exploration of other solar system planets and outer planets. A common feature for these various explorations is that the size of space launch vehicles, probes and satellites used for each mission is required to increase because the cost of escaping the Earth's atmosphere is still very expensive [1]. In order to reduce the launching cost, it is necessary to carry out many missions with a single launch, which requires large-sized space launch vehicles, probes and satellites.

The reason for the increase in the size of spacecraft is to load many exploration equipment, but also to load a lot of fuel. Basically, moving objects in the space gets energy by consuming fuel stored inside rather than supplying energy from the outside. So putting a lot of fuel means that spacecraft can conduct many missions over a long period of time. Many spacecraft uses liquid fuel such as liquid hydrogen or kerosene [3]. The efficiency of the liquid fuel itself is good, and there are advantages such as re-ignition and thrust control. However, there is a problem that the liquid fuel is not fixed in the fuel tank unlike the solid fuel. Unfixed fluids can generate sloshing motion in response to spacecraft motion [4]. In particular, the larger the amount of fuel loaded, the greater the sloshing motion, which must be considered in spacecraft for the accurate operation.

Except spacecraft, sloshing phenomenon is found in tank lorries carrying various types of liquids and in all other transports carrying large quantities of liquids, all of which are affected by the sloshing motion. Therefore, sloshing motion analysis has been analyzed in order to guarantee the stability of such a carrier. However, in most cases, the sloshing analysis is performed mainly for the gravity situation because the gravitational force or similar acceleration is applied to the carrier. In this case, the sloshing motion could be simulated as a pendulum model, and the accuracy of the sloshing motion was verified through various studies [4-5].

Spacecraft, on the other hand, differs from conventional sloshing research in that it should perform maneuvering through attitude control even in the absence of gravity or acceleration. The sloshing motion that occurs in such a micro gravity situation is different from the motion that occurs in the gravity situation [6-9]. And computational fluid dynamics (CFD) study was performed on the sloshing in the micro gravity condition. It focuses on comparing CFD results with experimental results after assuming a specific situation and improving CFD analysis model for CFD's high accuracy [10].

However, it is difficult to directly apply CFD model to the design of spacecraft attitude control because CFD analysis generally requires several minutes to several tens of hours of computation time depending on the model in single process [4]. And a considerable number of simulations are required when designing a controller for a system. In particular, much more computation is required when designing controllers for systems with nonlinear structures that are not expressible as transfer function. Although it is a CFD model that can derive calculation results in a few minutes, it takes an enormous amount of calculation time to design the controller. Therefore, another alternative model for the spacecraft attitude control design is needed. The purpose of this model is to extremely reduce the total calculation time within a few seconds by simplifying the structure of the sloshing motion which occurs in the micro gravity situation [7].

There is also a problem with the internal fluid mass change. General spacecraft consumes fuel to perform its mission, the amount of internal fuel continues to decrease. The amount of internal fuel affects the sloshing motion, which is an important factor regardless of gravity. Therefore, modeling of various fuel quantities should be performed instead of modeling limited to one fuel quantity condition.

In this paper, the sloshing phenomenon that occurs in the micro gravity situation is discussed in Chapter 2. In order to analyze the sloshing phenomenon occurring in the micro gravity situation, the environment is set up and CFD is performed on the defined environment and the result is derived. Analysis of the obtained CFD result data can suggest a suitable type of sloshing alternative model, and design variables to construct the model are defined. Parameter optimization technique is used to select these design variables appropriately. The next Chapter 3 consider change in internal fuel mass for realistic analysis. The sloshing motion, which varies with the amount of internal fuel, is calculated by CFD and the design variable of the alternative model is calculated. It suggests a general alternative model to cope with changes in internal fuel quantity, which is one of the important factors of sloshing motion. Finally, conclusions are presented in Chapter 4.

2 SLOSHING PHENOMENON & MODELING

2.1 Micro-gravity environments

The sloshing phenomenon refers to the movement of a fluid in a certain space, typically a fuel movement occurring inside a fuel tank. Such a sloshing phenomenon may occur differently depending on the surrounding situation. In particular, the sloshing phenomenon occurring in a micro gravity situation is greatly different from the sloshing phenomenon occurring in a gravity situation. In micro gravity, the fluid may float, and at this time, the fluid may be disconnected from external influences. This means that when the object moves, the external influence is discontinuous. To confirm the effect of sloshing occurring in such a micro gravity situation, the following micro-gravity environment condition is assumed.

Table 1: Micro-gravity environments setting

Type	Value
Gravity	$0\ \mathrm{m}/s^2$
Tank shape	Spherical
Radius	1 m
Simulation time	5000 sec
Liquid	Water at 293 K
Mass ratio of the tank volume	60 %

Water at room temperature is used as the internal fluid to more clearly identify the fluid motion. Because it is difficult to directly implement the liquid fuel actually used. Typical liquid fuels are liquid hydrogen and kerosene. Liquid hydrogen requires basically cryogenic and high pressure conditions to maintain a liquid state. In this case, a considerable amount of evaporation and condensation occur, and heat exchange due to cryogenic temperature is actively generated. These phenomena have a lot of influence on free surface analysis [11] and can be calculated only through some CFDs that provide the function of phase exchange between liquid and gas. In addition, kerosene is a mixture of hydrocarbons obtained by fractional distillation of petroleum. The density and various properties of kerosene depend on the mixing ratio, and the properties can affects the free surface analysis of the fluid. Therefore, the water at room temperature is assumed to be the internal fuel, completely eliminating various types of elements that may affect sloshing motion. It is assumed that it is stored in a spherical storage tank with a radius of 1 m. The amount of internal fluid is fixed at 60 %, and the analysis according to the change in the amount of fluid is covered in Chapter 3.
One of the most common forms of input applied to the fluid is the sinusoidal acceleration.

$$a = -f^2 \times d \times \sin\left(f \times t - \phi\right) \tag{1}$$

Where d is 1, f is $2\pi/1000$.
Fig.1 shows CFD analysis of the sloshing motion in the acceleration input.

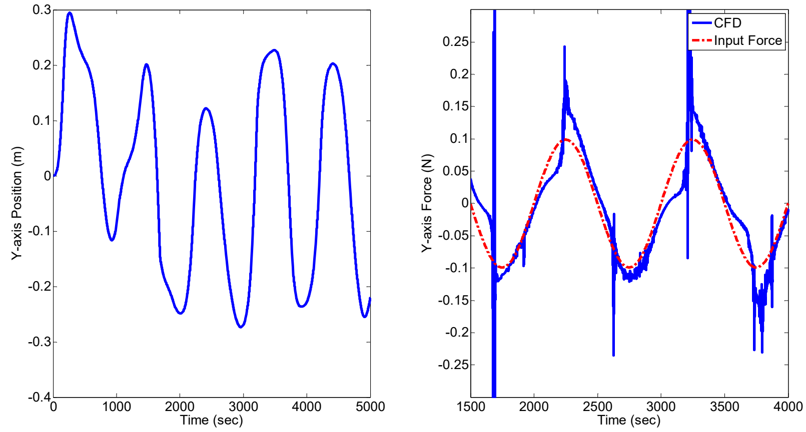

Figure 1: CFD Analysis Results with Input Force

Fig. 1 shows the results of CFD analysis for the configuration of Table 1. The graph on the left is the y-axis component of the fluid's center of mass, and the graph on the right is the y-axis component of the force applied by the fluid to the storage tank. Solid line is CFD result and dotted line is the input force. CFD result means the sloshing motion inside the storage tank, and the input force is calculated by multiplying the input acceleration by the fluid mass. The input acceleration means Eqn. (1), which is the acceleration applied to the fluid at this time. The specific CFD simulation settings are as follows.

Table 2 CFD Simulation Setting

Type	Value
Simulation Time	5000 sec
Interface tracking	Free surface or sharp interface
Fluid mode	Incompressible / Limited compressibility
Units	SI / Kelvin
Viscosity	0.001
Turbulence options	Renormalized group (RNG) model
Wall shear boundary conditions	No-slip or partial slip
Density	1000
Volumetric Thermal Expansion	0.00018
Specific Heat	4182
Thermal Conductivity	0.597
Method	Fractional Area/Volume Representation (FAVOR)
Total Cells	500000

According to the Fig.1, since the period of the input acceleration is 1000 seconds, a similar CFD result can be obtained. However, in the case of a position graph, it moves in a more complex form than a general sine wave because all fluids are not equally affected, some fluids move in the space according to the input acceleration, while others are blocked and spread around the storage tank to the opposite direction. This phenomenon can be more clearly identified by a small or large force compared with the input value at a certain period. In addition, there is a lag response of 30 to 40 seconds for the applied input, which means that the fluid particles that have been floating in the space need more time to reach the wall of the storage tank.

2.2 Sloshing phenomenon analysis

In order to model the sloshing motion, it is necessary to reflect the characteristics of the sloshing motion. According to CFD analysis results calculated in Chapter 2.1, the pattern appears more constant in the force data than the position data. Thus, the modeling is performed based on the force data acting on the tank, not the fluid's center of mass. Thus, the structure of the modeling system has a linear structure for easy and intuitive design parameter setting. Therefore, the response that is higher or lower than the reference input in a certain interval is ignored because it is a nonlinear characteristic that cannot be represented by a general linear structure. On the other hand, the lagged response can be represented using a linear structure, the modeling is performed with a focus on this. The following basic system structure is assumed for this purpose. In general, lagged response may conceptually have first, second or higher order lags. Among them, the first order lag or second order lag systems are the most common [12]. Eq.2 represents a second order lag system.

$$L(s)=\frac{\omega_n}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{2}$$

Here, the response of the system can be determined by appropriately defining ζ and ω_n.

At this time, the two design variables are determined using the parameter optimization. The optimization algorithm uses PSO algorithm, which is one of the metaheuristic methods. Because other optimization algorithms require a first order or second order derivative for the system. For example, the newton method, a typical optimization method, is one of the direct root methods, which uses the Taylor series expansion to the second order term. At this time, if the second order term can be calculated directly, it is called classical newton method. Otherwise, if the second order term cannot be calculated so it should be assumed and estimated using other algorithm, it becomes Quasi-newton method [13]. Of course, both method need a first derivative term. In general fluid motion, however, there is no analytic solution to obtain the first and second derivative term, and a considerable amount of computation is required to obtain a numerical solution. Therefore, optimization is performed using PSO algorithm that does not require a differential operation.

PSO algorithm is a method of finding the optimal solution by simulating the movement of insects swarm. The solution space represented by each design variable and a number of particles moving within it are defined. In this case, the solution space is two dimensional. First is damping coefficient and second is natural frequency. Therefore, the position of each particle in the two dimensional space represent a specific damping coefficient and natural frequency. Also, particles regards the objective function calculated based on its position as fitness. The required objective function is defined as the difference between the two data set, sloshing force data obtained through CFD and the force data calculated through the second-order system.

The difference is calculated based on least square method (LSM) [14].

$$J=\sqrt{X_{CFD}^2+X_{Modeling}^2} \tag{3}$$

The motion of the second-order system is determined based on the position of the particles, damping coefficient and natural frequency. If all the particles' fitness is calculated, best particle position can be determined. The optimal position of the entire group is also determined. And information about the optimal solution is provided to all particles. Each of the particles updates the own velocity to move in the next generation, based on the information about the provided global optimum and its current position and velocity, and the individual local optimal solution that it has had so far [15].

$$\vec{v}_i=C_1\otimes\vec{v}_i+C_2\otimes\left(\vec{p}_i-\vec{x}_i\right)+C_3\otimes\left(\vec{p}_g-\vec{x}_i\right) \tag{4}$$

$$\vec{x}_i=\vec{x}_i+\vec{v}_i \tag{5}$$

In this case, C_1, C_2 and C_3 are weights for each term, and the performance of the algorithm can be changed according to the value. In this study, 0.7, 0.1 and 0.2 are used. The position to determine the fitness of each particle in next generation is also calculated by using the updated velocity. Through the process, all particles move around in entire solution space to search the global optimum solution.

3 SLOSHING MODELING IN MASS VARIANT

The sloshing motion due to the fluid motion must be dependent on the amount of internal fluid. Particularly in the case of spacecraft, the amount of fuel must be constantly reduced as the mission is carried out. For the sloshing motion in the above-defined zero-gravity condition, a total of 9 mass level change are considered. For the same acceleration input, CFD analysis is performed taking into account the each mass conditions. Individual sloshing modeling is performed for each result. The optimal design variable change is calculated and analyzed for each situation.

3.1 Selected Design variable

As mentioned earlier, the design variables are determined using PSO algorithm. Boundary for the damping coefficient is 0 to 50, and for the natural frequency is 0 to 1. The value is determined through several trial and error. PSO algorithm is conducted within the boundary condition. Total number of particles are 100, the maximum generation is 50. Obtained optimum value is verified using comparison with true data, which is CFD data. The following graph shows the results of CFD analysis and the optimized second-order system determined using PSO algorithm.

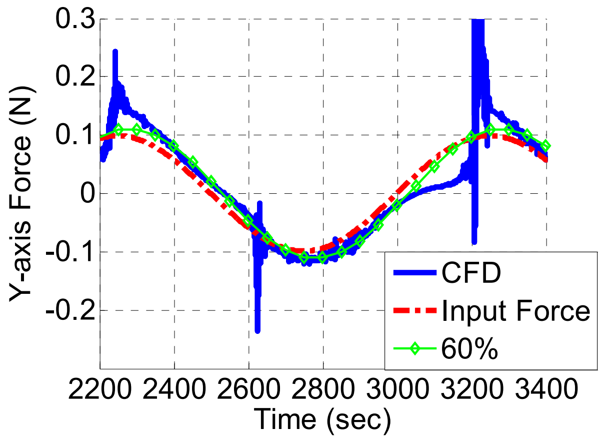

Figure 2: Performance of the second-order system

Although it is not possible to satisfy all the conditions, both the unexpected response and the out-of-pattern response, the second-order system can represent the lagged response of CFD to the input acceleration, and results is similar to CFD analysis.
In the same way, the results of the sloshing modeling performed while increasing the amount of internal fluid from 10% to 90% of the total fuel tank are as follows.

Table 3: Design variables

	Value								
Mass	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %
ζ	24.5988	19.8243	16.8380	16.6902	14.6344	13.4452	12.0547	7.6202	4.0253
ω_n	0.6338	0.6895	0.7379	0.7852	0.8185	0.8734	0.9461	0.9598	0.9990

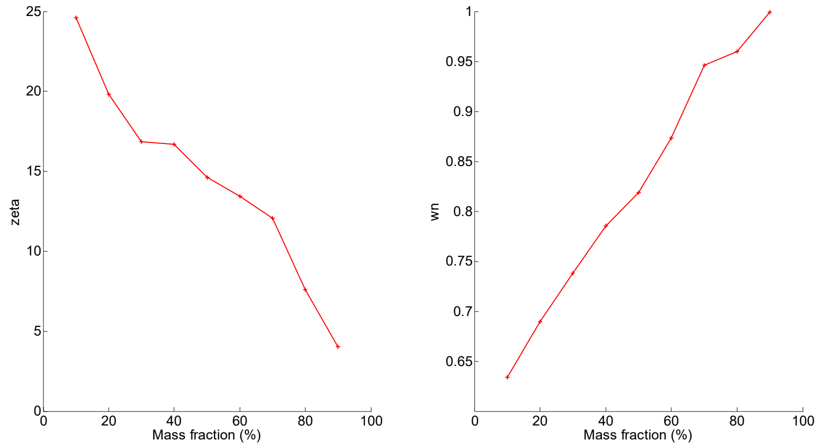

Figure 3: Design variables variation

According to Fig. 3, it can be seen that the change of the damping coefficient and the natural frequency have a nearly linear relationship with respect to the mass change.

3.2 Design variable analysis

According to the results of CFD analysis, except the overall motion pattern, the sloshing movement becomes weaker and stronger again. This is due to the internal fluid situation, which occurs when floating fluid particles are clustered or completely away from the wall of the storage tank within a certain intervals. However, the length of the interval is a short period of time compared with the entire pattern and the effect is canceled each other out. Therefore, the optimization algorithm works with a focus on satisfying the lag characteristics of the entire pattern rather than these local features. It can be confirmed by a derived relatively constant numerical design variable for the second-order system with respect to CFD analysis results in significant noise conditions.
The graph below shows the results of this optimization algorithm.

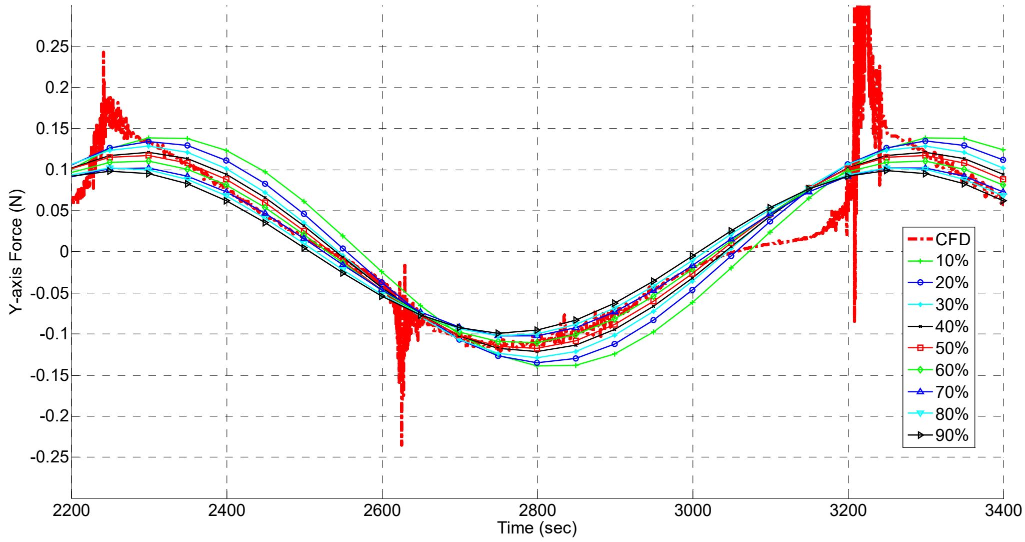

Figure 4: Response of each design variables

Fig. 4 shows the results obtained by applying the same inputs to the each second-order system shown in Table 3. In all cases, a similar type of response is observed. Each system has a different in the amount of lag response to the same input occurs. In fact, the smaller the amount of internal fluid, the greater the optimum damping coefficient and the smaller the natural frequency. Because the fluid must reach the opposite wall across the storage tank from its current position in order for the applied input to affect the storage tank. However, as the amount of internal fluid decreases, this process takes a relatively long time. This is represented by the big lag response of the system. The large damping coefficient acts to reduce overshoot if the second-order system is underdamped, and increases the lag response in the overdamped situation. Also, the lower the natural frequency, the slower the system response, which leads to an increase in the lag response. Therefore, in order to improve the performance of the modeling, the lag response of the system should be adjusted by appropriately selecting the damping coefficient and natural frequency.

4 CONCLUSION

This study analyzes sloshing motion and modeling changed according to the internal fluid mass. The sloshing motion is assumed to be the movement of the fuel inside the fuel tank of radius 1m in the micro gravity condition. At this time, the water of room temperature is used, not a liquid hydrogen or kerosene because liquid hydrogen is unstable and kerosene is mixture. This may have other effects on the sloshing motion. The motion of the internal fluid is analyzed by assuming sinusoidal acceleration input. In order to model the lag response to the input acceleration among various characteristics, a general second-order system is proposed in the form of sloshing modeling. The damping coefficient and the natural frequency, which are the design variables of the system, are selected by using the parameter optimization method. The PSO algorithm is used and it is known to be relatively fast convergence. The mass of the internal fluid is varied from 10% to 90% of the total fuel tank volume in units of 10%. CFD analysis is performed for each fluid mass and optimization is performed using the obtained results. As a results, a negative relationship can be confirmed for the damping coefficient, and a positive relationship can be obtained for the natural frequency. Each relationship appears in a nearly linear form. According to the obtained results, the smaller the internal mass, the larger the damping coefficient and the smaller natural frequency because the damping coefficient and the natural frequency greatly affect the lagged response. In the overdamped system, the larger the damping coefficient, the smaller the natural frequency, the greater the lagged response. The analysis of the design variables of the second-order system with various internal mass changes was performed. Although the exact design variable itself can be changed depending on the given conditions, it can be confirmed that the damping coefficient and the natural frequency are proportional to the first order for the internal fluid change. Therefore, it is possible to update the design variables of the sloshing model according to the desired internal mass by interpolating it.

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