A MULTIBODY SLOSH ANALYSIS FOR THE LUNAR RECONNAISANCE ORBITER

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ABSTRACT

The Lunar Reconnaissance Orbiter (LRO) undergoes a series of thruster maneuvers to attain lunar orbit. The first of the series of lunar orbit insertion (LOI) maneuvers is crucial to the success of the mission. Therefore, it is important to characterize the disturbances acting on the spacecraft during this phase of the mission. This paper focuses on the internal disturbance force caused by fuel slosh and its impact on attitude control. During the first LOI maneuver (LOI-1), approximately 50% of the total fuel mass is used or roughly 25% of the spacecraft's wet mass, during the 38-minute burn. The forces imparted on the spacecraft from the fuel are dependent on the fill level of the two fuel tanks. During LOI-1, the fill level in both tanks varies greatly and thus so does the disturbance level caused by the fuel. It is therefore necessary to account for the time-varying mass properties of the spacecraft and the effects of the varying fuel levels during the entire 38-minute maneuver.

Two simulations are developed in Mathworks's Simulink to analyze the fuel slosh effect. The first model, a baseline model, is a rigid body dynamics model where the fuel slosh is not modeled. The second is a multibody model, developed using a multibody dynamics toolbox, where each of the two fuel tanks and the remaining spacecraft body are treated as separate rigid bodies. The simulations are executed in a piece-wise fashion to account for the time-varying mass properties, and to accommodate the multibody toolbox. Disturbances caused by fuel slosh during both lunar and mission orbit insertions will be analyzed through simulation of different dynamics models. Results of the analysis will show the effects of the slosh disturbance on the spacecraft's attitude.

INTRODUCTION

In 2004, NASA was given the directive to return a manned mission to the Lunar surface by the year 2020 with the intent of a permanent manned presence. In order to achieve this goal it was determined that an unmanned Lunar mapping and science expedition was needed to attain a more accurate knowledge base of the Lunar topography, existing minerals and resources, and science related to better understanding of the Lunar environment. Together this data would be used to determine the best possible landing sites with the intent of establishing a permanent Lunar base. The Lunar Reconnaissance Orbiter (LRO) was specifically given the objective to gather this required information, and will launch in the Fall of 2008.

Soon after launch, LRO will be placed in a direct insertion trajectory to the Moon by the upper stage of the Evolved Expendable Launch Vehicle (EELV), the Atlas V 401 with a Centaur upper stage. The first use of the propulsion system takes place within 24 hours after launch to initiate a midcourse correction (MCC) for the final trans-lunar trajectory. This trans-lunar trajectory is a minimum energy transfer that will take 4 to 5 days to reach the point for the insertion burns. The Lunar Orbit Insertion (LOI) sequence of maneuvers will capture Lunar orbit in a quasi-frozen, highly elliptical orbit of 26 x 216 km. LOI is identified as a mission critical phase and therefore warrants the detailed investigation into possible sources of failure.

The original LRO propulsion system design called for the use of open tanks, i.e., no damping system. With a total fuel mass of 882kg; making up approximately 48% of the total spacecraft mass, the disturbance caused by propellant slosh was elevated by the LRO project as being a mission critical failure source. After a re-design of the propulsion system, LRO adopted two 40" oblate spheroid diaphragm TDRS-like (Tracking and Data Relay Satellite) tanks. Even though the new design has a high level of damping, it was necessary to make sure that propellant slosh is not a problem during LOI. During the first LOI maneuver, LOI-1, 50% of the total fuel is burned; and after lunar orbit is attained, approximately 10% of the total fuel is left. Therefore, if disturbances from fuel slosh were to be an issue, they would present themselves during this time. Since there is no re-design of the spacecraft's attitude controller once the maneuver is begun, we must ensure the controller can handle all known disturbances.

Figure 1 shows a mechanical model of LRO fully deployed and the propulsion system. The top tank, Tank A is identified in the image. Tank B, the bottom tank is within the structure and positioned below Tank A. Attitude control system thrusters (AT) are visible on the propulsion module and are identified. Both tanks are situated upright such that the propellant is under ullage.

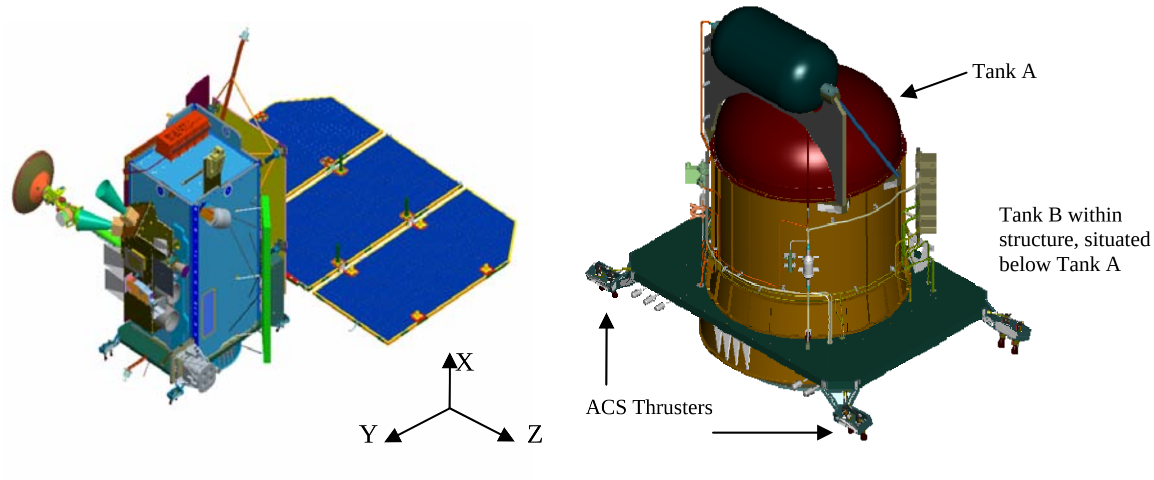

Figure 1. LRO Mechanical Model and Propulsion Module

DYNAMIC MODELS

TDRS Slosh Model

A good deal of work was conducted by Southwest Research Institute in the 1980s regarding fuel slosh for the TDRS tanks. A mechanical model representing fuel slosh in the TDRS tanks was developed and model parameters were determined experimentally for a liquid-under-ullage and liquid-over-ullage model. The two primary sources dealing with the TDRS model are [1] and [2].

The liquid-under-ullage mechanical model of the TDRS tanks is shown in Figure 2. In the model, the fuel is represented by two parts: a rigid mass, m_0; and the slosh mass, m_1, which is treated as a pendulous mass. The location mass of m_0 and m_1 is defined as the center of mass, cm, of the rigid and slosh fuel mass, respectively. The location of m_0 is h_0, defined from the tank geometric center. The location of m_1 is the distance L_1 from the hinge location, h_2. The hinge location is measured from the tank geometric center. The distance L_1, the pendulum length, is measured from the location of the pendulum hinge.

To model the diaphragm, a stiffness, K_θ and damping, C_θ, is added at the pendulum hinge location. The inclusion of a spring stiffness term was found to change the pendulum natural frequency[1], ω, to:

$$\omega = \left[\frac{K_\theta}{m_1 L_1^{\,2}} + \frac{a}{L_1} \right]^{1/2} \qquad (1)$$

where a is the acceleration caused by gravity, or the reversed thrust direction, as shown in Figure 2.

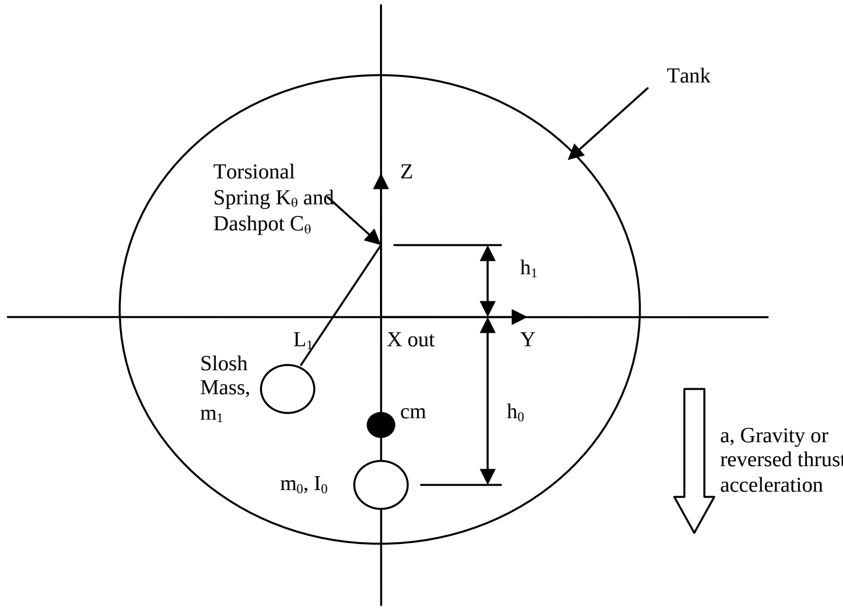

Figure 2. TDRS Mechanical Slosh Model

To ensure the validity of the model at various acceleration levels and at zero-g, similitude[1] concepts were employed in deriving the model parameters. The model parameters were then determined experimentally for four different fuel fill levels at 1 g. Experiments using various density liquids resulted in the conclusion that the model parameters determined experimentally at 1 g are valid for acceleration levels less than 1 g.

Analysis in [1] and [2] have shown that the level of disturbance caused by the slosh mass, m_1 is dependent on the percentage of mass participating in the actual sloshing motion. It was found from subsequent analysis that mass participation is largest when the tank fill levels are between 55% and 80%. Therefore, slosh disturbances will be largest when the fill fraction is between these levels.

Rigid Body Model

The rigid body model developed for this analysis is a subset of the LRO High Fidelity (HiFi) simulation. This model will be referred to as the "RigidBody" model. Controllers, sensors, and actuators not used by the Delta-V controller have been removed to reduce the execution time of the simulation. The components that are still included are attitude dynamics model, 3-axis gyro hardware model, insertion thrusters (NT) hardware model, attitude control thrusters (AT) hardware model, gyro processing, and a subset of the Delta-V controller (Reaction Wheel Control removed). The removal of the Reaction Wheel control does not impact the analysis because this portion of the controller is designed to maintain the reaction wheel speed.

Multi Body Slosh Model

Matlab's Simulink v7.1 SP3 was used to develop the LRO multi body model, referred to as the "MultiBody" model. In addition, the Modular Dynamic Analysis (MDA) Toolbox, a multibody dynamics toolbox developed by K&D Research, was used in modeling the multi body spacecraft dynamics with fuel slosh for each of the tanks. The fuel slosh in each tank was modeled as two revolute joints representing a spherical pendulum. The slosh model parameters are taken with some revision from [1] and [2]. Testing in [1] and [2] used water as the propellant; since the propellant in LRO is hydrazine, the maximum fuel mass had to be adjusted and all parameters needed to be scaled accordingly. The same HiFi components used in the RigidBody are also included in the MultiBody model with the exception of the attitude dynamics model.

ANALYSIS

During a Delta-V maneuver, in particular during LOI-1, a large quantity of fuel is used causing the spacecraft mass properties to vary significantly. This change in mass properties motivated the use of time varying mass properties. As the MDA does not allow for a time-varying set of parameters, the simulation was modified to be stopped and restarted. Once the simulation was stopped, the final states were saved, the slosh parameters were updated, and the simulation was restarted with the initial states being set to the final state of the previous run. This process of starting and stopping is executed every 30 seconds, which was found to be sufficient in terms of simulation execution speed and performance. Recognize that changing the mass properties induces a disturbance in the dynamics; simulations were found to reduce the effects of these disturbances when the simulations were run for less than forty seconds. For example, to run a complete LOI-1 simulation, the simulation would be started at 0 seconds and reinitialized every 30 seconds thereafter, until the end of the maneuver. Although complicated, this method is required to ensure the mass properties are accurately modeled throughout the burn.

For the RigidBody model, developed for baseline comparisons to the MultiBody model, simulations are implemented in the same fashion as for the MultiBody model, i.e. update parameters every 30 seconds. This was done to minimize the possible differences between the two simulations and allow the analysis to focus simply on the dynamics differences of interest.

Various simulation cases were run to determine the effects of slosh on LRO attitude performance, as shown in Table 1 and Table 2. A baseline case is where all parameters are their nominal values. The low damping case for the MultiBody model decreases the damping coefficient, C_θ, of the tank diaphragm to 10% of the baseline value. After establishing a baseline and studying the effect of a lowered damping coefficient, Monte Carlo simulations are performed for all the mission critical thruster maneuvers, where the Monte Carlo parameters varied is listed in Table 3. The initial slosh angles and rates are a normal distribution with a 1-sigma value as stated in Table 3. The thruster misalignments are either positive or negative 0.7 degrees. A normal distribution is not used as we want to see the maximum effect from these misalignments. One hundred simulations are executed in each of the Monte Carlo case.

Table 1. LOI-1 Simulation Cases

LOI-1 Maneuver	**MultiBody Model**	**Rigid Model**
Baseline	x	x
Low Damping	x	
Monte Carlo	x	

Table 2. LOI and MOI Simulation Cases

LOI-2, LOI-3, LOI-4, LOI-5, LOI-6, MOI-1, MOI-2, MOI-3, MOI-4	**MultiBody Model**	**Rigid Model**
Baseline	x	x
Monte Carlo	x	

Table 3. Monte Carlo Parameters

Monte Carlo	**Nominal Value**	**Variation**
Initial Slosh Angles (deg)	0	+/- 45 (1-sigma)
Initial Slosh Rates (deg/sec)	0	+/- 5 (1-sigma)
Attitude Thruster Misalignments (deg)	0	+/- 0.7 (peak)
Insertion Thruster Misalignment (deg)	0	+/- 0.7 (peak)

During thruster maneuvers, the LRO Flight Operations Team will be supplying the spacecraft with a target attitude at an update rate of 2 seconds. The analysis was based on the original update rate of 60 sec, so the different models update the target attitude ever 60 seconds. Lunar Orbit Insertion 1 undergoes a 90 degree slew to roughly track the velocity vector simultaneously with the thruster maneuver, while LOI-2 through MOI-4 are shorter maneuvers and the change in velocity vector is smaller.

The impact of slosh can be seen by examining a variety of variables. Spacecraft attitude error is a primary indicator of the spacecraft's performance. If slosh were a large enough disturbance, there would be a significant difference in the attitude error of the MultiBody simulation as compared to the RigidBody simulation, where significant is defined as any additional attitude error adversely impacting the attitude error requirement for that maneuver. It is also advantageous to look at the spacecraft angular velocity, where we would expect to see oscillation in the angular velocity caused by the moving fluid. Secondary variables to look at are the torques exerted on the spacecraft by the slosh, as well as the phase plane of the slosh in each of the two degrees of freedom. This will give us additional insight as to what is happening to the fluid.

SIMULATION RESULTS

Since the same analysis was conducted for the ten different thruster maneuvers listed in Table 1 and Table 2, below we'll present a representative analysis done for LOI-1.

LOI-1 Baseline

In this set of simulation cases, we'll characterize the nominal LOI-1 maneuver, and use it a baseline for comparison. The RigidBody and MultiBody models are both run with no variation in any parameters. The results are given in Figure 3 through Figure 6.

Figure 3, below shows the spacecraft attitude error throughout LOI-1. The obvious difference is that the MultiBody model yields a larger initial transient; on the order of 8 degrees in the y and z axes, while the RigidBody model shows an initial transient of 3 and 4.5 degrees in the y and z axes, respectively. Spikes are seen in the attitude error for both models at 60 second intervals, which are caused by the target attitude being changed. In the MultiBody model, there is a deviation compared to the RigidBody model starting at 23 minutes. This deviation is a result of the attitude error changing sign. The sign change in attitude error occurs because as the spacecraft center of mass migrates; the disturbance torque from the NTs in the z-axis goes from negative to positive.

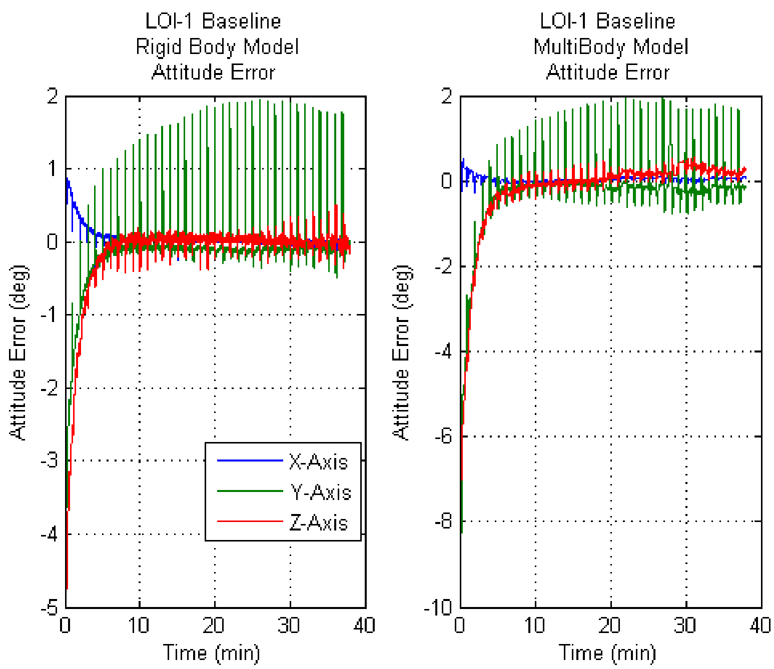

Figure 3. LOI-1 Baseline Attitude Error Comparison

Figure 4 is a comparison of the spacecraft angular velocity for the RigidBody and MultiBody models. The top plots indicate that the angular velocity of the spacecraft is affected by the propellant in both tanks sloshing. Two primary differences exist: the initial transient and a difference at 25 minutes. The bottom plots zoom in on the first five minutes of the simulation. They show that the initial transient in the spacecraft angular velocity is larger for the MultiBody model; 1 deg/sec compared to 0.8 deg/sec for the RigidBody case. In addition, the slosh appears to act as a damper by reducing angular velocity when the target attitude is updated every 60 seconds, which is seen by comparing the spikes that occur every 60 seconds in the bottom two plots of Figure 4. The second difference seen in the top two plots in Figure 3 occurs at a simulation time of 25 minutes. The difference is caused by the attitude changing signs as we saw in the discussion about attitude error.

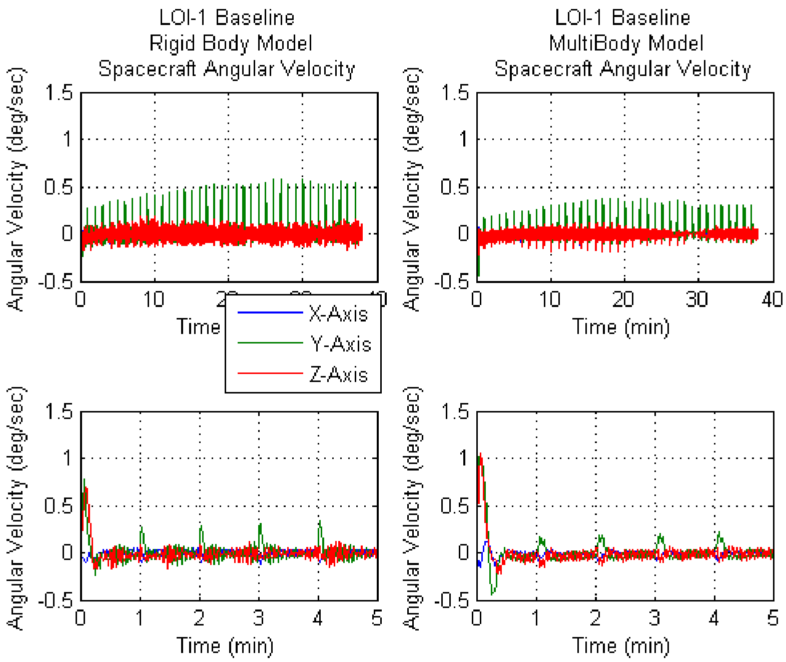

Figure 4. LOI-1 Baseline Angular Velocity Comparison

Now that we've looked at the effects of the slosh disturbance on the spacecraft, we will look at what is happening to the propellant in both tanks. The data below provides an idea of the fluid activity and level of disturbance caused by the propellant when it is laterally excited by the firing of thrusters. Since slosh is not modeled independently in the RigidBody model, only data from the MultiBody model will be analyzed.

Figure 5 has four phase plane plots of the propellant in Tank A and Tank B. Tank A is the top tank and is closer to the spacecraft center of mass; Tank B is the bottom tank and is further from the spacecraft center of mass. Since the slosh is modeled as a spherical pendulum, two axes of rotation are given, the z-axis and the y-axis. Looking at the axes, it can be seen that the rates and angles for the propellant is small. Also notice Tank B rates and angles for both axes are an order of magnitude larger than that of Tank A. The Y-Axis Tank A phase plane indicates that the slosh is exerting a constant torque on the spacecraft since the phase plane does not center around the origin. These four phase plane plots show that indeed the propellant is undergoing a sloshing motion.

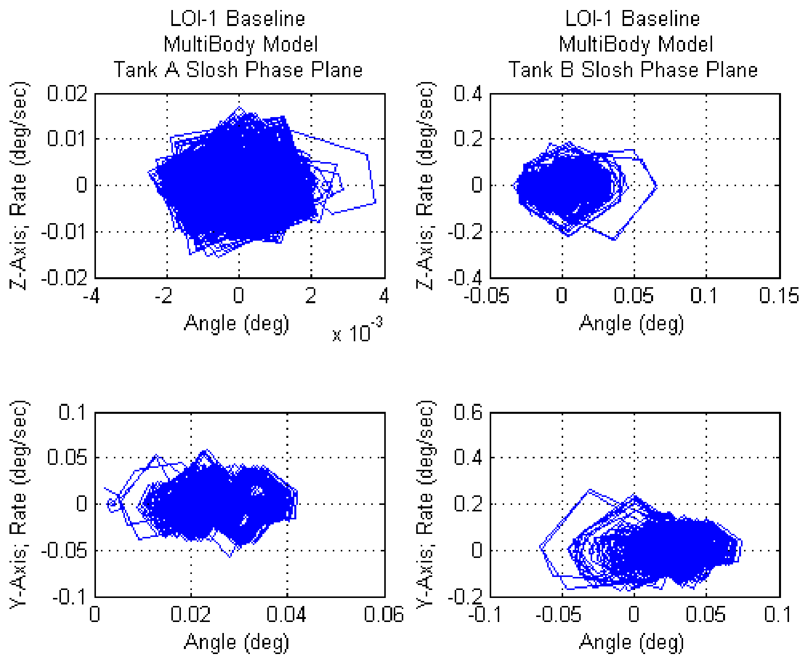

Figure 5. LOI-1 Baseline Slosh Angles and Rates

Another indication of the slosh activity is the torque exerted on the spacecraft by the pendulous mass, m_1. Looking at Figure 6, the magnitude of the disturbance the slosh exerts on the spacecraft is seen. A few points should be made regarding Figure 6. Slosh torques in Tank A are smaller than torques from Tank B, which is consistent with results seen in Figure 5. The Y-Axis torque from Tank A settles to a mean torque, consistent with previous results. Notice jumps in the torques occurring every 60 seconds. From Figure 6, we see that slosh is indeed excited during LOI-1 and explains the differences between the MultiBody and RigidBody model differences seen previously.

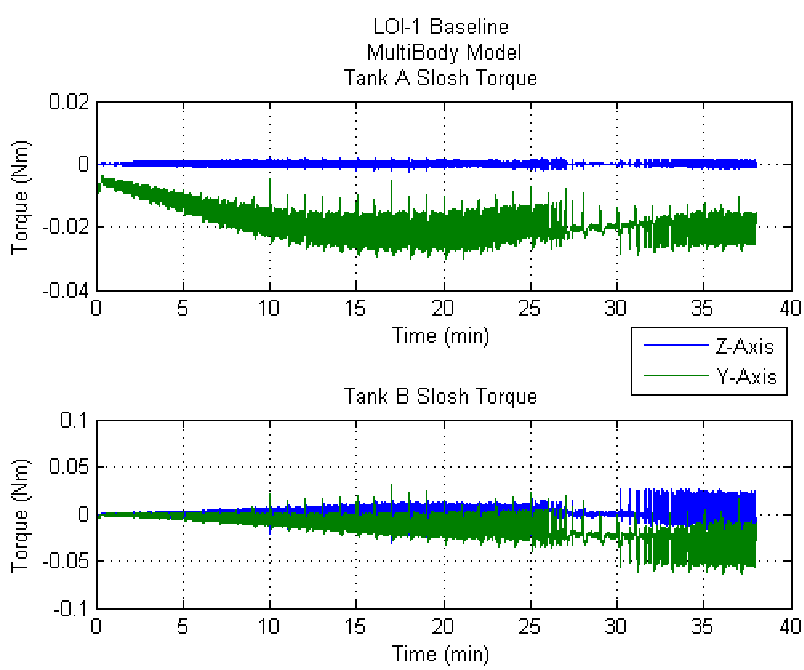

Figure 6. LOI-1 Baseline Slosh Torque

LOI-1 Low Damping

LOI-1 Baseline Cases indicate that slosh does not have a large effect on spacecraft performance. We now want to add conservatism to the slosh damping ratio to increase the effects of slosh so that we can identify situations where slosh may cause a problem; i.e. we want to break the system. In this simulation, the damping ratio is set to 10% of the baseline value. The Low Damping case will be compared to the Baseline MultiBody case.

Spacecraft attitude error for the Low Damping case is nearly identical to the Baseline case; i.e. they both look like Figure 3. In addition, spacecraft angular velocity is also nearly identical to the MultiBody baseline case; i.e. they both look like Figure 4. However, they are not the same, indicating that the changed damping coefficient has made an effect on the spacecraft.

Looking at the slosh torques, Figure 7, it can be seen that the torque levels are similar, yet the peaks of the oscillations are larger for the Low Damping case. Tank A shows torque peaks an order of magnitude larger than the Baseline case.

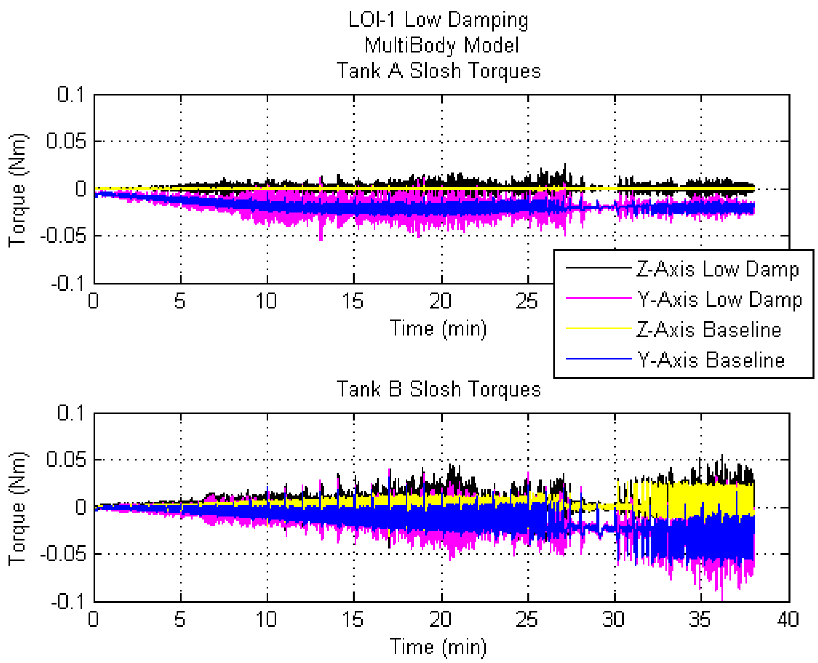

Figure 7. LOI-1 Low Damping Slosh torques

LOI-1 Monte Carlo

Previous simulations assumed the pendulous mass was at rest (i.e., not deflected) and there were no thruster misalignments when the Delta V maneuver began. In reality, there may be thruster misalignments and the slosh mass may be deflected and/or have some initial rate. One hundred simulations are executed with the variations listed in Table 3, as well as the lowered damping ratio. The results are compared to the MultiBody Baseline case.

Figure 8, shows the slosh torques in both tanks for all 100 simulation cases with the nominal value imposed over it in yellow. Notice for the 100 cases that the slosh causes a 1 Hz oscillation in the torque in both degrees of freedom for both tanks. This 1 Hz oscillation would seem more sinusoidal with a higher data output resolution. The torques are seen to be an order of magnitude or more higher in both tanks when the parameters listed in Table 3 are varied.

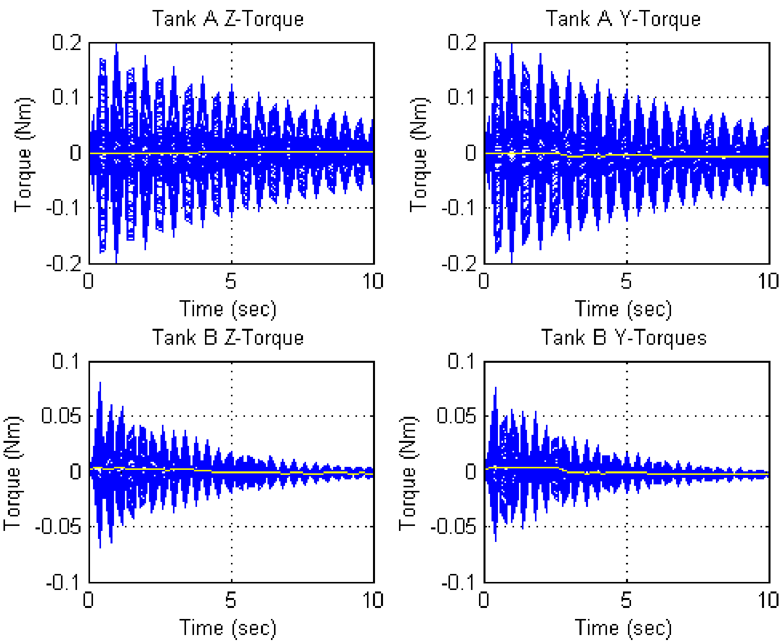

Figure 8. LOI-1 Monte Carlo Slosh Torques

Since the propellant is clearly excited in the Monte Carlo simulations, it is of interest to look at the effect it has on the spacecraft. Out of the 100 Monte Carlo simulations run, none of the cases found any significant divergence from the baseline spacecraft angular velocity or attitude error. There were differences, but nothing of consequence.

Remaining LOI and MOI Maneuvers

Similar analyses were conducted on the remaining lunar orbit insertion and mission orbit insertion maneuvers. These analyses did not present any information that was not extracted from the various LOI-1 simulations. For example, fluid fill level during LOI-1 went from 88.47% to 22.33% in Tank A, and from 94.12% to 65.69% in Tank B. This vast change in fill level covers the range where mass participation is greatest and thus slosh disturbance is greatest. Therefore, the remaining LOI and MOI maneuvers did not stress situations that have not been tested in the LOI-1 simulations.

In addition, there are differences in attitude error and angular velocity between the MulitBody and RigidBody model for the remaining maneuvers that are more significant than the differences shown for LOI-1, but nothing that the Delta V controller was not able to handle.

CONCLUSIONS

The simulations conducted for the MultiBody model indicate that slosh will not cause performance issues during thruster maneuvers, particularly mission critical phases such as LOI-1. The slosh torque is high in situations when the slosh is not at rest and when the fill level in the tanks is at some worst-case level. Even with the lower damping ratio and assuming worst case conditions, this analysis has shown that slosh does not adversely affect the spacecraft performance. Subsequent analyses on the remaining thruster maneuvers do not present any new information to characterize the fuel slosh on LRO’s tanks.

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2. Kana, D.D., Dodge, F.T., Pitman, F.R., “Extended Study of Liquid Slosh in the Tracking and Data Relay Satellite Hydrazine Tanks,” Final Report, Southwest Research Institute, August 1987.