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MODELING, SIMULATION, AND PARAMETER ESTIMATION OF LATERAL SPACECRAFT FUEL SLOSH

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I. Introduction

Predicting the effect of fuel slosh on a spacecraft and/or launch vehicle attitude control system is a very important and a challenging task. Whether the spacecraft is under spinning or lateral moving conditions, the dynamic effect of the fuel slosh will help determine whether the spacecraft will remain on its chosen trajectory. There are three categories of slosh that can be caused by launch vehicle and/or spacecraft maneuvers when the fuel is in the presence of an acceleration field. These include bulk fluid motion, subsurface wave motion, and free surface slosh. Each of these slosh types have a periodic component that is defined by either a spinning or lateral motion. For spinning spacecraft, all three types of slosh can play a major role in determining stability. Bulk fluid motion and free surface slosh can affect the lateral slosh characteristics. For either condition, the possibility for an unpredicted coupled resonance between the spacecraft and its on board fuel can have mission threatening affects. This on-going research effort aims at improving the accuracy and efficiency of modeling techniques used to predict these types of lateral fluid motions. In particular, efforts will focus on analyzing the effects of viscoelastic diaphragms on slosh dynamics.

II. Problem Definition

Propellant sloshing is a potential source of disturbance which may be critical to the stability or structural integrity of space vehicles, as large forces and moments may be produced by the propellant oscillating at one of its fundamental frequencies in a partially filled tank. This could cause a failure of structural components within the vehicle or excessive deviation from its planned flight path.[1] There are different kinds of liquid motions of varying complexity, among these is lateral sloshing. This is the type of liquid motion that occurs primarily in response to translational or pitching motions of the tank.[1] During portions of the launch profile, the spacecraft could be subjected to nearly purely translational oscillatory lateral motions as the launch vehicle control system guides the rocket along its flight path. Many research efforts have been dedicated to explore this type of slosh dynamics. Testing has been done to understand and measure the forces and torques generated by the liquid in lateral excitation modes at Southwest Research Institute (SwRI). Experimental set-ups for lateral slosh studies have been developed at SwRI to test and determine the characteristics of a model spacecraft fuel tank under these dynamic conditions.

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Previous research used mechanical analogs such as pendulums and rotors to simulate sloshing mass as a common alternative to fluid modeling. The research effort was aimed at developing a method whereby model parameters can be derived directly from experiment test data played against an arbitrary Matlab SimMechanics model of the mechanical analogs using the Parameter Estimator Toolbox (Figure 1).[2, 3, 4 and 5] A SimMechanics model incorporating the pendulum analog of the experiment was developed.

This previous research was the first step in automating the process of slosh model parameter identification using a MATLAB/SimMechanics-based computer simulation of the experimental SSTR setup. The parameter estimation and optimization approaches were evaluated and compared in order to arrive at a reliable and effective parameter identification process.[6]

Historically, it has been possible to predict free-surface lateral slosh of bulk fluid motion with a great deal of confidence and accuracy using codes such as the Dodge SLOSH program.[7] The SLOSH code assumes a pendulum as a mechanical analog for the slosh motion. Additional types of mechanical analogs (such as rotors and suspended masses) are being considered to develop a more generalized method of modeling fuel motion. The difficulty increases and the confidence of the model will diminish when a diaphragm or a bladder is introduced into a fuel tank.

Extensive analysis has been done on the different tank shapes and locations, as well as the use of Propellant Management Devices (PMDs). A summary of this analysis, like that reported by Hubert [8] shows the vast differences in possible behaviors of different designs. For example, a number of relatively simple mechanical models have been developed for cylindrical tanks with hemispherical end-caps mounted outboard of the spin axis. This type of tank has been popular in a number of spacecraft programs. Hubert also notes that one of the most difficult aspects of employing such mechanical models is in the selection of appropriate parameters in the model.

One of the most practical types of spacecraft propulsion fluid control devices has proven to be the diaphragm, which uses an elastomeric material to create an effective barrier between the inert gas under pressure and the liquid propellant. These devices are used to separate the fuel from the gas ullage (usually pressurized) so as to ensure a pure liquid flow to the spacecraft engines. They have become very popular with spacecraft designers since they can guarantee smooth engine performance in any orientation and gravity field (or lack thereof). They also do a very good job of ensuring that a very high percentage of the available fuel is utilized. The main advantages of currently available diaphragms over other PMDs are that they are easier to manufacture and they are light weight.[9] It has been found that the diaphragm shape can profoundly affect slosh behavior and that, surprisingly, many of these diaphragms will hold their initial shape throughout launch vibration and maneuvers.[5]

III. Method of Approach

Free surface slosh has a well defined resonant frequency. The only sloshing motion assumed to be taking place in this simplified model is a surface wave that in turn is simulated by the pendulum. The rest of the liquid is essentially at rest and can be treated like a fixed mass. Initial pendulum properties are found by the use of the SLOSH code developed at SwRI where it predicts the modes of the fuel tank with that of a pendulum.[10] The tank/fuel parameters such as shape, kinematic viscosity, and liquid fill level are provided as input to the program.

Using the tank/fuel parameters, the code can then determine the proper pendulum equivalent. The physical parameters given by the code include the liquid's fixed and pendulum masses as well as the pendulum length. First and second mode slosh data are also given by the code. The first mode parameters (sloshing mass) represent the majority of the propellant undergoing free surface slosh while the second mode represents a small correction factor for the first mode.

Using the code's data distributions along with the geometric/material characteristics obtained from the experimental setup, a computer simulation of the one DOF pendulum analog was developed using SimMechanics software.[11] The liquid chosen for testing was water which is an excellent and frequently used substitute for hazardous propellants. Water's fluid properties (density, viscosity, etc.) are nearly identical to those of hydrazine, the most commonly used propellant.

The experimental set-up used for testing is illustrated in Figure 1. The whole assembly consists of a linear actuator assembly that includes a force transducer attachment and the "fuel" tank. The tank is a spherical transparent container which is filled with the liquid's fill level defined for testing. The tank is excited by the linear actuator as it oscillates in a predetermined frequency and displacement amplitude. The forces due to fuel slosh will be measured using a force transducer mounted on the fixture.

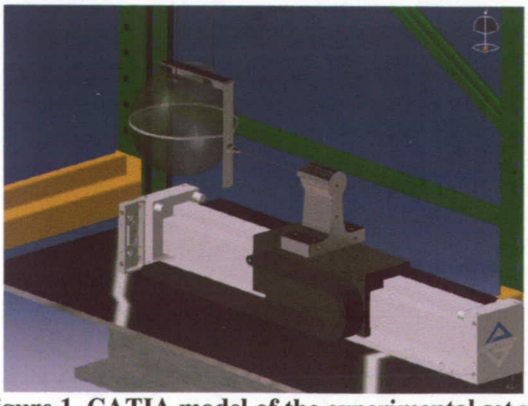

Figure 1. CATIA model of the experimental set up

A. Parameter Estimation with Different Liquids

The first step was to experiment with liquids of different viscosities in order to better understand the lateral fuel slosh effects. Liquids of varying viscosities and physical characteristics different from water were used. It was assumed than for higher viscosities the resonance frequency is slightly higher that the predicted value for an ideal liquid. [12] The SLOSH code was also utilized to obtain the model characteristics and properties for the new liquids. Using the same tank geometry and different fill levels, the SLOSH code provided mechanical system properties and they were compared with the previous results obtained with water. As predicted with the SLOSH code output, damping is a critical parameter when comparing the liquids with different viscosities. Parameters such as the slosh frequency and pendulum length remain the same for all liquids regardless of their viscosities. Modeling the system with a diaphragm will help to better understand the damping effects on the system. The SimMechanics model was updated and adjusted for simulation using liquids other than water. The parameters to be estimated were the initial flywheel angle, the angular velocity correction, the pendulum hinge spring constant, and the pendulum damping constant.

After obtaining the experimental data for the different fill levels (60%, 70% and 80%) for both glycerine and corn syrup, the experimental data was then imported to the Parameter Estimation Toolbox. With the use of MATLAB Parameter Estimation Toolbox, the simulation for glycerine and corn syrup under free surface slosh conditions were simulated. Figure 2 illustrates the comparison between the experimental data and the simulated data for corn syrup at a 60% fill level.

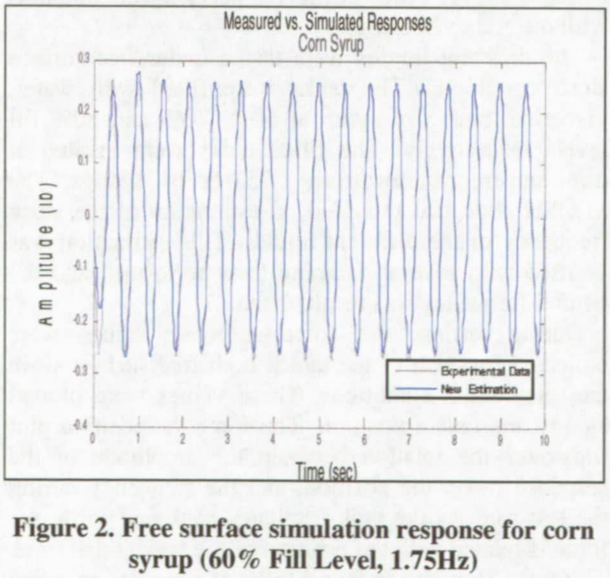

Figure 2. Free surface simulation response for corn syrup (60% Fill Level, 1.75Hz)

After obtaining the simulated estimation, it can be compared with the results previously acquired with water at same fill level. Table 1 illustrates all three liquids obtained with the MATLAB Parameter Estimation Toolbox. The results of Table 1 were compared and some of the values were as expected yet the damping value for glycerine was surprisingly lower than expected. The spring stiffness, on the other hand, increased as we tested each of the liquids.

Table 1 Comparison of results for water, glycerine and corn syrup

Parameter Estimation	Water	
60% Fill Level	Fixed Mass (lb)	Pendulum Mass (lb)
	3.21	3.055
Measured Test Frequency (Hz)	**1.757**	
Ang Velocity Correction (rad/s)	**-0.15193**	
Flywheel Initial Angle (rad)	**0.21297**	
Pend Spring Cons (ft-lb/rad)	**0.16766**	
Pend Damping Cons (ft-b/rad/sec)	**0.010487**	
Parameter Estimation	Glycerine	
60% Fill Level	Fixed Mass (lb)	Pendulum Mass (lb)
	4.052	3.856
Measured Test Frequency (Hz)	**1.757**	
Ang Velocity Correction (rad/s)	**-0.11375**	
Flywheel Initial Angle (rad)	**-4.8499**	
Pend Spring Cons (ft-lb/rad)	**0.26183**	
Pend Damping Cons (ft-b/rad/sec)	**0.004307**	
Parameter Estimation	Corn Syrup	
60% Fill Level	Fixed Mass (lb)	Pendulum Mass (lb)
	4.405	4.192
Measured Test Frequency (Hz)	**1.757**	
Ang Velocity Correction (rad/s)	**-0.042086**	
Flywheel Initial Angle (rad)	**-4.9441**	
Pend Spring Cons (ft-lb/rad)	**0.40412**	
Pend Damping Cons (ft-b/rad/sec)	**0.020734**	

B. SimMechanics Model

The SimMechanics model that was created (Figure 3) includes the pendulum mechanical analogy (describing the slosh behavior) and it also includes the new linear actuator assembly used to excite the experimental tank. The model consists of body, joint, sensor, and actuator blocks which are organized and arranged in a way that describes the actual behavior of the experimental set-up. The body blocks include the mass and inertia characteristics of the components in the system, then the joints blocks describe the way the bodies are connected and directly affect the other connected bodies. The actuator blocks specified the actual movement or force that either the bodies or joints have in order to follow the actual behavior of the system components. The main model sections are: the linear actuator assembly, the tank assembly, and the pendulum model assembly.

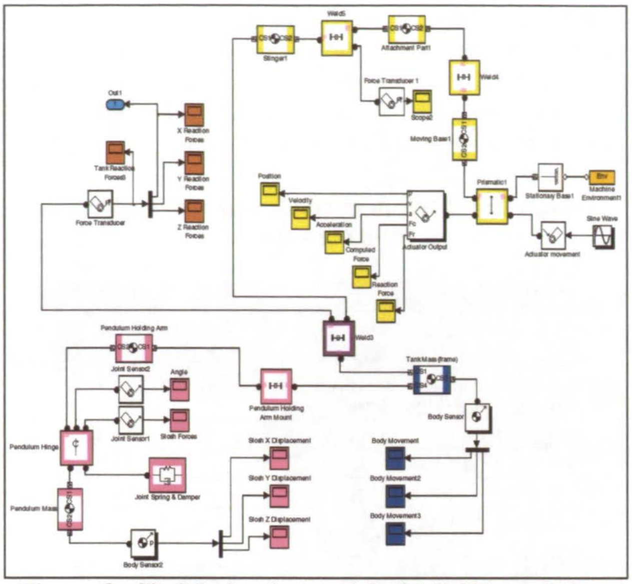

Figure 3. SimMechanics model of 1-DOF pendulum and linear actuator assembly

The model simulates the behavior of the experimental setup excited with the linear actuator and utilizing the one degree of freedom pendulum model for the behavior of the slosh. This model will be tested under several different conditions including the different liquids as well as the introduction of a diaphragm in the tank.

With the aid of the tools and interfaces of SimMechanics product, the complete modeling of the experimental set-up is arranged. The SimMechanics model animation of the linear actuator attachment assembly and the "fuel" tank are illustrated in Figure 4.

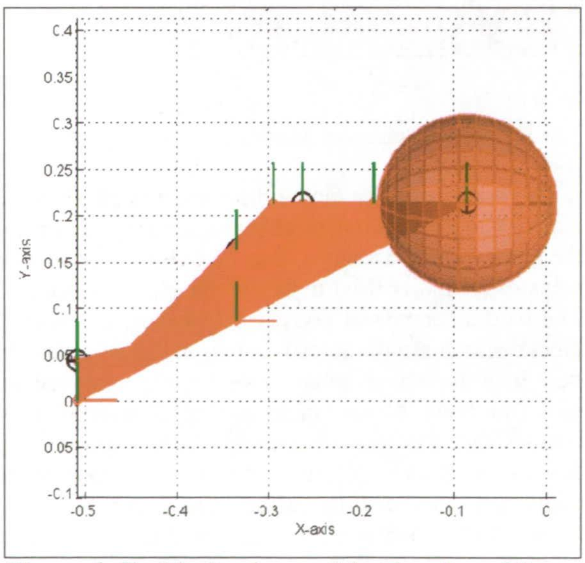

Figure 4. SimMechanics model animation of the linear actuator assembly

Once the body and joints blocks are defined and configured, the model animation can be used as a tool to verify the behavior of the system. This allows the user to catch errors early in the model build up process.

The introduction of diaphragms to this experimental set-up will allow for a more complete estimation of fuel slosh characteristics. Modeling the diaphragm and the subsurface inertial waves generated during lateral slosh in the presence of a diaphragm using SimMechanics will include the addition of springs, dampers, and rotors to the existing model.

C. Fuel Slosh with Diaphragm

The introduction of a PMD in the tank (in this case a diaphragm), could involve more complicated behavior than the previously researched free surface slosh. A step-by-step approach similar to the one used for the free surface slosh is utilized to estimate parameters in the presence of a diaphragm in the tank. The flexible diaphragm will be attached to the periphery of the experimental set-up tank wall.

Diaphragms provide a substantial level of slosh damping as a result of the combination of viscoelastic flexing of the diaphragm and the increased viscous effects at the liquid-diaphragm interface.[13] A diaphragm also increases the slosh natural frequency because of the constraints imposed on the free surface shape. The effective mass of liquid participating in the sloshing is slightly smaller than for a tank of the same shape and fill level without a diaphragm.

The stiffness of the diaphragm in the tank is an additional parameter that was not previously present in the former experimental set-up. How the stiffness of the diaphragm influences the results of the SLOSH code would be a very useful effect to quantify. It is further assumed that, as the stiffness of the diaphragm increases, the pendulum damping parameter will also increase as was observed in free surface tests of fluids with different viscosities.

The different liquids were tested under free surface slosh conditions. The tanks were filled with water, glycerine, and corn syrup at 60%, 70% and 80% fill levels respectively. The filled tanks were excited at different frequencies from 1.757Hz to 2.50Hz. The SLOSH code had provided an estimation of the slosh frequency of the different liquids. This estimation was verified with several damping tests performed and the natural frequency was recalculated.

During testing, the force response values were collected for each of the tanks, both free surface slosh and diaphragm conditions. These values were plotted against the tank's position. The force vs. position plot illustrates the relation between the amplitude of the response force, the position, and the frequency during the test run. As the tank oscillates back and forth, the force is related with the position of the tank at that time. The force response is found to be at a maximum when the frequency of excitation is closer to the resonance state. Resonance can be identified with the linear relationship between force vs. position which is illustrated during the different frequency tank tests. In an ideal case where a fluid is in resonance, the force vs. position plot will approach a straight line oscillating at a 45 degree angle. Once both the measured force and the tank position magnitudes harmonize and the behaviors of both agree, this is when the resonance frequency can be calculated.

While performing the free surface slosh tests, different liquids were tested besides water. Glycerine and corn syrup were also tested in the same conditions as water to evaluate the variation effects of the liquid's viscosity characteristics. It is assumed that for higher viscosities the resonance frequency is slightly higher than the predicted value for an ideal liquid.[12] Throughout the free surface testing, force vs. position plots were obtained for all liquids. The results of the plots were compared with the natural frequency estimation and calculated values. For the free surface tanks, the values estimated and the plots obtained correlated successfully.

Figure 5 illustrates the force vs. position plot obtained for the tank filled with glycerine at a 60% fill level excited at a frequency of 2.15Hz with displacement amplitude of 3mm.

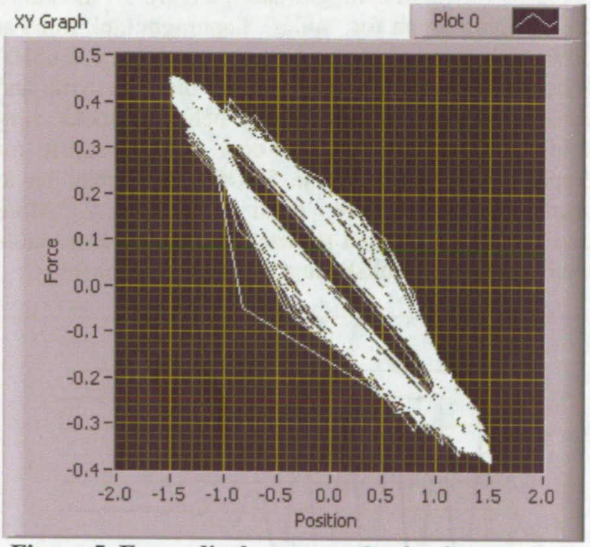

Figure 5. Force-displacement plot for free surface slosh approaching resonance (glycerine, 60% fill level, 2.15Hz, 3mm amplitude)

For the glycerine tests, the estimation for the natural frequency was slightly higher than with water tanks under free surface slosh conditions. Figure 6 illustrates the force vs. position plot obtained for the tank filled with corn syrup at a 60% fill level excited at a frequency of 2.375Hz with displacement amplitude of 3mm. Note that this resonance frequency is slightly hither than the glycerine. This verifies that the natural frequency does increase with fluid viscosity.

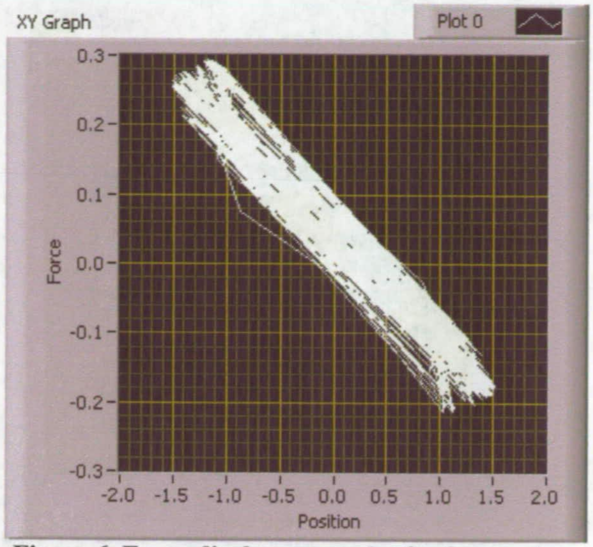

Figure 6. Force-displacement plot for free surface slosh at resonance (corn syrup, 60% fill level, 2.375Hz, 3mm amplitude)

The force vs. position plots allows corroborating the resonance estimation for the filled tanks. As the resonance is reached, the forces vs. position plots illustrate the phase shift that occurs. For both glycerine and corn syrup plots, it is evident that the resonance for these filled tanks was close to the test frequency measured. The free surface slosh conditions with the different liquids can be compared with the plots obtained with the diaphragm tanks. The diaphragm tanks included two different diaphragm materials for contrast. The first material is from a toy ball with the same size as the test tank. The thickness of this ball's material is about 0.609mm (.024in). Also, the material has over the surface "spikes" which are 6.35mm (.25in) tall and they are about 19.05mm (.75in) apart from each other. The other material used for the other diaphragm test tank was from a small yellow marine buoy. The thickness of this tank is the about 2.263mm (.081in). The "yellow" tank material thickness for this tank is over three times of the "spike" diaphragm tank. The thickness difference among the diaphragm materials will allow for a comparison and contrast of the effects the diaphragm has on the slosh behavior. The thickness characteristics and values can aid in the determination of other parameters as the stiffness of the system. Other parameters that can be determine with the diaphragm tank tests are the level of slosh damping and also the effective mass of liquid participating in the sloshing of the fluid.

Figure 7 illustrates the plot obtain for the "spike" diaphragm excited at the same frequency as glycerine in Figure 5. While the glycerine tank was very close to resonance under these testing conditions, the "spike" diaphragm tank was not experiencing the resonance characteristics at this point, (Figure 7).

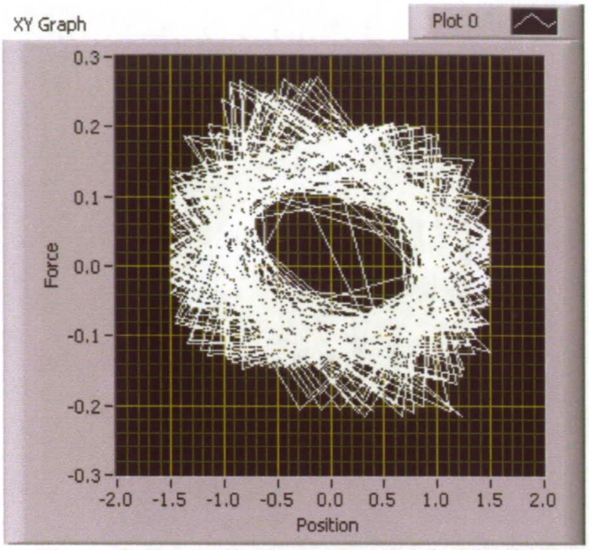

Figure 7. Force-displacement plot for "spike" diaphragm tank (water, 60% fill level, 2.15Hz, 3mm amplitude)

The same can be concluded for the case of the other diaphragm tested, "yellow" diaphragm, as shown on Figure 8. Both of the diaphragm tanks were filled with water for these tests at a 60% fill level.

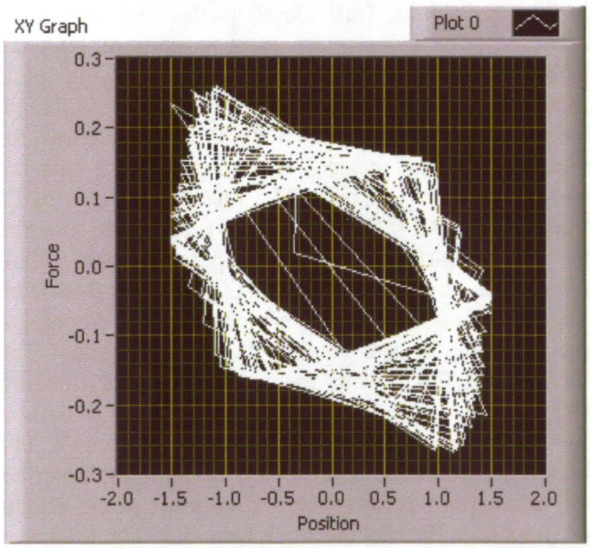

Figure 8. Force-displacement plot for "yellow" diaphragm tank (water, 60% fill level, 2.25Hz, 3mm amplitude)

Damping tests were also performed to study and determine the damping characteristics of the test tanks and to verify their natural frequency. Free surface slosh conditions were tested and compared with the test data obtained for the diaphragm tanks. The results for free surface slosh conditions were verified successfully as the estimated and the empirical data are in agreement. Figure 9 illustrates the damping graph of the data obtained for the corn syrup test tank filled at 60% and excited at a frequency of 2.375Hz. The linear actuator was set to excite the test tank at the liquid resonance frequency and then was stopped abruptly so that the damping characteristics of the fluid could be observed. Once the linear actuator stopped, the force response of the tank was recorded and plotted.

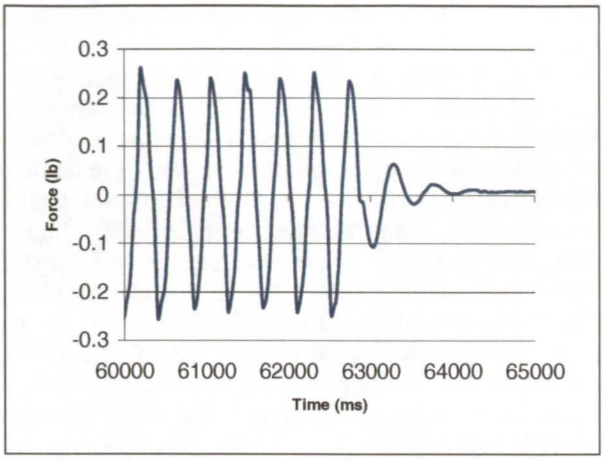

Figure 9. Force-time plot illustrating damping characteristics (corn syrup, 60% fill level, 2.375Hz)

The same graph was plotted for the empirical data obtained for the diaphragm tanks. Figure 10 illustrates the damping graph for "spike" diaphragm tank filled at 60% with water and excited at a frequency 3.65Hz. When visually comparing graphs of the corn syrup and spike diaphragm, the damping behavior looks very similar. This suggests that one way to adjust for diaphragm damping in the SLOSH code may be to change the viscosity input parameter. More investigation is needed to determine if this is a viable method and to establish the adjustment relationships.

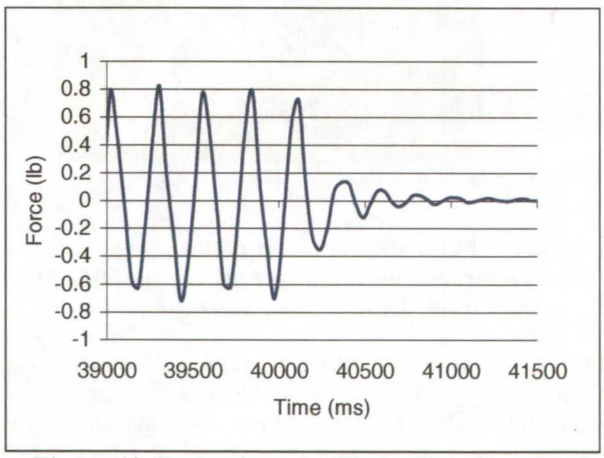

Figure 10. Force-time plot illustrating damping characteristics for "spike" diaphragm tank (water, 60% fill level, 3.65Hz)

Some of the parameters compared between different test runs were the force, logarithmic decrement, damping ratio, damped natural frequency, and natural frequency. The response forces measured with the force transducer appeared to be higher than with free slosh conditions when trying to reach resonance of the system. The force magnitude difference between both conditions (corn syrup and "spike" diaphragm) is about three times. Then, when recalculating natural frequency utilizing the data collected and solving the logarithmic decrement and damping ratio definitions, the values for free surface slosh were substantially close to the ones estimated and predicted. When considering the values for the diaphragm tanks, the data analysis is not as comparable with free surface slosh conditions. The natural frequency, damped natural frequency, response force, logarithmic decrement, and damping ratio seem to increase once the liquid is restricted as with the inclusion of a diaphragm.

The diaphragm tank tests performed were filled with water at the specified fill levels. These tests will be repeated but varying the liquid to glycerine and corn syrup. Subsequently, a contrast among the different liquids in the same diaphragm tank conditions can determine and solve for other parameters as the determination of the stiffness and damping coefficient. The calculated values will then be used as starting seed values for the parameter estimation process and to verify values obtained with the SimMechanics model.

IV. Conclusion

By extending the parameter estimation techniques previously developed to include the presence of a diaphragm, a greater number of real life missions can be analyzed. The on-going research will allow for earlier and easier identification of potential vehicle performance problems through improved simulation techniques. This current research and the collaboration between NASA's Launch Services Program, Southwest Research Institute, and Hubert Astronautics has led to a deeper understanding of the slosh issues confronting the spacecraft and launch vehicle community and has enabled the development of these new approaches to predictive simulation.

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14. ABSTRACT
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