Parameter Estimation of Lateral Spacecraft Fuel Slosh

Spacecraft Nutation Models

Predicting the effect of fuel slosh on the attitude control system of a spacecraft or launch vehicle is a very important and challenging task. Whether the spacecraft is spinning or moving laterally, the dynamic effect of the fuel slosh helps determine whether the spacecraft will remain on its intended trajectory. Three categories of slosh can be caused by launch vehicle or spacecraft maneuvers when the fuel is in the presence of an acceleration field. These are bulk-fluid motion, subsurface wave motion (currents), and free-surface slosh. Each of these slosh types has a periodic component defined by either a spinning or a lateral motion. For spinning spacecraft, all three types of slosh can greatly affect stability. Bulk-fluid motion and free-surface slosh can affect the lateral-slosh characteristics. For either condition, an unpredicted coupled resonance between the spacecraft and its onboard fuel could threaten a mission. This ongoing research effort seeks to improve the accuracy and efficiency of modeling techniques used to predict these types of fluid motions for lateral motion. Particular efforts focus on analyzing the effects of viscoelastic diaphragms on slosh dynamics.

Previous research used MATLAB SimMechanics to model free-surface fuel slosh with a simple one-degree-of-freedom (DOF) pendulum analog. The pendulum analog modeled a spherical tank undergoing free-surface slosh created by oscillating the tank via an electric motor attached to a locomotive arm assembly. A SimMechanics model incorporating the analog of the experiment was developed and tested. Parameters describing the simple pendulum models, such as spring and damping constants at the pendulum hinge location and pendulum length, characterized the modal frequency of the free-surface sloshing motion. The one-DOF model offered insights into free-surface fuel slosh and served as a stepping stone for the present research. Using the previous experimental setup, we tested different liquids undergoing free-surface slosh and estimated the various pendulum parameters using MATLAB's Parameter Estimator Toolbox.

The first step was to experiment with several liquids with different viscosities in order to better understand how that liquid property affects lateral fuel slosh and the resulting pendulum analog parameters. Liquids of varying viscosities and physical characteristics different from water were used. It was assumed that for higher viscosities, the peak amplitude of the reaction force on the tank would be lower than the values measured when using water. As predicted, pendulum damping, which determines the stiffness of the pendulum, was the critical parameter when comparing the liquids with different viscosities. The more damped the pendulum hinge, the less peak force there was at resonance. Parameters (such as the slosh frequency and pendulum length) remained the same for all liquids, regardless of their viscosities. The SimMechanics model was updated and adjusted for the simulation using different liquids. After obtaining experimental data at three different fill levels (60, 70, and 80 percent) for both glycerine and corn syrup, the data was imported into SimMechanics, where free-surface slosh conditions were simulated. Figures 1 and 2 compare the experimental data and the simulated data for glycerine and corn syrup at the 60-percent fill level.

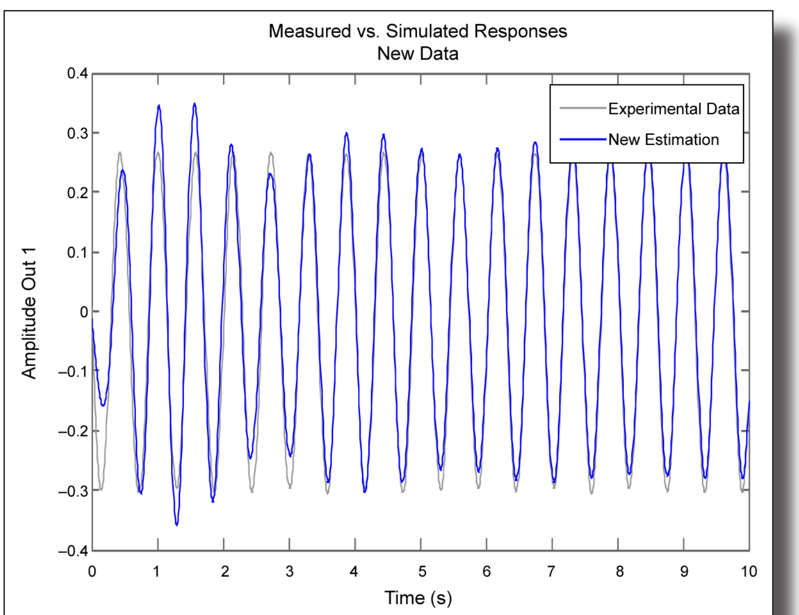

Figure 1. Glycerine: 60-percent fill level, oscillating at 1.75 Hz (unit = lbf).

In an ongoing effort for improvement, the locomotive assembly was replaced by a state-of-the-art shaker assembly. Four diaphragms, each with a different stiffness, were attached to the periphery of their tanks so that the effects of slosh on each could be studied (Figure 3). These new transparent spherical fuel tanks with diaphragms will be mounted on a fixture and linearly oscillated by the shaker. The forces at the tank wall, along the axis of lateral motion, will be measured by a force transducer mounted on the fixture, similar to what was done with the locomotive assembly.

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. It is assumed that, as the stiffness of the diaphragm increases, the pendulum damping parameter will increase, as was observed on free-surface tests of fluids with higher viscosities. The presence of a diaphragm in the fuel tank should also increase the natural frequency of the slosh because of the constraints imposed on the free-surface shape. In addition, the effective mass of liquid participating in the sloshing will most likely be smaller than that for a tank of the same shape and fill level without a diaphragm. That is, a greater percentage of fluid will behave as if it were attached to the tank. Figure 4 shows the new slosh test facility designed, fabricated, and installed at Embry-Riddle Aeronautical University to investigate the lateral sloshing of spacecraft propellant tanks.

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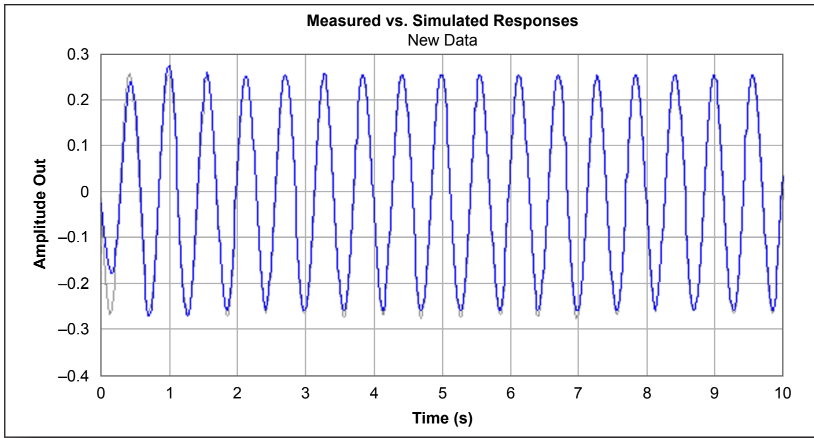

Figure 2. Corn syrup: 60-percent fill level, oscillating at 1.75 Hz (unit = lbf).

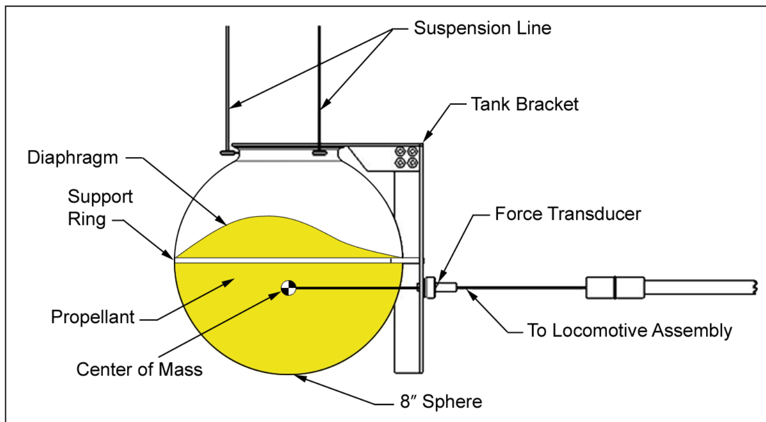

Figure 3. Experimental setup with the diaphragm.

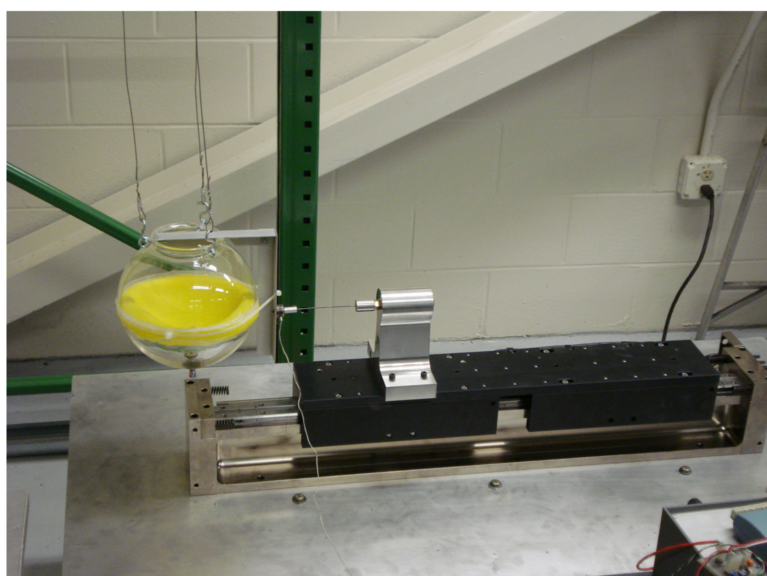

Figure 4. New slosh test facility at Embry-Riddle Aeronautical University.