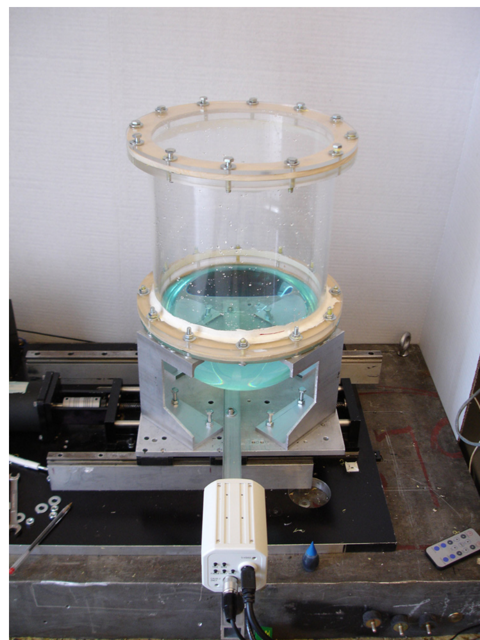
Modeling of Slosh Dynamics in Cryogenic Propellant Tanks in Microgravity Environments

Mission Data Feedback and Analysis

The slosh dynamics in cryogenic fuel tanks under microgravity is a pressing problem that severely affects the reliability of launching spacecraft. After reaching low Earth orbit, the propellant in a multistage rocket experiences large and cyclic changes in temperature as a result of solar heating. Tank wall heating can induce thermal stratification and propellant boiloff, particularly during slosh-inducing vehicle maneuvers. Precise understanding of the dynamic and thermodynamic effects of propellant slosh caused by these maneuvers is critical to mission performance and success. Computational fluid dynamics (CFD) analysis is used extensively within the space vehicle industry in an attempt to characterize the behavior of liquids in microgravity, yet experimental data to quantify these predictions is very limited and reduces confidence in the analytical predictions.

A novel approach designed to produce high-fidelity data for correlation to CFD model predictions is being developed with the assistance of Florida Institute of Technology (FIT) and Sierra Lobo, Inc. With few exceptions, previous work in slosh dynamics was theoretical or treated the mass of fuel as a variable of inertia only; such models did not consider the viscosity, surface tension, or other important fluid effects. The challenges in this research are in the development of instrumentation able to measure the required parameters, the computational ability to quantify the fluid behaviors, and the means to assess both the measurements and predictions.



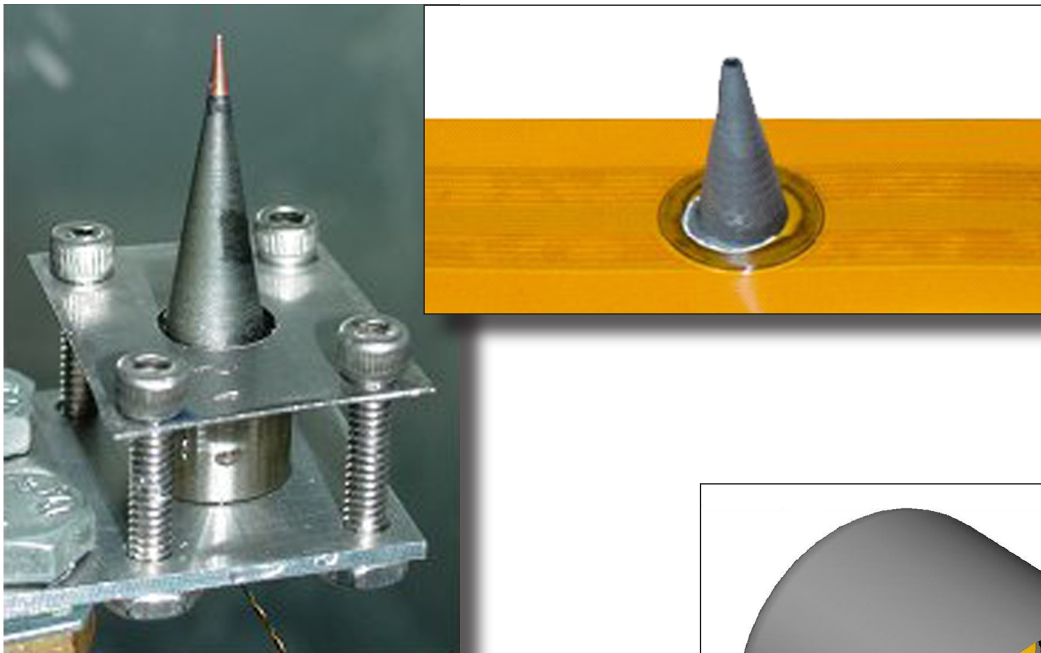
One-DOF ground test tank.

The design of this experiment bridges the understanding of slosh dynamics in microgravity by a comprehensive approach that combines CFD tools, dynamic simulation tools, semianalytical models of the predominant fluid effects, and an experimental framework that includes measurement and characterization of liquid slosh in one-degree-of-freedom (DOF) and two-DOF experiments, and ultimately experiments in a NASA low-gravity aircraft.

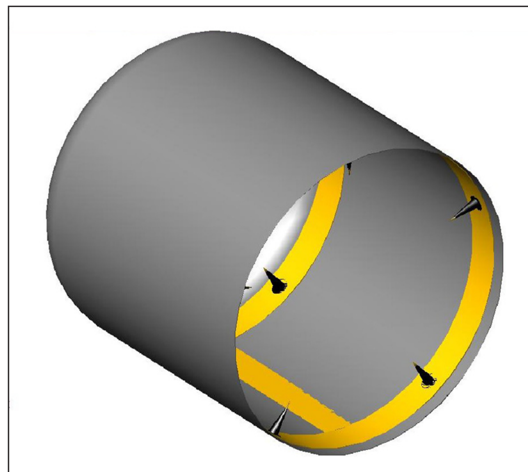
Slosh induced in test tank.

A one-DOF ground test tank and visualization system was developed by FIT to capture slosh images. Software was developed (1) for image processing, surface extraction, and wall-wetting behavior, (2) for ground verification of the CFD modeling, and (3) for the test and checkout of the flight instrumentation in development.

The reduced-gravity propellant-sensing system is based upon the Cryo-Tracker® system developed by Sierra Lobo, Inc., with NASA sponsorship, for cryogenic tank fill and drain operations. The system detects fluid levels and temperature by measuring



Low-gravity probe prototype test.



Tank instrumented with low-gravity probes.

the change in impedance in a diode junction as a result of the heat transfer in the vicinity of the sensing element. Characterization of slosh dynamics in microgravity, however, requires an instrument whose accuracy is also independent of the gravity field in which it operates. The innovation in this development is a sensor that exploits certain aspects of low-gravity fluid physics to allow the sensing area to be exposed to liquid only when bulk liquid is present.

The technologies developed in support of these experiments will be of great benefit to launch vehicles and spacecraft, and the microgravity data will be of considerable interest throughout the space exploration community.

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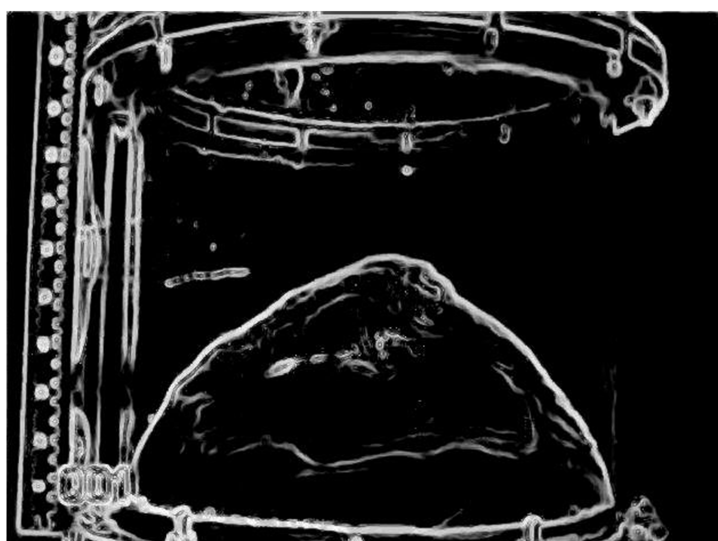

Binary stage of data extraction process.