Slosh Dynamics in the Orion Downstream Propellant Tank

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A slosh analysis of a scale model of the Orion Service Module (SM) downstream propellant tanks was carried out by a team of undergraduate researchers under the auspices of NASA's Systems Engineering Educational Discovery (SEED) program. Slosh modes, zero-g equilibrium propellant configuration, interface formation times, and dynamical instabilities in reduced gravity were explored over the course of two hours of parabolic flight maneuvers.

Research Objectives The key research objectives of this study are (1) to carry out a Linear Sloshing Analysis to identify frequencies of the fundamental symmetric and anti-symmetric slosh modes; (2) to establish the equilibrium free-surface configuration of propellant at different g-levels, and (3) to establish the nature of surface instabilities during high-g to low-g transitions. Each objective is pursued in the context of both experimental modeling and computational simulation using *Flow-3D*[1].

Experimental Design The model tank preserves the geometry of the Orion SM propellant tank (at 1/6 linear-scale) and includes internal structures representing the mass-gauging probe and the propellant management device (PMD). Our tank was constructed of acrylic and Lexan to permit visual observation of fluid motion. The propellant simulant used in the present study is a 60/40 ethanol/water mixture. Ethanol on acrylic achieves a contact angle of $\theta_c \approx 15°$, which is similar to the contact angle of the actual propellant (MMH) on steel. Sixty microgravity transitions were recorded at fill-fractions (ratio of the fluid surface height h to the tank radius R) h/R from 0.2-0.9.

Results A Linear Slosh Analysis examines the lowest resonant slosh frequencies present in the tank. Antisymmetric slosh frequencies are shown in Fig. 2 for a range of fill fractions h/R. Slosh frequencies in the full scale tank can be obtained from those in Fig. 2 by multiplying model frequencies by the factor $(R_{\text{model}}/R_{\text{actual}})^{1/2} \approx 0.4$. Flow-3D simulations of the free surface configuration of the (low contact angle) propellant at zero-g suggest that the spherical free surface associated with a clean cylindrical tank is modified by the presence of the mass-gauging probe. Capillary forces cause fluid wicking along the mass gauging probe and may adversely affect the accuracy of propellant volume measurements.

The free surface formation time (t_f) is the time for the fluid surface to obtain its equilibrium shape after a step reduction in gravitational acceleration [2]. For our tank, $t_f \approx 100$ sec., exceeds the time available in reduced gravity (≈ 20 sec./parabola). Accordingly, we were not able to verify equilibrium surface shape in zero-g. Instead, we examine the surface instability driven by the transition from accelerated motion to zero-g. This swirl instability is characterized by the rotation of the liquid surface plane about the vertical axis. The axial rotation of the slosh plane occurs at frequencies of approximately half the lowest anti-symmetric slosh mode. The amplitude of the slosh grows as the plane rotates until the fluid circulates vertically around the tank. We suggest that this swirl instability arises from the nonlinear interaction of surface waves as the pressure gradient in the fluid vanishes in the transition from high-g to microgravity.

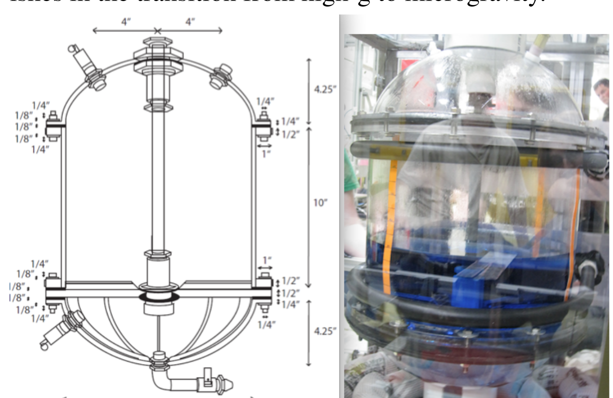

Figure 1: The slosh tank consists of a 12" OD cast acrylic cylinder with dome end caps. Fill fractions in the upper and lower compartments can be independently set.

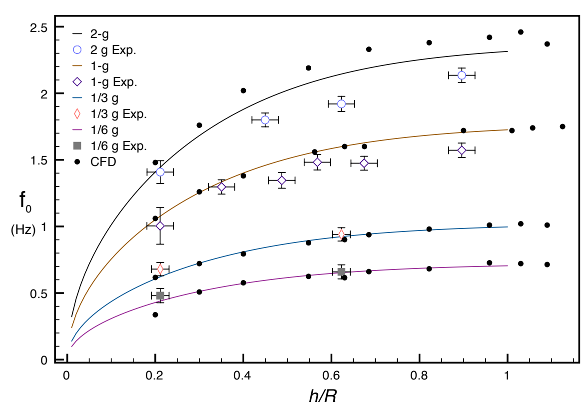

Figure 2: Lowest antisymmetric slosh-mode frequencies plotted against tank fill-fraction. Solid lines are are predicted curves derived from potential theory.

References

[1] Flow Science, Inc., http://www.flow3d.com

[2] Dodge, F., and Garza, L., Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low Gravity, *Trans. ASME J. of Appl. Mech.*, **34** (1967).