Scaling and Modeling of Propellant Sloshing and Zero Gravity Equilibrium for the Orion Service Module Propellant Tanks

Samantha Kreppel
Department of Physics, Carthage College, Kenosha, WI

Thesis Advisor: Dr. Jean Quashnock
SEED Advisor: Dr. Kevin Crosby

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Abstract

A scaled model of the downstream Orion service module propellant tank was constructed to assess the propellant dynamics under reduced and zero-gravity conditions. Flight and ground data from the experiment is currently being used to validate computational models of propellant dynamics in Orion-class propellant tanks. The high fidelity model includes the internal structures of the propellant management device (PMD) and the mass-gauging probe. The scaling of these structures in parallel with the scaling of the simulated propellant, Monomethalhydrazene (MMH), comprised the primary scientific focus during experimental design. In particular, this thesis addresses the geometric scaling of the Orion SM tank and the scaling of the Orion propellant properties through a scaling relation of the Bond number. A clear understanding of the fluid dynamics within the tank is necessary to ensure proper control of the spacecraft’s flight and to maintain safe operation of this and future service modules. Qualitative differences between experimental and CFD data are understood in terms of fluid dynamical scaling of inertial and capillary effects in the scaled system. Understanding slosh dynamics in partially-filled propellant tanks is essential to assessing spacecraft stability.
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1 Research and Experimental Context

1.1 Constellation Program

The Constellation Program was part of the NASA Authorization Act of 2005 signed by President George W. Bush in 2005 [1]. The program goals consist of gaining operational experience outside the Earth’s environment, developing technology necessary for missions in space, and conducting fundamental science [2]. The Constellation program allows for more time and experience in space to develop reliable systems for deep space science research [4]. To achieve these goals, the Constellation program consists of the development of new spacecraft and rockets.

NASA has initiated the process of designing two rockets, the Ares I and Ares V. Ares I has the primary function of launching mission crews into orbit, while Ares V is necessary to launch other hardware for use on missions and will have a heavier lift capacity than the Ares I rocket. In addition to these two boosters, NASA is designing a set of other spacecrafts for use in the Constellation Program. These will include the Orion crew capsule, the Earth Departure Stage and the Altair lunar lander [3].

The Orion component of the Constellation program is the crew module designed to hold four crew members for lunar missions and six crew members for International Space Station missions. The Orion consists of three primary parts: a Crew Module (CM), a Service Module (SM), and a Launch Abort System (LAS). The CM design is similar to the Apollo Command Module and can be reused for up to ten flights. The SM contains the primary propulsion systems. The SM will fuel, power, and provide life-support services to the Orion spacecraft. The SM contains two propellant and two oxidizer tanks with a total launch mass of 8300kg of propellant [8]. The LAS provides the capability for the SM to eject from the launch vehicle in case a problem occurs during the launch sequence [4].

The Altair Lunar Lander (Altair) is the primary transport vehicle to the moon and supports four crew members and 20 metric tons of cargo [2]. Although five times larger, the Altair is similar to the lunar module from the Apollo missions with two parts: an ascent stage and a decent stage. For lunar missions, the Altair transports the crew, consumables, and equipment to the surface of the moon. The Altair has been designed to land in the polar regions of the moon for more efficient data collection. Altair supports seven day lunar missions, but is not reusable and will likely be crashed into the moons surface after use [4].

Ares I serves as the long term crew launch vehicle, and consists of a five segment solid rocket booster capable of large payloads [2]. Ares I consists of a two-stage rocket with the Orion crew and launch abort system on top of the entire assembly [5]. The Ares I can launch the Orion to the ISS or into low earth orbit for lunar missions. For missions to the ISS, Ares I can accommodate payloads up to 52,000lb. For lunar missions, payloads up to 56,000lb can be launched [7].

Ares V is the heavy cargo launch vehicle designed for the Altair Lunar Lander. It can
transport 106 metric tons into low Earth orbit [2]. The entire Ares V assembly is 116\text{m} tall and represents an unmatched asset for lifting heavy exploration, scientific, and commercial payloads into Earth orbit or for lunar missions[4]. In time, such lift capabilities will enable NASA to undertake crewed missions to destinations beyond the moon and deeper into space [6].

1.2 Experimental Background

In fluid dynamics, slosh refers to the movement of liquid inside a hollow container. These dynamics are examined via a scale-model of the Orion Service Module (SM) downstream propellant tank. The dynamics of a fluid that interacts with the walls of its container are complicated and challenging to predict, particularly at low propellant volumes. The effects of sloshing on bodies in motion are significant with common example of ships, trucks, and rockets. In the particular case of space, understanding slosh dynamics in fluid tanks is necessary to ensure proper control of a spacecraft. The Orion spacecraft represents a major component in the next wave of human space exploration.

As a substantial portion of the initial weight of the SM is fuel, understanding of the propellant dynamics inside of the SM is critical. As the propellant level decreases throughout a mission, the effects of sloshing forces on the remaining fuel become more prominent. This sloshing can ultimately lead to wobble in a spinning spacecraft and self-amplifying oscillations that can result in failure of individual instruments or failure of the entire structure. The effects of sloshing remain prominent even when the propellant volume represents only 0.3% of the total spacecraft mass [9]. To investigate these effects, a scaled model of a downstream propellant tank was constructed to fly in reduced and zero gravity simulations.

Due to the significance of slosh dynamics, a considerable amount of research has been conducted in relation to slosh dynamics over the past sixty years. In the field of aerospace engineering, Graham and Rodriguez conducted the first study specifically related to propellant slosh in 1952 [10]. This research specifically studied the effect of fuel slosh through the use of airplane maneuvers. In particular, the fuel response to simple harmonic motion from plane pitching and yawing was studied. The results facilitated a general understanding of propellant slosh dynamics.

In 1964, research at the Lewis Research Center in Cleveland, Ohio analyzed experimental sloshing characteristics and related the movement of sloshing liquids to a pendulum [11]. The researchers employed a scaled version of a Centaur liquid oxygen tank, which was a spherical vessel with a cylindrical portion along the major axis of the tank. Three model tanks with varying complexity were tested. The initial setup was a clean or empty tank with no internal structures. The second setup consisted of an un baffled tank with a thrust barrel, fill pipe, annular spring ring and a vent pipe. The final tank included a baffle near the center of the tank in addition to the internal structures from the second setup. When compared the initial tank setup, it was found that the fundamental frequencies of the liquid were reduced due to dampening structures in the un baffled tank. The baffle that was used in the
third tank setup had only a slight effect on the natural frequencies of the liquid in the tank. This research provided considerable amount of information in relation to dampening slosh dynamics in a 1-g environment. However, research conducted in variable gravity conditions is more pertinent to fluid dynamics in space.

In 1969, Salzman and Masica conducted research that provided data for slosh dynamics under variable low-gravity conditions at the Lewis Research Center [12]. In particular, the lateral sloshing in cylinders was studied as a function of Bond numbers ranging from 0 to 800. The Bond number of a liquid is a dimensionless quantity that describes the ratio of gravitational forces, \( F_{grav} \), to surface tension forces, \( F_{st} \).

\[
F_{grav} = mg \tag{1}
\]

\[
F_{st} = \sigma L \tag{2}
\]

By dividing \( F_{grav} \) by \( F_{st} \), one derives the Bond number

\[
B_o = \frac{F_{grav}}{F_{st}} = \frac{mg}{\sigma L}. \tag{3}
\]

Mass can be written as \( m = \rho V \) which changes the ratio to

\[
B_o = \frac{\rho V g}{\sigma L}. \tag{4}
\]

Volume is then written as \( V = L^3 \) which simplifies the Bond number to

\[
B_o = \frac{\rho g L^2}{\sigma}. \tag{5}
\]

In Equation 5, \( \rho \) is the density of the liquid, \( g \) is the gravitational acceleration experienced by the liquid, \( L \) is the characteristic length of a drop of the particular fluid in use, and \( \sigma \) is the surface tension of the liquid. The Bond number is used mainly in the scaling the properties of liquids when gravitational forces and surface tension forces are considered dominant.

Salzman and Masica’s experimental setup involved the use of the Lewis Zero-Gravity Facility, containing a 155m long underground shaft. This shaft allowed for around 5 seconds of free-fall time and used a thruster to simulate low-gravity ranging from 1 to 18cm/s². A cylinder containing water was dropped from the top of the shaft in a controlled fall and decelerated using a cart filled with pellets of expanded polystyrene. During the free-fall and deceleration, a high-speed camera and a pulse generator monitored the tank. The study found that the liquid equilibrium position, which is the arrangement of the water in a zero gravity environment, was reached in less than 50ms. The results concluded that for liquid depth ratios (height of the liquid/radius of the tank) less than two, the natural frequency of liquid slosh is directly proportional to the liquid depth for all tested Bond numbers.

Finally, a more recent study was conducted at the Indian Institute of Technology, which validated several theoretical computer analyses [13]. The general experimental setup consisted of a Perspex cylindrical tank supported by a guidable platform, which was fixed to
a mechanically shakable table. Wave height sensors were used to measure changes in li-
quid levels. Later, the researchers added slosh baffles to study the magnitude to which the
slosh dynamics could be suppressed. Similar to the goals for this work, the study found the
analytical and experimental results to be in good agreement.

2 Experiment Description

The purpose of the experiment is to investigate the equilibrium position, settling time of
propellant sloshing, and response to simulated spacecraft maneuvers inside a scale-model of
the downstream SM tank in order to visually validate and improve current computational
models of slosh dynamics within the Orion downstream propellant tank. The equilibrium
position is the static configuration a fluid reaches in zero-gravity. The amount of time it
takes for a liquid transition from an equilibrium position to the bottom of the tank which is
referred to as the settling time. The settling time of a fluid is a function of fluid characteristics
and tank design. The settling time data will determine if the use of Reentry Control System
(RCS) thrusters are necessary to reach a faster, desired settling time for proper fuel feed
rates. More importantly, settling time data will validate current computational models and
the design of the dampening structures within the tank.

In order to provide a microgravity environment, this research is conducted on the Zero-
G plane through the NASA Systems Engineering Educational Discovery (SEED) Program.
Weightlessness is achieved through plane maneuvers known as parabolas. Before starting a
parabola, the plane flies level to the horizon at an altitude of approximately 24,000 feet. The
pilots then pull up, gradually increasing the angle of the aircraft to about 45° to the horizon
reaching an altitude of 34,000 feet. During this pull-up, passengers will feel a portion of
hypergravity around twice that of the earth. Next the plane does what is referred to as
a pushed over to create the zero gravity segment of the parabola. For the next 20-30 seconds
everything in the plane is weightless. A ”pull out” completes the parabola and prepares for
the next one. This maneuver is repeated 32 times with a five minute level-off or turnaround
half way through the parabolas.

With this purpose in mind, our tank is designed to replicate the specifications of the tank
described by the computational models but not necessarily designed to match the actual
propellant tank. Thus, the internal structures in our model is in accordance with the com-
putational model rather than operational. In order to provide accurate data, we account
for proper scaling of the tank, the dynamic forces and the propellant properties. As there
are over forty numbers and ratios used for scaling, perfect scaling of any fluid is unrealistic.
Therefore the Bond number and contact angle were the two properties taken into greatest
consideration.
2.1 Bond Number

Scaling analysis and dimensionless numbers play a key role in physics as they indicate the relative importance of forces, energies, or time scales. As previously described in the experimental background, the Bond number represents a dimensionless quantity that describes the relationship between gravitational forces and surface tension forces. In essence, it compares the importance of surface tension forces to body forces. A high Bond number is an indication that a fluid system is relatively unaffected by fluid surface tension. A bond number less than one is generally considered low and indicates that the majority of the dynamics of that fluid is determined by surface tension [14].

Perfect scaling of fluid properties requires the Bond to remain constant. Therefore direct calculations of the Bond number were not done. Rather, Equation 7 and Equation 8 were set equal to each other as seen in Equation 9.

\[ B_o = \frac{\rho_o g L_o^2}{\sigma_o} \]  \hspace{1cm} (6)

\[ B_s = \frac{\rho_s g L_s^2}{\sigma_s} \]  \hspace{1cm} (7)

The Bond number for MMH, \( B_o \), was set equal to our scaled fluid Bond number, \( B_s \)

\[ \frac{\rho_o g_o L_o^2}{\sigma_o} = \frac{\rho_s g_s L_s^2}{\sigma_s} \]  \hspace{1cm} (8)

Equation 9 can then be rearranged to represent a scaling relation which sets geometric properties equal fluid properties

\[ \frac{\rho_o g_o}{\sigma_o} = \frac{L_s^2}{L_o^2} \]  \hspace{1cm} (9)

For the purposes of this work, the gravity in the scaled environment and the full scale environment is equivalent

\[ \frac{\rho_o g_o}{\sigma_o} = \frac{L_s^2}{L_o^2} \]  \hspace{1cm} (10)

Then Equation 10 is reduced and set equal to the density divided by the surface tension of the scaled fluid

\[ \frac{\rho_o L_o^2}{\sigma_o L_o^2} = \frac{\rho_s}{\sigma_s} \]  \hspace{1cm} (11)

The Orion SM tank has been scaled down by 1/6 which makes \( \frac{L_s}{L_o} = 6 \).

\[ \frac{(0.88 \frac{g}{cm})6^2}{(34.3 \frac{dyn}{cm})1^2} = \frac{\rho_s}{\sigma_s} \]  \hspace{1cm} (12)

The scaled properties of the fluid should have a density to surface tension ratio of

\[ \frac{\rho_s}{\sigma_s} = 0.924 \frac{g}{cm^3} \]  \hspace{1cm} (13)
Numerous fluids were researched and compared to this scaled value. Table 1 displays a compilation of the fluids researched. As expected, a fluid with perfectly scaled properties was not found. No fluid was found to have a close relation to that of MMH. Ultimately, 60% Ethanol was chosen as the experiments simulated propellant. Although several other fluids were a closer match to the calculated scaled value. Due to research limitations, these fluids were unobtainable, simply cost prohibitive, or hazardous like Freon. Pure ethanol would have caused the acrylic tank to crack, and fluids like Vertrel XF would have dissolved any glues or sealants on the tank.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density, $\rho$ (g/mL)</th>
<th>Surface Tension, $\sigma$ (dyn/cm)</th>
<th>$\rho/\sigma$ (s$^2$/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMH</td>
<td>0.88</td>
<td>34.3</td>
<td>$(0.88/34.3) \times 36 = 0.924$</td>
</tr>
<tr>
<td>Perfluoroheptane</td>
<td>1.75</td>
<td>12.89</td>
<td>0.136</td>
</tr>
<tr>
<td>Vertrel XF</td>
<td>1.58</td>
<td>14.1</td>
<td>0.112</td>
</tr>
<tr>
<td>CFC-113 (Freon)</td>
<td>1.49</td>
<td>17.3</td>
<td>0.086</td>
</tr>
<tr>
<td>HCFC-141b (Genesolv)</td>
<td>1.34</td>
<td>18.2</td>
<td>0.074</td>
</tr>
<tr>
<td>Bromothane</td>
<td>1.47</td>
<td>25.9</td>
<td>0.057</td>
</tr>
<tr>
<td>Trichloroethane</td>
<td>1.44</td>
<td>25.9</td>
<td>0.056</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>0.90</td>
<td>23.6</td>
<td>0.038</td>
</tr>
<tr>
<td>Pure Ethanol</td>
<td>0.79</td>
<td>22.4</td>
<td>0.035</td>
</tr>
<tr>
<td>60% Ethanol-Water Mixture</td>
<td>0.90</td>
<td>26.48</td>
<td>0.034</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.79</td>
<td>25.2</td>
<td>0.031</td>
</tr>
<tr>
<td>Butanol</td>
<td>0.81</td>
<td>26.2</td>
<td>0.031</td>
</tr>
<tr>
<td>Salt Water (6M)</td>
<td>2.160</td>
<td>82.55</td>
<td>0.026</td>
</tr>
<tr>
<td>Water</td>
<td>1.00</td>
<td>72.8</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 1: Potential Scaled Fluids for MMH
2.2 Contact Angle

The contact angle describes the angle at which a liquid meets a solid surface. In essence, a contact angle is a measure of attractiveness between a liquid and air as well as a liquid and the surface on which it sits. More specifically, a contact angle is determined by the interactions across the three interfaces. As seen in Figure 1, a low contact angle equates to high wetting and a high contact angle [15].

![Figure 1: Contact Angle](image1.png)

It is critical to match the fluid properties of the model tank to the properties of the original propellant tank as closely as possible. 60% ethanol was found to have a closest suitable Bond number and similar contact angle characteristics. For MMH propellant and aluminum, the liquid droplet experiences high wetting due to the strong attraction to the solid, aluminum surface. Our NASA advisor, Jonathan Braun, suggests that the contact angle between MMH and aluminum is less than 10° (J. Braun, pers. comm.). The ethanol mixture we are using also exhibits a low contact angle measured by means of optical tensiometry.

Optical tensiometry is a geometric method for measuring contact angles. By this method, the contact angle is assessed directly by measuring the angle formed between the solid and the tangent to the drop surface.

![Figure 2: Contact Angle of 60% Ethanol on Lexan](image2.png)

A droplet of 60% ethanol on a sheet of Lexan has an approximate contact angle of 20° (Figure 2). In comparison, a droplet of water has a contact angle of roughly 40° on Lexan (Figure 3). The contact angle for ethanol on acrylic would be lower due to acrylic having a higher surface energy than that of Lexan. The acrylic tank more readily interacts with
the ethanol and reaches a contact angle close to the desired angle of 10°. Therefore, the tank was composed of acrylic and the fluid used was 60% ethanol. This water and ethanol mixture is the closest match to the scaled properties needed without damaging the acrylic or the adhesive used for the tank.

<table>
<thead>
<tr>
<th>Solid</th>
<th>Liquid</th>
<th>Contact Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>MMH</td>
<td>&gt; 10°</td>
</tr>
<tr>
<td>Lexan</td>
<td>60% Ethanol</td>
<td>20°</td>
</tr>
<tr>
<td>Lexan</td>
<td>Water</td>
<td>40°</td>
</tr>
</tbody>
</table>

Table 2: List of Contact Angles

3 Equipment Description

3.1 Tank

The tank used for this experiment is a 1/6 scale model of the Orion downstream SM tank. Our tank is comprised of a 0.25in thick acrylic cylinder with acrylic domes of like thickness bolted to either end. The cylinder has a height of 10in and an outer diameter of 12in. The domes are ellipsoidal, with outer diameters (OD) extending out along a major axis length of 12in and minor axis length of 4.25in (OD). At the base of the domes and at either end of the cylinder are flanges through which the sections are bolted together. The tank is filled via a 1/4in fitting attached to hose. There is a corresponding assembly on the lower dome for manual draining of the 60% ethanol. This assembly consists of tubing which attaches to a valve and allows the fluid to be drained out of the tank and into a sealable container. The total height of the tank is 19.5in. The internal structures of the tank are discussed further in the sections to follow. A diagram of the tank and all related components are shown in Figure 4 and Figure 5.
Figure 4: Tank Design
3.1.1 Propellant Management Device (PMD)

A Lexan plate, 0.5\textit{in} thick with a diameter 14\textit{in}, models the PMD plate that separates the bottom dome from the cylinder. In the scaled tank the PMD plate, unlike that of the actual propellant tank, is impermeable, which corresponds with the computational model which is being validated. The purpose of a functional PMD is to manage the flow of propellant within a tank to ensure gas free liquid transmission to the tank fuel line. PMDs can be made entirely from titanium which allows them to be used in the most corrosive propellants. As no moving parts are used, they are inherently reliable and used in satellites, solar system probes, and rockets [16].

It is important to note that the PMD is a simulated structure rather than operational for the purpose of this work. Also, located in the center of the PMD plate is a pop-up valve which opens to allow fluid to drain from the upper compartment into the lower compartment. The valve is controlled by hand via a rod extending from the pop-up valve to the top opening of the tank, where it is secured by the fill cap mechanism. This valve allows for the changing of tank fill fractions in flight during a level-off. Below the fill cap is a threaded plastic tube that serves to hold the rod which controls the pop-up valve in place.

![Figure 5: 60% Ethanol in Zero-G](image-url)
3.1.2 Stiffeners

Extending along the top of the PMD plate into the cylinder are eight acrylic radial stiffeners used to dampen propellant slosh frequencies. The stiffeners are constructed of 0.125in thick Lexan and have a cross-sectional area in a T-shape. The ratio of the height to the diameter of the stiffeners is 1.5.

3.1.3 Vanes

The lower dome has eight acrylic radial vanes running along the side of the dome. Rather than being flush against the dome wall, these vanes lie slightly above the dome to help regulate the flow of propellant towards the fuel line by means of capillary forces.

3.2 Propellant Simulant

Four fill levels in both the upper and lower compartments of the tank were studied using the scaled propellant, 60% ethanol. During flight turnaround, propellant simulant from the upper compartment was drained into the lower compartment via the drain plug at the center of the polycarbonate plate. On the first flight day, the upper compartment was initially 40% full and drained down to 30% while the lower compartment was initially be 2.5% full and fill to 76.5%. On the second flight day the upper compartment was filled to 20% of its total volume while the lower compartment began at a 3% fill level. Again, the fluid was drained during the turnaround portion of the flight, leaving 10% and 77% of the respective upper and lower compartments volume filled with propellant simulant.

![Figure 6: 60% Ethanol in Zero-G](image)
4 Initial Analysis

When considering an initial analysis of the six hours of flight data obtained, one must determine what dominates the fluid dynamics in microgravity. 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. In reduced gravity, the equilibrium shape of a fluid is governed by the balance of capillary, bulk pressure, viscous, and gravity forces. Surface Tension also plays an important role these fluid dynamics.

Surface Tension is a cohesive forces between liquid molecules. The molecules at the surface do not have other like molecules on all sides and consequently they cohere more strongly to those directly associated with them on the surface. This attraction between surface molecules makes it more difficult to move an object through the surface than to move it when it is completely submersed. Surface tension is represented as a ratio of the surface force, $F_s$, to the length, $d$, along which the force acts

$$\gamma = \frac{F_s}{d}. \quad (14)$$

Surface tension has SI units of N/m, but is typically measured in dynes/cm. For reference, water at 20°C has a surface tension of 72.8 dynes/cm compared to 22.3 for ethyl alcohol and 465 for mercury [17].

Capillary forces also influence the dynamics of a fluid especially in microgravity. Capillary motion is the tendency for fluids to flow against the direction of gravity. The distance, $h$, that the fluid will travel vertically against gravity is calculated using the following equation

$$h = \frac{2\gamma \cos \theta}{\rho gr}. \quad (15)$$

In Equation 15, $\gamma$ is the liquid surface tension, $\theta$ is the contact angle, $\rho$ is the liquid density, $g$ is the acceleration due to gravity, and $r$ is the radius of the container holding the fluid. It is important to note that in the case where gravity is reduced, capillary forces have an increased effect on governing fluid dynamics. Capillary height is directly related to the contact angle [18]. For contact angles less than 90°, the distance the fluid travels into the capillary tube is a function of the capillary dimension, and the properties of the fluid. For contact angles greater than 90°, the amount of force required to force a fluid into a capillary tube is a function of the capillary dimension, and the properties of the fluid. The capillary height is inversely proportional to the effective gravity. Therefore, fluids in microgravity environments are dominated by capillary forces.

Capillary action is also dependent on the adhesion and cohesion of a fluid. In Figure 7a, the adhesion between the tube wall and liquid molecules is strong enough to overcome the cohesion between the molecules and pulling up the wall to height $h$ and thus the liquid is said to wet the solid surface. If the adhesion is weak compared to the cohesion, the liquid
Figure 7: Surface Tension effects in Small Tubes

will not wet the surface and the level is depressed and said to be non-wetting as seen in Figure 7b [19]. Fluid capillary systems in a microgravity environment are classified into three primary categories: drops, jets, and liquid bridges. A drop is a single-connected blob of liquid completely surrounded by another fluid (isolated drop) or touching just a solid-liquid interface (a captive drop). A jet is formed by creating a liquid mass through a hole in a solid and then through the ambient fluid. A liquid bridge is a liquid mass extended between two solid supports and held together by surface tension and capillary forces in a weightless environment, and in case of disturbances the surface tension acts as a restoring force. Capillary action in zero-gravity is meaningless, but in a microgravity environment the capillary action in the full scale tank will be less than that of in our scaled model because the tank is 1/6 the size. Therefore, $r$ in Equation 15 is six times smaller for our tank in comparison to the Orion propellant tank.

In the case of ethanol, low surface tension provides minimal restoring forces. Therefore the ethanol is easily excited and flows in response to small perturbations. Once flowing, capillary forces dominate the fluid motion. Partially due to the low contact angle and surface tension, the fluid tends to follow the curvature of the tank. The ethanol wicks up the sides and even leaves a film of ethanol along the tank until the microgravity transitions into period of hypergravity. The fluid rarely breaks into sections and is therefore primarily along the tank wall although the ethanol does follow the rod within the tank in a similar fashion. With only slight instabilities, the ethanol quickly begins to slosh at a particular frequency and will wick-up the side of the tank upon any significant instability. In microgravity, high surface tensions fluids would be less reactive and dynamic as those fluids more readily absorb the energy from those instabilities.

Because the contact angle and surface tension for ethanol is close to that of MMH, the slosh data collected in this experiment should mimic the full scale Orion propellant tank and therefore provide useful visual data for validating Lockheed Martin’s computational model.
5 Future work

Although a great deal of work went into tank and simulant scaling, safety calculations, and
design, the flight data has yet to be fully analyzed and compared to Lockheed Martins
current computational models. Although the initial analysis of this work provides a starting
point, the task of reviewing the six hours of video data is left to two SURE students this
summer.

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