Characterization of Elastomeric Diaphragm Motion within a Spacecraft Propellant Tank

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Diaphragm propellant tanks are used in many spacecraft applications and predicting diaphragm behavior is critical for mission assuredness. Understanding the behavior of the diaphragm is also important during ground transportation and while the spacecraft is on the launch pad. During ground transportation, the tank is full of propellant, may be oriented either vertically or horizontally and the weight of the propellant applies loads to the diaphragm. While on the pad, the propellant tank, which is located near the top of the launch vehicle, can experience wind-induced oscillations. In both instances, if sloshing forces are large enough, diaphragm pull-out may occur or rubbing of the diaphragm on itself or against the tank wall may lead to weakening or tearing of the diaphragm. In this study two tanks are examined. A 16.5 inch diaphragm tank was subject to lateral sinusoidal excitations to induce slosh at three different fill fractions. The 50% fill fraction was investigated over a frequency range of 1 to 3.4 Hz and the 73% fill fraction between 0.5 and 1.35 Hz. Using a 54% fill fraction and a 1 Hz excitation frequency, a peak-to-peak amplitude sweep from 2.0 to 5.5 inches was performed, and a frequency sweep from 2 to 11.8 Hz with varying amplitude from 0.35 to 0.03 inches In all cases, the measured acceleration profile is correlated with diaphragm displacement measured using recorded images of the tank. For this size tank, the diaphragm did not exhibit any motion due to fluid sloshing forces over the fill levels, frequencies and displacement amplitudes examined. This contrast to a larger 40 inch tank which exhibited significant motion of the diaphragm in the 1 Hz excitation range. The 40 inch tank was transported in vertical, horizontal and inverted orientations and with fill fractions of 25% - 85%. In the horizontal orientation, for fill fractions 34% – 66%, the diaphragm rubbed with itself and the wall. For all other cases diaphragm rubbing did not occur. Excitation frequencies between 0.55 and 0.85 Hz were observed to cause sloshing motion of the fluid/diaphragm system. For the inverted horizontal orientation, the fluid can suddenly flip its stable state to the opposite horizontal quadrant of the tank, producing a violent motion.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>D</td>
<td>Diaphragm diameter, m</td>
</tr>
<tr>
<td>FF</td>
<td>Fill Fraction, liquid to tank volume ratio</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration, 9.81 m/s²</td>
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<tr>
<td>h</td>
<td>Liquid fill height within the tank, m</td>
</tr>
<tr>
<td>MA</td>
<td>Maximum Acceleration in direction of travel, g’s</td>
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<tr>
<td>R₀</td>
<td>Major tank radius, m</td>
</tr>
<tr>
<td>R₉ vert</td>
<td>Minor tank radius, m</td>
</tr>
<tr>
<td>t</td>
<td>Diaphragm thickness, m</td>
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<tr>
<td>TO</td>
<td>Tank Orientation, degrees</td>
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\( \omega_n \) = Sloshing frequency, Hz

I. Introduction

Elastomeric diaphragm tanks utilize positive expulsion technology for liquid propellant management and have been in use since the early stages of space flight \(^1\) - \(^4\). The term positive expulsion describes the use of a pressure differential to expel propellant from its storage vessel. Positive expulsion devices include diaphragms, bladders, pistons or bellows-based systems for fluid control and delivery. Two of the most practical types of spacecraft propulsion fluid control devices have proven to be diaphragms and bladders, which use elastomeric materials for an effective barrier between the pressurant gas and the liquid propellant. In most cases the diaphragms are hemispherical or hemispherical with an integral cylindrical section and the circular edge of the diaphragm is sealed against the shell. A typical elastomeric diaphragm tank assembly is shown in Figure 1.

![Figure 1. A typical elastomeric diaphragm tank assembly.](image)

The majority of such tanks are used in monopropellant hydrazine systems, and most diaphragms are made using ATK’s (formerly Pressure Systems, Inc.’s (PSI)) unique elastomeric reversing ethylene-propylene terpolymer (AF-E-332) material. Mounting is accomplished on a continuous flange parallel with and adjacent to the mid-plane. In the ATK diaphragm design the seal is created by a metallic retaining ring which is welded to the tank shell during the weld closure of the exterior pressure shell. Alternative designs achieve diaphragm retention by a clamping device that is mechanically fastened to an intermediate cylinder or by mechanically trapping the diaphragm directly between the upper and lower pressure shells. The diaphragm has ridges located on the propellant side to minimize residual propellant and produce greater than 99.9% propellant expulsion. Without these ribs, pockets might form preventing propellant from reaching the outlet port. Diaphragm tanks are typically easier to manufacture and have less severe folding patterns during operation than bladder tanks, whereas bladder tanks have a smaller sealing area and are easier to install, remove and replace \(^1\).

Spacecraft propellant tanks are filled prior to transportation to the launch pad and prior to stacking onto the launch vehicle. The spacecraft or upper-stage may be transported to the assembly/integration hangar or launch pad in the horizontal configuration and then rotated 90 degrees for stacking onto the booster stage. Depending on the mission propellant requirements, typical fill fractions range from 75% to 95%, and while the spacecraft is in the horizontal position for transportation, the fluid mass can provide significant pull-out forces on where the diaphragm is held by the clamping ring. The accelerations of the transportation vehicle, while small, can exert additional forces on the liquid and can even establish a resonance with some of the lower fluid slosh modes, leading to even larger induced forces.

In addition to ground transportation, similar concerns exist for having a more thorough knowledge of the diaphragms behavior once the vehicle is stacked and sitting on the launch pad. For example, wind sway concerns for long, slender rockets are an important consideration. The spacecraft tank, which is located near the top of the vehicle, can experience a sinusoidal oscillation associated with the interaction of the wind with the launch vehicle. Oscillations frequencies in the 0 to 3 Hz range with several inches of lateral displacement are common testing ranges.

Furthermore, if the diaphragm has folds in it that are in contact with each other, rubbing may occur during transportation that can weaken and fatigue the diaphragm material prior to flight. A rupture or tear in the diaphragm material would lead to complete loss of mission. Diaphragm rubbing is of particular concern in larger diameter tanks. For the ATK series of tanks, the elastomeric diaphragm material has the same thickness (0.07 inch) for all
tanks with 9.4 to 40 inch diameter, corresponding to a diaphragm thickness, t, to diaphragm diameter, D, ratio of \( \frac{t}{D} = 0.00745 \) to 0.00175. This suggests that the relative stiffness of the diaphragm is higher for the smaller diameter tanks and more flexible for the larger diameters. Many details associated with the history of elastomeric diaphragm design, fabrication and test, as well as a summary of the many tank sizes, ranging from 9.4 to 40 inches in diameter, and programs on which elastomeric tanks have been successfully used can be found in reference 4.

In order to achieve a better understanding of how tank transportation and pad wind sway can lead to diaphragm rub or excite natural slosh frequencies, a series of studies were performed using a 16.5 and 40 inch diaphragm tank. The objectives of these studies are to:

1) Investigate typical wind sway sinusoidal frequencies and tank fill fractions to determine if there is motion of the diaphragm during the excitation.
2) Investigate transportation acceleration levels, tank fill fractions, and tank orientations to determine if there is motion of the diaphragm during transportation.
3) Develop an experimental framework that can be used for future elastomeric diaphragm tank behavior studies for transportation and on-pad behavior.

Section II presents a literature review and brief historical account of positive expulsion technology elastomeric diaphragm tanks and a description of the 16.5 inch and 40 inch ATK tank used in this study. Section III presents the results of the on-pad wind sway environments for the 16.5 inch tank. Section IV presents the results of the ground transportation, in various orientations and fill levels, of the 40 inch tank. Section V presents conclusions.

II. 16.5 inch and 40 inch Diaphragm Tank Descriptions

The 16.5 inch diaphragm tank is one of the most widely used ATK tank products and one of the first diaphragm tanks designed by PSI/ATK. The 16.5 inch family of pressure vessels is constructed of 6Al-4V titanium, and the spherical variant of the family has a total volume of 2,300 in\(^3\). The ‘stretch’ version of the tank, which includes a cylindrical section between the two hemispherical domes has a total volume of 2,996 in\(^3\). The spherical variant of this tank has long history of service, including the Pioneer (PSI P/N 80157-1), Mariner (PSI P/N 80189-1, -101) and Mars Pathfinder (PSI P/N 80275-1) missions, and the stretch version has been used on several different programs including Telecom 1 (PSI P/N 80288-1) and Genesis (PSI P/N 80526-1).

In order to study the behavior of the elastomeric diaphragm in various excitation scenarios, a 16.5 inch diameter acrylic simulator tank is used. This 16.5 inch ‘stretch’ tank has spherical domes with a cylindrical section in between. Based on the hemispherical domes alone, the tank has a major radius \( R_0 \) and minor radius \( R_{\text{vert}} \) with values of \( R_0 = R_{\text{vert}} = 8.25 \) (0.20955 m), thus giving the domes a ratio of \( R_{\text{vert}}/R_0 = 1.0 \). The acrylic simulator tank was originally built to test the NASA Orion tank, P/N 80543. The elastomeric diaphragm material has a thickness of 0.07 inch, which gives a \( \frac{t}{D} = 0.0042 \) for the 16.5 inch tank. A schematic of the tank and a picture of the acrylic tank are shown in Figure 3.

![Figure 2. Schematic of the P/N 80543 Orion hydrazine tank.](image)
The 40 inch diaphragm tank is one of the larger tanks in the ATK diaphragm tank product line. The 40-inch oblate spheroid pressure vessel is constructed of 6Al-4V titanium, and the tank has a total volume of 28,144 in$^3$. This tank has a long history of service, starting with the Tracking and Data Relay Satellite (TDRS). ATK shipped the first TDRS tank in the late 1970’s. In order to study the behavior of the elastomeric diaphragm in various transportation loading scenarios, a 40 inch diameter acrylic simulator tank is used. The tank has a major radius $R_0$ of 20 inches and a minor radius $R_{vert}$ of 14, thus giving a ratio of $R_{vert}/R_0=0.707$. The acrylic simulator tank was originally built to test the TDRS diaphragm tank, P/N 80263. A schematic of the tank and a picture of the acrylic tank are shown in Figure 3.

![Figure 3. Schematic of the P/N 80263 TDRS hydrazine tank.](image)

The elastomeric diaphragm material has a thickness of 0.07 inch. As can be seen in the bottom of Figure 3, the diaphragm naturally folds onto itself at most intermediate fill levels, other than completely full and nearly empty cases. In the intermediate range, the diaphragm makes contact with itself or even with the edges of the tank wall.

Examples of 50% and 73% fill fractions (FF) for the 16.5 inch tank are shown in the upper portion of Figure 4. In these examples, the propellant side is down and the pressurant side is up. As can be seen from the photos, the diaphragm is relatively smooth and exhibits no folds or contact with itself or the tank wall. The lower images of Figure 4 show roughly the same two fill fractions, but for a 40 inch diameter acrylic simulator tank. Both tanks have the same diaphragm thickness of 0.07 inches. For the 40 inch tank, the diaphragm naturally folds onto itself at the 50% and 75% fill fractions.
Figure 4. Examples of elastomeric diaphragm in a 16.5 and 40 inch diameter tank, (a) 16.5 inch, 50% FF, (b) 16.5 inch, 73% FF, (c) 40 inch, 50% FF and (d) 40 inch, 75% FF. Images courtesy of NASA.

III. Theoretical Slosh Behavior of Spheroid Tanks

Prior to examining the behavior of the coupled diaphragm/fluid system it is useful to baseline the natural sloshing frequencies for a tank that contains no diaphragm. These natural sloshing frequencies can then be compared with the measured frequencies of the excited coupled diaphragm/fluid system to determine if the diaphragm acts as a damper or acts to further excite the system. Different diaphragm thicknesses can also be examined to determine the effect of diaphragm stiffness on the resulting system sloshing frequencies.

For smooth internal wall tanks without a diaphragm, the slosh frequencies are well known as a function of the tank geometry and fill fraction. Figure 5 provides an example of a plot showing the natural frequency parameter versus the liquid depth ratio, $h/R_{vert}$, for an oblate spheroid tank. The plot shows the first and second slosh modes for a range of $R_{vert}/R_0$ between 0.5 and 2.0 with 1.0 corresponding to the spherical tank case.
Although the 16.5 inch tank in this study is not a sphere (the tank has spherical domes but a cylindrical section in between), Figure 5 can be used to approximate the first and second slosh frequencies for the tank under study. For a typical fill level of 50\%, corresponding to $h/R_{\text{vert}}=1$, and with $R_{\text{vert}}/R_0=1$, the theoretical natural frequency parameter is about 1.2. Using $R_0=0.2096$ m (8.25 inches) and $g=9.81$ m/s$^2$, this corresponds to the first mode sloshing frequency of $f_1=1.36$ Hz. Figure 5 can also be used to estimate the first and second slosh frequencies for the 40 inch diaphragm tank under study in the transportation experiments as a function of the fill fraction and tank orientation. For a fill fraction of 50\%, corresponding to $h/R_{\text{vert}}=1$, and with $R_{\text{vert}}/R_0=0.707$, the theoretical natural frequency parameter is about 1.2. Using $R_0=0.508$ m (20 inches) and $g=9.81$ m/s$^2$, this corresponds to the first mode sloshing frequency of $f_1=0.8$ Hz. These results are summarized in Table 1.

Table 1. Summary of first and second sloshing frequencies of 16.5 and 40 inch spheroid tanks

<table>
<thead>
<tr>
<th>Tank Radius, $R_0$</th>
<th>$h/R_{\text{vert}}$</th>
<th>$R_{\text{vert}}/R_0$</th>
<th>$\omega_1(R_0/g)^{0.5}$</th>
<th>$f_1$</th>
<th>$\omega_2(R_0/g)^{0.5}$</th>
<th>$f_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2096</td>
<td>1</td>
<td>1</td>
<td>1.25</td>
<td>1.36</td>
<td>2.25</td>
<td>2.45</td>
</tr>
<tr>
<td>0.508</td>
<td>1</td>
<td>0.707</td>
<td>1.15</td>
<td>0.80</td>
<td>2.30</td>
<td>1.61</td>
</tr>
</tbody>
</table>

More details on liquid sloshing within moving containers can be found in References 7 – 9.

IV. 16.5 inch Diaphragm Tank Launch Pad Sway Study

To simulate the pad wind sway environment, the 16.5 inch tank was mounted on a fully controllable 1-DOF motion table, as shown in Figure 6, which is capable of exciting the tank over a range of frequencies and amplitudes of interest. The table uses linear bearings and is driven by a belt-system servomotor.
For frequencies up to 1.5 Hz, the experimental setup had the shock absorbing spring system locked (Figure 6). The system was unlocked over 1.5 Hz and the excitation frequency reduced to allow out-of-phase motion and reduce motor loading, achieving greater amplitudes by means of utilizing the natural vibration of the tank-spring system excited near its resonance region (the complete tank-spring system ran into resonance at a frequency around 2.4 Hz). Thus, the system capabilities were expanded through the use of a tuned spring.

The data collection is performed using LabView and is accomplished using a Basler acA-2400-agm GigE monochrome camera at 10 frames per second, a Linear Variable Differential Transformer (LVDT) to measure relative displacement between the motor stage and tank table, a capacitive force sensor, measuring the force applied to the table, and an accelerometer in the tank reference frame. Combinations that were examined, while Figure 7 illustrates the frequency ranges and amplitudes covered.

Table 2 summarizes the fill fraction, frequency range and peak-to-peak amplitude combinations that were examined, while Figure 7 illustrates the frequency ranges and amplitudes covered.

<table>
<thead>
<tr>
<th>FF (%)</th>
<th>Forcing Frequency (Hz)</th>
<th>Peak-to-Peak Amplitude (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.5 – 1.25</td>
<td>4.0</td>
</tr>
<tr>
<td>50</td>
<td>1.25 – 1.45</td>
<td>2.0</td>
</tr>
<tr>
<td>50</td>
<td>1.5 – 1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>50</td>
<td>2.0 – 2.4</td>
<td>0.4</td>
</tr>
<tr>
<td>50</td>
<td>2.0 – 3.4</td>
<td>0.2</td>
</tr>
<tr>
<td>73</td>
<td>0.5 – 1.35</td>
<td>4.0</td>
</tr>
<tr>
<td>54</td>
<td>1.0</td>
<td>2.0 – 5.5</td>
</tr>
<tr>
<td>54</td>
<td>2.0 – 11.8</td>
<td>0.35 – 0.03</td>
</tr>
</tbody>
</table>

The shape of the 54% fill fraction excitation curve in Figure 8 is due to a manual current (amplitude) limitation set to avoid hitting the linear stage hard limits.
The highest frequency examined was 11.8 Hz at a peak-to-peak amplitude of 0.03 inches with a 54% FF case, and the highest peak-to-peak amplitude examined was 5.5 inches at a frequency of 1 Hz for the 54% FF case. In none of the peak-to-peak amplitude vs. frequency combinations did the diaphragm exhibit any motion.

The typical shape of the diaphragm for 50% FF and the 73% FF was shown in photos (a) and (b) of Figure 4. The diaphragm is relatively smooth and exhibits no major folds. The diaphragm displacement was measured directly from the images collected on the 54% fill fraction tests. An image-processing algorithm (Figure 8) was used to detect the diaphragm right edge and approximating a quadratic function to its shape. The tank displacement is measured as the average position of three bolts (vertical line), reducing image detection inaccuracies. The change of the distance between the detected edge and the tank was measured at a specific height. For each of the tests described in Table 2, the diaphragm did not exhibit any movement or change in shape during the forced excitation tests.
The measurement for the 2.0-11.8 Hz is within the noise bounds. No specific frequency excites the diaphragm within this frequency range. The amplitudes measured are within the 1 image pixel distance (0.06 in), which is the smallest discrete interval that can be distinguished by the data collection system.

V. 40 inch Diaphragm Tank Transportation Study

The 40 inch diameter tank used for testing was mounted on a steel test rig with full 360 degree rotation capability, mechanically lockable every 10 degrees with manual action. This test rig was rigidly attached with bolts and straps to the load compartment of a commercial moving truck, as shown in Figure 9. The photo shown in Figure 9 is shown from the direction toward the front of the truck, i.e. in the direction of forward truck travel. Appropriate piping and auxiliary systems were connected to the propellant hemisphere of the tank in order to fill and empty the tank with water (hydrazine has a specific gravity of 1.008 at 20 °C). The water weight was measured, and along with compensation for temperature, the volume of water within the tank was estimated to establish the tank fill fraction, FF. A pressure control system was installed to the pressurant hemisphere (using compressed air) and during several of the tests a positive pressure was applied in an attempt to determine if the positive pressure in any way altered the diaphragm dynamics during a test.

Lighting was installed on the propellant side of the tank, while two cameras were installed looking at the pressurant hemisphere, each offset 45° from the travel direction (axis) of the truck. Regardless of the tank orientation angle, the lighting and the camera orientation do not change with respect to the tank. The cameras are labeled in accordance with a viewer on the camera-side (pressurant dome) of the tank, or in the configuration shown in Figure 9 looking towards the back of the truck, or in the opposite direction of forward truck travel. The right and left cameras both point toward the center of the tank and are 90° apart. These two cameras are identical IDS model 5580CP with a resolution of 2560 x 1920 pixels and a 24 bit per pixel color depth. The lens attached to the camera is a Thor Labs MVL4WA, with a focal length of 3.5 mm and an aperture of f/1.4. The image sampling rate was set to 5 Hz, with simultaneous triggering. The cameras used Ethernet connectivity and were powered using Power-Over-Ethernet.

Two Inertial Measurement Units (IMU) consisting of a 3-axes accelerometer, a 3-axes gyroscope and a magnetometer were also used. The IMU is a CH Robotics UM6. The first one was placed in a tank-reference frame (which rotates with the tank as the tank orientation, TO, is varied), while the second one was placed on a truck-reference frame (this IMU does not rotate with the tank and is used for data redundancy and to ensure that the accelerations seen by the rig where exactly those experienced by the truck that no damping was taking place). The IMUs were sampled at a frequency of approximately 50 Hz, 10 times higher than the camera. The data was low-pass filtered to 5Hz.
All the data collection system was run from a single laptop inside the truck cabin. The data collection software running under Windows was custom-made for this application, able toparse and store the data from both IMUs and both cameras simultaneously. All the data was time stamped to the millisecond precision. Three sets of tank orientations were investigated, as shown in Figure 10. Because of the accelerating and decelerating transportation motion of the transport vehicle, the 90° TO and 270° TO are equivalent.

Since the IMUs are mounted to the support frame of the tank (see Figure 9) and since the support frame is rotated to achieve different TO angles, the orientation of the IMU changes with the TO angle. In Figure 10, the y-axis of the IMU is always out of the page, or pointing to the drivers left of the truck, regardless of the TO. In the 90° TO case, the positive z-axis points in the direction of truck forward travel and the positive x-axis points downward; in the 0° TO case, the positive x-axis points in the opposite direction of forward truck travel and the positive z-axis points downward; in the 180° TO case, the positive x-axis points in the direction of truck forward travel and the positive z-axis points upward. This choice is made so that the camera viewing angles and the IMU coordinate system are always in the same orientation with respect to each other, regardless of TO. The redundant IMU located on the truck bed also has the same orientation as the 0° TO case. When examining the results presented in Section IV, it is important to note the coordinate system of the x-, y-, and z-axis accelerations. Figure 10 also shows the viewing angles of the two cameras with respect to the tank frame and the IMU located in the tank frame. With respect to the tank/IMU frame, the right camera points in the direction of the positive x-axis, negative y-axis and positive z-axis, whereas the left camera points in the direction of the positive x-axis, positive y-axis and positive z-axis.

A summary of the tests conducted and observations is presented in Table 3. The tank orientation, TO, is in accordance with Figure 10; the fill fraction, FF, which is based on a percentage of the total volume of the tank...
The liquid is stable in one quadrant, although a peak in acceleration may make it switch quadrants violently, especially if there is a cross-component (XY) of acceleration. Small accelerations produce some motion, no indication of excitation of a particular slosh frequency. The liquid is stable to one side, unlikely to swap quadrants under heavy acceleration. Small accelerations produce some motion, no indication of excitation of a particular slosh frequency.

To accompany Table 3, Figure 11 provides a schematic representation of the diaphragm configurations for generally high, medium, and low FF cases. The upper portion of Figure 11 shows a notional representation of the shape that the diaphragm will take given the tank orientation, TO, and the fill fraction, FF. The shape of the diaphragm for the high FF is depicted by the solid lines, the medium FF is depicted by the dashed line, and the low FF is depicted by the dotted line. Note that for all FF cases, the liquid completed fills the region between the tank and the diaphragm, and the liquid is free to slosh within this space. The sloshing motion is primarily driven by the acceleration acting in the vertical direction (Y).
dome and the diaphragm, but for image clarity, the water cross hatching is only shown with respect to the low FF case. Regardless of the TO, these images demonstrate that the diaphragm is least wrinkled during the high and low FF, and the most wrinkling, folds, bends and undulations can be found in the medium FF cases. Further, for the medium FF cases, the liquid has the most available mass for sloshing and produces the largest slosh forces on the diaphragm. In terms of diaphragm folding, and more importantly rubbing of the diaphragm on itself or against the tank walls, the medium FF cases are of the most concern.

The lower portion of Figure 11 provides an image of the actual diaphragm configuration for the 40-inch acrylic tank for a high FF in the 90° case (left), a medium FF for the 0° case (center), and a medium FF for the 180° case (right).

From Table 3 and from Figure 11, it can be seen that for all fill fractions the diaphragm is folded on itself for the 90° and 0° TO. This is the expected result because of the geometry of the hemispherical diaphragm within the tank. When the tank is inverted to the 180° TO case, and for the FF cases examined (53.8% – 89.4%), the weight of the water causes the hemispherical diaphragm to occupy the pressurant side of the tank in an essentially unfolded manner, such that the ripples in the diaphragm do not make contact with each other and hence there is no rubbing of the diaphragm with itself or with the edges of the tank for all 180° TO cases examined, regardless of maximum transport vehicle acceleration, MA. Note that for the 180° TO cases, a positive pressure of 2 psi was introduced in the pressurant side of the tank to counterbalance the force associated with the mass of the water. The reason for doing so was to maintain a positive pressure on the propellant side, enough to force water out of the outlet port regardless of the inverted position.

For the 90° TO cases, and for the FF examined (72.7% – 85%), the diaphragm always had folds that were in contact with itself or in contact with the edges of the tank. In this orientation, regardless of the maximum acceleration of the transport vehicle (or the changes in acceleration of the transport vehicle), no rubbing of the diaphragm on itself or with the walls of the tank were observed. In the 90° TO case, most of the water mass settles to the bottom of the tank and causes the diaphragm “fill-up” with water and occupy the bottom portion of the tank. While there are folds in the diaphragm that are in contact with each other (and the diaphragm is also in contact with the sides of the tank), regardless of the maximum transport vehicle acceleration, up to 0.157 g (about 1.5 m/s²), no rubbing of the diaphragm with itself or with the sides of the tank was observed. In the 90° TO case, the water mass

Figure 11. Schematic representation of diaphragm configurations for High, Medium, and Low FF.
seems to be sufficient to damp any noticeable movement of the diaphragm due to the motion of the transport vehicle.

In the 0° TO cases, and for the FF examined (24.6% – 72.7%), the diaphragm is also always folded on itself and also makes contact with the side walls of the tank. In this orientation, the diaphragm ‘floats’ on top of the fluid and has the highest ability to move, as compared with the 90° (and 270°) and 180° cases. In this configuration, the diaphragm was observed to rub on itself or on the tank walls depending on the FF. For either the very low FF case (24.6%) or the higher FF cases (72.7%), the diaphragm was not seen to rub on itself or against the tank walls. For the intermediate cases of FF (34.4% – 64.6%), the diaphragm was observed to rub upon itself and/or against the walls of the tank. This behavior can be explained because in the low fill level case the diaphragm is settled to the lower part of the tank by its own mass and there is not enough water in the tank to displace upward and cause it to ‘float’ on the water in a more wrinkled manner. For the higher FF cases, there is enough water to raise the diaphragm within the tank and to un-wrinkle it. Further, the FF is now high enough that the water occupies a significant portion of the upper dome and the amount of fluid that is sloshing during the motion of the transport vehicle does not create sufficient forces to displace the diaphragm. Both the lower and the higher FF cases cause the diaphragm to stretch, adding more stiffness to the water-diaphragm dynamic system. In the intermediate range of FF, where the diaphragm is in its most wrinkled configuration as the FF is now in the range to keep the diaphragm floating in the mid portion of the tank, the fluid slosh forces are the largest, with minimum added stiffness provided by diaphragm stretch. Within this range of FF, the combination of the most wrinkled diaphragm and the largest fluid slosh forces generated from the motion of the transport vehicle result in the diaphragm rubbing on itself, or against the walls of the tank, during the transportation tests. It should be noted, however, that it is very unlike that a spacecraft propellant tank or an upper-stage would be operated within this range of FF. However, these tests do indicate that to avoid diaphragm rub, the 0° TO case is the most susceptible to rubbing of the diaphragm with itself or against the tank walls, and the intermediate fill fractions are the most conducive to creating a geometry of the diaphragm and fluid slosh forces for rubbing.

The next set of figures provides more details on the diaphragm dynamics in the various cases presented in Table 3. Images from the cameras and data from the IMU are shown for each of the cases. Figure 12 shows data from Case 4, which corresponds to a 90° TO, 80.5% FF, and 0.153 g MA. The upper portion of the figure shows 6 images taken from the camera and the lower part of the figure shows the measured IMU acceleration traces. In this case, very low diaphragm displacement amplitudes were observed for all acceleration values. This is explainable by considering that the 90° case forces stretch in the diaphragm, increasing the overall system stiffness. This scenario can be considered as a stable configuration, in which the water tends to occupy the lowest portion of the tank (refer to Figure 11 90° TO), constrained on the top by a stretched diaphragm, an ideal case for reducing induced slosh. Note that red solid line axes are located in the same location in each image frame. The dash-dotted lines are placed with respect to characteristic features that are seen in the images for easier image comparison. In the images of Figure 12, the dash-dotted lines are placed to qualitatively track the center of mass of the liquid within the tank. The data shown in Figure 12 indicates minimal displacement of the fluid, even for the instances with the highest changes in transport vehicle acceleration.
Figure 12 Data from Case 4, 90° TO, 80.5% FF, 0.153 g MA.

Figure 13 displays Case 7, with a 0° TO, 64.6% FF and 0.177 g MA. The particular interest for this scenario is showing that for the 0° TO case and medium FF (see Figure 11) it is possible to excite frequencies that induce slosh, regardless of their amplitude not being the maximum. The data in this figure demonstrates that for a 0.06 g single-amplitude acceleration and 0.83 Hz quasi-sinusoidal excitation it is possible to induce a motion of at least 2 inches in the diaphragm. This situation for a medium FF diaphragm rubbing is of concern. In the images shown in Figure 13 the dash-dotted lines track the position of folds in the diaphragm.

From the data collected in Cases 7 and 8 (64.6% and 49.5% FF, respectively) it can be demonstrated that excitation frequencies between 0.55 and 0.85 Hz are the cause of significant sloshing motion, suggesting that the natural slosh frequency of the system is near those values. From Figure 5 the theoretical first mode sloshing frequency is 0.80 Hz for a FF of 50% without a diaphragm, confirming that for these cases the stiffness added by the diaphragm to the dynamic system is small.
Figure 14 displays data from Case 8, also with a 0° TO, a 49.5% FF and 0.181 g MA. Here the interest is focused in a slower but more intense acceleration change, from -0.11 to 0.177g in 1.3 seconds, causing the entire mass of water to displace from one side of the tank to the opposite side of the tank, creating the maximum displacement observed in any of the 0° TO test cases.
Figure 15 is a snapshot of Case 13, an inverted case (180° TO), with a 77.5% FF and 0.21 g MA. In the particular instant shown a full side inversion is depicted, with an XY changing acceleration component that induces the rotation of the fluid. The dash-dotted lines on the images qualitatively track the approximate CG of the fluid. This situation is of particular importance for studying tear-off situations, since the diaphragm is already under stress and the water motion adds a significant dynamic component. Furthermore, it is interesting to note that cross components of linear accelerations caused by transportation can induce circumferential rotations in the liquid.

Figure 14 Data from Case 8, 0° TO, 49.5% FF, 0.181 g MA.

Figure 15 Data from Case 13, 180° TO, 77.5% FF, 0.21 g MA.
VI. Conclusions

In the first experiment conducted, a 16.5 inch diameter tank with an elastomeric diaphragm was subject to lateral sinusoidal excitation motion to induce slosh at three fill levels, 50%, 54% and 73%. A series of sinusoidal excitation tests were performed to determine if the tank diaphragm would exhibit any motion in this range. No combination of amplitudes and frequencies starting from 4.0 inches at 0.5 Hz to less than 0.1 inch at 11.8 Hz, at the three fill levels examined, produced any measurable sloshing motion of the diaphragm, suggesting heavy over-damping induced by the diaphragm.

A 40 inch tank with an elastomeric diaphragm was transported in various orientations and at various fill fractions to simulate ground transport of the spacecraft. During these tests the acceleration profile of the transport vehicle was measured and correlated with stereo images of the diaphragm during transport. This work characterizes the diaphragm shape and motions during transportation in vertical, horizontal and horizontal inverted tank orientations for fill fractions of 25% - 85%.
The study demonstrated that in the horizontal tank orientation, for fill fractions between 34% and 66%, diaphragm rubbing can occur. However for all other fill fractions and tank orientations, the diaphragm did not rub, even if folded upon itself. For the 0° tank orientation case and medium fill fractions, induced fluid sloshing can be a cause of concern for diaphragm rubbing with itself or with the side walls of the tank. For cases examined in this study, the range of excitation frequencies between 0.55 and 0.85 Hz were observed to cause sloshing motion of the fluid/diaphragm system, close to the theoretical natural sloshing frequencies, suggesting a lightly damped water-diaphragm system. For the 180° tank orientation case and at medium and low fill fractions, the fluid can flip its stable state to the opposite horizontal quadrant of the tank, and if cross component horizontal accelerations are present, the fluid can also undergo a circumferential rotation about the vertical axis of the tank. These scenarios are likely candidates for inducing significant forces on the diaphragm, which if large enough could result in diaphragm pull-out from the tank attachment and retaining ring.

The behavioral contrast between the two tanks observed (16.5 and 40 inch diameter) suggests that the larger tanks are prone to dynamic sloshing forces due to a lower diaphragm stiffness and damping, whereas the smaller diaphragm tanks introduce a high stiffness and overdamping, effectively mitigating all dynamic effects.

Future studies will focus on examining wind-induced launch pad slosh with higher frequency input and sinusoidal displacement. Various tank diameters, fill fractions and tank orientations will be investigated to further develop an improved understanding of diaphragm behavior and characterization over a range of tank motions.

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