Characterization of Elastomeric Diaphragm Motion in a 16.5 inch Diameter Tank under 1-DOF Sinusoidal Excitation

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Diaphragm tanks are used in a variety of launch vehicle and spacecraft applications. Characterization of diaphragm behavior is important for mission assuredness. Knowing the shape and behavior of the diaphragm is also important during ground transportation and while the vehicle is on the launch pad. During transportation, the tank is filled with propellant and the tank may be oriented either vertically or horizontally which applies loads to the diaphragm. While on the launch pad, the propellant tank, which is located near the top of the vehicle, can experience a sinusoidal oscillation associated with wind loading on the launch vehicle. In either case, if sloshing forces are large enough, diaphragm pull-out may occur or rubbing of the diaphragm on itself or against the tank can lead to weakening or tearing of the diaphragm. In this study a 16.5 inch tank with an elastomeric diaphragm was subject to lateral sinusoidal excitation motion to induce slosh at two fill levels. The 50% fill level was investigated over a frequency range of 1 to 6.8 Hz and the 73% fill level was investigated between 1 and 2.7 Hz. The measured acceleration profile is correlated with stereo images of the diaphragm. The diaphragm did not exhibit any motion due to fluid sloshing forces over the fill levels and frequencies examined. This is contrast to large tanks, such as 40 inch diameter, which exhibit significant motion of the diaphragm in the 1 Hz excitation range. The lack of diaphragm motion in the 16.5 inch tank is attributable to the higher relative stiffness of the diaphragm, which has the same thickness as the 40 inch tank.

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Nomenclature

D = Diaphragm diameter, m

MA = Maximum Acceleration in direction of travel, g

R_0 = Major tank radius, m

R_{vert} = Minor tank radius, m

t = Diaphragm thickness, m

TO = Tank Orientation, degrees

LVDT= Linear Variable Differential Transformer

I. Introduction

ELASTOMERIC diaphragm tanks have been in use since the early stages of space flight as an effective means for propellant management [1] – [4]. Elastomeric diaphragm tanks utilize positive expulsion technology for liquid propellant control and delivery. 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. 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. A typical elastomeric diaphragm tank assembly is shown in Fig.1.

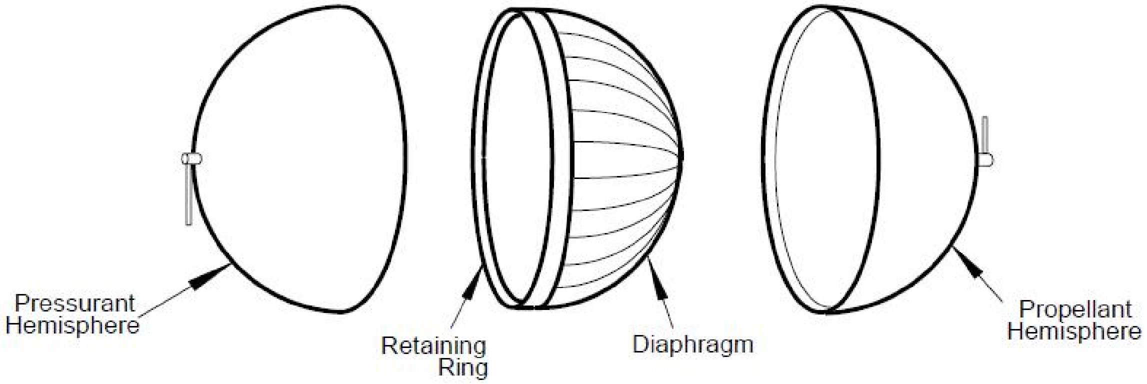


Fig.1 A typical elastomeric diaphragm tank assembly Error! Reference source not found.

Diaphragm tanks are positive expulsion devices with an internal membrane to separate the propellant compartment from the pressurant compartment. Fig.1 illustrates the typical embodiment of a diaphragm tank. In most cases the diaphragms are hemispherical or hemispherical with an integral cylindrical section and the outermost edge of the open-end of the diaphragm is sealed against the pressure shell. In the ATK diaphragm design the sealing bead is retained 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 a mechanically trapping the diaphragm directly between the upper and lower pressure shells. 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 as compared with diaphragm tanks [1].

The spacecraft propellant tank(s) 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 hanger 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, thus leading to even larger induced forces. Furthermore, if the diaphragm has several 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, ration of $t/D = 0.00745$ 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. Furthermore, the fluid mass inside the tank scales with the radius cubed (for a spherical tank) and the diaphragm area scales with the radius squared; this means that for two tanks with the same fill reaction, a tank that is twice as large in diameter has 8 times the propellant mass and twice the force per unit diaphragm area.

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. Similar concerns exist for developing an improved understanding of diaphragm rub during launch pad sway.

In order to achieve a better understanding of how tank transportation can lead to diaphragm rub or excite natural slosh frequencies, a series of studies were performed using a 16.5 inch acrylic tank. Specifically, the objectives of this study are to:

1) Perform a range of tests that include typical wind sway sinusoidal frequencies, tank fill levels, and tank orientations to determine if there is motion of the diaphragm during the excitation.
2) Determine the range of tank fill levels, associated with a specific tank orientation, during which diaphragm rubbing and folding was observed during the excitation.
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 ATK tank used in this study. Section III provides a description of the experimental set-up used to simulate on-pad wind sway environments. Section IV presents the results and the findings of this study, and Section V presents a summary and conclusions.

II. Tank Description and Tank Slosh Overview

The 16.5 inch diaphragm tank is one of the most widely used ATK diaphragm tank products and one of the first diaphragm tanks designed by PSI/ATK. The 16.5 inch oblate spheroid pressure vessel is constructed of 6Al-4V titanium, and the tank has a total volume of 2,300 in^3. This tank has long history of service, including the Pioneer, Mariner and Mars Pathfinder missions. 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 study the behavior of the elastomeric diaphragm in various excitation scenarios, a 16.5 inch diameter acrylic simulator tank is used. The tank has a major radius R_0 of R_0=8.25 inches (0.20955 m) and a minor radius R_{vert} of 5.83 inches, thus giving a ratio of R_{vert}/R_0=0.707. The acrylic simulator tank was originally built to test the NASA Orion tank, P/N 80543, [5]. A schematic of the tank and a picture of the acrylic tank are shown in Fig.2.

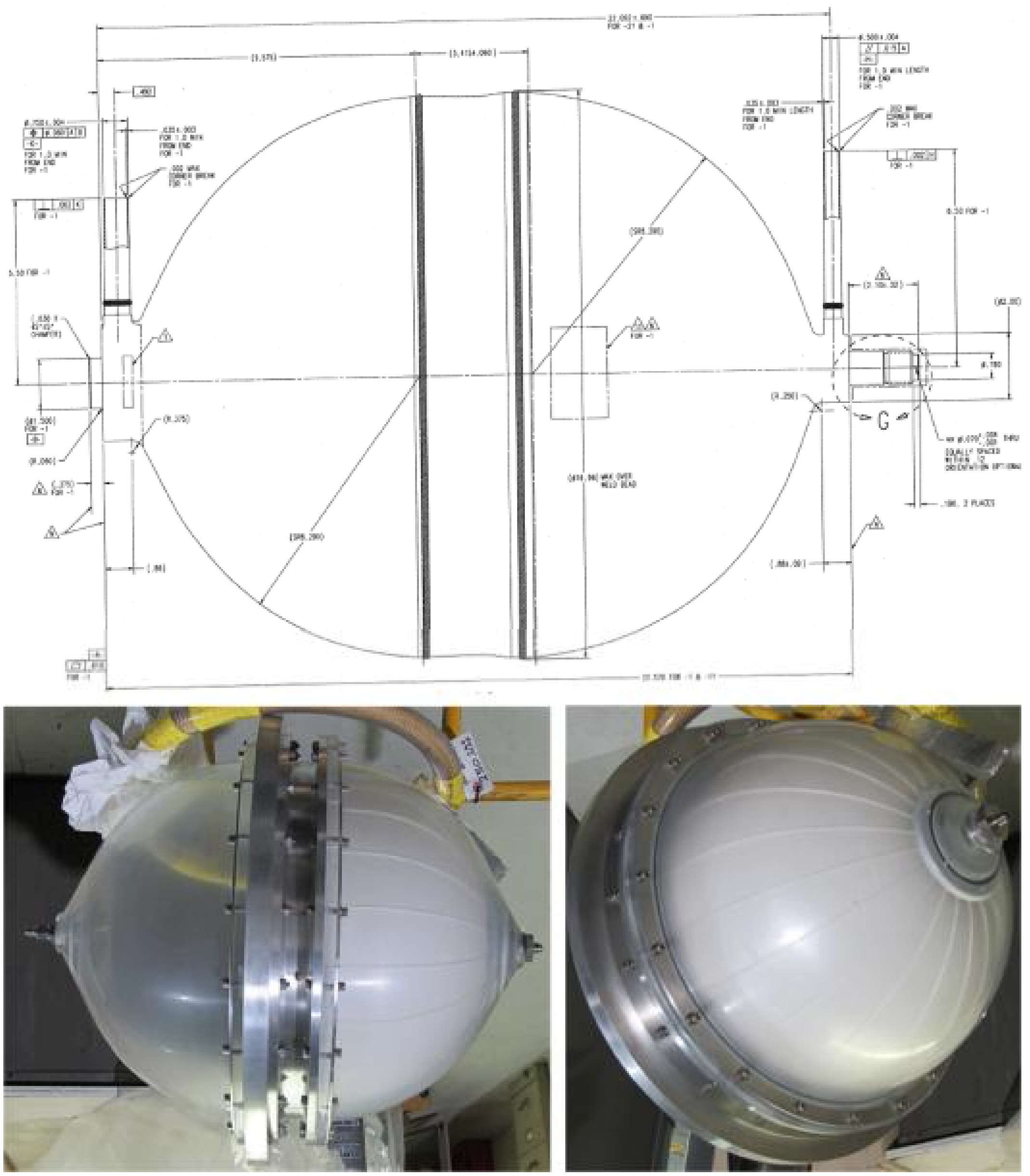
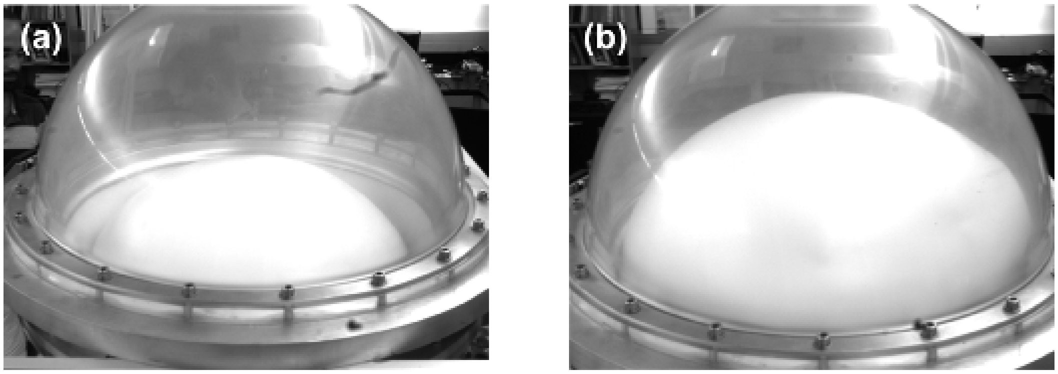


Fig.2 (upper) schematic of the P/N 80543 Orion hydrazine tank, and (lower) pictures of the 16.5 inch acrylic simulator tank

The acrylic simulator tank is nominally stored at the ATK Commerce, CA facility. The empty tank was shipped to the Florida Institute of Technology's Aerospace Systems And Propulsion (ASAP) Laboratory for the testing.

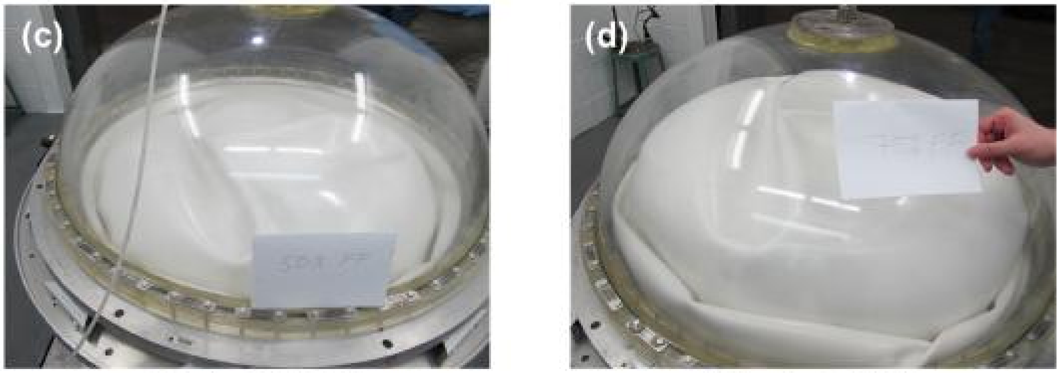
The elastomeric diaphragm material has a thickness of 0.07 inch, which gives a t/D=0.0042 for the 16.5 inch tank. The diaphragm has ridges located on the propellant side to minimize propellant residual and the tanks are designed to produce greater than 99.9% propellant expulsion. Without these ribs, pockets might form to prevent propellant from reaching the outlet port.

Examples of 50% and 73% fill fractions (FF) for the 16.5 inch tank are shown in the upper portion of Fig.3. 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.



16.5 inch, 50% FF

16.5 inch, 73% FF



40 inch, 50% FF

40 inch, 75% FF

Fig.3 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.

The lower images of Fig.3, 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.

One of the objectives of this study is to understand and quantify the interaction between the diaphragm and the fluid motion within the tank as a result of excitations that occur during transportation or while the vehicle is on the launch pad. 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, [6]. Fig.4 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.

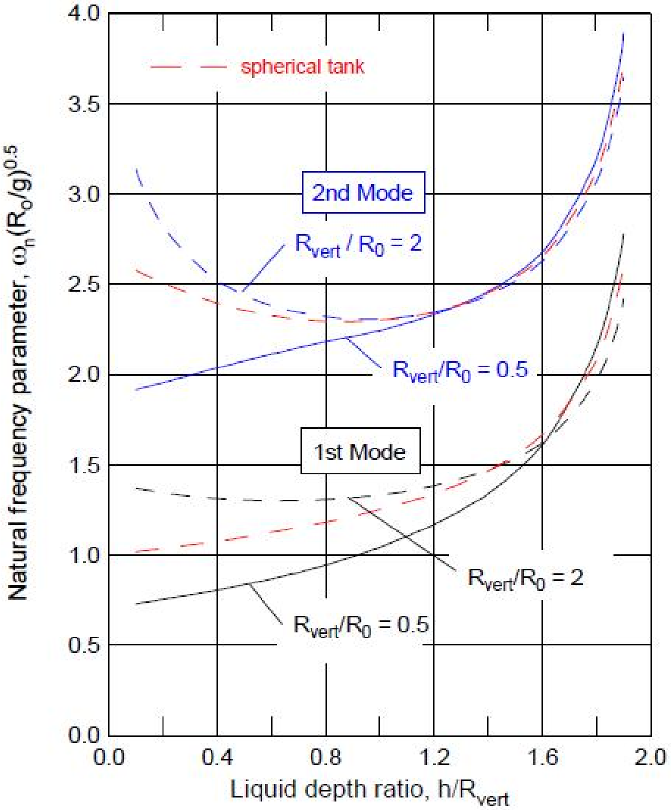


Fig.4 Theoretical sloshing frequencies for an oblate spheroid tank, [6]

Fig.4 can be used to estimate the first and second slosh frequencies for the tank under study. For a typical fill level of 50%, corresponding to $h/R_{vert}=1$, and with $R_{vert}/R_0=1$, the theoretical natural frequency parameter is about 1.2. Using $R_0=0.20955$ m (8.25 inches) and $g=9.8$ m/s^2, this corresponds to the first mode sloshing frequency of 1.36 Hz. More details on liquid sloshing within moving containers can be found in References [7] – [9].

III. Experimental Set-up

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 Fig.5, 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.

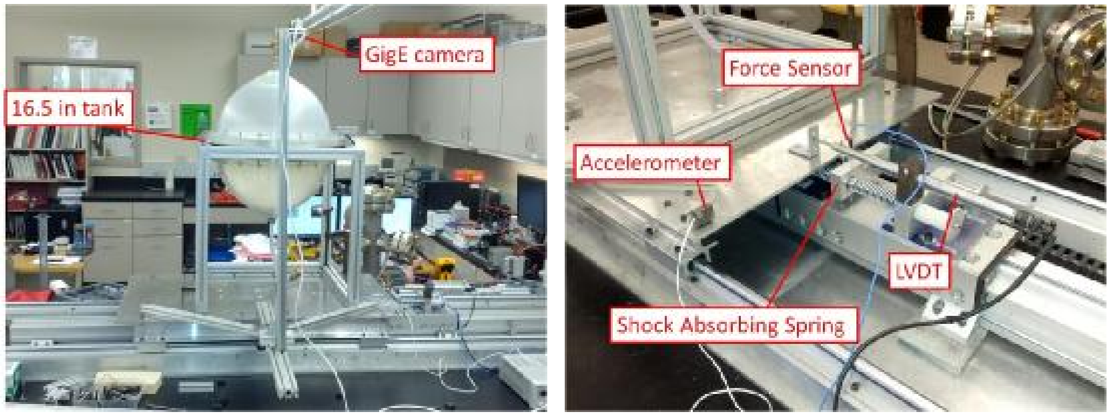


Fig.5 Experimental setup of 16.5 inch tank on 1-DOF table (left). Sensors depicted: LVDT, accelerometer and force sensor (right)

The data collection is accomplished using LabView (Fig.6), and data is collected using:

- Two 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
- An accelerometer in the tank reference frame.

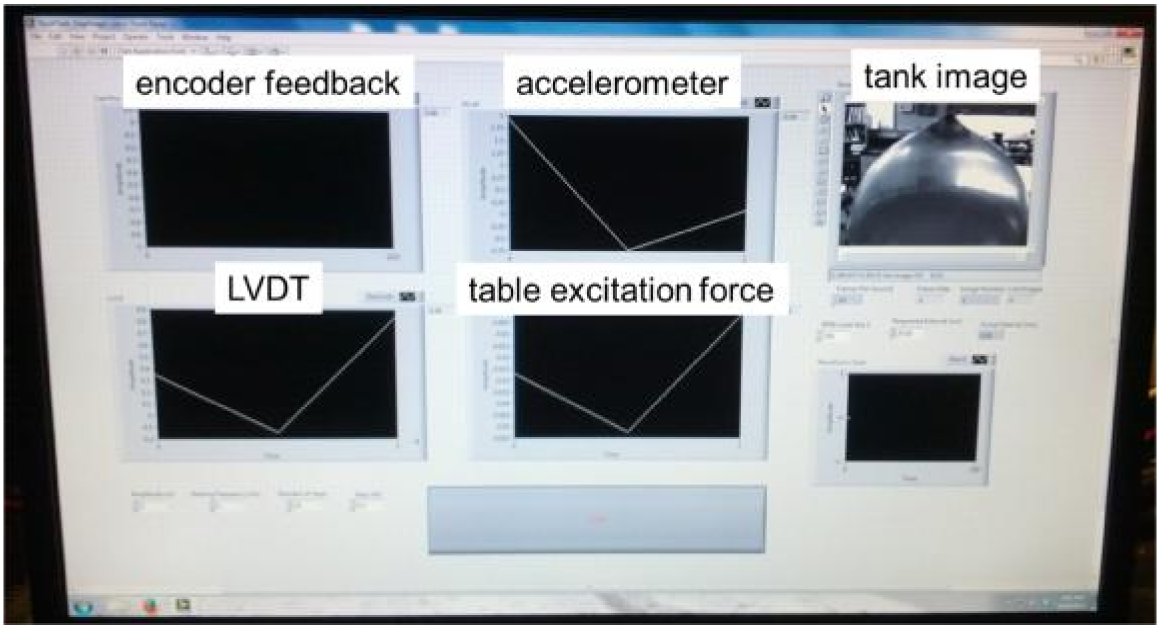


Fig.6 LabView data collection system screenshot

IV. Tests and Results

A total of 68 tests were completed over a range of frequencies to determine the natural frequency of the water-diaphragm system as to determine as well as to determine if any motion of the diaphragm occurs while the tank is under excitation. Two fill levels were examined, 50% and 73%. Table 1 shows a summary of the tests cases, starting at 1Hz with single amplitude of 2 inches. The amplitude was reduced as the frequency was increased due to hardware limitations.

Table 1 Summary of 16.5 inch tank diaphragm motion characterization tests

Test	FF (%)	Frequency (Hz)	Amplitude (in)	Test	FF (%)	Frequency (Hz)	Amplitude (in)
1	50	1	2	51	73	1	2
2	50	1.1	2	52	73	1.1	2
3	50	1.2	2	53	73	1.2	2
4	50	1.3	2	54	73	1.3	2
5	50	1.4	2	55	73	1.4	2
6	50	1.5	2	56	73	1.5	2
7	50	1.6	2	57	73	1.6	2
8	50	1.7	2	58	73	1.7	2
9	50	1.8	2	59	73	1.8	2
10	50	1.9	2	60	73	1.9	2
11	50	2	2	61	73	2	2
12	50	2.1	2	62	73	2.1	2
13	50	2.2	2	63	73	2.2	2
14	50	2.3	2	64	73	2.3	2
15	50	2.4	2	65	73	2.4	2
16	50	2.1	2	66	73	2.5	2
17	50	2.2	2	67	73	2.6	2
18	50	2.3	2	68	73	2.7	2
19	50	2.4	2				
20	50	2.5	2				
21	50	2.5	1				
22	50	2.6	1				
23	50	2.7	1				
24	50	2.8	1				
25	50	2.9	1				
26	50	3	0.5				
27	50	3.2	0.5				
28	50	3.4	0.5				
29	50	3.6	0.5				
30	50	3.8	0.5				
31	50	4	0.2				
32	50	4.2	0.2				
33	50	4.4	0.2				
34	50	4.6	0.2				
35	50	4.8	0.2				
36	50	4	0.1				
37	50	4.2	0.1				

38	50	4.4	0.1
39	50	4.6	0.1
40	50	4.8	0.1
41	50	5	0.1
42	50	5.2	0.1
43	50	5.4	0.1
44	50	5.6	0.1
45	50	5.8	0.1
46	50	6	0.1
47	50	6.2	0.1
48	50	6.4	0.1
49	50	6.6	0.1
50	50	6.8	0.1

For frequencies up to 3 Hz, the experimental setup had the shock absorbing spring system locked (Fig.5). Due to the fact that the 1-DOF table is a belt-driven system and was not designed for high frequencies with these amplitudes, the system was unlocked over 3 Hz and the excitation frequency reduced to allow out-of phase motion and reduce motor loading, using the natural vibration of the tank-spring system to excite it in its resonance region (the complete tank-spring system ran into resonance at a frequency around 4.8 Hz). Thus, the actual single amplitude motion in the tank was kept between 1 and 2 inches, without a need for heavy accelerations in the motor drive.

Fig.7 depicts the typical shape of the diaphragm for 50% FF (left) and the 73% FF (right). As can be seen from the images, the diaphragm is relatively smooth and exhibits not major folds.

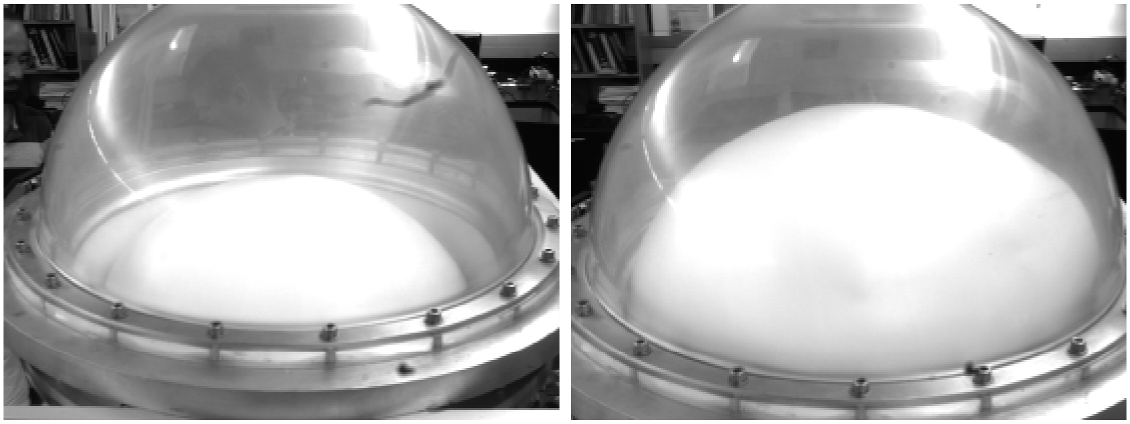


Fig.7 Diaphragm shape for fill levels of 50% (left) and 73% (right)

Fig.8 shows an example of encoder feedback for Test number 11 at 2.0 Hz.

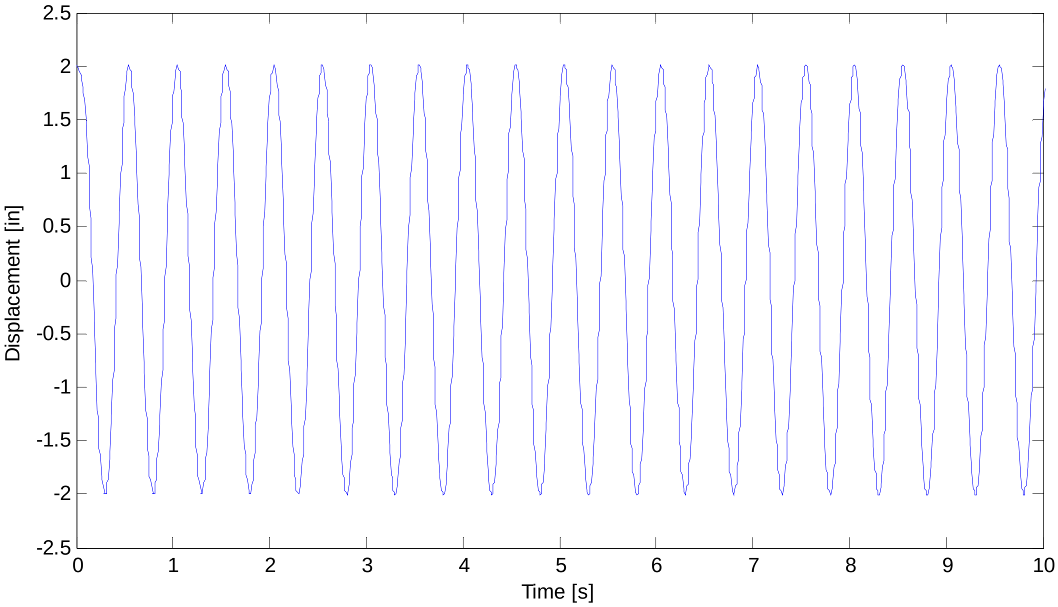


Fig.8 Encoder feedback for test 11, 2 Hz with 2 inch displacement amplitude

The encoder feedback displacement vs. time plot shown in Fig.8 is typical of all tests performed in Table 1.

V. Conclusions

In this experiment a 16.5 inch diameter tank with an elastomeric diaphragm was subject to lateral sinusoidal excitation motion to induce slosh at two fill levels, 50% and 73%. 69 tests in total were run covering the entire frequency band from 1 to 6.8 Hz for the 50% fill level and 1 to 2.7Hz for the 73% fill level. In none of the fill levels and frequencies the diaphragm showed any sloshing motion.

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