Modal Evaluation of Fluid Volume in Spacecraft Propellant Tanks

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Abstract

Propellant mass-gauging in unsettled (sloshing) fluids is an important and unsolved problem in spacecraft operations and mission design. In the present work, we demonstrate the efficacy of the experimental modal analysis technique in determining the volume of fluid present in model spacecraft propellant tanks undergoing significant sloshing. Using data acquired over approximately 37 minutes of time in zero-gravity conditions provided over two years of parabolic flights, we estimate the resolution of the technique at low tank fill-fractions where other mass-gauging techniques are known to fail.

Introduction

Accurate spacecraft propellant volume measurement in a microgravity environment has been identified by the NASA Exploration Systems Architecture Study (ESAS) final report as an area requiring further development [NASA, 2005]. The microgravity environment renders direct volume measurement using traditional buoyancy- and level-based techniques ineffective. Instead, indirect methods are currently used to establish propellant volume. Commonly used indirect gauging methods include equation-of-state estimations (for pressurized systems), measurement of spacecraft dynamics, and burn-time integration. Each of these gauging methods introduces uncertainty into the propellant volume measurements. Measurement error increases as the tank empties. It is important to minimize this uncertainty to reduce required unusable propellant reserves, decreasing the total mass of the spacecraft. These methods are also accompanied by the mass of the associated hardware. As launch costs approach $10,000 per pound, any attempt at reducing the spacecraft mass through decreased propellant reserves or reduced hardware mass can represent a significant cost savings [Peters, 2004].

Fluid sloshing in microgravity presents another challenge to propellant volume gauging. Propellant states are characterized as being either settled, in which the fluid is quiescent and in mechanical equilibrium with its container, or unsettled in which the propellant sloshes within the tank. Currently, no propellant volume gauging method functions accurately while the fluid is sloshing. This limits the utility of current methods. The time required for a sloshing fluid to settle into a quiescent state is called the settling time and depends on the geometry and material properties of the tank as well as the fluid properties of the propellant. Depending on the size of the tank, this settling time can be on the order of hours.

Previous work has shown the viability of experimental modal analysis (EMA) as a propellant gauging method, and identified the resolution of the technique as better than 10% of the total volume of the model tank with the fluid in an unsettled, sloshing state [Finnvik *et al*., 2011]. In the study reported here, we estimate the resolution of EMA at low tank fill-fractions where accuracy is the most important and other indirect techniques fail. We also demonstrate that the resolution of the technique over a range of fill-fractions can be as little as 1.5% in volume between 30% and 70%, and 7.4% in volume between 0% and 20%.

Modal Analysis

Modal analysis is a commonly used technique in the analysis of structures. Acoustic forces are applied to the structure through discrete impacts, continuous white-noise functions, or chirp functions, and the vibrational response of the structure is recorded through sensors affixed to the surface of the structure. Natural vibrational modes of the structure will be excited resulting in an increased amplitude in sensor response at the excited mode frequencies. The resonant modes are calculated by means of a Frequency Response Function (FRF). The FRF is the ratio of the Fourier Transform of the response to the Fourier Transform of the input. Graphing the FRF results in peaks at the natural vibrational modes of the structure. In practice, a Fast Fourier Transform (FFT) algorithm is used to efficiently calculate the Fourier Transform, with the input measured by a monitor sensor placed immediately next to the actuator to measure the signal actually being output by the actuator. This allows for real-time monitoring of the vibrational characteristics of the structure.

Both the FFT and the FRF are complex valued functions, but only the real portion of the function which contains amplitude information is of interest, as the EMA technique looks for the increased amplitude at the frequencies corresponding to the natural vibrational modes. The use of more sensors provides a more complete picture of the vibrational characteristics of the structure, and with enough sensors, the three dimensional shape of the structure can be reconstructed.

The EMA technique has been used to characterize the behavior of fluid-filled structures during earthquakes [Malhotra *et al*., 2000]. It has also previously been applied to propellant gauging, which found that the dominant effect of the fluid loading was an increase in the effective mass of the fluid/tank system, lowering the frequency of the natural resonant modes [Finnvik *et al*., 2011].

Research Objectives

The central objective of the current study is to determine the resolution of the real-time, non-invasive EMA technique in determining propellant volume of a model spacecraft propellant tank in a microgravity environment under unsettled conditions. Prior work suggests that fluid loading is correlated to the contact area between the fluid and the internal surface of the model tank [Finnvik *et al*., 2011]. Under sloshing conditions, this contact area is continuously changing as the fluid rolls around inside the tank. The effect of variable contact area on the resolution of the EMA technique will be examined. Influences of the geometry of the model tank will also be examined.

Experiment Design

NASA's microgravity research aircraft simulated a microgravity environment by flying parabolic maneuvers. The flights on which this experiment was performed were conducted as a part of NASA's Systems Engineering Educational Discovery (SEED) student flight program. These flights were conducted in April 2012.

A schematic diagram of the experiment is shown in Fig. 1. Two identical model tanks were used in this study. The schematic diagram of the tank is shown in Fig. 2. Each tank is a steel cylinder of diameter 15.1 cm and length 39.4 cm, with two approximately hemispherical end caps welded to the cylinder for a total length of 49.2 cm and a total volume of 2.0 gallons. The tank also has two feet welded to the body for mounting, as well as six ¼" NPT ports. To the first tank are attached pressure and temperature gauges, fill and drain valves, a transfer line, and a pressure-release valve. The same equipment is attached to the second tank, without the pressure and temperature gauges. In this study, the tanks were oriented vertically.

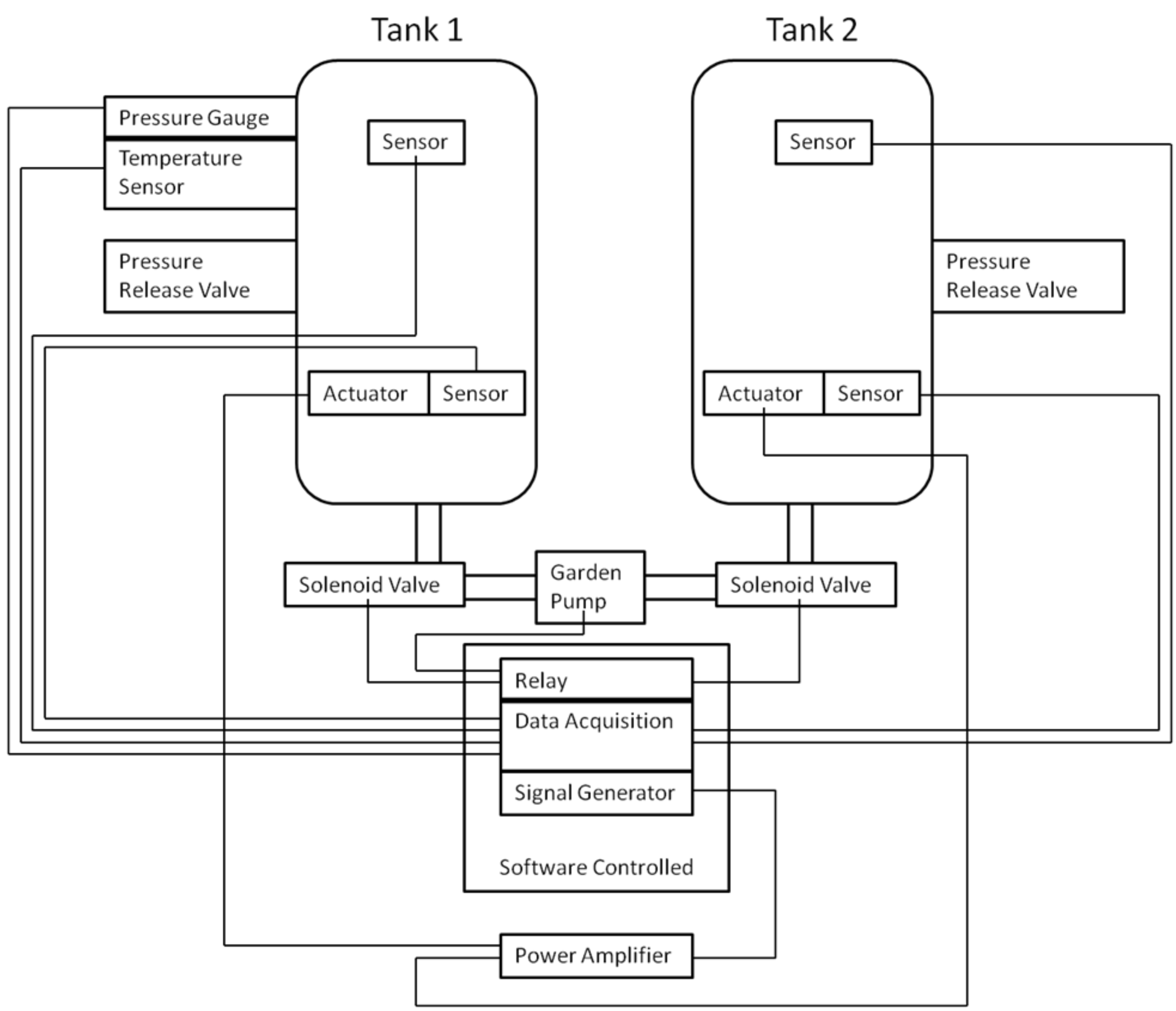

Figure 1. Schematic diagram of the EMA experiment.

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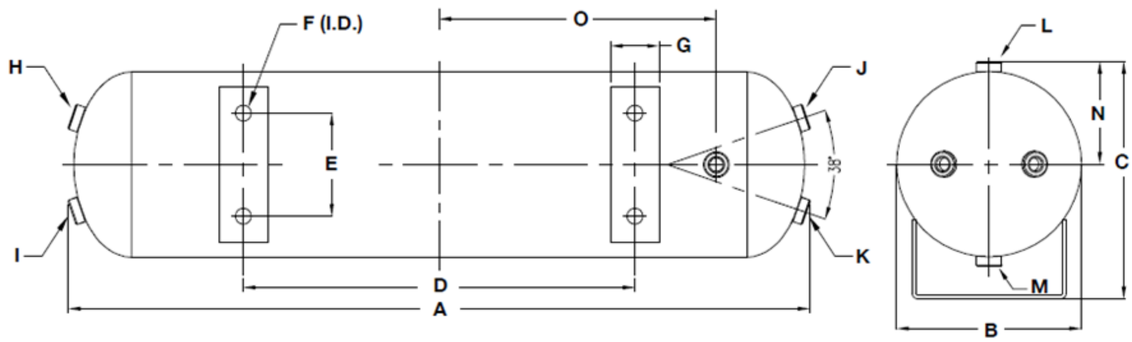

DIMENSIONS

Part Number	A	B	C	D	E	F	G	
91022	491.7	151.0	193.5	210.5	84.0	5.1	40.0	
	H	I	J	K	L	M	N	O
91022	1/4" (F)	1/4" (F)	1/4" (F)	1/4" (F)	1/4" (F)	1/4" (F)	83.5	169.0

* All measurements in millimeters, unless otherwise noted.
** All fittings are NPT, unless otherwise noted.

Figure 2. The schematic of the model spacecraft propellant tank [Viair, 2011].

In flight configuration, the first tank was initially filled to 46%, while the second tank was left empty. After every five parabolas, fluid was transferred from the first tank to the second by means of solenoid valves and a garden pump. The volume transferred was measured both by a flow meter and a PVT method. The fluid used in this study was tap water.

The research team used a custom designed software interface programmed in the National Instruments LabVIEW environment to control all data acquisition and fluid transfer operations for the experiment. The touch-screen user interface was designed to be as simple as possible, as the microgravity environment greatly complicates trivial tasks such as pushing buttons. A screen-shot of the interface is shown in Fig. 3.

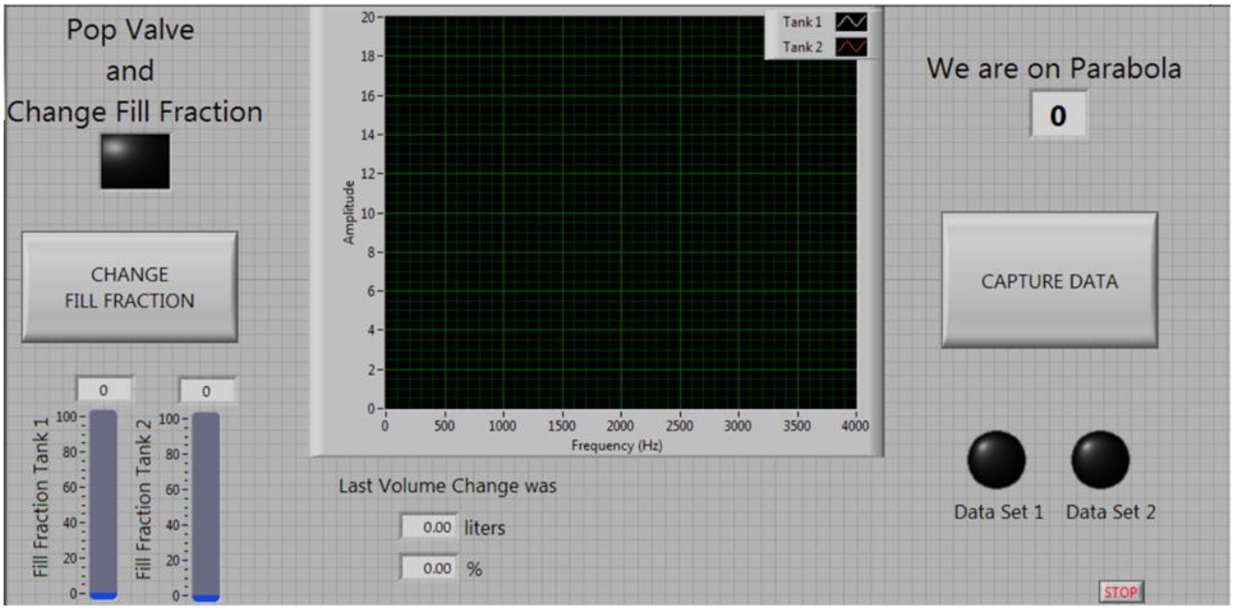

Figure 3. Screen-shot of the software user interface.

Results

A typical FRF spectrum for an empty tank in 1-g is shown in Fig. 4, with a frequency resolution of 1.0 Hz. Many different vibrational modes appear in this spectrum, but the mode of interest lies at about 834 Hz. The placement of the sensors on the tank has a large effect on the amplitude of each mode, as placing the sensor at a location that is a node for a given mode would remove that mode from the FRF spectrum.

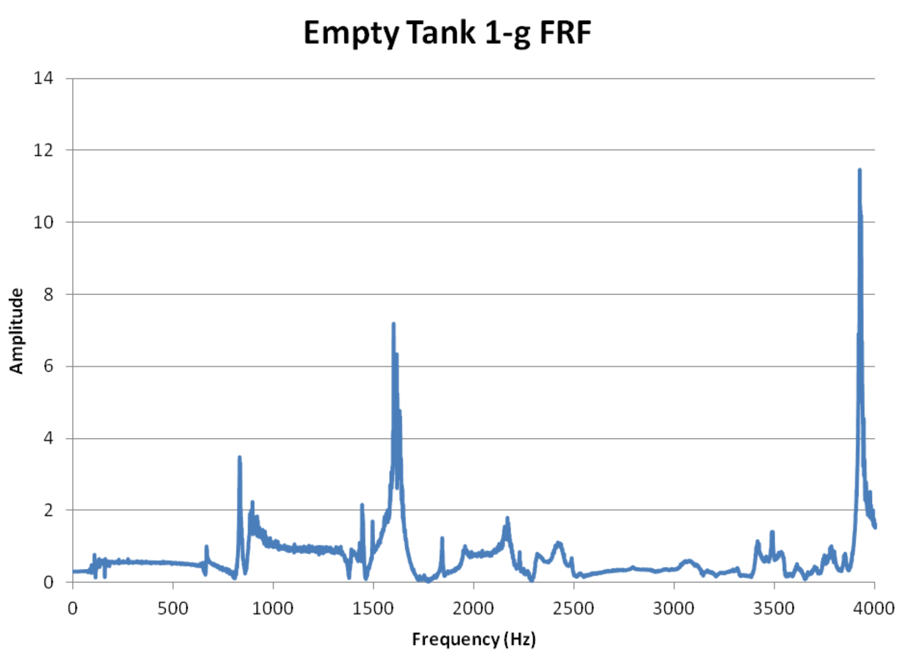

Figure 4. Typical 1-g empty tank FRF.

The experiment was extensively tested on the ground with the tanks filled to different levels. Typical FRF spectra for a tank containing varying volumes of settled fluid in a 1-g environment are shown in Fig. 5, again with a frequency resolution of 1.0 Hz. The downward shift in resonant frequency with increasing fill fraction is clearly evident.

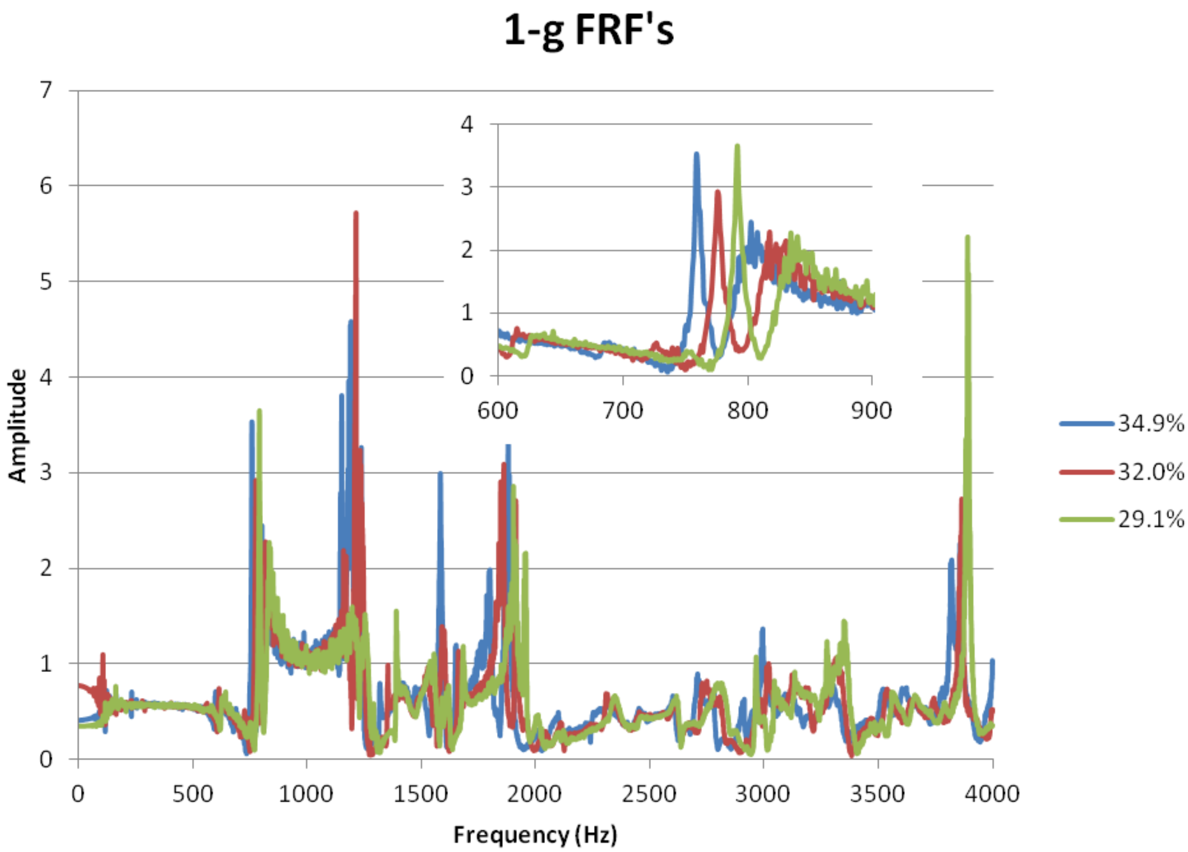

Figure 5. Typical 1-g FRF spectra at varying fill fractions. Inset shows the mode of interest.

In microgravity, a total of 12 different fill fractions were tested on each tank. Selected FRF spectra of varying fill fraction from the same tank as that in Figs. 4 and 5 are shown in Fig. 6, with a frequency resolution of 1.0 Hz. The fluid was sloshing inside the tank for the entire time the data was recorded. This data shows the same relationship between resonant frequency and fill fraction as the ground data in Fig. 5.

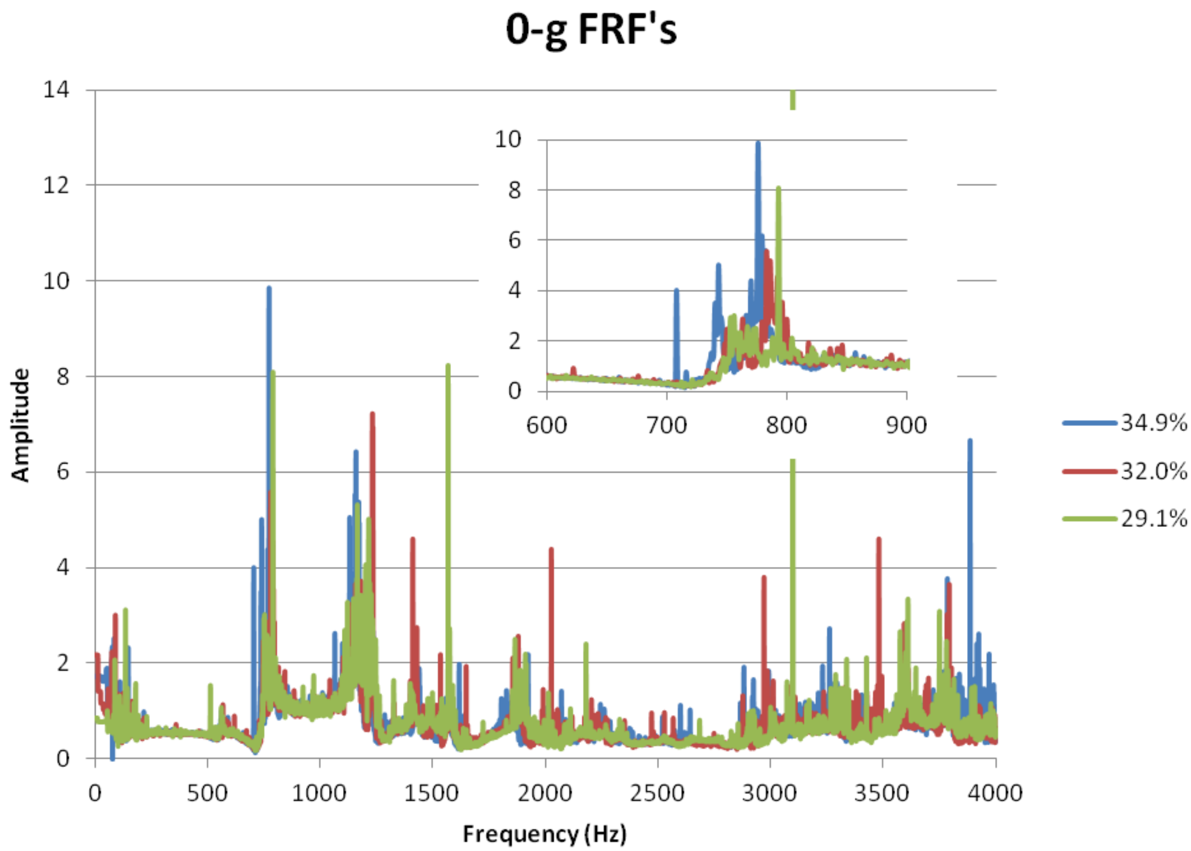

Figure 6. Selected 0-g FRF spectra at varying fill fractions. Inset shows the mode of interest.

Fig. 7 shows a summary of all of the ground data and flight data collected as a part of this study, as well as previously reported data from flights conducted in 2011, plotting the mode frequency versus the fill fraction [Finnvik *et al*., 2011]. Error bars representing the standard error are included for the flight data only, but would be smaller than the data symbols for the ground data.

Discussion

The central objective of this study was to determine the resolution of EMA in determining propellant volume in a model spacecraft propellant tank. Based on the three highest fill fractions of tank 1, the resolution between 30% and 70% is 1.5% of the total volume. Looking at the plots of the 1-g data in Fig. 5 and the 0-g data in Fig. 6, there is a marked decrease in the clarity of the peaks in the 0-g data as a result of fluid sloshing in 0-g. Due to this, it is possible that the resolution of the technique would approach the 1-g resolution after the fluid settles in the tank, removing the problem of variable fluid contact area.

Based on the three lowest fill fractions of tank 1, the resolution below 20% is 7.4% of the total tank volume. This drastic reduction in resolution can be attributed to the geometry and construction of the model tank used in this study. The point where the resolution changes is closely correlated with the point where the end caps are welded to the cylindrical tank body. The end caps themselves, being roughly hemispherical, have drastically different vibrational properties than the tank body. Secondly, the weld between the end caps and the tank body represents a discontinuity in the vibrational structure. As the sensors are mounted to the tank body, the technique is capable of measuring the fluid volume only after the lower end cap is filled, and before the cylindrical body is filled. This problem is easily corrected by choosing a tank of a different geometry, such as a simple closed cylinder.

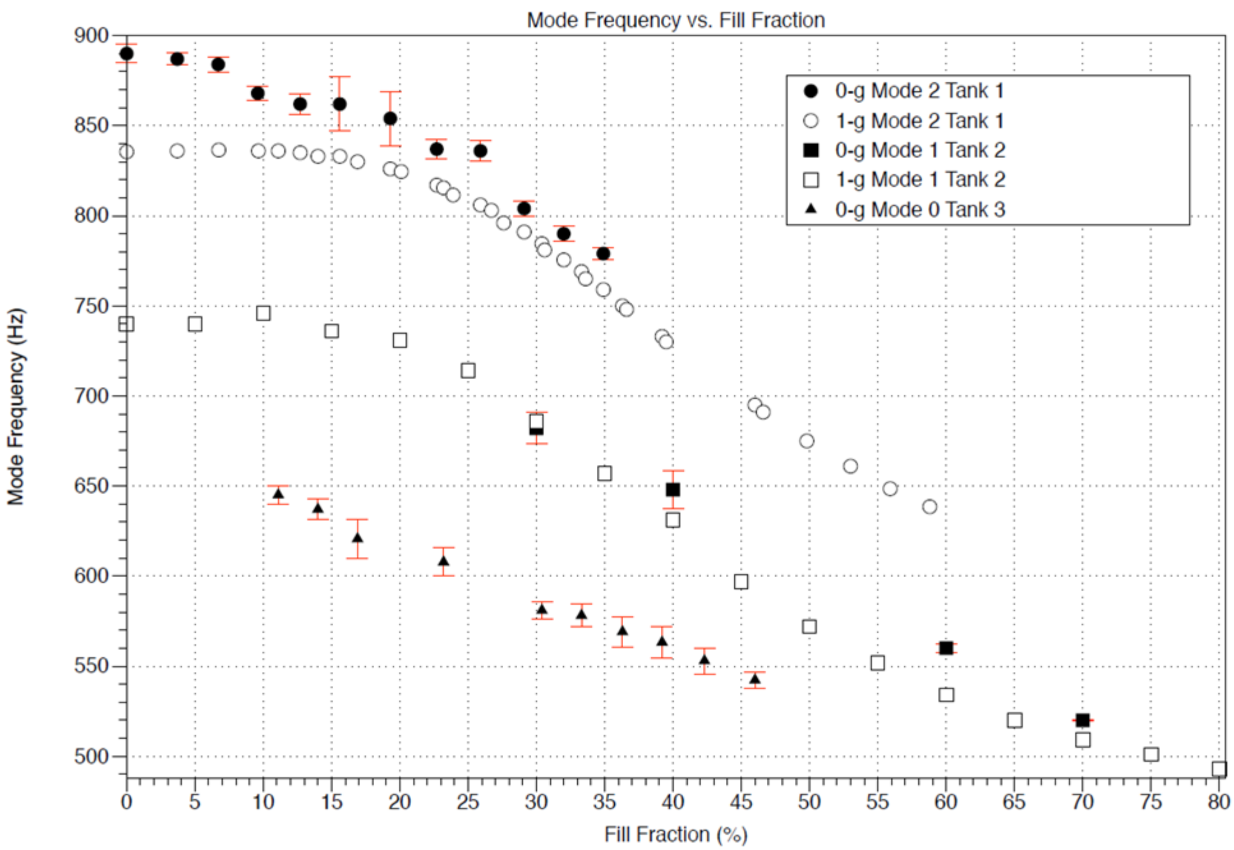

Figure 7. The mode frequency versus fill fraction relationship for all of the flight and ground data collected.

This study has shown that the EMA technique is viable as a non-invasive, real-time propellant volume measurement technique, with a resolution of about 1.5% of the total tank volume between 30% and 70% fill fraction, when used on unsettled, sloshing fluids. The EMA technique warrants further study to determine the resolution of the technique when applied to settled fluids in microgravity.

Acknowledgments

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