Published in final edited form as:

Acta Astronaut. 2019 June ; 159: 499–507. doi:10.1016/j.actaastro.2019.01.050.

Modal Propellant Gauging: High-resolution and non-invasive gauging of both settled and unsettled liquids in reduced gravity

Kevin M. Crosby^{a,*}, Nehemiah J. Williams^b, Rudolph J. Werlink^c, and Eric A. Hurlbert^b

^aDepartment of Physics and Astronomy, Carthage College, Kenosha, WI, 53140, USA

^bNASA Johnson Space Center, 2101 NASA Parkway, Houston, TX, 77058, USA

^cNASA Kennedy Space Center, Florida, 32899, USA

Abstract

The modal response of a liquid-filled tank to external acoustic excitation can be used to infer with high resolution the mass of contained liquid, the mass flow rate of liquids into and out of the tank, and changes in tank pressure. Both contained liquid mass and internal ullage pressure affect the modal response of the tank walls through fluid mass-loading of the tank walls and pressure-induced wall stiffening, respectively. Modal Propellant Gauging refers to the technology that exploits these shifts in modal frequencies to infer the mass of propellant in a tank. MPG is a non-invasive gauging technology that has demonstrated gauging resolutions of 1% for settled propellants and 2–3% for unsettled, sloshing propellants. Extensive parabolic flight testing of the MPG system on model tanks has been conducted to validate the technology in reduced gravity. MPG testing on a qualification tank for the Orion Program's European Service Module has also been conducted and is reported here. Finite element modeling of the Orion ESM "upper" tank is discussed and compared with measurement data. Three computational approaches to mass determination, Peak Tracking, Point Sensor, and Spectral Density methods, are described here. Use cases are defined and analyzed in the context of the Orion ESM Qualification tank data, and an implementation scheme for continuous mass gauging on the Orion ESM is discussed.

Keywords

Propellant Mass Gauging; Modal analysis; Orion ESM *MSC: 70J10, MSC: 76M22*

1. Introduction

Accurate, low-power, and non-invasive propellant gauging has long been identified in NASA technology roadmaps as a critical investment area [1]. Gauging inaccuracies famously plagued the Apollo moon landing and have remained a challenge to mission planning through launch mass constraints, extended mission lifetimes, and the advent of regulatory compliance requirements for satellite end-of-life operations.

*Corresponding author. kcrosby@carthage.edu (K.M. Crosby), nehemiah.j.williams@nasa.gov (N.J. Williams), rudolph.j.werlink@nasa.gov (R.J. Werlink), eric.a.hurlbert@nasa.gov (E.A. Hurlbert).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.actaastro.2019.01.050>.

Low gravity propellant gauging is particularly challenging because traditional buoyancy-based methods are ineffective and probe-based measurements are compromised by both sloshing and by the surfacetension driven equilibrium configuration of liquid in the propellant tank during weightlessness. Most gauging technologies currently in use suffer from increasing estimation errors near end-of-life, where errors in contained liquid mass estimates can grow to 10% or more of tank volume [2]. A survey of current methods and their limitations is provided by Dodge [3].

The Modal Propellant Gauging program addresses several of the drawbacks associated with traditional gauging technologies. In particular, MPG affords high-resolution gauging of propellant in both sloshing and settled states. MPG is effective in reduced gravity, does not suffer reduced resolution near end-of-life operations, and is non-invasive, requiring no tank penetrations or design alterations. Parabolic flight testing of MPG on scale model tanks demonstrates effective low-gravity gauging of unsettled, sloshing liquids across a fill-level range of 10–70% with resolutions between 2 and 4% [4]. Laboratory testing of settled 1-g gauging results in sub 2% resolution for fill fractions between 0 and 70% in scale model tanks [4,5].

The purpose of this report is to describe the results of modeling and full-scale testing of MPG in the Orion ESM QM tank and to introduce the computational approach to real-time gauging developed for the Orion program.

2. Modal Propellant Gauging implementation

The detailed experimental implementation of MPG has been described in the literature [4]. Here we provide a brief overview of the operational principles and implementation of MPG in thin-walled tanks. In MPG, the exterior of the tank wall is subject to a broad-band acoustic excitation by means of a white noise signal with bandwidth in the range of 50–3000 Hz. The white noise signal is a low-amplitude excitation driven by a digital white noise signal sampled at 100 kSamples/second and delivered through a PZT actuator affixed to the exterior of the tank by means of low-impedance double-sided tape and epoxy. The PZT actuator is a thin, flexible patch that can operate as either an actuator by converting electrical signals into mechanical vibrations, or in reverse, as a sensor, by converting mechanical vibrations into electrical signals. The signal is amplified by a piezo driver that delivers the amplified white noise signal to the PZT actuator at an RMS amplitude of 100 V.

The broadband excitation of the tank wall excites resonant frequencies that can be isolated through an automated modal analysis of the tank response at various locations away from the actuator. The essential experimental approach is illustrated in Fig. 1. PZT sensors identical to the actuator convert the acoustic response of the tank at two locations to electrical signals that are sampled and recorded by an ADC at a sample rate of between 16 and 25kSamples/sec.

The sensor nearest the actuator is deemed the “monitor” sensor and samples the input excitation, $x(t)$. A sensor located away from the actuator samples the response of the tank, y

(*i*). The Fourier Transforms of these signals, $X(\omega)$ and $Y(\omega)$ are related by the Frequency Response Function, $H(\omega)$. For linear systems,

$$Y(\omega) = H(\omega)X(\omega). \quad 1$$

An FRF is constructed from the pair of sensor time series via a ratio of the FFTs obtained from each time series. For sub-scale tank testing, only 2–3 sensors are used in a full MPG implementation. For full-scale testing of MPG on the Orion QM tank, we use eight PZT patches that can be sampled in pairs of monitors $x_i(t)$ and sensors, $y_i(t)$, with $i = 1 \dots 8$.

The FRF, $H(\omega)$, identifies and isolates the modal frequencies present in the tank's excitation spectrum. $H(\omega)$ contains information about structural damping, modal mass, and modal stiffness. Shifts in the modal frequencies indicate structural changes in the tank properties such as effective mass or wall stiffness variations.

At a fixed sampling rate, the frequency resolution of an FRF, Δf , is related simply to the length of the time series T used to construct the FRF: $\Delta f = 1/T$. The frequency resolution in turn dictates the maximum resolution in fill fraction discrimination. In order to increase the resolution of the mass gauge, longer time series must be obtained.

Modal frequencies of interest are those for the lowest modes, typically in the range $f < 200$ Hz for empty tank resonances in both full-scale and model tanks. For $f < 200$ Hz, a sampling rate of 16k Samples/sec. is approximately 40 times larger than the Nyquist frequency, ensuring adequate waveform reproduction.

2.1. Modal mass

The influence of contained liquid on the modal response of a tank is via its effect on modal masses. The modal mass matrix for a system with n degrees of freedom consists of n “effective” mass elements that correspond to unique modal frequencies in the usual way: the effective mass of the k -th mode is the fraction of the total mass that contributes to the natural vibration of the k -th mode at frequency ω_k according to

$$\omega_k \propto m_k^{-1/2}. \quad 2$$

Each element of the modal mass matrix represents the weighting of the corresponding mode shape when the structure is excited by an external source. Modes with high effective mass participate strongly in the structural response to excitation while modes with low effective mass are less involved in the response dynamics.

The central observation underlying the MPG approach is that the effective mass components of the modal mass matrix associated with dominant mode shapes are sensitively dependent on the amount of liquid in contact with the tank inner-walls. This dependence can be exploited to uniquely correlate modal resonance peaks with tank fill-fractions, even under sloshing conditions, as we demonstrate in Section 6.3. Further, for thin-walled metal tanks,

the low-lying modes are under-damped and well-separated, so that the modal response of the tank at low frequencies, can be approximated as a finite set of single-DOF harmonic oscillators.

A wealth of research on fluid mass-loading of vibrating plates and other model systems suggests that increases in effective mass occur for structures immersed in fluids for all resonant frequencies below a critical frequency f_c that depends on the density ratio between fluid and structure [6]. In our case, we are interested in the effect of varying amounts of fluid (liquid) contact with the structure for *a single mode*. We typically track the lowest 1–2 mode(s) because we are interested only in frequencies well below f_c . We therefore expect that, in accord with Eq. (2), fluid mass-loading will have the effect of lowering the resonant mode frequencies.

2.2. Modal stiffness

In analogy to the discussion of modal mass contributions, each of the low-lying modes behaves as if it were a single-DOF harmonic oscillator of modal stiffness K_k , so that each mode is well-described by $\omega_k = (K_k/m_k)^{1/2}$. Tank wall stiffness is sensitively dependent on the ullage pressure in the tank. For thin-walled tanks at low pressure, variations in the tank pressure due to draining, filling, or pressurizing operations can have a significant effect on the modal frequencies of low-lying modes ($\omega_k \ll \omega_c$) [7]. Changes in pressure can therefore confound mass measurements as the stiffness effect on modal frequencies is counter to the effect of changes in effective mass. This complication is addressed and a prescription for “deconvolving” the effects of stiffness and mass is provided in Sec. 6.3.

3. 1-G scale model tank results

Initial results for settled mass gauging using MPG have been reported in the literature [4]. Here, we summarize these results and indicate their relation to the Orion data. The test rig is shown in schematic in Fig. 2. The rig, which was also used in the parabolic test flights, consists of two 10-L cylindrical COPVs connected via a flow loop with solenoid valves and pumps to transfer metered quantities of water between the tanks. The tanks are 37-cm in length and 16.5-cm in diameter and are equipped with pressure and temperature transducers to allow the independent calculation of fill levels via the PVT method.

Optical flow sensors and liquid level gauges are used redundantly to obtain measurements of fill level to within 0.5% of the tank volume. The pumps and valves for transferring liquid between the tanks are controlled by software to ensure consistent volume changes. For purposes of eliminating pressure effects, tank pressure is maintained at atmospheric pressure and liquid fill level is established via flow metering.

The test rig is shown in Fig. 3. The rig was used for both ground tests and parabolic flight tests of MPG. The COPVs are interchangeable with transparent polycarbonate tanks of the same internal volume. These are used for correlating slosh state with modal mass estimates provided by the MPG software.

In both ground and flight tests, one tank is filled to an initial fill level between 50 and 70% while the other is initially empty. In laboratory testing, 10-s of time series data is obtained and processed into FRFs at each fill fraction. Fill changes are effected by a flow loop that transfers a metered amount (between 0.5 and 1.5% of the fill volume) of water from one tank to the other, while maintaining ullage pressure at zero (gauge).

Representative modal response data is shown in Fig. 4. These data span a small range of fill fractions and illustrate the resolution of the modal gauging for settled 1-g liquids. Modal peak resolution in Fig. 4 is well within 1.5%. Tank pressure was constant throughout the experiment.

Peak frequencies for the lowest mode as a function of fill fraction are illustrated in Fig. 5. The decrease in mass gauging resolution at lower fill fractions occurs as the fill-level drops below the hemispherical dome cap at the bottom of the tank. Fill levels less than 10% of total tank volume are typically below this dome cap and require additional sensors positioned on the dome cap to accurately gauge modal response in these fill ranges. The small size of the test article did not allow for additional sensors to be placed on the dome caps.

4. Low-gravity MPG

A series of five parabolic flight campaigns, conducted through the NASA Flight Opportunities Program, served to validate the MPG concept and demonstrated real-time gauging in unsettled (sloshing) weightless conditions. Flights were provided by the ZERO-G Corporation aboard the company's modified 727B aircraft. Each para-bola provides approximately 20 s of clean ($<0.01g$) microgravity, which is too short of a time for the liquid to settle into its equilibrium zero-g configuration. The contained liquid sloshes almost continuously within the tanks during the microgravity portions of the flights. For this reason, the parabolic flight tests represent the outer envelope of anticipated performance capability for the MPG approach and gauging resolution is compromised relative to laboratory testing.

4.1. Equilibrium surface configurations

The essential principle of the MPG approach is that fluid "mass loads" the tank wall and thereby increases modal mass contributions in proportion to the surface area of the tank wall in contact with the liquid. In weightless conditions, two fundamental challenges to the technique present themselves.

The first complication arises from the transient slosh of liquid during spacecraft maneuvering. The settling time for sloshing liquid is a function of tank diameter and liquid properties, and can be on the order of hours for the large tanks in booster stages. It is desirable to develop a gauging approach that provides accurate mass gauging during propellant slosh.

The second challenge to the MPG approach for low-gravity liquids is the potential for multiple, energetically equivalent zero-gravity equilibrium surface configurations for the same volume of contained liquid. If contained mass (or volume) is estimated via a proxy

measurement of contact area between tank wall and contained liquid, a non-uniqueness of the equilibrium liquid surface distribution may result in multiple effective modal mass measurements for the same contained liquid mass. We treat each of these complications in subsequent sections.

4.2. Parabolic flight test data

Parabolic flight testing was conducted according to a similar protocol as outlined above for laboratory testing. Each parabolic flight consisted of 30–40 parabolas, for which MPG data was taken at a sequence of fill fractions. The fill fraction was constant during each parabola and changed between each set of five parabolas. Modal FRFs calculated over 10-s windows were averaged across the five parabolas to obtain a “slosh-averaged” modal response for each fill-fraction.

A LOESS fit of each zero-g FRF was calculated in a 500 Hz window around the lowest mode at each fill fraction. These data for representative fill fractions are illustrated in Fig. 6. As suggested by Fig. 6, it is possible to obtain resolutions approaching 1% for sloshing liquids. Two caveats pertain. While small liquid mass changes on the order of 1% of total tank volume may be resolvable in measurable shifts in modal frequencies, it is not always possible to uniquely correlate these modal frequencies to contained liquid mass.

FRF data from parabolic flights is summarized in Fig. 7. It is evident from Fig. 7 that, 1-g and 0-g modal responses are related, but are not identical. We should not expect them to be. The average contact area between liquid and tank wall increases in reduced gravity as surface adhesion drives the liquid along the tank surface. More tank-liquid surface contact area increases the effective modal mass and drives down the resonant mode frequencies. This effect is pronounced at higher fill fractions. At low fill fractions, the lowest-mode frequencies are slightly higher for weightless tanks than for tanks in the laboratory. This observation can be understood to follow from the difference in boundary conditions between a tank in free-fall and a tank physically constrained to the surface of the earth.

5. Orion ESM QM tank

The Orion ESM provides power, life support fluids, navigation, and propulsion to the Orion spacecraft. The four ESM propellant and oxidizer tanks have a combined capacity of 9000 kg. Each pair of tanks is operated in series, with an “upper” tank feeding a “lower” tank.

Here we briefly describe the ESM QM tank on which MPG testing was conducted. The QM tank, illustrated in Fig. 8, is used to qualify the compliance of the upper and lower FM tank to the specified structural environments and to the functional requirements of both upper and lower FM tanks. The QM tank is a cylindrical titanium shell of diameter 1.2 m and height 2.1 m, with hemispherical end caps. In gross proportion, it is similar to the scale model tanks described in Sec. 3. The QM tank has PMD and slosh control structures associated with both upper and lower FM tanks. As such, the QM tank has a more complex modal spectrum than would be expected in the FM tanks.

5.1. Finite Element Modeling of MPG on the Orion ESM "upper" tank

In support of the MPG experimental work, Finite Element Modeling (FEM) simulations were carried out on a simplified Orion ESM "Upper Tank model using COMSOL [8]. Primary objectives of FEM analysis include describing mathematically the modal response to propellant filling of the Orion ESM tank both as a predictive tool, as well as to understand and evaluate sensor placement with respect to the tank's modal behavior. Further investigations will include prediction and understanding both the effects of tank internal pressure and the effects of loading propellants in both micro-gravity and 1-g settled conditions on tank modal behavior. The current investigations focus on modeling of the micro-gravity 0-G fill condition.

5.1.1. Geometry and materials model description—An Orion ESM Upper Tank CAD model of like dimensions (e.g. length, radius, and volume) to the QM tank described above was constructed using the Creo 3.0 CAD tool and imported into COMSOL [8]. With the COMSOL metaphysics tool, the Structural Mechanics branch using the Shell interface was applied to the model to approximate a 3D solid geometry in which the in-plane surface is thin but where bending is present. Within the Shell interface, to approximate the variable wall thickness of the actual Orion ESM tank, an averaged wall thickness-to-radius (t/R) ratio approach was selected. A linear elastic isotropic material (titanium alloy) was imported from COMSOL's Material Library and applied to the geometry with the following material properties: $E = 114.8$ GPa, $\nu = 0.3$, and $\rho = 4313$ kg/m³. The model presented here does not include internal structures (e.g. baffles) or propellant feed line connections but only simulates how the tank body behaves with respect to propellant fill levels.

5.1.2. Grid generation—To demonstrate grid independence of the simulation results, three physics-controlled mesh sizes were applied to the Orion ESM shell geometry from the COMSOL mesh settings: Finer, Extra Fine and Extremely Fine. The meshed geometries are displayed in Fig. 9. All three meshes use primarily triangular cells which allow for variable node placement especially on curved surfaces such as those on the tank domes and those concentrated points around the propellant tank constraint tabs. Simulation results show agreement for all three grid sizes, thus the Extra Fine (middle mesh in Fig. 9) was used for all of the simulations.

5.1.3. Mathematical model—Using the COMSOL Shell physics interface, the Eigenfrequency study solver calculates the eigenmodes or eigenfrequencies for a line-ized model. In structural mechanics, the eigenfrequencies correspond to the natural frequencies of vibration and the eigenmodes correspond to the structural or modal displacement of the geometry at specific natural frequencies [8]. The Eigenfrequency study solver finds solutions to the following differential equation relating stress, σ to the eigen-value, λ for a shell geometry:

$$-\rho\omega^2 u = \nabla \cdot \sigma$$

where u represents the displacement field and the eigenvalue, λ , is related to the angular frequency by $-i\omega = \lambda$. The z -plane stresses satisfy $\sigma_z = 0$, $-1 \leq z \leq 1$.

The “geometric non-linearity effects” setting in COMSOL was also included in the model to account for pressure effects on shell curvature-finite thickness interactions [9].

5.1.4. Boundary conditions—The Orion ESM tank is constrained to the spacecraft in the following manner: 48 tabs connect the upper tank to the structure and 24 tabs connect the lower tank. In COMSOL, the upper tabs are constrained in $x - y - z$ coordinates with the Fixed Constraint boundary condition. The lower tabs use the Prescribed Displacement boundary condition with zero-displacement applied to the radial and transverse directions; the lower tabs are allowed translation in the z coordinate direction (taken as the direction along the tank’s long axis). Rather than use a complex fluid-structure-interaction (FSI) model, a simplified isotropic “Added Mass” approach was used in COMSOL as a boundary condition to model the inertial load effects of propellant on the tank. In the isotropic model, the mass as a function of fill level is applied to the inner wall of the entire tank structure, simulating the approximate behavior of the propellant in micro-gravity. A fill factor h , was introduced and varied from 0 to 1 in increments of 0.05 to simulate propellant loading conditions. In this way, the fluid mass as a function of fill level is given by

$$M_f(h) = \rho_f V_f h$$

where ρ_f is the incompressible fluid density ($\rho_f = 876 \text{ kg/m}^3$ for MMH) and V_f is the total (liquid) fluid volume.

To simulate the effects of internal tank pressure, a negative Face Load with a prescribed pressure was applied to the model surface to simulate a pressure applied radially outward. Simulations of internal pressure include a 1 bar pressure load condition for all propellant fill levels.

5.1.5. COMSOL FEM simulation results—Simulations of varying the propellant fill level were performed for the first 20 modes with an internal pressure of 1 bar in COMSOL. Fig. 10 shows the results of the varying modal frequencies as result of increasing or decreasing the fill level and by inference the propellant tank mass for Modes 1, 4 and 6. The simulation results in Fig. 10 demonstrate that there is a definitive influence on the tank structural modes from the presence of the propellant mass. The qualitative trends suggest that the inertial mass effect by the fluid mass on the tank is strongest at the lower fill levels ($h < 50\%$) but is less pronounced as the tank becomes full. These results are qualitatively consistent with similar studies (e.g. Refs. [4,10]).

Fig. 11 shows the mode shapes for the Orion ESM propellant tank as simulated in COMSOL with an internal pressure of 1 bar for the first, fourth, and sixth modes for the empty tank case ($h = 0$). These modes include circumferential (n) and axial (m) displacement nodes of the following pattern, $(n, m) = (5, 1)$ at 98 Hz for the first mode, $(6, 1)$ for the fourth and $(4, 1)$ for the third mode. Thus the nodal displacement is stronger in the circumferential (breathing mode) direction than axially for the lower modes with empty tank frequencies $f < 200 \text{ Hz}$. Stronger nodal displacement near the tank center suggests that sensor output may be

enhanced at these locations relative to locations where nodal displacements for frequencies of interest are less pronounced. This is in keeping with experimental findings.

6. MPG mass determination algorithms

Three methods have been developed to translate the structural response of an acoustically excited tank into estimates of contained propellant mass. Two of the methods discussed here (PTM and SDM) use frequency domain information (modal response), while the third (PSM) uses time domain information. There is an underlying equivalency between these methods: the time domain data must, of course, contain the same information as the frequency domain data. However, computational efficiencies can be exploited in several use cases, making the choice of mass determination algorithm dependent on the particular flow conditions and sensor locations.

6.1. Point sensor method

Acoustic excitations on the surface of a tank wall couple to the contained liquid, inducing small amplitude excitations in the liquid. For the portion of the tank wall in contact with the liquid, surface wave amplitudes are reduced as acoustic energy is shared between tank wall and liquid excitations. Further, in 1-g, the liquid surface describes a relatively flat meniscus, which represents a discontinuity in effective mass. The impedance change for surface waves traveling along the tank wall near the meniscus causes scattering of higher frequency waves, further reducing the surface wave energy below the meniscus.

When the fill fraction in the tank is changing, this change in surface wave amplitude can be detected as the fill level passes by the position of a PZT sensor. For example, as a tank drains, we should expect a sensor positioned initially below the liquid level to register an increase in amplitude as the liquid level drops below the position of the sensor. With knowledge of the sensor position the instantaneous position of the liquid level can be determined.

It is also possible to extract estimates of instantaneous flow rate by measuring the rate of change of sensor output amplitude during a fill-level crossing. Here, “instantaneous” really refers to the average change across the height of the sensor. Given the small size of the sensor relative to the tank dimensions, “instantaneous” is an appropriate approximation.

Note that the PSM makes use of the time series data from a single sensor and does not require transform calculations. By positioning sensors at regular locations along the length of a cylindrical tank, the flow rate and instantaneous contained mass can be reconstructed by monitoring the RMS output of each sensor for slope changes associated with a liquid level change.

In Fig. 12, the RMS output of a sensor positioned along the length of the Orion QM tank during a drain cycle is shown. PSM is a sensitive indicator of the local flow rate when the sensor position and geometry are known. PSM has been demonstrated in a 1-g laboratory setting, but is not suited for 0-g applications where the liquid surface will have a more complex configuration at all fill levels. For this reason, PSM is best suited for accelerated

conditions when the liquid level changes rapidly, such as during an engine burn. It is also important to note that the PSM is sensitive to effective stiffness changes in the tank wall, typically mediated through pressure changes within the tank ullage.

6.2. Peak tracking method

When modal peaks are well-separated and the damping is low, it is possible to implement a standard peak finding algorithm to identify modal peaks and then track shifts in these modal frequencies for the low-lying modes as the contained liquid level changes due to engine burns, filling, or draining. Fig. 4 illustrates the possible utility of this approach. The peaks in Fig. 4, representing the same resonant frequency at different fill fractions, are easily distinguished by the eye and can be tracked via a peak-finding algorithm. Indeed, the data in Fig. 5 are obtained from an automated peak-finding and tracking algorithm.

However, automated peak tracking is confounded by slosh and pressure-induced stiffness changes within the tank. The latter complication is addressed in the following section. The former challenge is evident in Fig. 6 where slosh-broadening of the peaks makes identifying and tracking peaks challenging.

6.3. Spectral Density Method

The modal response of thin-walled tanks is particularly sensitive to variations in pressure [7]. Pressure sensitivity complicates each of the mass measurements discussed above at low tank pressures. An example of the pressure dependence of PZT sensor output is shown in Fig. 13 where the time series from a sensor on the Orion ESM QM tank is plotted during a fill and drain cycle in which the tank was filled at a rate of 0.15 kg/sec and then drained through a series of high flow-rate steps. The amplitude of the sensor output drops monotonically during the initial fill portion of the cycle. The amplitude drop occurs as the pressure in the tank rises from 1 bar to 2 bar while the contained mass increases at a constant rate.

For applications in which the tank pressure variations produce larger effects on the RMS output of a point sensor or on modal peak shifts than concurrent mass changes do, it is necessary to develop a gauging approach that isolates changes due to contained mass from tank wall stiffness effects induced by pressure changes. The SDM introduces an integral quantity that depends only on modal mass and not on the pressure in the tank.

6.3.1. Spectral density functions—The “spectral density” is the Fourier Transform of a correlation function of a stationary, random input signal. For instance, the auto-spectral density is the Fourier Transform of the autocorrelation function,

$$S_{xx}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-i\omega\tau} d\tau, \quad 3$$

where R_{xx} is the autocorrelation function of a random stationary process. For a system defined by a single input signal $x(t)$ and a single output signal $y(t)$, the auto-spectral densities of the input and output signals, $S_{xx}(\omega)$ and $S_{yy}(\omega)$ are related via the FRF, $H(\omega)$,

$$S_{yy}(\omega) = |H(\omega)|^2 S_{xx}(\omega). \quad 4$$

In MPG, the input signal, $x(t)$ is a broadband white noise signal, for which the input auto-spectral density (hereafter referred to as the “input spectral density”) is a constant, $S_{xx}(\omega) \equiv S_0$. The constant S_0 is the average value of the input spectral density. In this case, the output spectral density is $S_{yy}(\omega) = |H(\omega)|^2 S_0$.

When the damping is small for all frequencies away from resonance (as it is for thin-walled metallic tanks), many structures exhibit modal responses to acoustic excitations that are well-approximated by a linear sum of single DOF simple oscillators, each described by the single-DOF FRE

$$H_k(\omega) = (K_k - m_k \omega^2 + i c_v \omega)^{-1} \quad 5$$

for each mode k , where c_v is the viscous damping coefficient. The approximation of a lightly-damped, well-separated single-DOF simple oscillators is an appropriate one for the case of a thin-walled metallic tank and Eq. (4) and Eq. (5) suggest an approximate analytic expression for the output spectral density function,

$$S_{yy} = \frac{S_0}{(K_k - m_k \omega^2)^2 + c_v^2 \omega^2}. \quad 6$$

Eq. (6) can be used to extract modal mass parameters from output excitation signals and is the basis for the Spectral Density Method described below.

6.3.2. Moments of the spectral density function—In general, for a random, stationary signal, the mean-square value of the signal is related to the spectral density of the signal by

$$\langle y^2(t) \rangle = \int_{-\infty}^{\infty} S_{yy}(\omega) d\omega \quad 7$$

and so, in terms of the input spectral density, the mean square value of the output signal can be evaluated via

$$\langle y^2(t) \rangle = S_0 \int_{-\infty}^{\infty} |H(\omega)|^2 d\omega. \quad 8$$

In experimental applications, frequencies are of course limited to $\omega \geq 0$, while the analytic expressions for spectral densities are most conveniently expressed as two-sided functions ranging over $-\infty < \omega < \infty$. To facilitate implementation of spectral density calculations on actual data, we consider only the physically measurable, one-sided spectral densities that range over $\omega \geq 0$.

In the current approximation, we have an exact expression for the FRF $H(\omega)$, given by Eq. (5). In this case, the one-sided integral $\int_{-\infty}^{\infty} |H(\omega)|^2 d\omega$ can be calculated. Using the methods of Newland [11], after Ref. [12], we find the mean-square output to be

$$\langle y^2(t) \rangle = S_0 \int_0^{\infty} \frac{d\omega}{(K_k - m_k \omega^2)^2 + c_v^2 \omega^2} = \frac{S_0 \pi}{2K_k c_v}.$$

Eq. (9) is an exact result for a single-DOF simple oscillator. It is also a useful approximation for the k -th mode of a system of single-DOF simple oscillators. Note that Eq. (9) essentially defines the zeroth moment of the spectral density function $M_0 \equiv \int_0^{\infty} S_{yy}(\omega) d\omega$, with higher-order moments given by

$$M_n \equiv S_0 \int_0^{\infty} \omega^n |H(\omega)|^2 d\omega. \quad 9$$

In particular, we are interested in M_2 , the second moment of the spectral density. An exact result for M_2 can be obtained using the methods of Newman, and we find

$$M_2 = \frac{S_0 \pi}{2c_v m_k}. \quad 10$$

Eqns. (9) and (10) constitute a set of measurable quantities that can be used to track modal mass and stiffness separately. M_0 depends on the modal stiffness, while M_2 depends only on the modal mass. The two quantities are related by the resonant frequency of the single-DOF system, $K_k = m_k \omega_k^2$.

The utility of the spectral moments M_0 and M_2 depends in part on the extent to which the application can be approximated as a lightly-damped single-DOF system, and therefore to the degree that the experimental system is well-approximated by the FRF defined in Eq. (5). The lowest-lying modes in the modal response of a thin-walled tank satisfy the constraints of these approximations. We further make the assumption that the modal mass of the lowest ($k = 0$) mode is a relatively good proxy for the contained liquid mass.

6.3.3. SDM results for the Orion ESM QM tank—The quantity M_2 can easily be computed in real-time over a narrow range of frequencies around the lowest resonant mode.

While the integral in Eq. (10) extends over all frequencies, in practice, it is necessary to isolate the lowest mode in order to adhere to the approximation of a single oscillator. For this reason, the computation of M_2 is restricted to a range of frequencies of 100 Hz around the lowest mode.

Fig. 14 shows the correlation between M_2 and the known liquid mass during a drain cycle operation from 1600 to 1400 kg in the Orion ESM QM tank. The tank pressure varied significantly during this drain cycle, rendering peak-tracking and point sensor estimations of mass difficult. However, M_2 shows the expected inverse relationship to contained liquid mass.

Each data point in Fig. 14 represents a calculation of M_2 over a frequency range of 100 Hz that isolates the lowest mode frequency. The FRFs used in calculating M_2 were each computed across a 30-s time series window at a sample rate of 16 kSamples/sec.

The data in Fig. 14 suggests an algorithm for determining the contained liquid mass in settled propellant tanks. Periodic calculations of M_2 can be used to construct the mass change between measurements. If the initial mass m_i is known at the beginning of a time interval, the final mass m_f at the end of a time interval can be readily obtained: $m_f/m_i = -M_{2f}/M_{2i}$. While this is strictly true for the $k=0$ modal masses, Fig. 14 indicates that the relationship is useful for contained mass change ratios as well.

7. In-space propellant gauging on the Orion ESM

The methods and results discussed here provide a roadmap for full-scale tests of in-space propellant gauging during both dynamic events and coast mission phases. An Orion ESM tank with MPG sensors distributed along its length is shown in Fig. 15. The eight sensors can be operated as either simultaneous point sensors or as pairs of modal response sensors. The contained propellant mass can be interrogated either continuously using SDM to track modal mass changes, or periodically via point sensor data that indicate the motion of contained propellant across sensor locations.

8. Summary

The MPG project has demonstrated 1–2% gauging resolution in both sub-scale laboratory testing and full-scale Orion ESM QM tests. Zero-g gauging resolutions of 3–4% in unsettled sloshing liquids in sub-scale COPV tanks has also been demonstrated. Three mass gauging methodologies, Point Sensor, Peak Tracking, and Spectral Density methods, have been described and characterized under continuous-drain conditions that most closely replicate a flight application. The SDM approach offers the potential for modal mass gauging in flight applications in which the tank pressure is changing, a circumstance that can complicate both PSM and PTM at low gauge pressures.

Finite element simulations of zero-gravity modal response of the Orion “upper” tank were used to validate the MPG concept that modal frequencies are dependent on the thickness of the adhered liquid layer. The COMSOL simulations produced the expected relationship

between contained liquid mass and lowest-mode resonant frequencies and produced mode frequencies in rough agreement with those measured in the Orion ESM QM tank.

Full-scale low-gravity testing under settled conditions is critical to TRL advancement and we have suggested the broad contours of a full-scale flight test on a future Orion mission. To be addressed in such a test are the robustness of the MPG technology to multiple surface configurations for the same liquid volume in zero-g, the influence of in-flight vibrations and noise on sensor resolution, and the effects of pressure-stiffened tank walls on the gauging methods discussed in this article.

Acknowledgments

This work was supported under grants #NNX16AP67G and #80NSSC18K0272 from the National Aeronautics and Space Administration and through student funding provided by the NASA Wisconsin Space Grant Consortium. Support of the NASA Flight Opportunities Program, the ZERO-G Corporation, and the Carthage College Summer Undergraduate Research Experience program is gratefully acknowledged.

Nomenclature

c_v	viscous damping coefficient
E	Young's Modulus
f	linear frequency, Hz
$H(\omega)$	frequency response function
h	fill level
i	imaginary unit
K_k	modal stiffness of the k th mode
M_f	liquid mass
M_n	n th moment of the spectral density function
m_k	modal mass of the k th mode
N	sample length of discrete time series
S_{xx}	(auto-) spectral density of input signal
S_{yy}	(auto-) spectral density of output signal
$X_i(\omega)$	Fourier transform of (input) time series $x_i(t)$
$x_i(t)$	time series recorded from i th PZT sensor
$Y_i(\omega)$	Fourier transform of (output) time series $y_i(t)$
$y_i(t)$	time series recorded from i th PZT sensor
ν	Poisson Ratio

ω circular frequency, Hz

ρ mass density

Subscript

i PZT sensor index

k mode index

$n = 0, 1, 2, \dots$ order of spectral density moment

Acronyms/Abbreviations

CAD Computer Assisted Drawing

CM Crew Module

CMA Crew Module Adapter

COPV Composite Over-wrapped Pressure Vessel

DOF Degree of Freedom

ESM European Service Module

FEM Finite Element Model

FFT Fast Fourier Transform

FM Flight Model

FRF Frequency Response Function

LOESS “Local regrESSion

MMH MonoMethyl Hydrazine

MPG Modal Propellant Gauging

PMD Propellant Management Device

PSM Point Sensor Method

PTM Peak Tracking Method

PVT Pressure-Volume-Temperature (Equation of State gauging method)

PZT Lead Zirconate Titanate

QM Qualification Model

RMS Root Mean Square

SDM Spectral Density Method

TRL Technology Readiness Level**References**

- [1]. NASA, NASA Technology Roadmaps TA 2, In-Space Propulsion Technologies, Tech. Rep, National Aeronautics and Space Administration, 2015.
- [2]. Yendler B, Review of propellant gauging methods, 44th AIAA Aerospace Sciences Meeting and Exhibit, No. January, American Institute of Aeronautics and Astronautics, 2006, pp. 1–7.
- [3]. Dodge F, Propellant Mass Gauging: Database of Vehicle Applications and Research and Development Studies, Tech. Rep, Southwest Research Institute, 2008 NASA/ CR—2008–215281.
- [4]. Crosby K, Rundle T, LeCaptain K, Werlink R, Modal propellant gauging in low gravity, AIAA SPACE 2016, American Institute of Aeronautics and Astronautics, 2016.
- [5]. Finnvik S, Metallo S, Robinson J, Crosby K, Werlink R, Modal evaluation of fluid volume in spacecraft propellant tanks, Proceedings of the Wisconsin Space Conference, 24 10.17307/wsc.v0i0.87.
- [6]. Leniowska L, Influence of damping and fluid loading on the plate vibration control, Arch. Acoust. Q 33 (2008) 531–540.
- [7]. Fung YC, On the vibration of thin cylindrical shells under internal pressure, J. Aeronaut. Sci 24 (9) (1957) 650–660.
- [8]. COMSOL, Comsol Structural Mechanics Module Users Guide, version 5.3 URL <http://www.comsol.com>.
- [9]. Piacsek A, Abdul-Wahid S, Taylor R, Resonance frequencies of a spherical aluminum shell subject to static internal pressure, J. Acoust. Soc. Am 131 (6) (2012) EL506–EL512 10.1121/1.4721647. [PubMed: 22713029]
- [10]. Lindholm U, Breathing vibrations of a circular cylindrical shell with an internal liquid, J. Aero. Sci 29 (9) (1962) 1052–1059.
- [11]. Newland D, An Introduction to Random Vibrations and Spectral Analysis, third ed., Longman, 1993.
- [12]. Norton MP, Karczub DG, Fundamentals of Noise and Vibration Analysis for Engineers, Cambridge University Press, 2003.

Fig. 1.

Experiment concept. A PZT patch actuator is adhered to an experimental tank partially filled with water. Broadband white noise is introduced to the tank through the actuator. The Frequency Response Function is computed from the FFTs derived from the sensor and monitor signals. In actual implementation, up to 8 sensors can be distributed across the tank and sampled simultaneously.

Fig. 2.

Experiment Schematic. PZT sensors convert structural vibrations to millivolt analog signals that are amplified and digitized by a data acquisition system. Real-time FFT and FRF calculations identify resonant modes and track mode shifts during propellant transfer. PVT calculations, optical flow sensors and liquid level indicators provide independent measures of instantaneous fill levels in each tank.

Fig. 3. Flight rig for the MPG experiment. The two central COPVs each have a capacity of 10 L and can be swapped out for clear polycarbonate tanks for correlating MPG resolution with slosh.

Fig. 4. Modal Response of Settled 1-g Scale Model Tanks. Lowest mode response is shown for 15 fill fractions between 10 and 31%. Peaks are resolvable at sub 1.0% resolution in this range of fill fractions. Each curve is an average of five FRFs calculated from five 10-s time series.

Fig. 5. Lowest Mode Frequencies and fill fraction under 1-g lab conditions. The propellant simulant is in equilibrium. Error bars on mode frequencies represent the standard error in five measurements. Error bars on fill level are 0.25% and result from limitations in the independent estimation of liquid levels.

Fig. 6.
LOESS Fit of Zero-g FRFs. Curves correspond to the indicated fill fraction. Slosh significantly reduces the sharpness of modal peaks. Each curve represents an average of five parabolae, each producing a single 10-s time sample.

Fig. 7.

1-g and 0-g Lowest Mode Frequencies vs. Fill Fraction. Error bars on flight data represent standard errors in measurements of five parabolas at each fill fraction.

Fig. 8. Orion ESM QM Tank. The tank volume is approximately 2250 L. The QM tank has both the slosh baffles present in the ESM “upper” FM tank, as well as the PMD present in the “lower” FM tank.

Fig. 9.
Grid comparison characterized by fill level as a function of frequency.

Fig. 10.
Modal frequency as a function of fill fraction for the first, fourth and sixth mode.

Fig. 11.
Mode shapes for the first (left), fourth (middle) and sixth (right) modes for the empty tank fill level ($h = 0$).

Fig. 12.

RMS Output of Sensor Orion QM Tank. Amplitude jumps as liquid drops below sensor. Gauging accuracy depends on estimation of transition time across sensor. The dotted horizontal lines represent the upper and lower extent of the sensor (in units of contained mass at the location of the sensor's top and bottom). Vertical lines represent the extent of the transition zone through which the RMS output of the sensor changes as the liquid level drops across it. The slanted line indicates the mass of the contained liquid during the drain.

Fig. 13.

Sensor Output, Contained Mass, and Tank Pressure. These data were taken on the Orion ESM QM Tank during drain cycling between 480 and 680 kg of water. The tank is initially filled at a constant rate from 480 to 680 kg, and then drained in steps back to 480 kg. Ullage pressure in the tank is measured at the top port.

Fig. 14.

M_2 vs. contained mass across a 200 kg drain cycle of the Orion ESM QM tank from 1600 to 1400 kg. The linear fit line has slope -0.96 .

Acta Astronaut. Author manuscript; available in PMC 2020 June 01.