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Modal Propellant Gauging in Low Gravity

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Abstract

We present results from parabolic flight testing of a low-gravity propellant gauging technology that relies on detection of resonant acoustic mode shifts due to changes in the tank's effective mass as liquid propellant is removed from the tank. The modal propellant gauging (MPG) method is shown to be (1) relatively robust against sloshing, (2) of comparable effective resolution to existing gauging methods for settled propellant, and (3) particularly robust at low fill-fractions where conventional gauging methods are known to be inaccurate. Lab (1-g) measurements of gauging resolution show no more than a 1.0% error for fill-fractions between 10–50% of total tank volume. Data for sloshing liquids in zero-gravity suggest an error of no greater than 1.5% over the same range of fill fractions. An algorithm for the real-time identification of modal response behaviors in zero-g is presented and demonstrated to accurately associate zero-g frequency response functions with the equivalent 1-g FRF, allowing for the automated assignment of fill levels. Gauging applications for small satellite missions and for propellant transfer operations in orbital fuel depot concepts are considered.

I. Introduction

Mission architecture studies of long-duration spaceflight programs have identified propellant mass gauging as a “critical-path” technology.¹ Also on the critical path for a sustained human presence beyond LEO are on-orbit propellant storage facilities, which will require robust and accurate propellant gauging and metering.² Low-gravity gauging is also essential to reducing launch mass, extending mission lifetimes, and affording compliance with international requirements regarding end-of-life (EOL) deployment of satellites to graveyard orbits.³

Low-gravity gauging technologies in wide use include those that depend on bookkeeping, equations of state, and thermal mass estimation. Bookkeeping methods employs flow rate monitors or, often, just as assumptions about flow rates during thruster firings, to estimate the total amount of propellant consumed over time. Such methods accumulate error over time and therefore introduce growing uncertainties in the estimate of remaining propellant mass and resulting estimation of EOL.⁴

Equation of State methods rely on the inference of the liquid volume fraction within a tank pressurized by an external pressurizing gas (usually, Helium) based on measurements of

pressure and temperature and the application of the ideal gas law (or other appropriate equation of state) to the ullage gas. In the PVT approach, the tank is considered isothermal, and method accuracy depends in part on the validity of this assumption. As in the case of bookkeeping methods, propellant mass estimates derived from applications of PVT methods are increasingly inaccurate at lower fill fractions, resulting in reduced accuracy near EOL.⁵

Thermal mass estimates rely on measurements of the temperature change induced in a propellant tank by external heating. Thermal response is compared to simulation results based on a tank-specific thermal capacitance model computed over a range of fill fractions. The uncertainty of propellant mass estimates based on TPG methods depend sensitively on the sophistication and fidelity of the tank thermal model.⁵

In addition to low-gravity methods, settled propellant levels may be estimated using capacitance probes and various versions of impedance sensors. These electrical measurements are performed on settled liquids and are therefore used only during thrusting maneuvers and are subject to error induced by adhered liquid on sensors. A complete review of extant gauging technologies, their flight heritage, and their limitations is provided in the work of Dodge.⁴ Each family of methods has relatively reduced accuracy at low tank fill fractions and therefore propellant gauging is a limiting factor in the estimation of EOL. Error estimates on most gauging methods range from 1% to 20% or more. For example, errors in the computed estimate of consumed propellant via the bookkeeping methods are typically around $\pm 3.0\%$.⁵ Adding additional propellant mass to account for gauging errors can result in significant launch costs and/or reduced mission life.

Zimmerli *et al.* have demonstrated low-gravity gauging of propellant levels using a radio frequency probe to measure electromagnetic eigenmodes for a tank containing a dielectric fluid.⁶ Zimmerli achieves a $\pm 1\%$ gauging accuracy for settled liquids under normal gravity but significantly lower accuracies for sloshing liquids in low-g fields.

In the work reported here, we introduce a complementary method of low-gravity propellant gauging that relies on realtime modal analysis of acoustic resonances in a propellant tank. The Modal Propellant Gauging (MPG) approach has the advantage of increased accuracy at low propellant fill fractions, is effective in both settled and sloshing propellants, and does not employ invasive hardware. Additionally, lab and parabolic flight testing suggest that the MPG method has gauging resolutions that are better than bookkeeping and PVT methods and comparable to the best TPG methods at low fill fractions, with gauging resolutions approaching 1.0% for settled propellant and 1.5–2.0% for unsettled (sloshing) propellants.

II. Modal Analysis

Experimental Modal Analysis is a standard technique in the evaluation of structures and their response to external driving forces such as vibration. The goal of EMA is to introduce broad band source of vibrations into a structure and record the resonant response of the structure. The resonant response comprises the spectrum of resonant frequencies (modes) and the corresponding patterns of deformation in the structure (mode shapes).

The acoustic forces applied to the structure can be in the form of discrete impacts, continuous functions, or chirp functions. In the present experiment, we use low amplitude broad-band white noise across a spectral range from 100Hz through 10kHz to drive structural resonances in a model tank. By introducing broadband white noise to the surface of a model propellant tank, we ensure that the full set of structural resonant frequencies is present within the applied signal. Therefore, natural vibrational modes of the structure are excited resulting in an increased amplitude in sensor response at the excited mode frequencies.

Resonant modes are obtained by computing a transfer function from the acoustic responses of the structure at different points on its surface. In our case, we compute frequency response functions (FRFs) from vibrational responses at three different locations on a model tank. The FRF at a given location is the ratio of the Fast Fourier Transform (FFT) of the response signal at the sensor location to the FFT of the signal at a reference location chosen to be physically close to the actuator providing the white noise input. The reference signal is provided by a “monitor” sensor. In this way, the FRF shows distinct spectral peaks at the locations of the active resonant modes.

We denote the time series recorded by the monitor sensor as $x_0(t)$, and the time series recorded by the i -th ($i = 1, 2$) sensor as $x_i(t)$. The Fourier Transforms of these voltage signals in frequency-space are denoted by $X_i(\omega)$. In terms of the transforms, the FRF of the i -th sensor data is computed according to

$$H_i(\omega) = \frac{X_i(\omega)}{X_0(\omega)}. \quad (1)$$

$H_i(\omega)$ is a complex valued function and the utility of any particular representation of the FRF is often model-dependent. However, for lightly damped systems like the model tank considered here, the imaginary component of $H_i(\omega)$ shows clear peaks at the frequencies ω_k of the resonant modes and so we consider only the imaginary components of the $H_i(\omega)$ spectra in this paper. The experimental concept implementing the real-time acquisition of FRF spectra from a partially filled propellant tank is illustrated in Fig. 1. For clarity, only a single sensor/monitor pair is illustrated in Fig. 1.

Data from multiple sensors ($n - 2$) can be used to reconstruct geometric properties of the tank. In our case, we are less interested in the known geometric properties of the tank than in tracking frequency shifts of its primary vibrational modes. For this reason, we consider here only the mode frequencies and not the mode shapes.

III. Fluid-structure Interactions

The modal effective 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 effective 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 contributions participate strongly in the structural response to excitation while modes with low effective mass contributions 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 resonance peaks with tank fill-fractions, even under sloshing conditions, as we demonstrate in Section V.

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.⁷ 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 2–3 modes because we are interested only in frequencies below f_c . We therefore expect that, in accord with Eq. 2, fluid mass-loading will have the effect of lowering the resonant mode frequency.

That we obtain unique correlations between liquid volume and resonant mode frequencies even in zero gravity follows from the fact that liquids in solid containers in zero gravity wet the container surface completely with a contact angle of zero. At sufficiently low fill fractions, the tank volume is occupied by vapor with all of the liquid adhered to the inner surface of the tank. In this way, the liquid layer contributes to the effective mass of the tank.

IV. Experiment Design

The MPG testbed consists of two one-gallon cylindrical steel tanks connected via a flow loop with solenoid valves and pumps to transfer metered quantities of water between the tanks. The tanks are 14.5-in in length and 4.5-in 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.

Each tank is outfitted with three PZT sensors and one PZT actuator that applies the low-amplitude white noise signal to the tank surface. Two of the sensors are located at empirically determined locations chosen to avoid nodes in the primary modes of interest. The third sensor serves as the monitor and is located adjacent to the actuator. The monitor

signal acts as the reference or input signal for the computation of the FRF as it faithfully reproduces the actuator signal without introducing structural resonances.

The tanks used in the present study have lowest-mode resonances of around 760 Hz and we record resonant modes up to 1500 Hz for the purposes of identifying fill levels. Sensor data are sampled in one-second windows of 40 kSamples/second, yielding a frequency resolution of 1.0 Hz. The sample rate of 40kHz is more than 26 times the Nyquist frequency, providing assurance that modal peak parameters can be reasonably extracted and fit to models. FRFs are computed in real-time for each pair of sensor and monitor outputs. The process of identifying the fill level from a measured FRF is automated through the use of cross-correlation analysis with laboratory data as described in Sec. VI.

A schematic overview of the experiment design is shown in Fig. 2 and the flight rig itself is shown in Fig. 3

V. Results

A portion of 1-g laboratory data obtained for non-sloshing liquids at fill levels between 10% and 31% is shown in Fig. 4. Note that the FRF peaks for fill levels separated by less than 2% of the total fill-volume are easily distinguished. The peaks in the range indicated are high-Q resonances and are separated from adjacent peaks at the same fill level by an anti-resonance. In the range considered in Fig. 4 we observe *light modal coupling* (low modal density), indicating that peak detection and isolation is possible. Simple structures such as cylinders and spheres will all exhibit a range of modal frequencies in the light coupling regime.⁸

The data in Fig. 4 are in qualitative agreement with the principle that mode frequencies scale with effective mass components according to $\omega_k \propto m_k^{-1/2}$. The n effective modal mass components m_k must satisfy $M = \sum_k^n m_k$ where M is the total mass of the system. However, the m_k are not equal and so we cannot expect that the mode frequencies are simply related to the total mass according to $\omega \propto M^{-1/2}$. Further, there are significant geometric contributions to modal frequencies that alter the simple dependence of Eq. 2 for structures like our tank. These effects are most pronounced near the hemispherical caps where weld seams introduce nodes into the mode shapes. We do however find that the mode frequencies are a function of the total system mass and this relationship is demonstrated in Fig. 5.

To investigate the efficacy of the MPG technology in low gravity, our team carried out a parabolic flight test program spanning 180 zero-gravity parabolas. Parabolic flights were carried out aboard NASA's modified C-9 Parabolic Aircraft at Ellington Airfield through the Johnson Space Center Reduced Gravity Office and aboard the Zero G Corp. B727-200. Parabolic flights afford approximately 20 seconds of zero gravity per parabola. The settling time for the liquid in our model tanks far exceeds the 20 second limit and so the tanks never "settle." Instead, the liquid continues to slosh chaotically throughout the parabola, presenting a time-varying contact fraction between tank and liquid. A central objective of the parabolic flight testing was to determine whether sloshing would attenuate, shift, or destroy the tanks' resonances. A second objective was to assess the gauging resolution of the MPG approach under sloshing, non-equilibrium conditions.

Shown in Fig. 6 are a selection of FRF data between 10% and 16% fill fractions for both flight and lab (1-g) measurements. The data in Fig. 6 suggest that gauging resolutions of at least 1.5% can be obtained even in zero-g, unsettled conditions. While the parabolic flight data are considerably noisier and subject to greater variability in peak amplitude and sharpness, low fill fractions are still consistently resolvable and distinguishable at frequency resolutions of at least 1.5%. In zero g, sloshing liquid results in variable contact area between tank walls and liquid. We suggest that this variability is responsible for the peak-broadening observed in the 0-g data.

VI. Algorithmic Determination of Fill Fraction

In order to automate the process of identifying fill fractions through modal frequency information, we have designed and implemented software that performs the following operations.

To account for the variability introduced by sloshing zero gravity, we average five FRFs over one-second windows to produce a single FRF per fill-fraction. The zero-g FRF is smoothed via the application of a Savitzky-Golay filter which increases the signal/noise ratio without significantly modifying the signal.⁹

The flight software then performs a cross-correlation search with a library of 1-g FRF data taken at 1% fill increments and determines the best-fit 1-g FRF for the averaged flight data. We represent the portion of the averaged and filtered zero-g FRF near the lowest resonant mode as the discrete series $H_n^0(\omega_n)$ where n spans the range of $N = 200$ Hz around the mode frequency of interest. Similarly, the set of all 1-g FRFs is represented by the set of discrete series $H_n^1(\omega_n)$. The biased cross-correlation measure is computed according to

$$c_{01}(m) = \frac{1}{N} \sum_{n=0}^{N-m} H_{n+m}^0(\omega_{n+m}) H_m^{1*}(\omega_m) \quad m \geq 0. \quad (3)$$

Cross-correlations are computed for each pair of zero-g and 1-g response functions and a match is determined by identifying the maximal value of c_{01} from among those with p-values of $p = 0$.

Peak extraction determines the modal frequency associated with the associated ground data and the correlation analysis provides the uncertainty in the fit. This method can be carried out essentially instantaneously and produces positive correlation coefficients with p-values of $p = 0$ in almost all cases.

VII. Summary

Propellant gauging in low gravity is a critical-path technology for sustained human presence in deep space. Further, the lack of robust low-gravity gauging methods generates significant added costs to satellite mission plans.

We have demonstrated here that low-gravity gauging of unsettled propellant in cylindrical tanks may be accomplished through the measurement of acoustic surface modes in a partially filled tank with gauging resolutions that match current methods for settled propellant. The approach discussed here shows high gauging resolution at relatively low fill fractions (10 – 30% of full tank volume) and does not require settling burns. The MPG approach has the additional benefits of being inexpensive, consumes modest power, and introduces very little additional mass to the propellant system.

Not considered here are the effects of pressure on the modal signature of a propellant tank. Our experiments were conducted at pressures within a few psi of atmospheric (or aircraft cabin pressure). Propellant tanks under pressure will experience mode shifting relative to their unpressurized modal spectra. These shifts are quantifiable and do not present a challenge for implementation of MPG. Also not considered here are temperature effects resulting from the use of cryogenic propellants. As with pressure effects, temperature effects on tank-wall stiffness produce measurable shifts in resonance spectra and can be quantified in a straightforward way. There are limitations to the use of cryogenics on parabolic aircraft that prevent straightforward testing of MPG with cryogenic propellant simulants. However, MPG tests with cryogenic propellant simulants are underway at Kennedy Space Center to quantify the effects of both operational pressures and temperatures on modal spectra. In addition, future work focuses on extending the MPG approach to accommodate real-time gauging of propellant transfer operations for on-orbit propellant depot applications.

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Nomenclature

f_c	Critical frequency for fluid mass-loading to affect mode frequencies
i	sensor number
k	mode number
$H(\omega)$	Frequency Response Function
M	System mass
m_k	Effective modal mass element of the k th mode
N	sample length of discrete time series
ω	Frequency, Hz
$X_i(\omega)$	Fourier Transform of time series $x_i(t)$
$x_i(t)$	Time series recorded by i th PZT sensor

Subscript

i	PZT sensor index
k	Mode index
m, n	frequency index

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Figure 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.

Figure 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.

Figure 3.
Flight rig for the MPG experiment.

Figure 4.

1-g Frequency Response Functions recorded for liquid in equilibrium with a vertical cylindrical tank. Fill fractions range from 10% to 30% in 1.5% increments.

Figure 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

Figure 6.
Lowest Mode Frequencies and fill fractions. Both lab and flight (0-g) data are shown.