Microgravity Propellant Gauging Using Experimental Modal Analysis

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Introduction

Microgravity propellant gauging is a critical-path challenge in the space flight industry.

- Communications satellites are dependent on reliable measurements of propellant volume to determine operational lifetime
- By international agreement, satellites are required to have enough propellant to send them into a “graveyard” orbit
- Satellite launch costs average over $10,000 per pound

Propellant Gauging in Microgravity

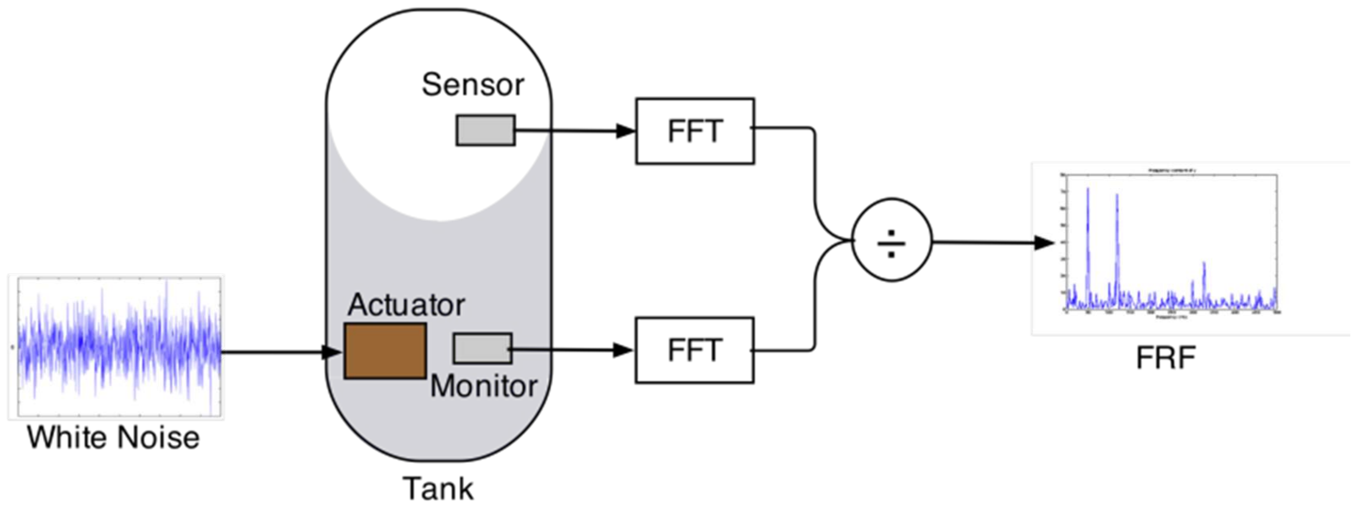
Conventional methods for gauging liquid propellant volumes are ineffective in microgravity.

- Spacecraft must rely on indirect techniques, including equation-of-state estimations, settled gauging, and burn-time integration
- These methods have significant uncertainties leading to increased mission cost, decreased spacecraft lifetime, and reduced mission capabilities

We are developing a non-invasive fuel gauging technology based on the real-time measurements of a tank's acoustic resonant modes

Experimental Modal Analysis

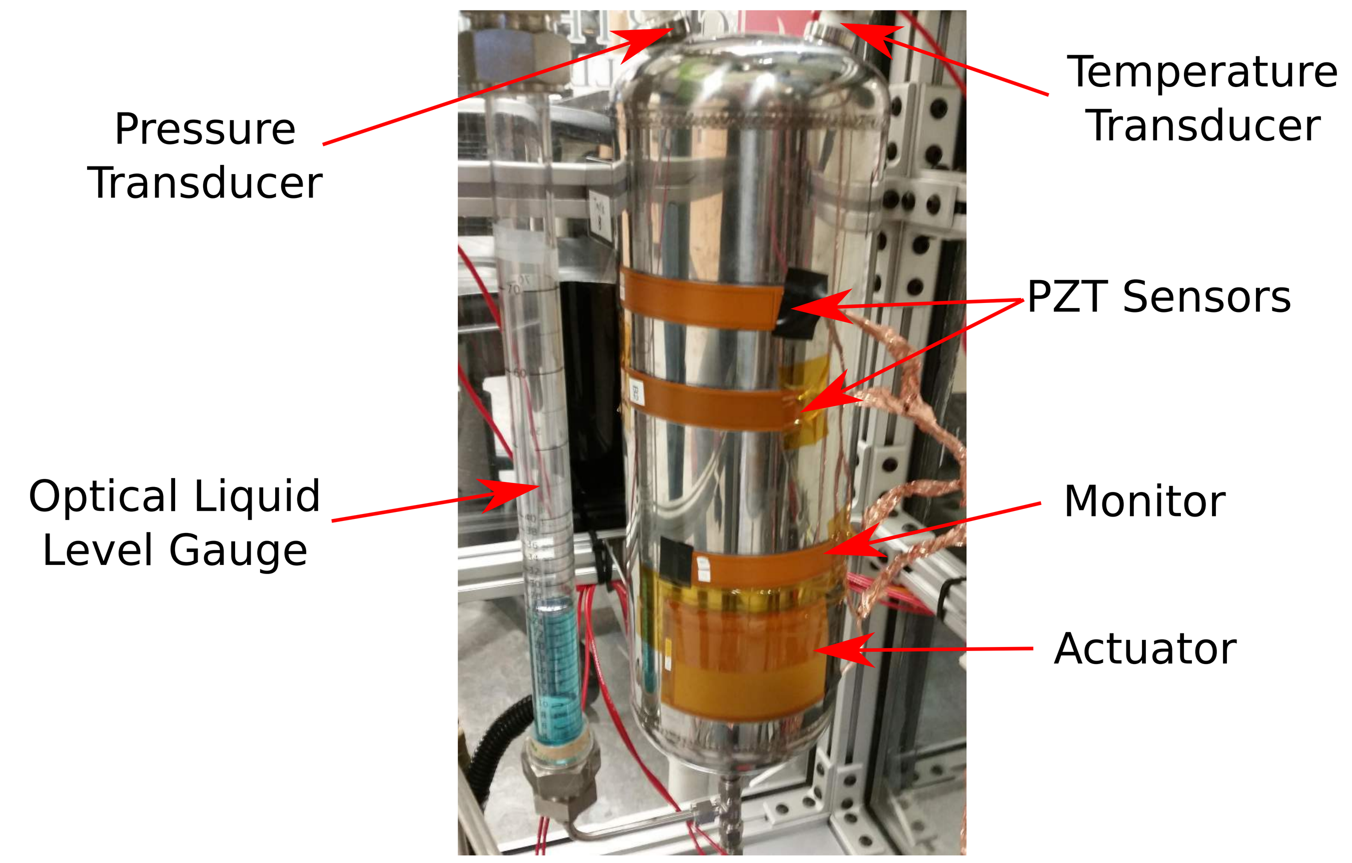
Experimental Modal Analysis (EMA) is a standard technique in structures characterization and analysis. EMA involves recording the vibration spectrum of a solid object and using the spectral characteristics to infer structural properties of the object. In our experiment, we stimulate all acoustic resonances of a model tank by applying a broad-band white noise signal.



A piezoelectric (PZT) actuator, driven by the white noise signal, vibrates the propellant tank, while additional PZT sensors record the tank's response at multiple locations. A Frequency Response Function (FRF) is computed to determine the resonant frequencies, or modes, of the tank. The FRF is computed as the ratio of the Fast Fourier Transform (FFT) of an output signal to the FFT of an input signal. The FRFs show that the tank's resonant modes shift to lower frequencies as the tank fill level increases.

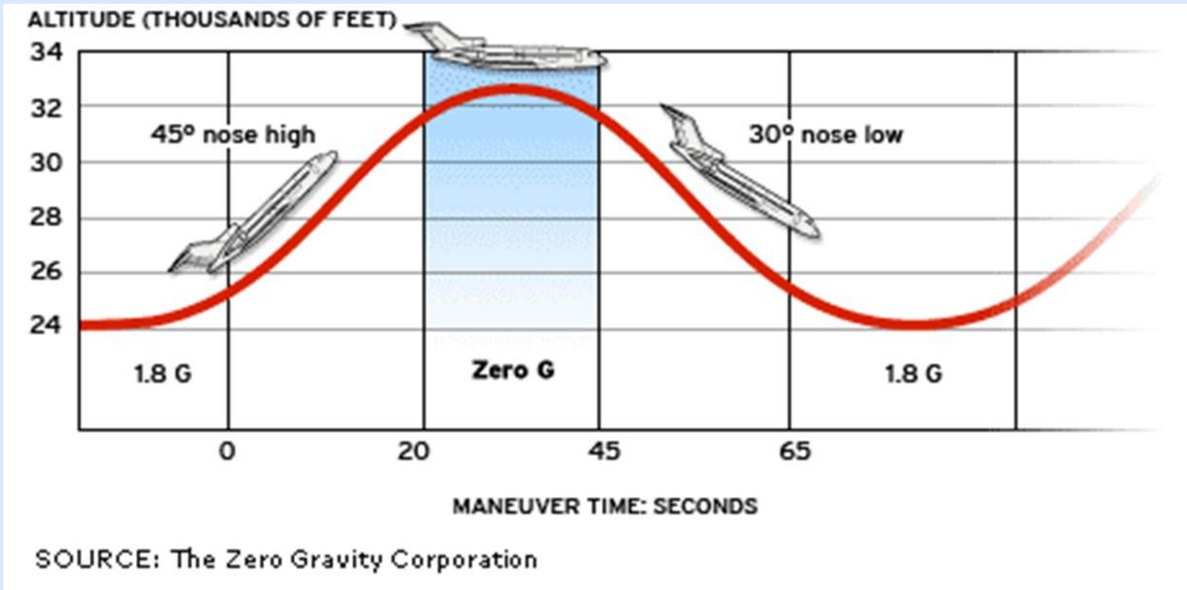
Parabolic Flight Experiment Design

- Two one-gallon stainless steel tanks filled with water as propellant simulant
- Pressure and temperature transducers attached to the top of each tank to independently measure tank volume
- Clear liquid level gauges on each tank allow for visual determination of tank volume



- Rig composed of an aluminum frame with Lexan walls houses experiment
- Laptop mounted on top of rig to control experiment in flight; additional monitor to display data in real-time
- Single button press required each parabola, otherwise autonomous

Parabolic Flights



Flight days:

- June 9th-12th, 2015 aboard NASA's C-9 "Weightless Wonder"
- February 25th & 27th, 2016 aboard Zero G's "G-Force One"

Results

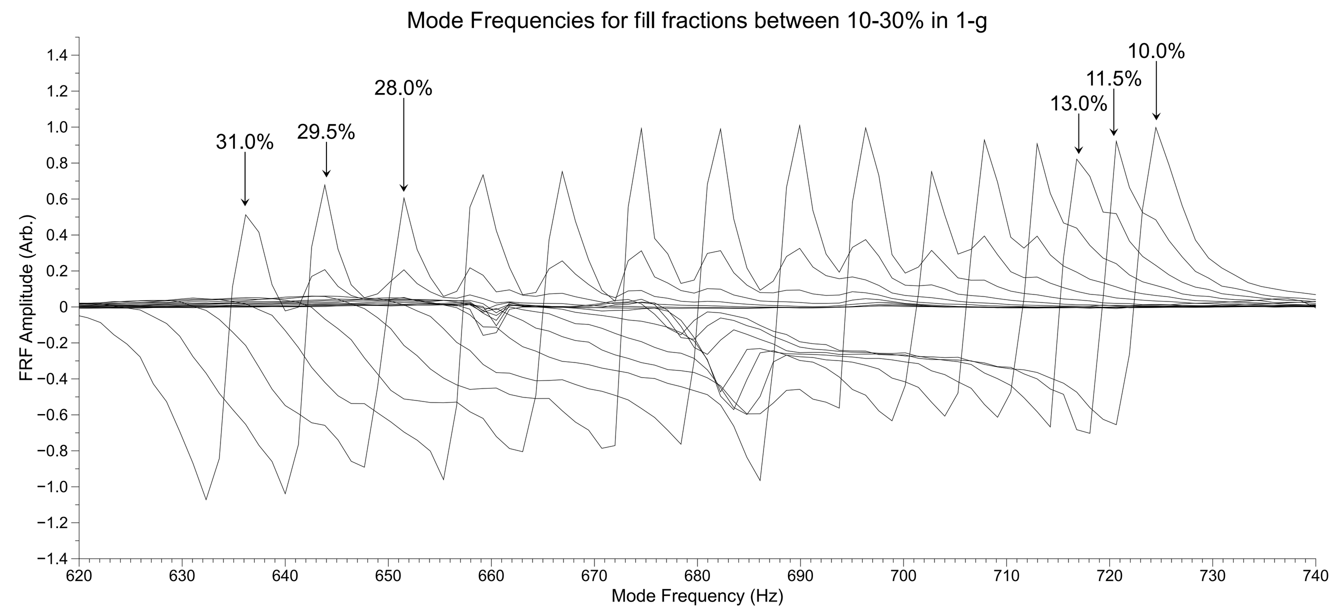


Fig. 1: Selected FRF data for fill levels between 10 and 31% of the tank volume in 1-g.

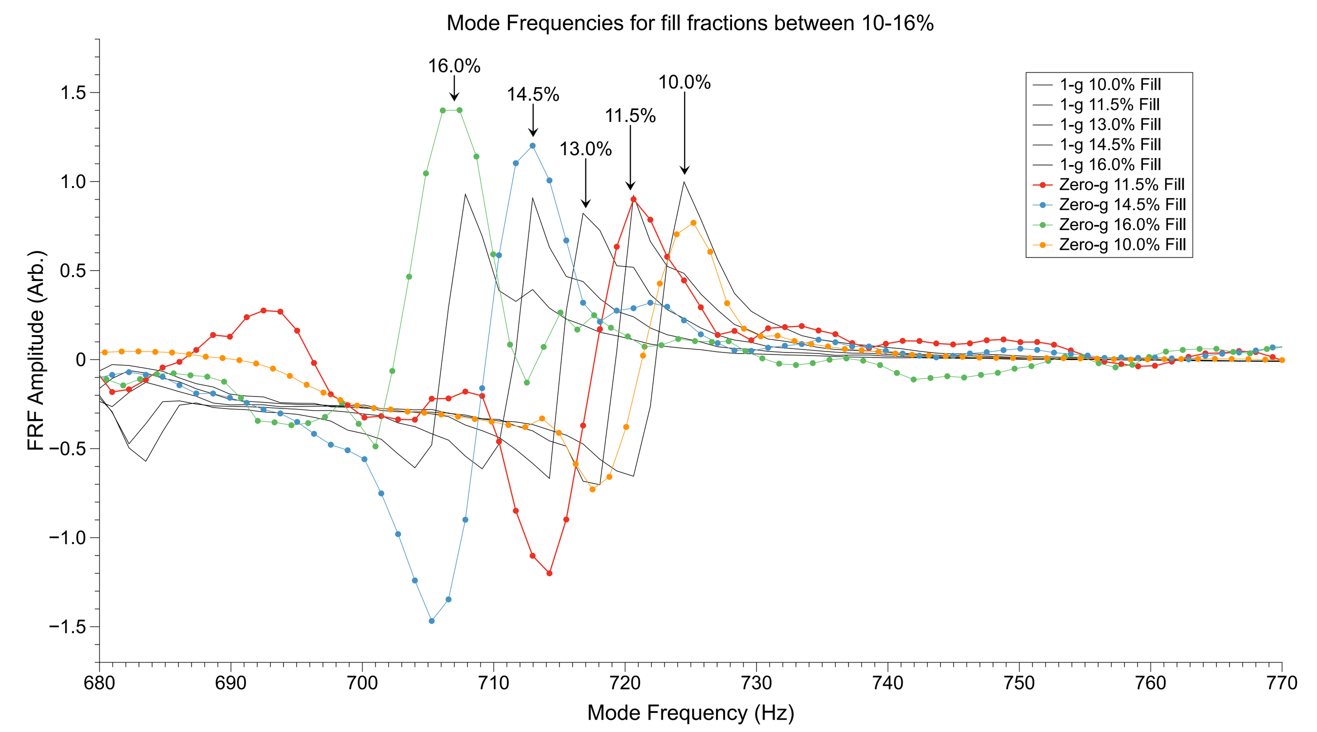


Fig. 2: Lowest Mode Frequencies and fill fractions. Both lab and flight (0-g) data are shown.

- An algorithm for the identification of modal response behaviors in 0-g was developed to accurately associate 0-g FRFs with the equivalent 1-g FRF, allowing for the automated assignment of fill levels
- Fig. 2 shows FRF data between 10% and 16% fill fractions for both flight and lab (1-g) measurements
- The data in Fig. 2 suggest that gauging resolutions of at least 1.5% can be obtained in zero-g, unsettled conditions
- Although 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%

Future Work

Current work includes: (1) Improving independent volume estimation; (2) Addition of in-tank cameras to allow correlation studies of propellant slosh and FRF peak width; (3) Developing the MPG technology for cryogenic propellant simulants

Acknowledgements

We would like to thank Zero Gravity Corporation, the NASA USIP program, and the RGO Office at Ellington Field for providing the parabolic flights, the Wisconsin Space Grant Consortium for financial support, and previous Carthage Microgravity teams for their work on this experiment. Supported by NASA grant NNX13AR65G.