Tank Health Monitoring and Propellant Mass Gauging via Modal Analysis

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1.0 Introduction

My summer internship experience with NASA Kennedy Space Center's Advanced Engineering Development Branch (NE-L6) has been focused on collecting and processing data to aid in developing Modal Propellant Gauging (MPG) for use in future Orion/SLS missions. The MPG project is an effort to develop a non-invasive low-cost propellant mass gauging technology for application to existing spacecraft propellant tanks in both low-gravity and earth-loading applications.

2.0 Experimental Modal Analysis

Experimental Modal Analysis (EMA) involves recording the vibration spectrum of a solid object and using the spectral characteristics to infer the structural properties of the object. The EMA technique requires that all acoustic resonances in the tank structure are stimulated by applying a broadband white noise signal. Tank response is measured at discrete locations on the surface of the tank and the Fourier Transforms of the response and input functions are computed in real-time. Finally, the Frequency Response Function (FRF) for each structural response is computed by taking the ratio of the response FFT to the input FFT. The resulting FRF is a complex-valued function in which the real part is a function of the effective mass of the vibrating object and the imaginary part is related to the rate of energy dissipation through structural damping. Adding fluid to a tank lowers the real part of the frequency by increasing the effective mass. In addition, fluid in a closed tank changes the imaginary part of the frequency by damping the vibrations.

3.0 Estimating Propellant Mass from Discrete Fill Calibration Curve-Fit

3.1 Experiment Setup

Myself and intern Ethan Woller were given a data acquisition unit (DAQ), a white noise generator, an amplifier, a scale, and a small linerless composite tank fitted with 5 piezoelectric (PZT) sensors to perform modal analysis, as shown in Figure 1. Sensor 1 functioned as the actuator, exciting the walls of the tank. Sensor 3 functioned as the monitor, recording the input signal and Sensor 4 served as a true sensor, recording the input signal and the modal response of the tank. We filled the tank in discrete 5% increments and wrote data from the PZT sensors to MATLAB to later perform FRFs. Once the tank had been filled we drained the fluid into a large bucket atop a scale at a continuous rate and wrote the time-stamped scale readings to MATLAB. The time-stamped raw sensor data was aligned with the scale data and used in the analysis discussed in Section 3.2.

3.2 Results

To perform modal analysis on the tank I wrote MATLAB programs to collect data from the DAQ, perform FRFs over varying durations of time, and to average the FRFs to reduce noise. I found that the lowest mode of the empty tank is around 1050 Hz and the lowest mode of the tank when filled is around 500 Hz, shown in Figure 4. I wrote a MATLAB program to find the lowest mode frequency responses for 20 different fill fractions at 5% tank volume increments. I then used the peak frequencies and corresponding fluid masses to generate a log-log mass-frequency plot to produce a calibration curve to estimate tank fluid mass during a continuous drain. To produce the calibration curve I found the equation of the linear best-fit produced from the log-log mass-frequency plot of a discrete fill in 5% increments for FRFs. In this linear fit the dependent variable represents the logarithm of frequency and the independent variable represents the logarithm of mass.

Data from a continuous drain test was collected and processed to produce 1-second FRFs and find corresponding peak frequencies and actual fluid masses to test the resolution of the calibration curve. The log of peak frequency for each fill level was processed and substituted as the dependent variable in the calibration curve equation. This equation was then solved for the dependent variable, the log of the estimated mass. The logarithm base, 10, was then raised to this value to determine the estimated mass. In Figure 3 below the estimate masses can be seen as the orange dots and the blue line represents the true mass of the system. The domed portion of the tank covers the first ten pounds (indicated via yellow line) and the last ten pounds (indicated via purple line). These portions are mentioned because the mass estimates in these regions are not accurate due to the change in tank geometry. The average resolution of this fit is +/- 3.18 %, or +/- 1.59 lbs. When only considering the region between 10-40 lbs, the average resolution is +/-2.32%, or +/-1.16 lbs.

4.0 Orion Use Case Analysis

The MPG technology is in consideration for propellant monitoring for future Orion/SLS missions. To assist in these considerations I analyzed an Orion-Gateway mission profile and determined the use-case of MPG within the mission structure.

4.1 Assumptions

My simplified analysis assumes the mission profile presented in "Options for Staging Orbits in Cis-Lunar Space", Ryan Whitley and Roland Martinez (1), represents current Orion plans. The following analysis assumes full Orion ESM prop tanks at first lunar flyby per Whitley/Martinez and assumes propellant and oxidizer drain at the same rate.

4.2 Analysis

The mission profile outlines four burns and corresponding delta-v's: Flyby I (178 m/s), Insertion (250.5 m/s), Departure (221.5 m/s), and Flyby II (190 m/s). This lends a total Orion-Gateway Earth-NRO transfer mission cost of 840 m/s. The burn-profile analysis assumes a total vehicle dry mass of 17000 kg, a useable propellant mass of 8685 kg, and a residual + contingency prop mass of 5% of the total propellant mass - 434 kg, for a total wet mass of 26119 kg. This burn-profile will also assume an ISP of 315 s, a maximum delta-V capability of 1250 m/sec, and a single engine thrust of 26089 N. Resulting burn times and total mass of propellant burned during the four events was calculated by myself and intern Ethan Woller through using the rocket equation and is presented in Table 1. I used these results to determine the burn rate per tank, 2.1 kg/sec. I produced a representation of the mission profile, events, and corresponding burn durations in relation to tank fill fractions that is shown in Figure 2.

4.3 MPG-Orion Use Case Recommendation

To generate a notional gauging plan for the mission profile, it is assumed that at least 1 GB of storage will be dedicated to modal/RMS data for each tank and 8 PZT sensors will be attached to each tank. A single cell of a CSV file contains 7 bytes of data, therefore 8 sensors collecting data at a sampling rate of 16384 samples/sec will write 917.56 KB per second. Each tank can then collect 1089 seconds of data if 1 GB of storage is dedicated to modal data for each tank. Data should be taken during burns to perform Root Mean Square Method calculations and data should be taken during static states between burns to perform SDM calculations. Collecting data during burns will require 737 seconds, leaving 352 seconds to take data during static states between burns. Static state SDM measurements should be made during settled states. Data should then be taken during the 5.1 day period between trans-lunar injection (TLI) and the first lunar Flyby to profile the behavior and frequency response of a full tank in zero-g. Data could also be taken during static states at 83.16%, 61.05%, 42.94%, and at 28.41%. The remaining 352 seconds would allow for 70 seconds of data to be taken at each of the five static fill levels.

5.0 Conclusion

In the second half of my internship I will be assisting in writing the algorithms to employ the Spectral Density (SD) Method of MPG. This method will allow for the use of MPG in pressurized tanks as the SD does not depend on pressure, unlike the current MPG method. The current SD method physically models the propellant tank as a single damped harmonic oscillator; to ensure this is an accurate assumption I will need to teach myself about state space modeling and control theory. Mastering these topics will allow me to make progress in ensuring that physically modelling the tank as a single damped harmonic oscillator is the correct approach rather than modelling the tank as a set of coupled damped harmonic oscillators.

Kennedy Space Center has provided an excellent premise to learn and grow through. I have enjoyed the first five weeks of my internship and look forward to the remaining five weeks.

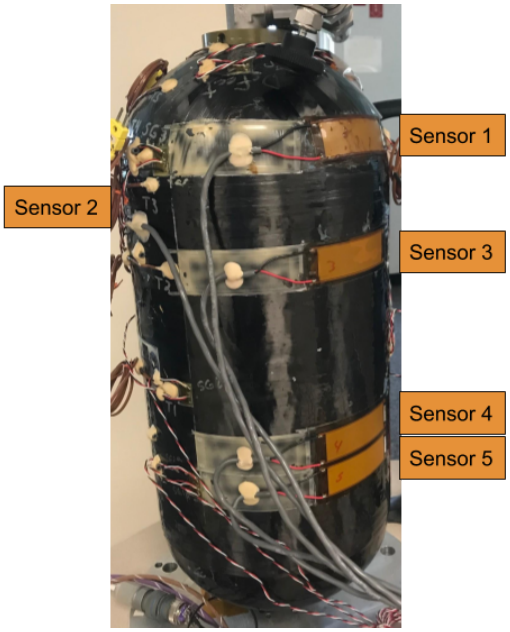

Figure 1. Tank Diagram

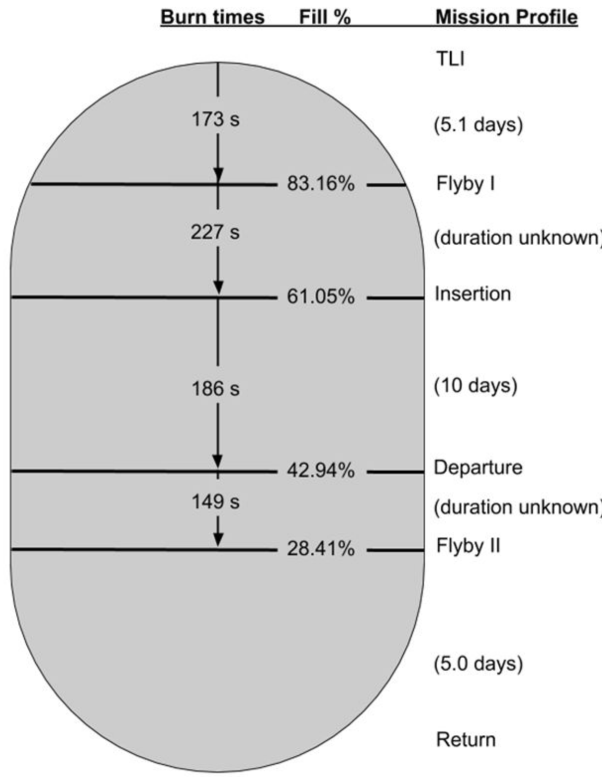

Figure 2. Mission Profile in relation to tank fill % - Dimensions to scale with Orion tanks

	Delta - V (m/sec)	**Total Prop Burned (kg)**	**Prop Burned/tank (kg)**	**Burn Time**
Flyby I	178.0	1462	365.5	173.2
Insertion	250.5	1920	480.0	227.4
Departure	221.5	1573	393.0	186.3
Flyby II	190.0	1262	315.5	149.5
Total	**840.0 m/sec**	**6217 kg**	**1554 kg**	**736.4 sec**

Table 1. Propellant and Burn Time Profile

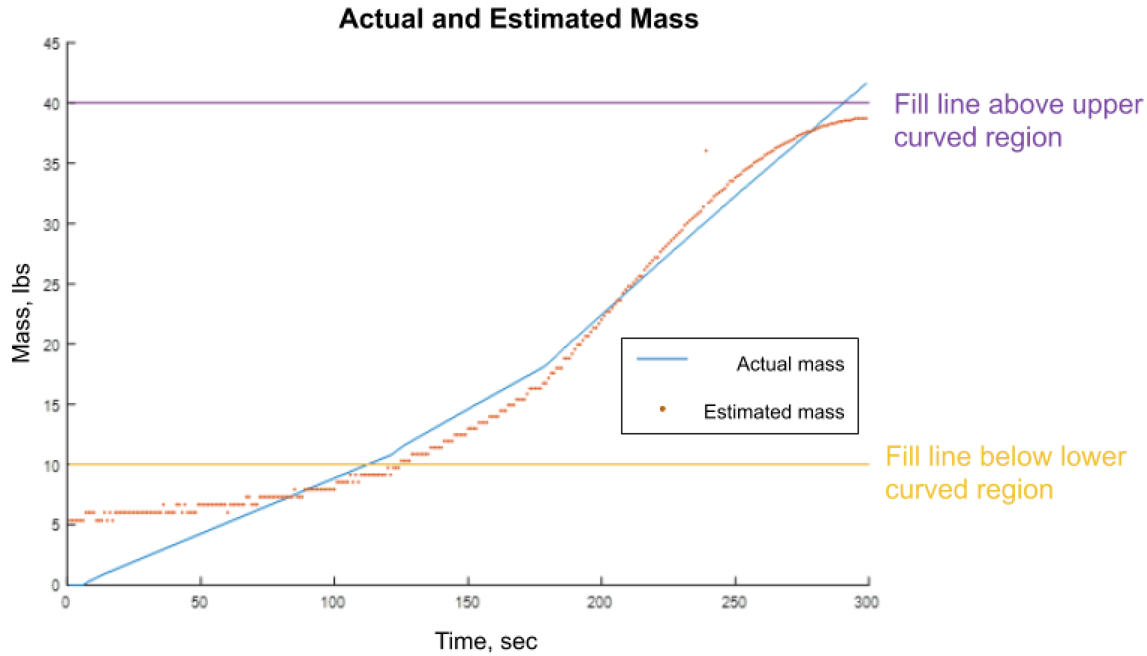

Figure 3. Actual and estimated mass of fluid within tank during a continuous drain test

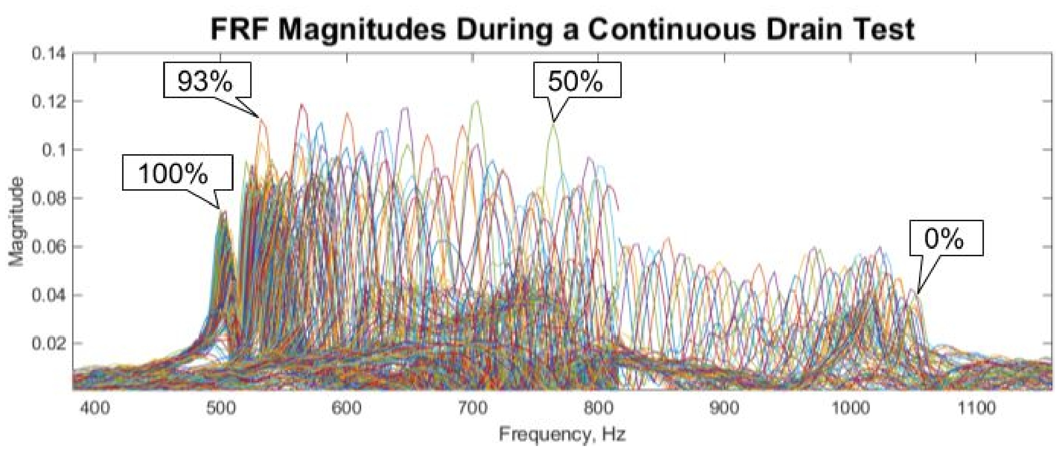

Figure 4. Processed FRFs, each averaged over 3 seconds in one second intervals during a continuous drain test

(1) Whitley, R., & Martinez, R. (2015, October 21). *Options for Staging Orbits in Cis-Lunar Space*. Retrieved July 1, 2019, from https://ntrs.nasa.gov/archive/nasa/.