Modal Evaluation of Fluid Volume in Spacecraft Propellant Tanks

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Introduction: Low gravity propellant mass gauging is identified in NASA's Exploratory Systems Architecture Study as a primary research challenge. The future of manned spaceflight beyond LEO relies in part on the development of accurate and robust methods of mass gauging in both settled and unsettled propellant states.

In the present study, we describe the use of experimental modal analysis (EMA) to infer fluid levels in model spacecraft propellant tanks in a microgravity environment provided by parabolic flights.

Modal Analysis Technique: EMA involves the application of acoustic forces to test structures. Natural resonances of the test structure are excited by the applied force, and sensors affixed to the structure record the amplitude of the acoustic response across the range of resonating frequencies.

Typically, EMA involves the computation of frequency response functions (FRF) to determine the resonant frequencies present at each sensor location. The FRF shows peaks at the frequencies where a sensor records a strong resonance that is not present in the spectrum of the input signal. Modal techniques can therefore be used as real-time diagnostics of structural properties. Fluid loading increases the effective mass of the loaded structure, resulting in a decrease in the structure's resonant frequencies.

Experimental Design: Our experimental rig consists of cylindrical steel tanks of diameter 15.3 cm, and total length including two spherical end caps of 48.3 cm. The tanks each have a capacity of two gallons. PZT sensors affixed to the surface of each tank record the vibrational response to the white noise signal presented to the tank surface via a PZT actuator. Fluid fill levels are independently calculated by means of both a flow totalizer and PVT methods. Water is used as the propellant simulant in all tests.

Results: The fundamental resonance at representative fill fractions with a settled fluid under 1-g lab testing is illustrated in Fig. 1. The structure's effective mass increases with fluid load, resulting in a continuous decrease in the frequencies of tank resonances.

In the reduced gravity of parabolic flight, fluid instabilities cause the fluid to slosh resulting in continual variation of the contact area between fluid and tank wall. As a result, the frequencies of resonant modes drift around their means with periods on the order of the average slosh period of 1-2 seconds. To compensate for this effect, we average over multiple 1.0 second FRF data windows. A set of sample averaged FRFs is shown in Fig. 2.

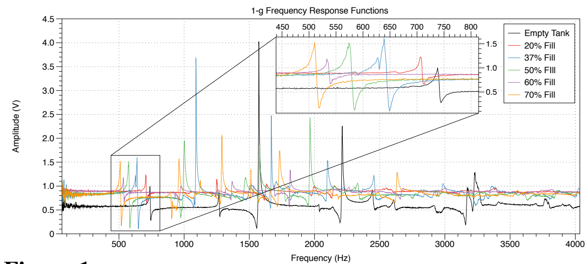

Figure 1: 1-g Frequency Response Functions recorded for settled fluid with tank in vertical position. Inset shows blow-up of fundamental mode and demonstrates the decrease of mode frequency with increasing fill-fraction.

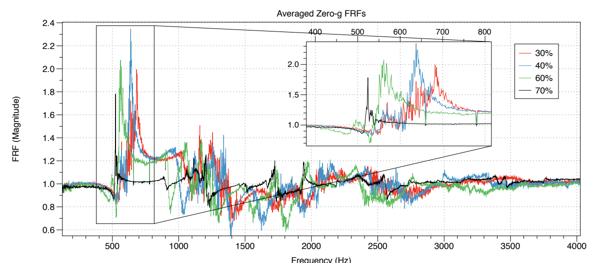

Figure 2: 0-g Frequency Response Functions. Inset shows blow-up of fundamental mode and demonstrates the decrease of mode frequency with increasing fill-fraction.

The resolution of the EMA technique in discriminating between fill fraction can be estimated from the summary data presented in Fig. 3.

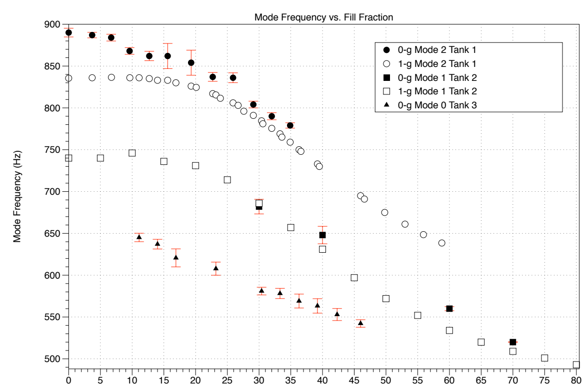

Figure 3: Variation of representative mode frequencies with fill fraction for both 1-g settled fluid configurations and 0-g slosh-averaged fluid. Error bars on the flight data represent standard error in the data, while error bars for the 1-g data are not depicted, but would be smaller than the data symbol.

The flight data in Fig. 3 have a typical frequency resolution that is better than 5% across fill fractions between 10% and 70%. Nodes in the tank structure near tank weld seams correlate well with a loss of resolution between fill-fractions.