Spectral mass gauging of unsettled liquid with acoustic waves

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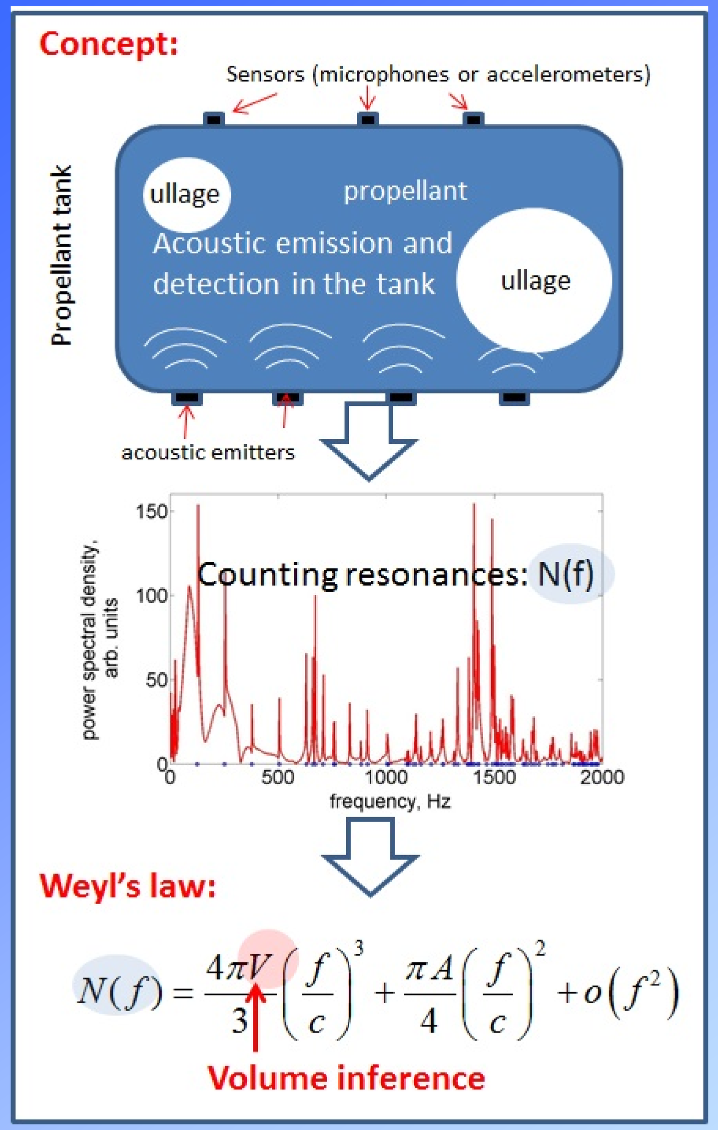

•Mathematical basis:

Weyl's Law relates the acoustic resonances counting function in a cavity to the cavity volume [1]

•Concept of mass-gauging:

1. Excite acoustic resonances in the ullage (or in the liquid);
2. Count the resonances up to a cut-off frequency f ;
3. Use Weyl's law to infer the volume

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[1] W. Arendt, R. Nittka, W. Peter, and F. Steiner. Weyl's law: Spectral properties of the Laplacian in mathematics and physics. In W. Arendt and W. P. Schleich, editors, Mathematical Analysis of Evolution, Information, and Complexity. Wiley-VCH, Weinheim, 2009.

Abstract: Propellant mass gauging is one of the key technologies required to enable the next step in NASA's space exploration program. At present, there is no reliable method to accurately measure the amount of unsettled liquid propellant in a large-scale propellant tank in micro- or zero gravity. Recently we proposed a new approach to use sound waves to probe the resonance frequencies of the two-phase liquid-gas mixture and take advantage of the mathematical properties of the high frequency spectral asymptotics to determine the volume fraction of the tank filled with liquid. We report the current progress in exploring the feasibility of this approach in the case of large propellant tanks, both experimental and theoretical. Excitation and detection procedures using solenoids for excitation and both hydrophones and accelerometers for detection have been developed. <3% accuracy for mass-gauging was demonstrated for a 200-liter tank partially filled with liquid for various unsettled configurations, such as tilts and artificial ullages.

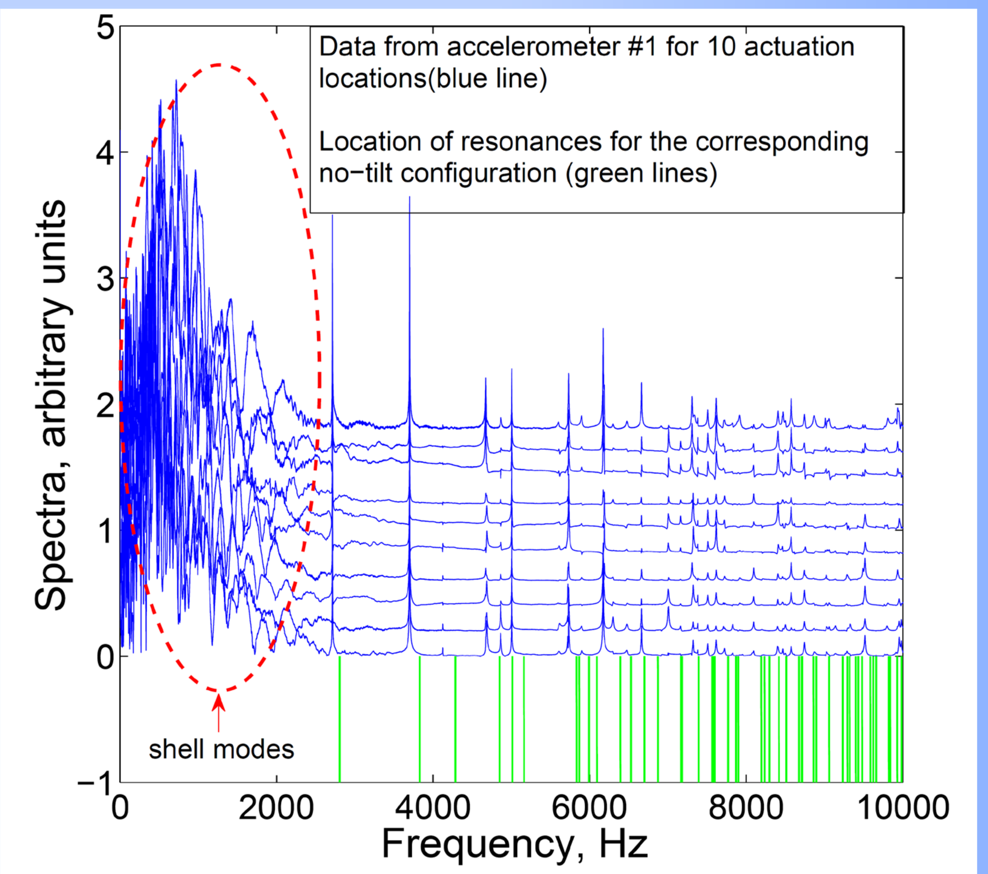

Fig.2. (a) Hardware used for liquid modes counting; (b) Actuation technique for the acoustic emission was developed using solenoid actuator . The solenoid actuator was attached to the tank wall from the outside and applied a short ping to excite acoustic resonances in the liquid compartment; (c-d) The detection was performed using accelerometers attached to the wall from the outside as well; (e-f) Measurements were performed on settled liquid and "unsettled", by either tilting the tanks or immersing air-filled balloons in the liquid.

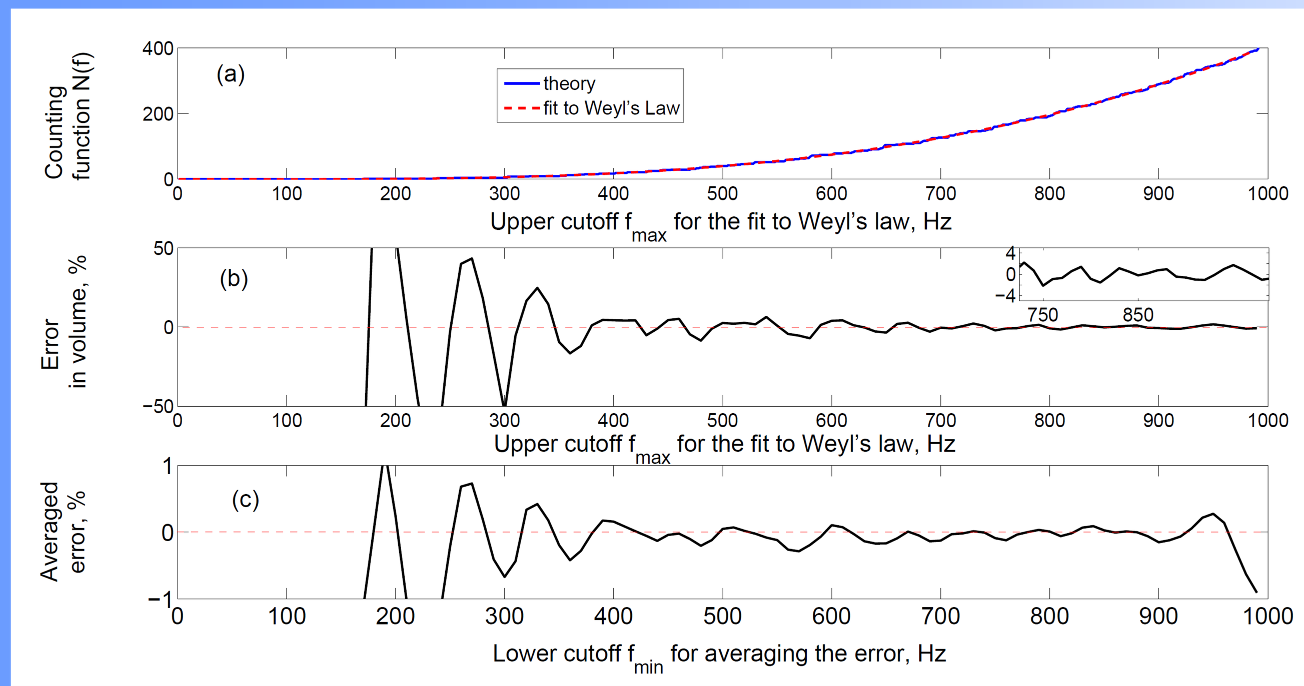

Fig.1. Model calculations: (a) Counting function for a cylindrical tank, R=2.5m, H=4m filled with LOx; (b)Error in inferred volume as a function of the cutoff frequency; (c) Averaged error in the range between a lower and upper cutoff as a function of the lower cutoff for f_{max}=1kHz. Error is seen to be <2% for N>300. Averaged error is <0.3%.

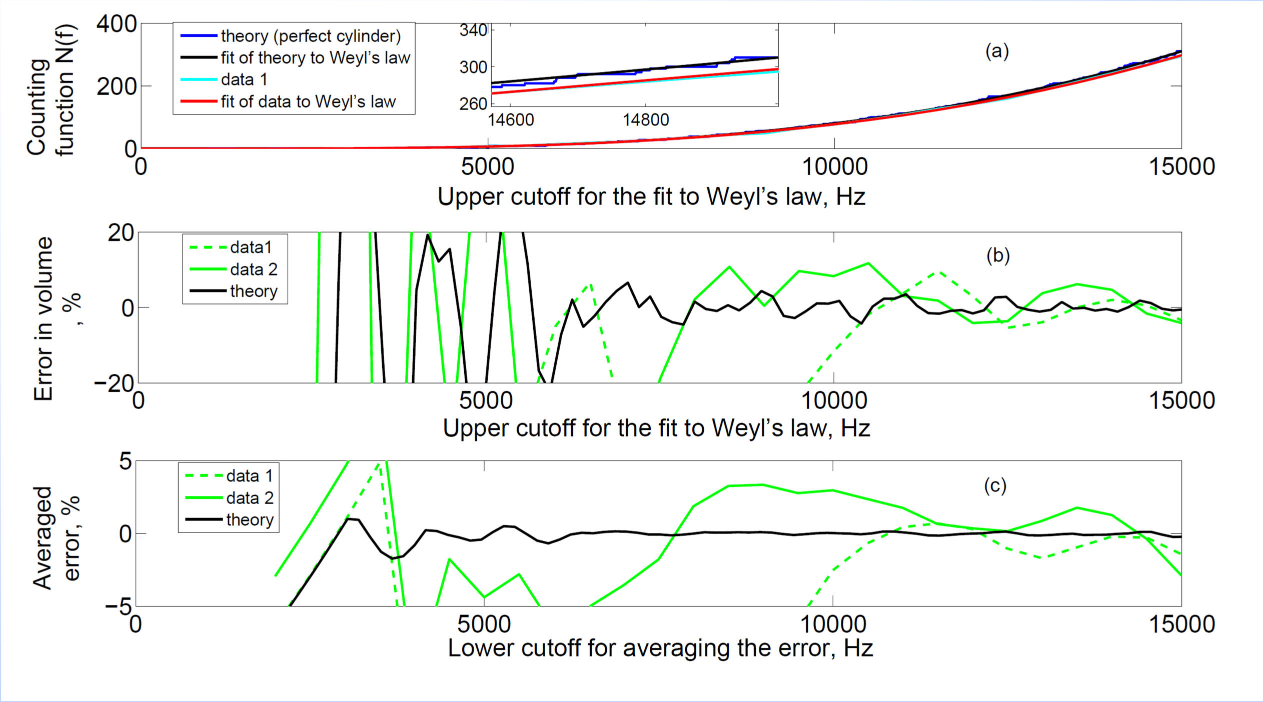

Figure 4. Data for 100 liters of water in the 200-liter tank, tilted by 18 degrees. 10 excitations locations have been used on the wall. Data 1 corresponds to detection by the hydrophone. Data 2 corresponds to detection by three accelerometers. Theory corresponds to ideally cylindrical shape of water in the absence of the tilt: (a) N(f); (b) the error in the inferred volume; (c) the averaged error for f_{max}=15kHz. Averaging over the oscillations produces the average error of < 3% for the volume estimation. The data are compared to theoretical calculations for ideally cylindrical shape of water in the absence of the tilt. Since 18 degrees is a small perturbation of the water shape the counting function is only slightly perturbed compared to the ideal case. On the other hand, we note that the variation of the error with the upper cut-off, Figure 3 (b), is significantly affected by the perturbation.

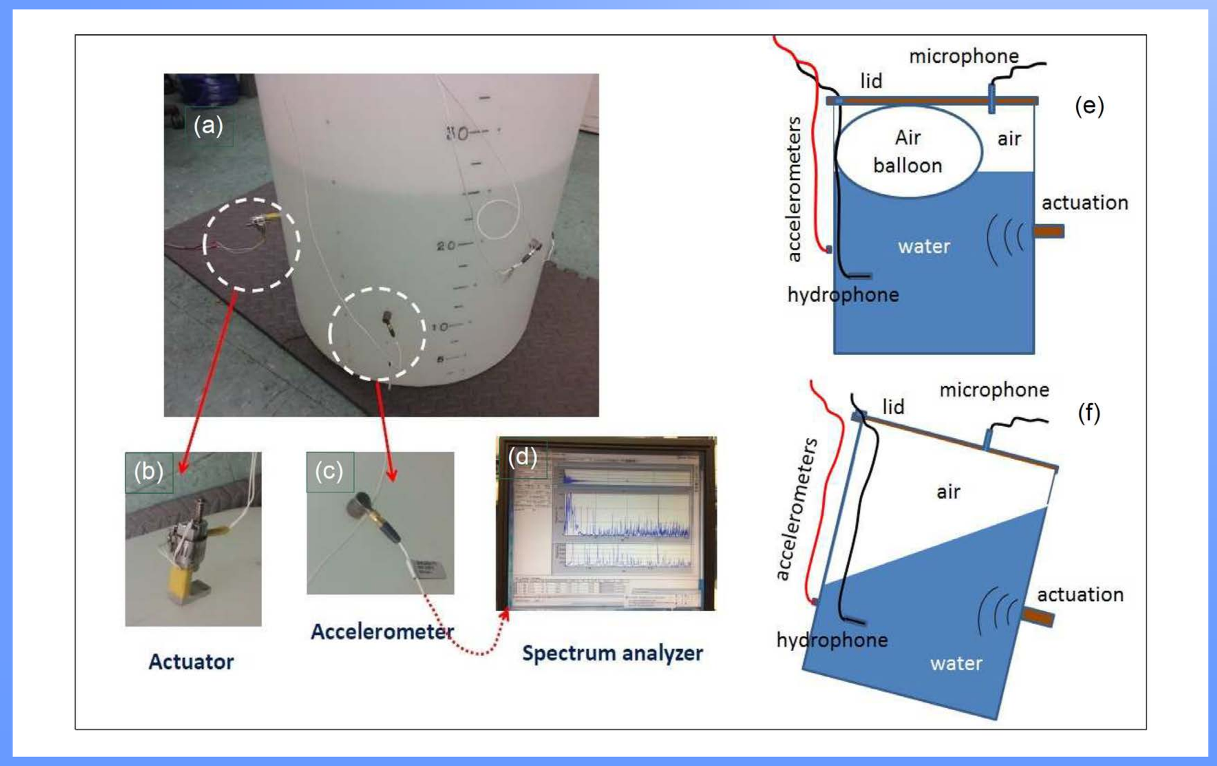

Fig.2 Hardware used for liquid modes counting: (a) 200-liter plastic tank; (b) Actuation technique for the acoustic emission was developed using solenoid actuator . The solenoid actuator was attached to the tank wall from the outside and applied a short ping to excite acoustic resonances in the liquid compartment; (c-d) The detection was performed using accelerometers attached to the wall from the outside as well; (e-f) Measurements were performed on settled liquid and "unsettled", by either tilting the tanks or immersing air-filled balloons in the liquid.

Summary of the results:

- ✓ Results of our ongoing work on the spectral mass gauging approach that uses the mathematically rigorous results about the high-frequency asymptotics of the acoustic eigenfrequencies;
- ✓ We assessed convergence properties of the error in volume inference with the counting number, and the contribution and scaling of effect of dissipation on the resolution of peaks.
- ✓ We performed mode counting of liquid (water) in partially filled tanks for a variety of unsettled configurations and filling levels.
- ✓ A completely nonintrusive technique has been developed for liquid modes actuation and detection using solenoids for actuation and accelerometers for detection mounted on the exterior wall of the tank;
- ✓ Using this technique for liquid (water) gauging in large 200 liter plastic tanks an accuracy of < 3% has been achieved for "'unsettled"' configurations created with a tilt.