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Spectral mass gauging in mid-size propellant tanks

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Abstract

The measurement of propellant mass in upper stage tanks during 0g coasting phase is a challenge given the unknown location and shape of the liquid in microgravity. Nevertheless, an accurate mass gauging at any stage of a mission would allow a more efficient use of propellant. Most of current mass measurement technologies have large estimation errors and/or limited measurement range. The recently proposed Spectral Mass Gauging technique uses acoustic waves to probe the resonance frequencies of the liquid-gas mixture to determine the liquid volume in the tank. We present an experimental study of the application of this technique on mid-size (300 L) tanks.

1. Introduction

Ensuring an accurate and reliable method to gauge liquid propellant in a low gravity environment is a key aspect to successfully sustain human presence in space. However, a liquid contained in a tank adopts an unknown configuration in microgravity, which makes propellant mass gauging challenging.

Several approaches have been proposed to address mass measurement in low gravity. These techniques can be classified into two different types: model-based methods and model-free methods. The methods that rely on modelling the configuration of the liquid are constrained by the tabulated configurations of the liquid. Model-free methods are independent of liquid configuration, which is advantageous since the approach can be generalized to different tank geometries and possible configurations.

Classical mass gauging approaches for space application include bookkeeping, which relies on the accuracy of the thruster flow rate prediction, Pressure–Volume–Temperature (PVT), which uses the ideal gas law to estimate a propellant volume based on telemetry temperature and pressure readings, and thermal Propellant Gauging System (PGS), based on measuring the thermal capacitance of a tank containing liquid fuel and pressuring gas by measuring the thermal response of the propellant tank to heating and comparing the observed temperature rise to simulation results obtained from a thermal model. Nevertheless, all of these techniques suffer from different problems: the bookkeeping technique tends to an uncontrollable accumulation of errors with time, the PVT method loses accuracy when pressure drops due to propellant draining, and thermal PGS has lower accuracies at the start of the mission, which increases with time as the tank load decreases due to temperature rise sensitivity [1].

The mass gauging techniques that have been developed to higher TRL are two model-based methods, namely, the radio frequency mass gauging (RFMG) [2] and the Modal Propellant Gauging (MPG) technique [3]. Both approaches use pattern matching algorithms to compare the measured radio waves (RFMG) or acoustic (MPG) resonance frequencies with a database of the eigen-frequencies that are known for a series of liquid configurations. The best match between the measurements and the available options in the dataset is used to predict the liquid volume.

The Spectral Mass Gauging (SMG) technique has been recently proposed [4]. This approach is based on spectral invariants of the acoustic response of a tank with respect to the liquid configurations. In an application of SMG, sound

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waves are used to probe the natural modes of the liquid-filled tank, and the mathematical properties of the modal spectral density are used to determine the liquid volume. The modal resolution generally increases with the characteristic size of the tank. Independence of the SMG on the knowledge of liquid configuration in the tank makes it an attractive technique for the management of cryogenic propellants stored in the tanks of space vehicles in orbit such as upper stages. The feasibility of the SMG approach in microgravity has been recently tested and demonstrated [5], and it will be tested again soon as part of an integrated experiment that was selected for a suborbital flight within the NASA Fight Opportunities Program [6].

In Section 2 the SMG technique is presented. An experimental setup to study the application of the SMG in mid-size (300 L) tanks is introduced in Section 3. Section 4 contains results obtained for different experimental configurations. Conclusions are presented in Section 5.

2. Spectral Mass Gauging technique

In his work in 1911, Weyl demonstrated that the high frequency asymptotics of the spectrum of the Laplacian in a three dimensional spatial domain with Dirichlet boundary conditions depends on the domain only through its volume [7]. Later research on the topic provided rigorously justified asymptotic expansion formulas for the large eigenvalue asymptotics in the case of various differential operators and boundary conditions as well. Applied to acoustic resonators filled with liquid, Weyl's Law can be written as:

$$N(f) = \frac{4\pi V}{3c_L^3} f^3 + \frac{\pi A_+}{4c_L^2} f^2 - \frac{\pi A_-}{4c_L^2} f^2 + o(f^2), \qquad f \to \infty \tag{1}$$

where N(f), is the liquid mode counting function up to frequency f, V is the volume of liquid in the resonator, A_+ is the area of the liquid surface adjacent to a rigid wall (Neumann boundary condition), A_- is the area of the liquid surface adjacent to a compliant wall (Dirichlet or pressure release boundary condition), and c_L is the speed of sound in the medium of the resonator, i.e., the liquid.

The leading order term in Eq. (1) is proportional to the liquid volume while being independent of the liquid shape (unlike the second order terms which depend on the areas that enclose the resonator). Thus, it is possible to infer the liquid volume provided that the number of liquid modes can be accurately measured experimentally. The determination of the liquid volume by means of the SMG technique requires first to identify the liquid modes in the Fourier spectrum. Next, the experimental curve for the counting function, $N_{exp}(f)$, is built and fitted to a third order polynomial of shape $Af^3 + Bf^2$. Finally, from the determination of the fitting coefficient A, and the speed of sound in the liquid, the volume of liquid can be computed from $V = 3Ac_L^3/4\pi$.

3. Experimental setup

The experimental setup was designed considering the scientific objectives of the experiment. Figure 1 shows a diagram of the experimental setup, which consists of three main subsystems: the test cell (a 300 L tank) containing distilled water at different fill-levels, a subsystem for the generation of an acoustic actuation within the test cell (function generator, power amplifier and piezoelectric transducer), and the data acquisition subsystem (accelerometers, NI-DAQ and computer). Figure 2 shows pictures of the tank and the equipment used for the acoustic actuation and data acquisition subsystems.

3.1 Test cell

The Spectral Mass Gauging technique is tested in a 300 L liquid-storage cylindrical tank with dimensions (diameter x height x thickness) of Ø633 x 950 x 2 mm made of aluminium 5754. This is an easy to model cylindrical geometry valid as a first approximation to real tanks used for liquid propellant storage in spacecraft. Following previous studies of the SMG technique conducted in small tanks (volume of the order of 1 L), which presented some inherent problems related to their size [5], this mid-size model was designed so that it could provide a test bed for larger tanks, which are expected to be a better fit for this application. Previous studies of the technique show that a simplified model of a tank with cylindrical geometry made of polymeric material had been used to test SMG, which yielded promising preliminary results [4]. In order to use a similarly simple geometry but closer to the reality of the tanks used in satellites and spacecraft to store liquid propellant, it was decided to maintain the cylindrical geometry and to change the material to

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a light metal. Other improvements with respect to the experimental setup in [4] are in the acoustic actuation, data acquisition and processing.

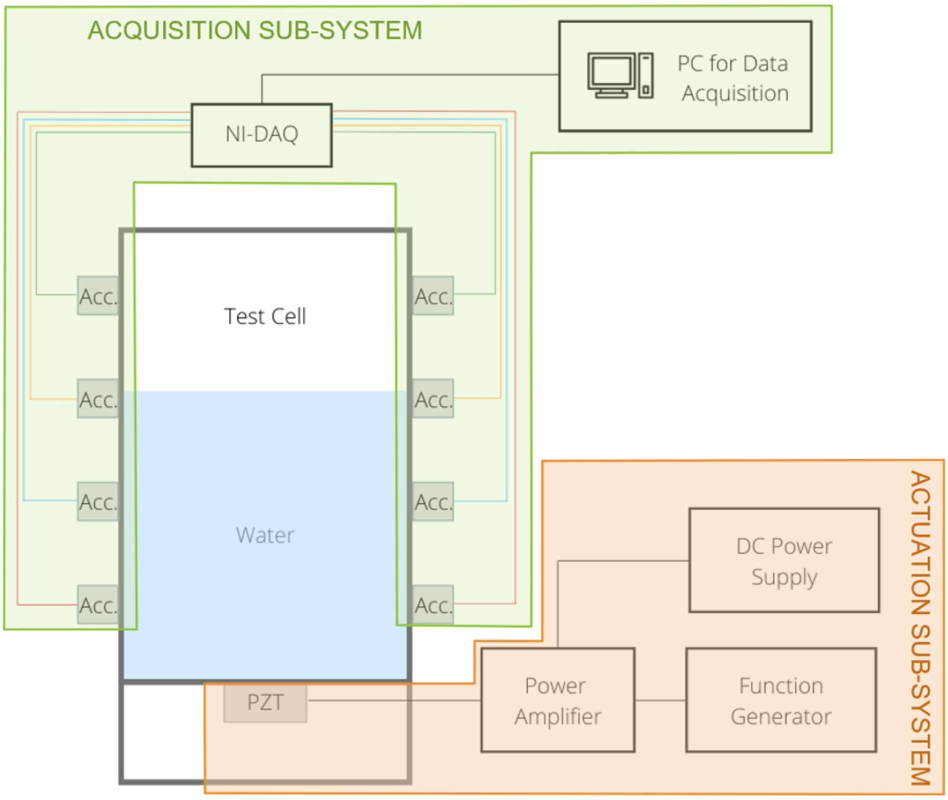

Figure 1: Diagram of the experimental setup (PZT: piezoelectric transducer; Acc.: accelerometer).

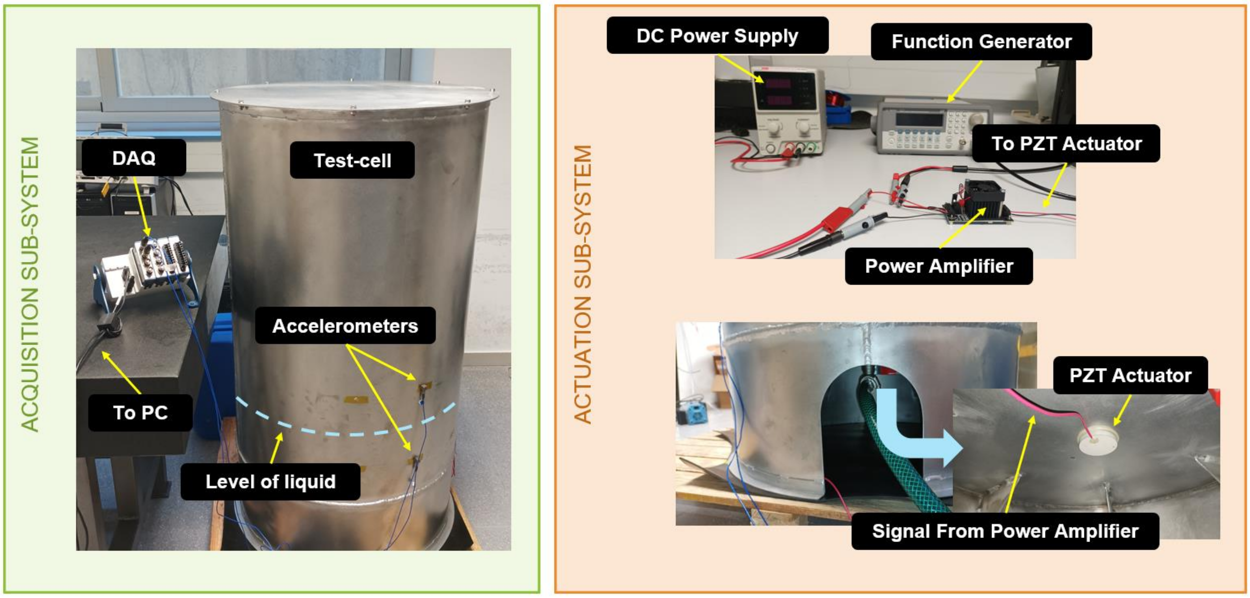

Figure 2: Test cell, acoustic actuation system and data acquisition subsystems.

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3.2 Acoustic actuation

Research carried out recently shows that it is possible to implement the SMG technique using different types of actuators to generate the acoustic field within the system, such as solenoids or piezoelectric transducers [4, 5]. A piezoelectric actuator attached to the outer side of the structure of the test cell is a particular effective way of transmitting the acoustic wave to the system. The properties of the piezoelectric transducer (PZT) used in this study are summarized in Table 1 as given by the manufacturer.

Table 1: Properties of the PZT actuator

Material	APC 840
Dimensions	Ø50x10 mm
Resonant frequency in the radial direction	42.6 kHz
Resonant frequency in the thickness direction	200.5 kHz

The PZT is attached to the centre of the outer face of the bottom wall of the test cell using conductive epoxy adhesive. The PZT is connected to a power amplifier through two wires: one glued to its bottom surface using the same conductive epoxy adhesive (see Figure 2), and another one in contact with the skirt of the tank, since the structure of the tank is conductive and is thus connected to the upper surface of the PZT. The power amplifier, which has a gain of 20 V/V, is fed by a signal whose parameters can be manually selected in the screen of the function generator. As for the signal applied to the PZT, a sinusoidal tone burst excitation was used, which has been found to generate promising results with small tanks in previous tests. This type of signal provides a means to excite the modes of the system in a broad band of frequencies. The applied burst signal is characterized by the frequency, number of cycles and amplitude.

3.3 Data acquisition

At the same time that the acoustic excitation is applied to the system, its response is measured using IEPE accelerometers with a nominal sensitivity of 100 mV/g from PCB Piezotronics. The sensors are attached to the outside surface of the cylindrical wall of the test cell. With the aim of studying the dependence of the obtained measurements on the placement of the sensors, multiple accelerometers are distributed in different configurations along the cylindrical wall of the tank.

Data are acquired by means of a CompactDAQ-9174 and two National Instruments 9234 modules with a sampling rate of 51.2 kS/s/channel, where the connectors for eight accelerometers can be accommodated. The time signal from the accelerometers is converted and recorded by means of a LabVIEW code in the PC for its later treatment and analysis.

4. Experiments and data analysis

A preliminary set of different experiments was performed in the tank with 60 L of distilled water to observe the influence of two parameters of the experiment: the accelerometer placement and the central frequency of the actuation signal. For each experiment, an acoustic actuation is applied to the experimental system and the response is measured by the accelerometers. After the data have been acquired, the time signals recorded by the sensors are post-processed in the frequency domain by performing their Fast Fourier Transform to obtain the corresponding spectra.

The amplitude of the excitation applied to the PZT was kept constant at the maximum available voltage from the power amplifier (300 V_{p-p}), while the central frequency was varied between the different tests.

4.1 Accelerometer placement

The influence of the location of the accelerometers is tested by comparing the spectra recorded by a pair of sensors: one of them above the level of the liquid and the other one below the level of the liquid (see Figure 2). We studied

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these two cases for two different actuations: a sinusoidal tone burst at a central frequency of 8.33 kHz and at 25 kHz. Figures 3 and 4 show the frequency spectra for 25 kHz and 8.33 kHz, respectively. For both excitations, some of the peaks that are present in the case of the accelerometer that is placed below the liquid level (blue), do not appear in the readings from the accelerometer above the liquid level (red). This can be attributed to the liquid eigenmodes being more effectively measured when the sensor is placed closer to the mass of liquid.

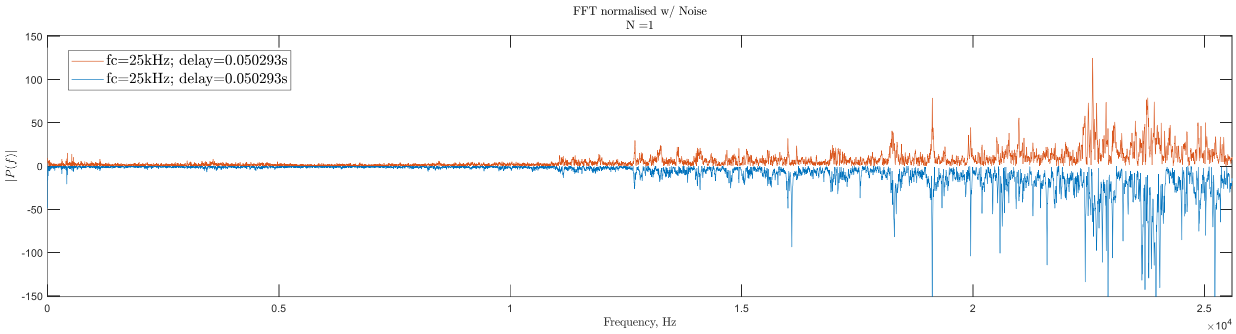

Figure 3: Frequency response to a sinusoidal tone burst excitation with a central frequency of 25 kHz. Upper spectrum (red) shows the FFT of the signal recorded by an accelerometer placed above the level of liquid, while lower spectrum (blue) corresponds to an accelerometer placed below that level (≈ 20 cm for 60 L of distilled water).

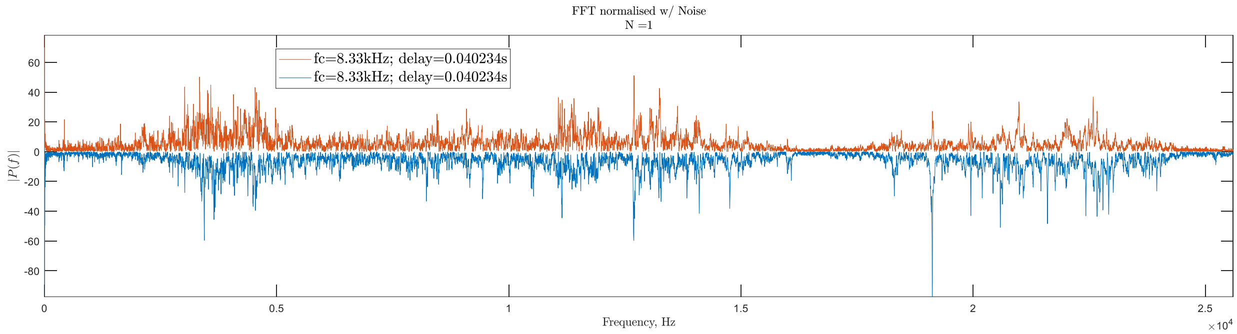

Figure 4: Frequency response to a sinusoidal tone burst excitation with a central frequency of 8.33 kHz. Upper spectrum (red) shows the FFT of the signal recorded by an accelerometer placed above the level of liquid, while lower spectrum (blue) corresponds to an accelerometer placed below that level (≈ 20 cm for 60 L of distilled water).

4.2 Central frequency of the actuation

Figure 5 shows a side-by-side comparison between the spectra obtained with two different central frequencies for the excitation. It becomes apparent that different central frequencies of the excitation lead to differences in the envelopes of their spectra, being the main frequency bandwidth of excitation centred at the central frequency.

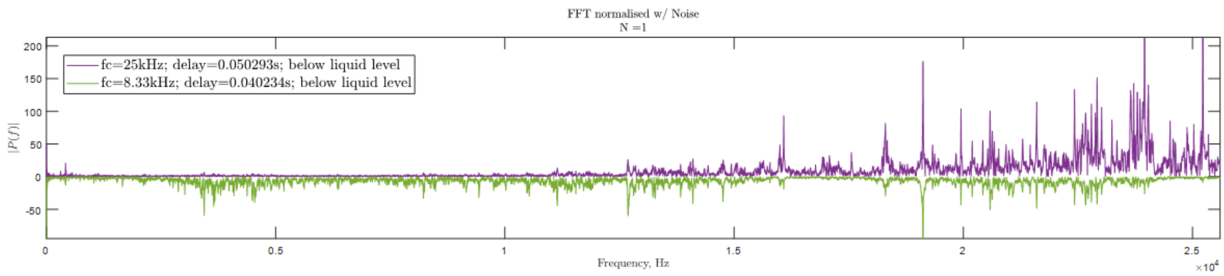

Figure 5: Frequency response to a sinusoidal tone burst excitation with different central frequencies: 25 kHz for the upper spectrum (purple), and 8.33 kHz for the lower (green). Both signals recorded by accelerometers placed below the level of liquid (≈ 20 cm for 60 L of distilled water).

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In the frequency regions where both signals were able to effectively excite modes, there is a clear correspondence between the locations of such modes. Clear examples of that can be observed at frequencies of 19.1 kHz or 19.9 kHz.

4.3 Liquid volume estimation

It is possible to infer the volume of the liquid contained in the tank by counting the peaks in the spectrum and fitting them to Weyl's asymptotic formula for liquid mode counting. We consider two cases for the volume determination: the FFT of the signal from the accelerometer placed below the liquid level, with central frequencies of 8.33 kHz and 25 kHz. The analytical procedure to determine the liquid volume constitutes an improvement from the procedure introduced in [5].

Figures 6 and 7 show the mode counting function obtained for the cases studied with two different actuations. Dirichlet boundary conditions all over the limits of the domain of the liquid provided the closest match between the theoretical and the experimental mode counting curves. Given the envelope of the FFT depends on the central frequency applied to the acoustic actuation to a large extent, the spectra tend to flatten away from that central frequency. Therefore, in the flatter regions of the spectra shown in previous figures, no peaks could be identified. This is particularly problematic for the case of the actuation at 25 kHz as seen in Figure 6, where the first identified peak is located at 12.7 kHz while Weyl's predicted that first liquid mode is at 2.3 kHz. Thus, the experimental counting curve falls far below the theoretical one. However, for the case of the actuation at 8.33 kHz (Figure 7) results correlate better to the theory since it is possible to identify peaks starting at 1.7 kHz, closer to the first liquid mode predicted by theory. Nevertheless, the experimental and theoretical curves start to diverge at frequencies higher than 5 kHz. The density of liquid modes increases with frequency, up to a point where the frequency difference between consecutive liquid modes outweighs the resolution of the FFT, leading to the inability to differentiate peaks that are too close from each other.

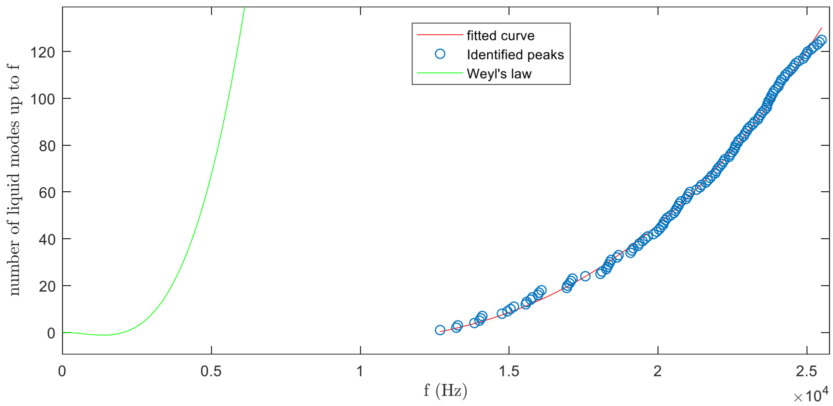

Figure 6: Experimental counting function built from the identified peaks, $N_{exp}(f)$, in blue, its corresponding fitted curve in red, and the theoretical counting function, N(f), in green. Test performed for an acoustic actuation with a central frequency of 25 kHz and 60 L of distilled water.

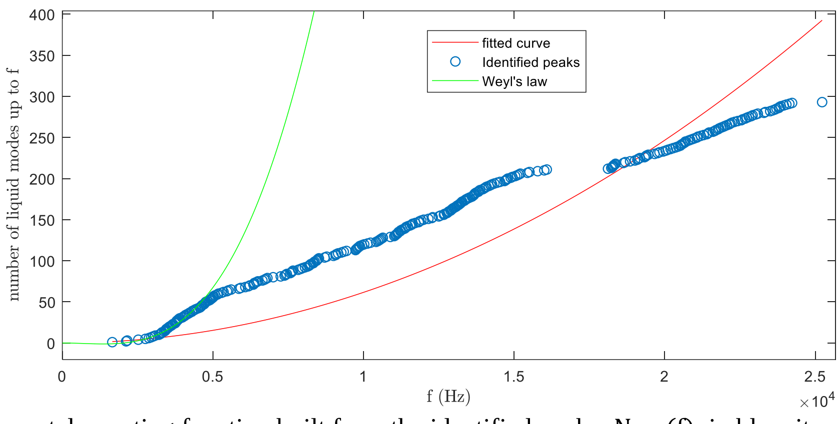

Figure 7: Experimental counting function built from the identified peaks, $N_{exp}(f)$, in blue, its corresponding fitted curve in red, and the theoretical counting function, N(f), in green. Test performed for an acoustic actuation with a central frequency of 8.33 kHz and 60 L of distilled water.

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Figure 8 shows the fitting of the experimental counting function to the theoretical curve for a cut-off frequency of 4.5 kHz, which was fixed from the observations made in Figure 7. The estimated volume by means of the SMG technique for this case yields a value of 54.1 L, which represents an error of 9.8% with respect to the actual volume contained in the tank.

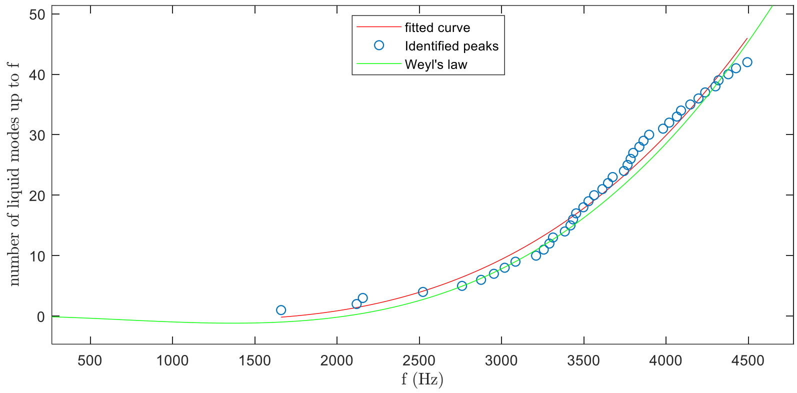

Figure 8: Experimental counting function built from the peaks identified up to a cut-off frequency of 4.5 kHz, $N_{exp}(f)$, in blue, its corresponding fitted curve in red, and the theoretical counting function, $N(f)$, in green. Test performed for an acoustic actuation with a central frequency of 8.33 kHz and 60 L of distilled water.

5. Conclusions

A setup for testing the technique of Spectral Mass Gauging in mid-sized tanks is presented. The performed analysis is targeted at obtaining a set of parameters that would provide the best results in terms of optimising the excitation and the identification of the liquid spectral modes present in the system.

The central frequency of excitation has a great influence on the amplitude and the distribution of the modes that can be excited. In particular, different central frequencies of a sinusoidal tone burst excitation show differences in the envelopes of their spectra, being the main bandwidth of excitation centred at the central frequency.

More spectral modes are identified when accelerometers are below the level of the liquid. In view of an application of the SMG approach in microgravity conditions, we do not foresee a major issue since in most cases a liquid layer will cover the internal tank walls due to capillarity.

Further testing of the SMG technique on the ground and in microgravity platforms is required to achieve a full understanding of the physics behind the phenomenon.

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References

[1] B. Yendler, 2006. Review of Propellant Gauging Methods. In: *44th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics*. 1–7.
[2] G. A. Zimmerli, K. R. Vaden, M. D. Herlacher, D. A. Buchanan, and N. T. Van Dresar. 2006. Radio frequency mass gauging of propellants. *NASA Technical Report TM-2007-214907.*
[3] K. Crosby, R. Werlink, and E. A. Hurlbert. 2021. Liquid Propellant Mass Measurement in Microgravity. *Gravitational and Space Research*. 9 : 50-61.
[4] L. Delzeit, J. Feller, B. Helvensteijn, A. Kashani, M. Khasin, V. Osipov. 2021. Spectral Mass Gauging of Liquids with Acoustic Waves. In: *50th International Conference on Environmental Systems.*

DOI: 10.13009/EUCASS2022-7550

[5] T. Fili, G. Quintana-Buil, and R. González-Cinca. 2022. Spectral mass gauging in terrestrial gravity and microgravity conditions. *Acta Astronautica*. 194: 174-184.
[6] G. Quintana-Buil, S. C. Abecia-Hernanz, W. Mangram, M. Khasin, F. K. Chang, and R. González-Cinca. 2022. Integrated acoustic technology for boil-off control, mass gauging and structural health monitoring in cryogenic fuel tanks. In: *8th Space Propulsion Conference,* Estoril (Portugal).
[7] H. Weyl. 1911. Ueber die asymptotische verteilung der eigenwerte. *Nachr. Ges. Wiss. Gött. Math.-Phys*. Kl. 110–117.