LIQUID HYDROGEN MASS GAUGING: SENSOR CONCEPTS FOR FUTURE HYDROGEN AIRCRAFT TANKS

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Abstract

The safe and precise measurement of liquid hydrogen (LH_2) tank levels is a key challenge for the use of hydrogen as a sustainable aviation fuel. The envisioned large cylindrical hydrogen tanks differ greatly from today's integrated wing tanks. While traditional Fuel Quantity Indication Systems (FQIS) rely on tens of capacitive probes, temperature sensors, compensators and high/low-level sensors to achieve the required robustness, the necessary sensor systems for an LH_2 FQIS that meet future requirements remain unknown. Although multiple LH_2 level measurement principles have been applied in industry, automotive, and space applications, no complete system has yet been developed at the scale and performance required for future LH_2 aircraft. Historically, there have been test flights powered by turbines or fuel cells using LH_2, but for these prototypes no full FQIS was developed; instead, fuel duration was estimated, or a single probe was used.

This paper focuses on identifying the requirements of today's FQIS, addressing both robustness and precision. While regulations regarding LH_2 fuel systems for civil aviation (ISO/AWI 19888, SAE AS6679) are still under development, existing standards for LH_2 systems in the automotive sector can be combined with the requirements of modern FQIS and current LH_2 aircraft design studies to provide insights into the operational requirements and challenges of LH_2 FQIS systems.

In addition, an overview of measurement concepts for LH_2 fill-level sensors is presented, along with initial experimental results obtained from tests with capacitive probes in cryogenic nitrogen, non-invasive vibro-acoustic methods, and temperature-based fill-level sensors.

Keywords

liquid hydrogen, fuel level sensors, zero emission flight, fuel quantity indication system(FQIS).

1. INTRODUCTION

A reliable Fuel Quantity Indication System (FQIS) is essential for the safe operation of any aircraft. FQIS have evolved into complex systems, incorporating multiple fallback sensors and redundancies. Over the past 35 years of the A320's service, numerous incidents involving the FQIS have been documented, including cases where fuel tank leakages were correctly detected, as well as cases where the FQIS overestimated the remaining fuel, leading to engine flame-outs. In other instances, the FQIS issued false low-level warnings [1]. Fortunately, in all cases the crew managed to land the aircraft safely; nevertheless, it underscores the need for robust and accurate FQIS.

With the transition to liquid hydrogen (LH_2)-powered aircraft, the fuel system undergoes significant changes, incorporating large cylindrical, thermally isolated tanks at the rear of the aircraft instead of integrated wing tanks. Handling LH_2 is considerably more challenging than handling conventional Jet A-1 fuel. The two primary challenges in storing LH_2 are maintaining the extremely low temperature of 20 K to keep hydrogen in its liquid state, and mitigating hydrogen diffusion through materials, a phenomenon known as hydrogen embrittlement.

Although ground-based and space applications have accumulated extensive experience in handling LH_2, the requirements for LH_2 aircraft tanks are fundamentally different. Rocket fuel systems are designed for single-use missions, whereas aviation fuel systems must remain reliable throughout the aircraft's entire operational lifetime of approximately 30 years. This challenge is further compounded when cryostat tanks are permanently integrated into the airframe, making it unclear whether sensors can be accessed for maintenance or replacement. Currently, the tanks, interfaces, and sensors for LH_2 aircraft are still under development, with critical challenges remaining in safe refueling, venting, and state monitoring [2].

Despite the extensive literature on LH_2 tanks, a dedicated Fuel Quantity Indication System for LH_2 aircraft has not yet been fully described. In conventional wing integrated jet fuel tanks, fuel gauging is typically performed using multiple capacitive probes or, in some cases, ultrasonic sensors. However, the fundamentally different tank geometry and material properties of LH_2 compared to jet fuel necessitate further investigation to identify suitable sensor concepts for future hydrogen aircraft [3].

2. FUEL QUANTITY INDICATION SYSTEMS

2.1. Requirements

The Fuel Quantity Indication System (FQIS) is a critical component in aircraft, as its failure can lead to catastrophic consequences. Numerous regulations and guidelines, including ARINC 611-1, CS 25.1309, SAE AS405C, SAE AIR5691, and S1000D, define requirements and best practices for the FQIS.

The primary objective of an FQIS is to measure fuel quantity as accurately and reliably as possible, while minimizing weight, cost, and system complexity. Depending on the measurement technique, additional fuel properties such as dielectric constant, speed of sound, density, temperature, and conductivity may also need to be monitored.

The declared accuracy of an FQIS significantly impacts the required fuel load. Less accurate systems necessitate additional fuel to account for potential uncertainties, whereas more precise systems reduce the need for contingency fuel. However, multiple studies have shown that increasing accuracy beyond 1% does not provide economic benefits to airlines, as it does not enable a more refined fuel-loading process. Nevertheless, inaccurate readings that underestimate fuel levels can still increase operational costs due to the extra weight.

For aircraft the size of an Airbus A320 or Boeing 737, a 1% measurement error corresponds to approximately 240 kg of fuel, while on an Airbus A380, the same error equates to around 2,500 kg. The cost of carrying this additional fuel can accumulate substantially over time.

The required accuracy of modern large commercial or military transport aircraft FQIS, adherence to the accuracies specified in ARINC 611-1 is common, as illustrated in Figure 1, where accuracy requirements increase as the remaining fuel on board (FOB) decreases as shown in equation 1.

$$\pm\Big(\text{FOB} \cdot 1\% + \max(\text{FOB} \cdot 1\%)\Big) \quad (1)$$

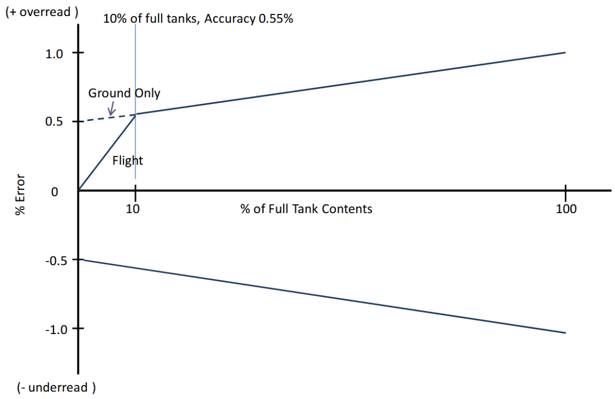

FIG 1. ARINC 611-1 specified fill level accuracy [4]

Ensuring FQIS reliability is essential. Regulatory standard CS 25.1309 mandates that equipment and systems must be designed such that catastrophic failure conditions are extremely improbable and cannot result from a single failure. Hazardous failure conditions must also be extremely unlikely. Consequently, system components are required to demonstrate adequate reliability and redundancy to satisfy these stringent requirements.

According to ARINC 611, if a single probable fault leads to reduced accuracy in all tank indications, the resulting accuracy must not be worse than twice the operational accuracy goal. To enhance resilience against sensor failures and increase the mean time between failures (MTBF) of the entire FQIS, a redundant sensor architecture is recommended.

Figure 2 illustrates a monitored redundant sensor architecture, where two independent measurement principles and electronics are employed to calculate the fuel mass, allowing cross-verification of sensor measurements.

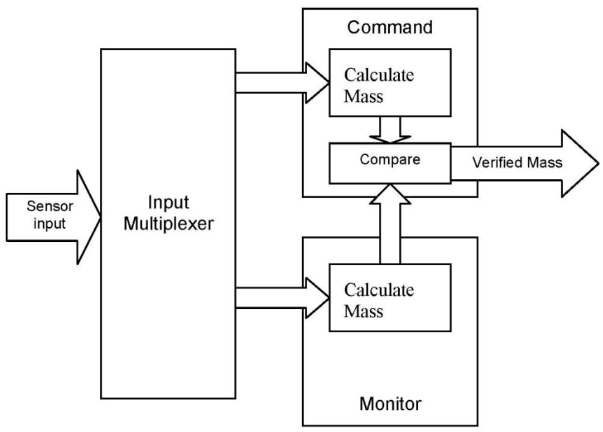

FIG 2. Monitored redundant system architecture [4]

2.2. Modern FQIS Architectures

The FQIS of modern aircraft such as the A320 contains a variety of sensors within the wing tanks. Because of the complex geometry and redundancy requirements, a total of 14 capacitance fill-level probes are installed per wing to monitor the fill level, as shown in the schematic in Figure 3. Additionally, HIGH and LOW level sensors are implemented, which operate on a separate connection and evaluation unit independent from the continuous fill-level sensors. The LOW level sensors are placed in pairs and trigger a low-level alert when both sensors are dry for more than 30 seconds. Additionally, Magnetic level indicators can be uses for manual fuel gauging on the ground. A detailed description of the operating states of the A320 FQIS can be found in the literature [3].

Secondary sensors are required to monitor the temperature and density of the fuel in order to enable a precise conversion from the measured fill level to the fuel mass, taking into account the tank geometry, flight angles, and fuel density.

3. LIQUID HYDROGEN FUEL STORAGE

In order to achieve the required volumetric energy densities, hydrogen must be stored in its liquid state at around 20 K ($-253°$C) and 8 bar. To maintain this extremely low temperature, LH_2 must be stored in a cryostat, which is a tank that provides thermal insulation, reduces the ratio of surface area to volume, and can withstand pressure differences. While spherical cryostats offer the best performance with respect to minimizing ambient heat transfer, cylindrical tanks are used in most mobile applications where installation space is limited. Although future tanks may incorporate carbon fiber reinforced polymers (CFRP), early models are likely to be fabricated from aluminum.

Vacuum insulation combined with multi-layer insulation (MLI) has proven ideal for weight-sensitive applications, as it thermally decouples the outer and inner tank of the cryostat [6]. Figure 4 shows a typical MLI layout.

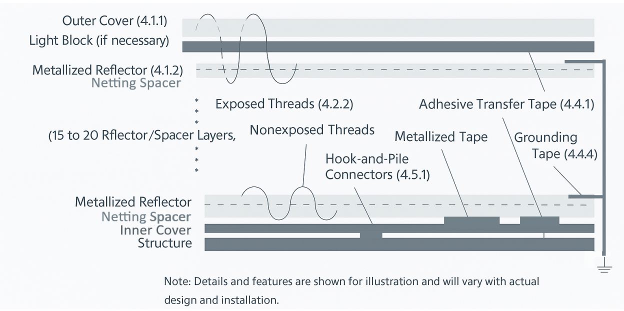

FIG 4. Typical MLI stacking arrangement [7]

Since some heat transfer into the tank is unavoidable, the resulting l-off must be vented to maintain a safe pressure level. A commonly cited acceptable boil-off rate is 0.1% of the hydrogen mass per hour [8]. Boil-off becomes costly when LH_2 is stored for extended periods without utilizing the boil-off gas (BOG).

During operation, more hydrogen is consumed than the BOG flow alone can provide. Therefore, the LH_2 must either be actively heated to increase BOG production or a LH_2 pump must be employed to extract sufficient hydrogen from the tank [9].

Many mobile LH_2 tanks cannot be opened once fabricated. Figure 5 shows the schematic of a liquid hydrogen tank used in BMW cars manufactured in the early 2000s. The diagonally placed capacitance probe cannot be removed once the tank is sealed, which implies that the probe was designed to operate reliably throughout the entire service life of the tank without maintenance or replacement.

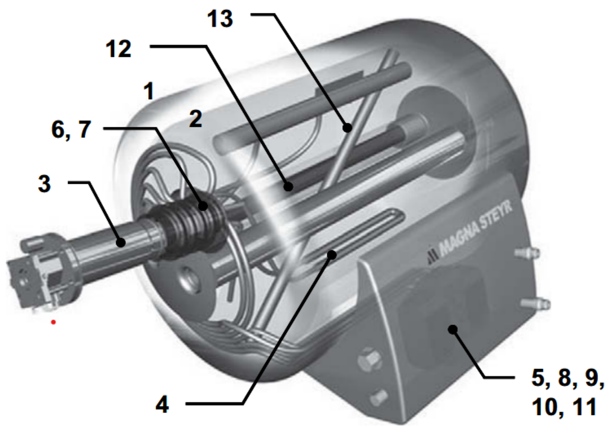

FIG 5. Liquid hydrogen tank system (Source: Magna Steyr and BMW) [10]

1 Outer tank 2 Inner tank 3 Coupling (Johnston-Cox) 4 Heater 5 Heat exchanger 6 Cryogenic filling valve 7 Cryogenic return valve 8 Pressure regulation valve 9 Shut-off valve 10 Boil-off valve 11 Safety relieve valve 12 Support post 13 Liquid level sensor

3.1. Liquid hydrogen fuel storage standards

In order to ensure that the proposed fuel system complies with applicable regulatory frameworks, it is essential to review the relevant certification norms and standards. The standards *ISO/AWI 19888-1 Aerial Vehicles: Part 1: Liquid Hydrogen Fuel Storage System* and *SAE AS6679: Liquid Hydrogen Storage for Aviation*, which are intended to define the certification requirements for liquid hydrogen fuel systems in aircraft, are currently under development and have not yet been formally published.

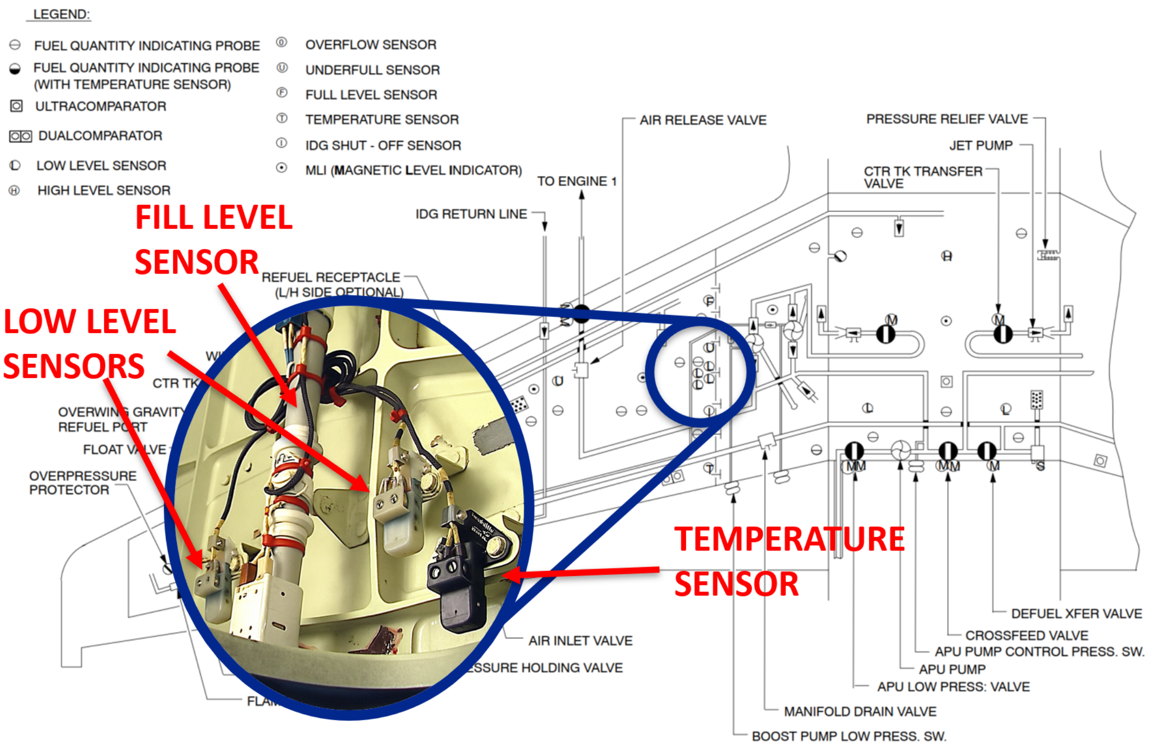

FIG 3. Fuel System Basic Schematic A318/319/320 [5]

In the absence of finalized aviation-specific standards, reference can be made to established standards from the automotive sector, such as *ISO 13984* and *ISO 13985*, which address the storage and handling of liquid hydrogen. These documents primarily emphasize explosion prevention, acceleration and crash testing, and provide guidance on the selection of suitable materials as well as the implementation of appropriate venting procedures.

3.2. Liquid hydrogen aircraft studies

In the absence of a fully realized liquid hydrogen-powered aircraft, conceptual design studies such as the *DLR EXACT* program and the *FlyZero* project provide valuable insights into prospective tank configurations and integration strategies. The outcomes of these studies are expected to strongly influence the applicability and suitability of various fill-level sensing methods.

Although the space industry has accumulated several decades of experience with LH_2, the design of tanks for commercial aviation remains an area of active development. In order to anticipate future requirements and fuel tank architectures, existing Fuel Quantity Indication System (FQIS) standards for conventional Jet-A1 aircraft may be used as a reference point, supplemented by LH_2-specific standards originating from the automotive sector, in conjunction with the most recent conceptual design studies.

It is anticipated that the LH_2 tanks will be located in the aft section of the aircraft, supported by a bed of rigs with additional radial mounts, as illustrated in green in Figure 6. The front tank is projected to have a diameter of 3.4 meters, with inner and outer wall thicknesses of 3–4 mm each, and a total capacity of approximately 30 m^3, corresponding to roughly 1700 kg of LH_2 when filled to 80%. The insulation thickness is expected to be on the order of 10 cm [8].
The primary interfaces are located at the poles of the tanks, implying that all sensors and fuel lines must be routed through these points. This configuration represents a critical boundary condition when designing invasive sensing systems.

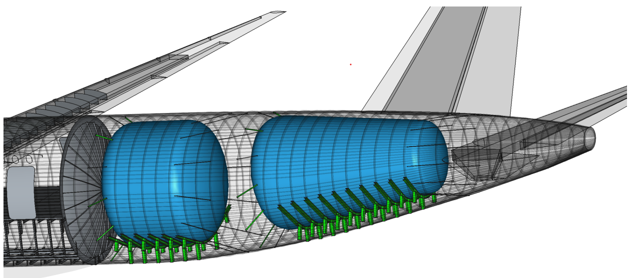

FIG 6. LH_2 tank placement of the DLH25 concept, courtesy of DLR SL [11]

4. LIQUID HYDROGEN FILL LEVEL SENSORS

To provide an overview of the distribution of measurement principles, an automated web search was conducted to categorize the methods employed in LH_2 level sensing. Using the Google API, the queries *"liquid hydrogen level sensor"*, *"liquid hydrogen gauge"*, *"LH2 fill level sensor"*, *"cryogenic level* *sensor hydrogen"*, and *"liquid hydrogen tank level measurement"* were executed to retrieve texts from 500 websites and PDFs containing articles, research findings, and specifications of commercially available sensors. The documents were then scanned for relevant keywords and clustered into primary categories of physical sensor principles, as illustrated in Figure 7. Approximately 37% of the query results could not be classified and were excluded from the dataset.

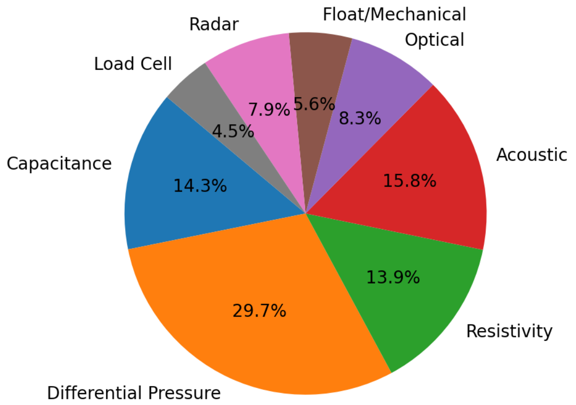

FIG 7. Distribution of measurement principle of LH_2 level sensors

The most commonly employed method in the industry involves the use of differential pressure sensors to determine the hydrostatic pressure, which is directly proportional to the fill level. However, this approach is primarily applied in ground-based systems, as fluctuations in density, temperature, liquid sloshing, and accelerations can significantly distort the measurements.

Capacitance probes are frequently used to estimate the fill level by measuring the change in capacitance induced by the varying dielectric constant between the liquid and gaseous hydrogen. For this measurement technique, it is essential to know the local density of the liquid, which is strongly correlated with temperature, since the dielectric constant is directly proportional to the liquid density.

Resistive Temperature Devices (RTDs), such as diodes, platinum elements, resistors, or thermocouples, can be employed to track the liquid–gas interface by assessing changes in the heat capacity of the surrounding medium. This is achieved by introducing a small heat pulse and subsequently measuring the rate at which the temperature returns to equilibrium. RTDs have been implemented as point sensors in the external LH_2 and oxygen tanks of the Space Shuttle Discovery [12].

Although the use of ultrasonic distance sensors at LH_2 tank temperatures is unlikely [13], alternative acoustic measurement techniques—such as surface acoustic wave (SAW) sensors [14] or vibro-acoustic methods [15]—can be employed for fuel gauging.

Optical methods, including the fiber Bragg grating (FBG) technique, utilize a laser reflected by gratings within an optical fiber. Each fiber can contain hundreds of gratings, each with a unique signature, which stretch or contract depending on the temperature, enabling discrete measurements of strain and temperature [16].

A straightforward, non-invasive approach for directly determining the fuel mass is the use of load cells. Load cells measure changes in the resistance of a strain gauge induced by deformation due to the force exerted by the fuel mass under gravity or other accelerations. Implementation of this method is challenging when the tank is supported at multiple points, as interface pipes transfer forces and varying accelerations and flight attitudes must be considered.

Although some companies claim to use radar to reliably detect the liquid–gas interface [17], no peer-reviewed publications verifying these claims were identified.

5. EXPERIMENTAL INVESTIGATIONS OF CAPACITANCE PROBES FOR CRYOGENIC LIQUID LEVEL MONITORING

Capacitance probes are widely used in commercial aircraft to measure fuel levels. However, the difference in permittivity between gaseous hydrogen and liquid hydrogen (LH_2) is approximately three times smaller than that between kerosene and air, resulting in reduced sensitivity if the same sensor layout is applied.

Since the liquid and gaseous phases of hydrogen exhibit distinct permittivity values, a functional relationship between the measured capacitance and the liquid level can be established for a coaxial (two-cylinder) capacitance probe, as expressed in Equation 2. In this formulation, $C(h)$ denotes the capacitance as a function of the liquid level h, ε_0 is the vacuum permittivity, and r_i and r_a represent the inner and outer radii of the cylindrical electrodes, respectively. The relative permittivities of gaseous and liquid hydrogen are denoted by $\varepsilon_{r,\mathrm{GH_2}}$ and $\varepsilon_{r,\mathrm{LH_2}}$, while H represents the total sensor height.

In addition to continuous level measurement, capacitance probes can also be employed for discrete level detection or for density estimation, as the permittivity is directly proportional to the liquid density.

$$C(h) = \frac{2\pi\varepsilon_0}{\ln\left(\frac{r_i}{r_a}\right)} \cdot (\varepsilon_{r,Gh2}(H-h) + \varepsilon_{r,Lh2} \cdot h) \tag{2}$$

To increase the sensitivity of a capacitance probe, several design modifications can be considered: enlarging the diameters of the cylindrical electrodes, reducing the gap between them, or introducing additional cylinders to form a multi-cylinder configuration. However, requirements regarding the minimum permissible gaps must be observed, both to avoid capillary effects and to prevent electrical arcing. Furthermore, due to spatial constraints, increasing the electrode diameters is not always feasible.

In our experiments, a three-cylinder configuration, as illustrated in Figure 8, was investigated. The results confirmed a direct increase in sensitivity, consistent with the theoretical expectation that the total capacitance corresponds to the sum of the capacitances between the outer and middle cylinders and between the middle and inner cylinders, when the outer and inner electrodes are connected in parallel.

FIG 8. 3 cylinder stainless steel capacitance probe with 3d-printed PETG spacer

Furthermore, we investigated the suitability of capacitance sensors designed for Jet-A1 in accurately measuring the fill level of cryogenic liquid nitrogen (LN_2). Figure 9 presents analytically calculated capacitance curves for Jet-A1/Air, LH_2/GH_2, and LN_2/GN_2, along with numerically predicted capacitance curves obtained using COMSOL Multiphysics and experimental data from the LN_2 laboratory tests.

For the LN_2 experiment in collaboration with our project partner AUTOFLUG, a laboratory cryostat was filled with LN_2, and a capacitance probe was placed inside. The LN_2 was allowed to boil off over a period of two weeks while the mass was continuously monitored using load cells. While the capacitance initially exhibited the expected linear behavior, several discontinuities were observed, as shown in Figure 9. The early jumps are suspected to be the result of changes in the measurement wiring setup when the test bed was relocated. The elevated capacitance values observed near tank depletion are likely attributable to condensation of ambient water vapor, as the cryostat was left uncovered to allow steady boil-off. Prior to the discontinuities in the data, the measured capacitance was approximately 12% lower than the analytically predicted values, which is consistent with parasitic capacitance introduced by the wiring and evaluation electronics.

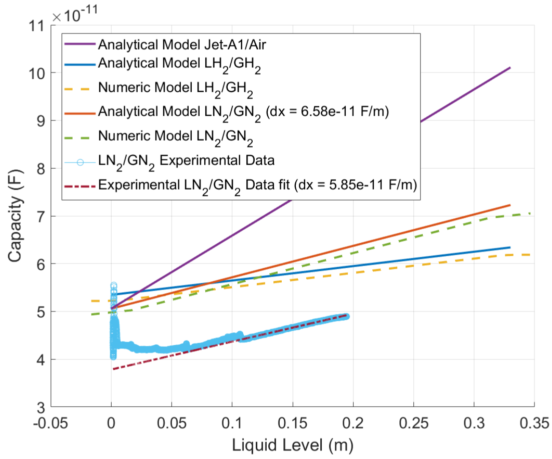

FIG 9. Comparison of analytical, numerical and experimental data on capacitance probe sensitivity

6. EXPERIMENTAL INVESTIGATIONS OF A NON-INVASIVE VIBRO-ACOUSTIC MODAL GAUGE

Vibro-acoustic modal gauging is performed by exciting the tank externally and measuring its frequency response using an accelerometer. Variations in the eigenmode frequencies reflect changes in the total system mass and can therefore be used to determine the fill level. As this measurement method can be implemented non-invasively, without penetrating the tank or introducing additional heat bridges, it is particularly attractive for gauging cryogenic liquids.
This method has demonstrated accuracies of 1–2% in both sub-scale laboratory experiments and full-scale tests with volumes up to 2250 liters [15]. In addition, a patent filed by Airbus describes an acoustic modal gauging system for LH_2 tanks intended for future aircraft applications [18].

We further investigated how different fuel distributions within the tank, resulting from variations in flight attitude, affect the measurement accuracy. Figure 10 shows the laboratory testbed, which consisted of an acrylic water tank instrumented with an inertial measurement unit (IMU) to record roll and pitch angles.

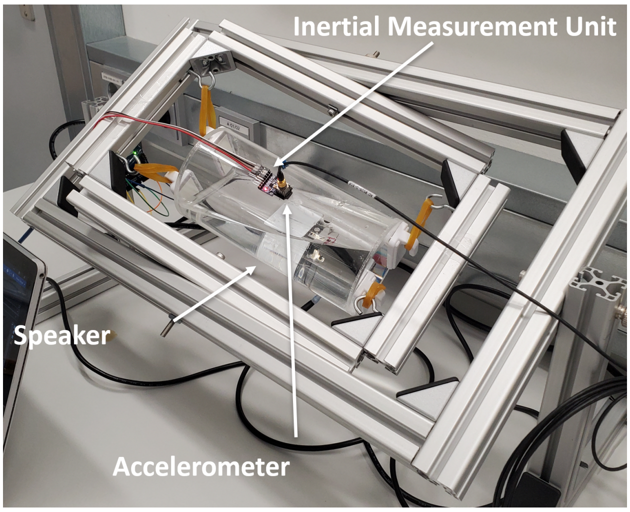

FIG 10. Acoustic modal gauge test rig for simulating flight states

It can be observed that with increasing fill levels, the lower eigenmodes shift toward lower frequencies, while their amplitudes decrease, as shown in Figure 11. A clear correlation with the total system mass can be obtained by applying a simple peak-picking approach and tracking the frequency of the lowest eigenmode.

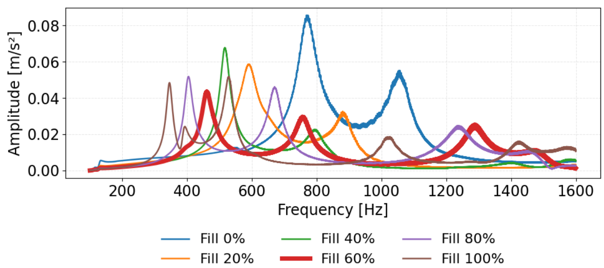

FIG 11. Frequency response for varying fill levels

When varying the roll and pitch angles, a noticeable impact on the frequency response can be observed, as shown in Figure 12. Some eigenmodes shift toward lower frequencies, while others shift toward higher frequencies. To ensure accurate fuel mass estimation under such conditions, these effects must be studied in greater detail, and an evaluation algorithm must be developed that can reliably distinguish between eigenmode shifts caused by flight attitude and those resulting from changes in fill level.

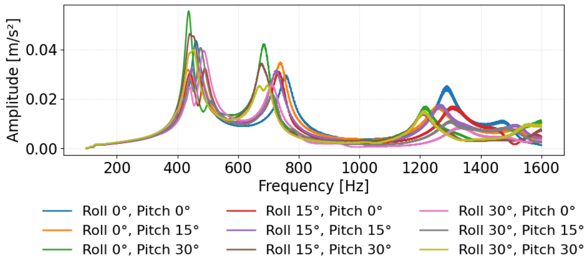

FIG 12. Frequency response varying pitch and roll angles

7. RESISTIVE TEMPERATURE DEVICES AS CRYOGENIC FILL LEVEL SENSORS

Resistive Temperature Devices (RTDs) can be used to track the liquid–gas interface by introducing a small heat pulse and subsequently measuring the rate at which the temperature returns to equilibrium. According to the literature, the heating pulse typically requires approximately 3 W of electrical power [19].

We designed an PCB, shown in figure 13 consisting of ten PT-1000 elements, each placed in series with a 220 Ω resistor, to investigate the extent to which the heating power can be reduced and the pulse duration shortened while still reliably tracking the liquid–gas interface. A MOSFET is employed to deliver the pulse with an adjustable voltage to the resistors, which produce heat that is directly measurable by the PT-1000 elements. While initial tests have been conducted in water, further experiments are planned using liquid nitrogen and liquid hydrogen in the coming months.

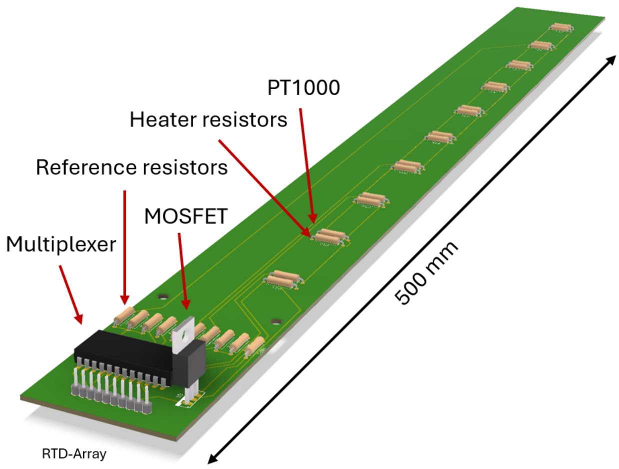

FIG 13. RTD Probe containing 10 PT 1000 elements and heater resistors

8. CONCLUSION AND OUTLOOK

Selecting a suitable fill-level sensor for an LH_2 aircraft tank is a complex task. It requires meeting the stringent reliability and accuracy requirements of the

Fuel Quantity Indication System (FQIS) specified in aviation regulations, while also accounting for the unique cryogenic properties of LH_2 and the novel tank geometries and integration strategies proposed for future hydrogen-powered aircraft.

Although various fill-level sensing concepts have been developed and tested in laboratory environments for gauging LH_2, none have been specifically designed to meet the stringent standards of the aviation sector. Most existing concepts are intended for ground-based applications or spacecraft and are therefore not directly transferable to commercial aircraft operations. In particular, integration strategies that facilitate maintenance must be further developed.

We experimentally investigated capacitance probes in liquid nitrogen and found that they operated as expected, without encountering issues related to thermal contraction of the stainless-steel probe or plastic spacers. Furthermore, a laboratory setup was constructed to collect data on the frequency response characteristics of an acoustic modal gauge, taking into account varying flight angles. In addition, an RTD probe was designed and fabricated, and initial tests measuring the water level have been performed.

Future work includes further investigation of capacitance probes through cyclic testing in liquid nitrogen, transitioning to a multi-cylinder design to increase the capacitance sensitivity, and conducting measurements in liquid hydrogen. Additionally, we plan to develop an algorithm that accurately calculates the fill level of a tank using the acoustic modal gauge in combination with flight-angle data. Finally, the RTD probe will be further studied to determine the extent to which the heating power can be reduced and the pulse duration shortened while still reliably tracking the liquid–gas interface in cryogenic conditions.

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