

Structural Health Monitoring on Liquid Hydrogen Tanks for Aviation Using MEMS, Shape Memory Alloy Strain Sensor and H₂ Leakage Sensors [†]

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Abstract

The aviation industry is adopting liquid hydrogen (LH₂) for sustainable flight, requiring robust safety systems. This work is an example of adaptation of a Micro-Electro-Mechanical Systems (MEMS)-based structural health monitoring (SHM) system for LH₂ tanks, developed in the H2ELIOS project. It uses a multisensor approach that combines MEMS sensors to monitor vibration and acceleration, shape memory alloy (SMA) strain sensors for measuring tank expansion, and hydrogen leakage sensors to prevent false alarms. This SHM technology detects cracks and delamination of material and coating, enabling predictive maintenance via digital twins and ensuring structural integrity.

Keywords: LH₂; SHM; MEMS; shape memory alloy strain sensors; hydrogen leakage sensors

1. Introduction

The aviation industry is undergoing a significant transformation as it seeks to reduce its carbon footprint and transition to sustainable energy sources. LH₂ has emerged as a promising alternative to conventional jet fuel due to its high energy density and zero carbon emissions when burned. However, the storage and handling of liquid hydrogen present unique challenges, particularly in terms of structural integrity and safety. Structural health monitoring (SHM) systems are critical for ensuring the safe operation of liquid hydrogen tanks in aviation. In this work we present applications of Micro-Electro-Mechanical Systems (MEMS) and hydrogen leakage sensors in SHM for liquid hydrogen tanks, focusing on their role in detecting structural anomalies and preventing catastrophic failures.

2. Methods

In the project H2ELIOS, Fraunhofer used multi-sensor approach for structural health monitoring (SHM) to ensures reliable and redundant oversight of the tank and its supporting systems (see Figure 1).



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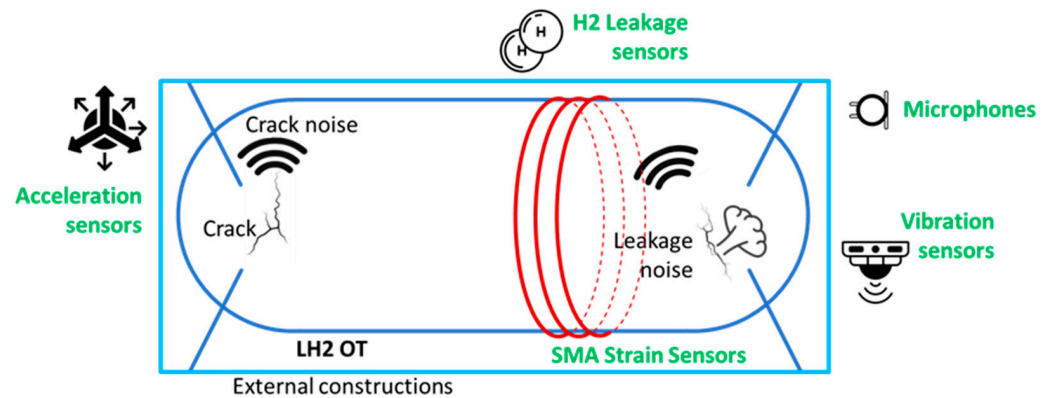


Figure 1. Presented approach to the SHM concept of LH₂ Tank.

This monitoring approach detects critical issues such as cracks and delamination for safeguarding the structural integrity. Additionally, SHM facilitates comprehensive data logging, enabling detailed failure analysis and the development of digital twins to enhance predictive maintenance and optimize tank performance in aviation applications.

We design, develop, fabricate, and perform a component testing of SHM sensors to meet the specific demands of LH₂ tank applications. A variety of MEMS sensors are implemented to measure various physical quantities, including acceleration, vibration, sound/ultrasound, sensors for hydrogen leakage detection, and those for strain (using shape memory alloys) [1,2] are available. Some of the sensors are developed in-house [3]. In order to recognize a leakage and avoid false alarms H₂ leakage sensors and microphones for detection of leakage sound are also included in the monitoring system as well as chemical hydrogen leakage sensors.

Sensors are placed in sensor boxes (IP 68 standard housing) and connected to each other with industrial CAN bus. Exact geometry of the tank material model over the whole temperature range is essential. Material of the outer tank was investigated over a wide temperature range to provide a material model, which are required for accurate digital twin [4,5].

Below, sensors used in a proposal SHM system as well as preliminary results on subcomponents are described in detail.

3. Sensor System Development and Test Results of the Subcomponents

The approach described in this paper can be supported by the following layer-based representation:

The first layer is a network of strain sensors responsible for direct measurement of cracks on the surface of the tank and at critical locations. These sensors are used to detect and immediately communicate the crack information.

The second layer of sensors is designed to decide on the consequences of the crack resulting in leakage of hydrogen. In this layer, chemical leak detection sensors with different sensitivity and response time can be placed. One of the purposes of the second layer is to avoid false alarms at the first layer of sensors, and to distinguish non-critical cracks and acoustic emission events at the tank surface and support constructions that are not related to critical issues.

The third layer is for prognosis and maintenance. The sensors in this layer are not directly for immediate crack detection, but to obtain and accumulate long-term information about the whole system. These sensors are temperature, pressure and vibration sensors. The aim is to monitor and accumulate data on the long-term degradation process of the system.

Changes there, together with the digital twin of the system, can provide information for predictive maintenance and additional non-destructive inspection. An example is a

long-term change in the vibration profile. These changes may indicate subcritical cracks in the tank itself or in the supporting constructions [5].

3.1. Shape Memory Alloy Strain Sensors

Since cracks can be only a few micrometers in size, a network of strain sensors with a mesh density of a few centimeters would be much appreciated. From a technical point of view, common metallic strain gauges are a possible choice for this.

New approaches, such as the SMA-based strain sensors are possible. Conventional metallic strain gauges are poorly suited for fiber-reinforced polymer components due to their limited elasticity and fatigue life [6]. SMA strain sensors offer an alternative, exhibiting high elasticity for accurate static and dynamic strain measurement, even under cyclic loading [7,8].

To realize this technology, development efforts have focused on sensor fabrication and low-temperature validation. Different SMA wire contacting variants were manufactured, with the final design optimized using crimp elements and soldering. Concurrently, the durability of special adhesives (Araldite and DECH) was successfully verified through mechanical load tests on structural materials at room temperature and in cryogenic conditions down to $-196\text{ }^{\circ}\text{C}$ (see Figure 2).



Figure 2. CFRP materials for the SMA strain sensors (a) and their tests in cryogenic environment (b).

However, it should be noted that conventional strain gauges have a long history in structural health monitoring (SHM) for aviation. SMA strain sensors are a relatively new addition to the field and must demonstrate their reliability over the long term in different temperature ranges and application fields.

Further information about fatigue life and performance degradation, acquired through experiments, should be obtained to ensure the specifications of SMA strain sensors, particularly at cryogenic temperatures and for various substrate types.

3.2. Hydrogen Leakage Sensors

Hydrogen leak detection systems are critical for safety, continuously monitoring tanks and fuel cells for any release of gas. Comprising multiple sensors and a central control unit, the system uses highly sensitive sensors at key points—like valves and connections—to detect even low concentrations of hydrogen due to its high flammability. The system provides real-time monitoring, triggering immediate alarms or automated safety protocols. This enables early intervention, preventing potential hazards from escalating and ensuring the safe, reliable operation of the entire hydrogen system.

A comparison measurement of commercial-available sensors and two sensors developed within the project (CNT-based and Pd-based) was carried out, whereby our devices

show a similar or even slightly better response behavior (sensitivity, response time) at hydrogen concentrations up to 10,000 ppm (1 vol.-%). Some specifications of H₂ leakage sensors with different sensor operational principles are shown in Table 1 below.

Table 1. Comparison table on some H₂ gas leakage sensors.

Sensor Name	Sensor Operation Principle	Sensitivity	Response Time
FHG ENAS Sensor 1 (Pd/Ti) *	metal films	200 ppm	<5 s
FHG ENAS Sensor 2 (Pd/Ti) *	metal films	300 ppm	<4 s
Alders H2-CNI I2C	calorimetric	100 ppm	<5 s
Membrapor H2/C-40000	electrochemical	12.5 ppm	<45 s
Rainbow RS-H2M-D12	MEMS	0.1 ppm	<10 s
Winsen MQ-8	solid state semiconductors	100 ppm	<20 s
FHG ENAS Sensor 3 (CNT) * [5]	CNT electrodes	10 ppm	<15 s

* FHG ENAS internal sensors designation.

It should be noted that, unlike commercially available third-party sensors, FHG ENAS sensors are still laboratory demonstrators in development (TRL 3–4).

3.3. MEMS Based Inertial Sensors and Microphones

Our team see an important role for wideband (10–20 kHz) inertial vibration sensors. This type of SHM sensors is able to perform in situ experimental modal analysis, and proven to be quite sensitive even in superimposed noisy conditions. The vibration profile of construction is anyway a keystone for SHM, proven on many buildings and constructions. Less expensive industrial MEMS sensors are a good choice for this, and also from the point of view of mass, size, and power consumption. MEMS acoustic emission (AE) sensors are a good addition for strain sensors on the surface of the tank. AE sensors monitor a small area (about 0.1...1 m²) around the sensor placement. Redundance, different frequency ranges, and AE events are necessary to monitor. It is desirable to have a mesh network of these sensors with a density of about 20...50 cm on the tank surface, as well as on critical support constructions. There are enough mechanical vibration excitation sources in planes, thus passive monitoring will work. MEMS AE and vibration sensors, designed, fabricated and implemented in the system are shown below (see Figure 3).

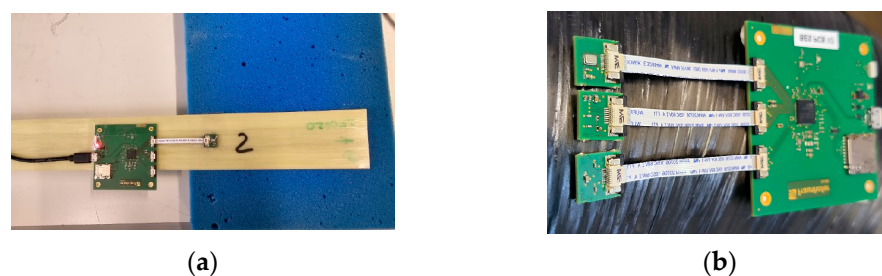


Figure 3. MEMS vibration sensor patch on test material (a) and on H₂ tank (b).

Monitoring of the tank surface is not enough. External construction, pipelines and other tank subsystems outside also may be a source for critical issue, that influence integrity of the tank. From mechanical points of view mechanical connection from subsystem to the tank and from tank to interior of the plane are most critical. These sites should also be equipped with strain sensors or MEMS AE sensors.

MEMS and ultrasound microphones have shown themselves to be surprisingly sensitive. They were able to detect cracks (pencil lead breakage test) and delamination events from a distance of several decimeters, even in a noisy environment (see Figure 4).

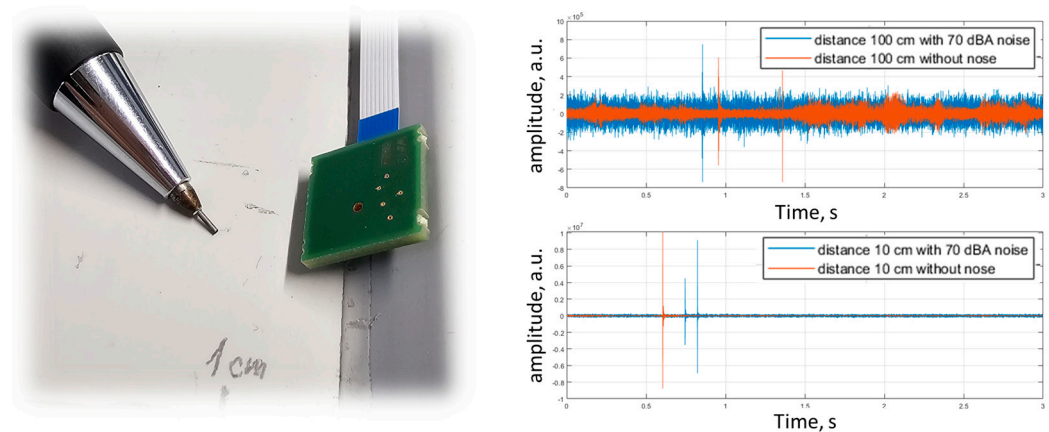


Figure 4. Test on subcomponent: AE events detection in noisy environment.

The proposed MEMS-SHM approach, which uses inertial sensors and microphones and is supported by H₂ leakage sensors, could be a significant advancement in structural health monitoring (SHM) systems. It could enable the creation of scalable and, most importantly, cost-efficient redundant sensor networks.

The current TRL of the FHG MEMS sensors presented in this paper is between 4 and 5. Different sensor units with a standardized package and interface are currently assembled. The subcomponents of these units are tested in FHG laboratories. The next stage involves placing many units (14 in the current setup) on a LH2 tank to prove their ability to acquire data during a series of tank field tests. If the test is successful, the MEMS-based SHM system may achieve TRL 5.

Although it is difficult to make such assessments at this stage in the development of this SHM system, we can assume the following high-level characteristics in field-test conditions: minimum H₂ concentration detection starting from 100 ppm and spatial resolution of sensor networks: some cm.

The minimum crack size that can be detected by the proposed system is difficult to estimate because digital twins with a matched tank material model are required [5].

The sampling rates or bandwidth ranges of MEMS/AE sensors can currently be very high. Highly sensitive, high-precision microphones and vibration sensors can produce raw data at several Mb/s. CAN bus, even in a serial configuration, can, in principle, handle this load. The main limit of the CAN bus is regarding bus speed and cable length. For signal transmission above 50 m the bus speed has to be lower than 1 Mbit/s. Also, error frames and arbitration phases cost bus time reducing the total bus capacity in the proposed configuration to seven transmitter-boxes with 100 data packages per second per bus. This means, that data acquired at much higher data speeds (e.g. ultra sonic microphone with sample rate of 192 kHz), is preprocessed and reduced to statistical data (av, std, min, max) at bus speed.

3.4. Firmware on Example of Hydrogen Leakage Detection Sensors

Hardware solutions, such as PCB design, and firmware development for CAN bus data transfer protocol, including calibration and programming, are provided (see Figure 5a). The control electronics are based on a powerful microcontroller that reads out the values of the sensor elements using special readout electronics. In addition to the developed sensors, other commercially available sensors for determining air pressure, temperature and humidity are also installed in the system and read out accordingly via various digital interfaces such as SPI and I²C. The recorded sensor data is continuously queried, pre-processed in the microcontroller (calculation of average, standard deviation, minimum and maximum value of a data package) and finally sent (as a CAN bus slave) to a higher-level CAN master device.

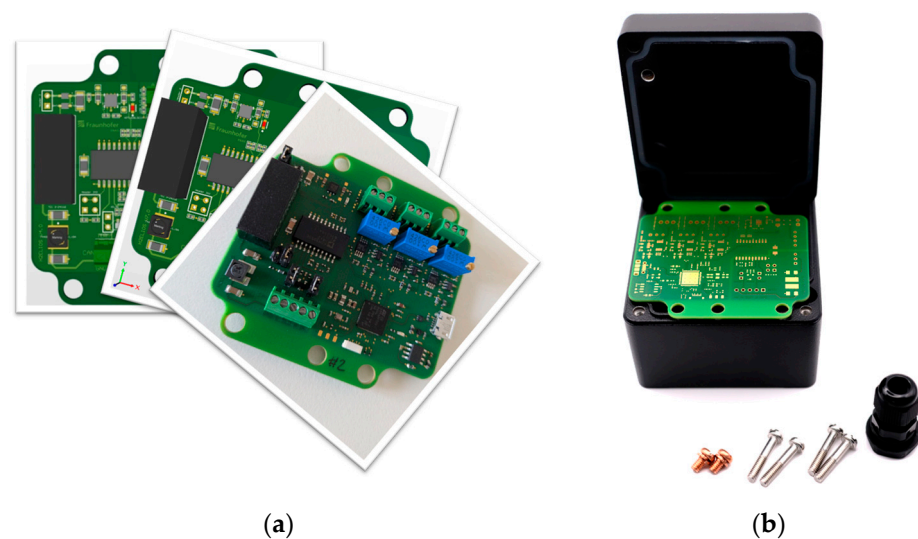


Figure 5. PCBs for sensor patch, developed for different sensors sets (a) and universal sensor box (b) according IP68 standard.

All electronic boards (sensor, data handling and processing) are placed in IP68 die-cast aluminum housings. One of these sensor boxes can be seen in Figure 5b.

3.5. Data Flow, Firmware

For communication with a CAN master device the CAN-FD Interface with a bus speed of 500 kbit/s is used. The CAN-FD standard allows up to 64 byte data payload per package. Each sensor-box sends telegrams with specified CAN IDs. The payload contains preprocessed data from multiple sensors at the time of sending, depending on the hardware configuration of the sensor box. The power supply of the sensor boxes is done via external power supply per CAN bus. As the CAN master device, a laptop equipped with the CAN-to-USB adapters “Kvaser U100” interface adapters, which is capable to communicate with CAN-FD format and Bus speeds up to 8 Mbit/s, is used. The adapter converts the CAN bus signal (CAN High and CAN Low) to USB data, which is received and recorded by the connected computer. For recording the software tool from “Kvaser CanKing” is used. This allows us to configure the interface Adapters, CAN bus data filters and logfiles accordingly.

4. Conclusions

In this paper, we present the results of our work on a project to create a SHM system for an aviation tank containing liquid hydrogen. We selected the most promising technologies for the defined tasks and according to the identified SHM objectives:

- strain sensors covering a large surface area of the tank and other viable structural spots;

- acoustic emission sensors capable of detecting specific cracks on the tank surface and supporting structures;
- wideband inertial sensors placed on external constrictions for permanent in situ experimental modal analysis, which can improve information on the tank system during operation.

These sensors are useful for the early stages of introducing and establishing these systems in aviation, especially given the lack of long-term experience and experimental data on this type of tank in a flight environment [5]. Distinguishing between false positive and false negative alarms is therefore important. This is why chemical H₂ leakage sensors are essential and are also included in the monitoring system for LH₂ tanks. We have completed testing of the subcomponents. Now we are preparing the tests on an LH₂ tank demonstrator.

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Abbreviations

The following abbreviations are used in this manuscript:

MEMS	Micro-Electro-Mechanical Systems
SHM	Structural Health Monitoring
LH ₂	Liquid Hydrogen (H ₂)
SMA	Shape Memory Alloy

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