33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

SIGMOIDAL SENSING DEVICES FOR MONITORING TO IMPROVE MAINTENANCE OPERATIONS IN AERONAUTICS

Pfeiffer, H.[3], Sekler, H [2] & Wevers, M.[1]

[1] KU Leuven, Dept. of Materials Engineering (MTM), Kasteelpark Arenberg 44, bus 2450, 3001 Leuven, Belgium
[2] Deutsche Lufthansa AG, Aircraft System Engineering, FRA L/OME331,
Rhein Main Airport, 60546 Frankfurt, Germany

Abstract

Sensing systems, especially when used for interrogating the structural integrity of aircraft in traditional inspections or for structural health monitoring, are frequently working in a quasi-linear mode. However, this approach leads to difficulties in some cases like weak signal contrast with respect to interfering baseline fluctuations, especially when structural health monitoring is involved. For the latter, an interesting alternative is offered by specific highly non-linear sensing devices that provide sigmoidal response curves. They produce, at a pre-defined operation point, a sharp sensor response that ideally only depends on a specific damage parameter representing in this way a material-based threshold. Moreover, this sharp sensor response ideally ranges over many orders of magnitude exceeding in this way baseline variations.

This paper reports on the categorisation and classification of those sensors that already exist in operational aircraft or are still at a conceptual level. The existing sensors are airborne-validated to determine the water leakage in floor structures of Boeing 737 and Boeing 747 aircraft and the other sensors will be documented with conceptual studies on the leakage monitoring of hydraulic liquids in aircraft, fuel leakage, bleed air detection, moisture in composites and somewhat related as a structural health monitoring (SHM) application, also the detection of ice in fuel tanks of aircraft.

Keywords: Structural health monitoring, fuel, hydraulics, corrosion, ice detection

1. Introduction

Sigmoidal sensing devices are here defined as a sensing technology showing a clear sigmoidal, thus S-shaped response curve tailored to a pre-set damage range, or even to a certain damage size, but with a large change in magnitude exceeding diverse baseline variations. A good example are electrical fuses that only provide signals on a certain threshold-specific overcurrent without specifications on position or the absolute amount of overcurrent. An apparent shortcoming is the limited range of damage that is measured, but this drawback can be highly compensated by the extraordinary signal-to-noise ratio (SNR) even approaching infinity in some cases. A principal scheme of the sensing principle with respect to quasi-linear sensors is shown in Figure 1.

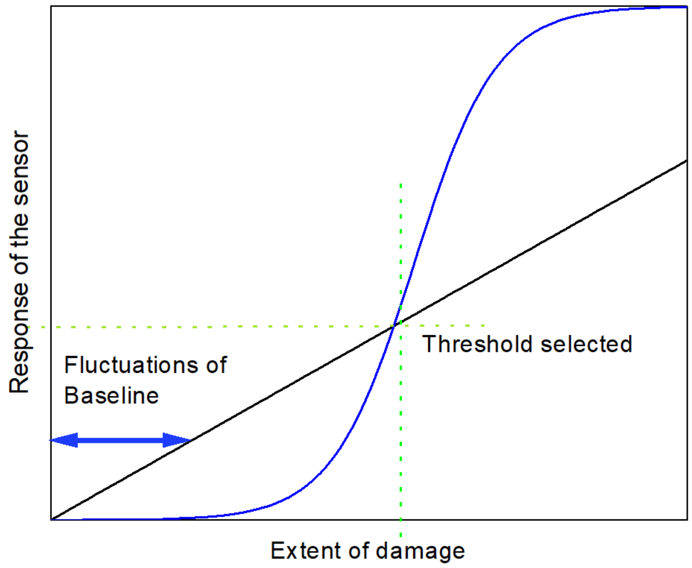

Figure 1 Schematic sensing principle for sigmoidal sensing devices in structural health monitoring. The essential difference with quasi-linear sensors is the limited detection range that however leads to an clearly enhanced probability of detection in that area.

Suited physico-chemical concepts need to be chosen that show the desired "S-shaped" response curves (Figure 2), in order to obtain the discontinuous behaviour as a function of the intended damage-related parameter. Those useful "large-effect" phenomena can be categorised into: i) mechanically-driven fracture, ii) phase transitions, iii) chemical degradation, incl. absorption.

A well-known, commercial example is a crack propagation gauge providing the stepwise changes of an electrical current caused by a progressing crack front; their use in structural health monitoring of aircraft was also already proposed and reported in Pitropakis et al. [1]. Another example is "comparative vacuum monitoring (CVM)". A propagating crack causes a loss of vacuum [2] in dedicated capillaries within the on mounted gauges that can be monitored by emerging air flows. Very recently, a similar approach was proposed when using pressure-medium-filled capillaries inside materials fabricated via additive manufacturing. Here, not a flow-change, but a pressure drop indicates the presence of a crack [3].

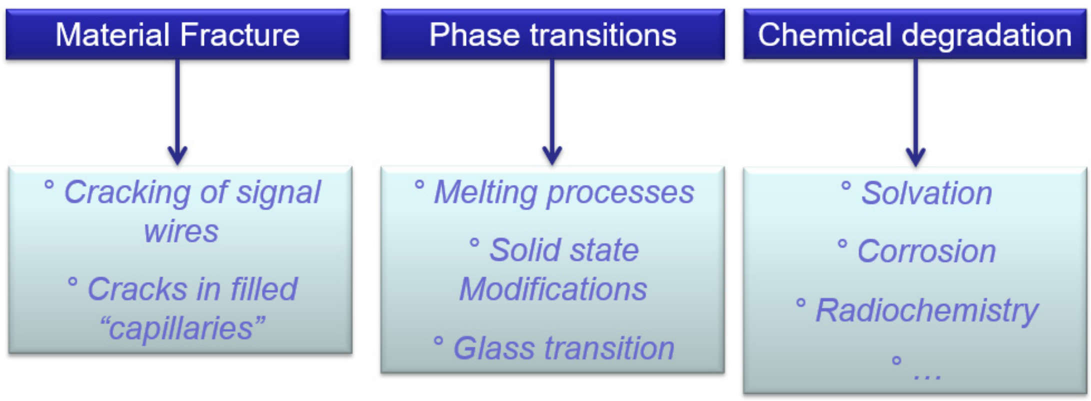

Figure 2 Selected principal options for "step-function behaviour" in sensing material.

Other options are provided by phase transitions, e.g. melting processes, solid state modifications or glass transitions. Fenwal elements are used in commercial aircraft where they are applied for bleed air systems; these are "alarm wires" containing a salt mixture that melts at pre-set temperature ranges, establishing in this way an electrical current. Another example refers to solid state modifications in graphite material being applied for PTC elements (positive temperature coefficient) to protect electric circuits against overheat [4]. A more recent technology of percolation sensors also already implemented in aircraft refers to water uptake in particles filled hydrophilic polymers disrupting electrical percolation conductivity to detect water leakage (developed by the contributing authors). A similar approach was validated for leakage detection of kerosene whereby oil-absorbing elastomers are used in the particles filled polymer sensor and the absorption of kerosene disrupts the electrical percolation conductivity [5].

Chemical reactions provide further options for monitoring, e.g. when filaments or metallic wires are used to sense corrosive conditions in engineering structures. Also the detection of ester-type hydraulic liquids as applied in aviation is possible and here the solvation of electrically conductive composites made of acrylics is used as detection mechanism [6].

2. Applications

Different examples are shown here demonstrate and partially originally developed in our lab that show the usefulness of sigmoidal sensing devices for supporting MRO operations. The technology readiness levels (TRL) are different, in some cases, the systems are flight-proven over many years, sometimes, full-scale models were tested; other examples are just validated on lab scale, but always under highly relevant testing conditions. It must be generally stated that

2.1 Example using mechanical fracture

A typical example for a highly non-linear sensing devices is given by crack propagation gauges. They are glued on the area of investigation. They are e.g. used at fatigue testing to follow the crack propagation at a known crack initiation point [7]. Those gauges can for validation purposes from commercial sources (Vishay) and usually consist of a series of metallic wires that successively break leading to a stepwise change of the overall electrical resistance that can in practice also be measured by a typical voltage drop. Within the intervals between the periodic "steps", the crack gauges are essentially insensitive to crack propagation, thus, one can state that those highly non-linear sensing devices establish a kind of "digitisation" of material testing. This is an interesting analogy to the digital data world, here we have a loss of resolution compensated by a gain in faultless, digitised signal transmission. For testing the suitability for crack monitoring, fatigue tests were performed. Two different tests were carried out with the same parameters and number of fatigue cycles. One test without a hole in order to monitor the consistency of the measurements of the gauge during fatigue and another test with a hole that was responsible for the crack initiation (Figure 3).

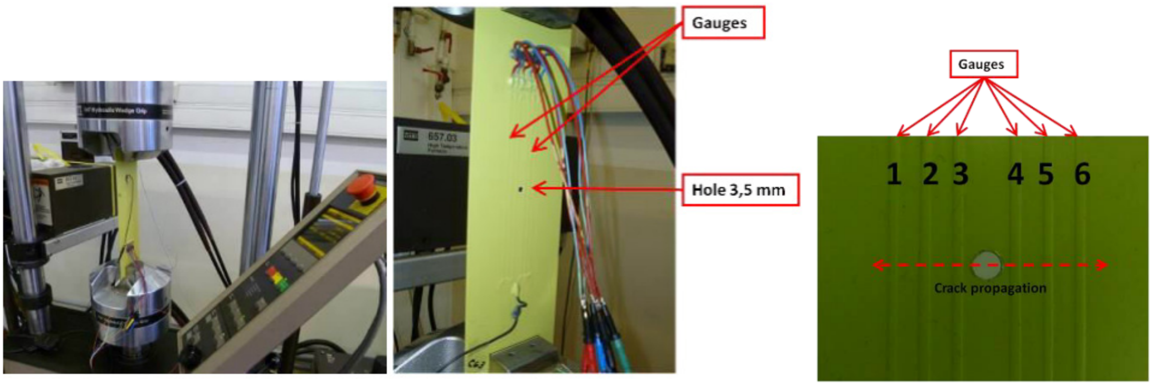

Figure 3 Al 2024-T3 plate set-up (Left: Fatigue test – Right: six embedded crack gauges).

The aluminium alloy 2024-T3 plates were subjected to a fatigue load of minimum 8 kN and maximum 12 kN. The fatigue test was performed on a servo-hydraulic 810 MTS testing machine by MTS Systems Corporation. The maximum dynamic load for this fatigue machine is 80 kN. The frequency of the cyclic loading was 15 Hz and 135,000 cycles were applied. To initiate the crack, a hole with a 3.5 mm diameter was drilled in the middle of the plate. 135,000 fatigue cycles are enough to create a significant crack size of ~12 mm on the plate at each side of the hole. Six crack gauges were embedded, three on the left and three on the right side of the plate.

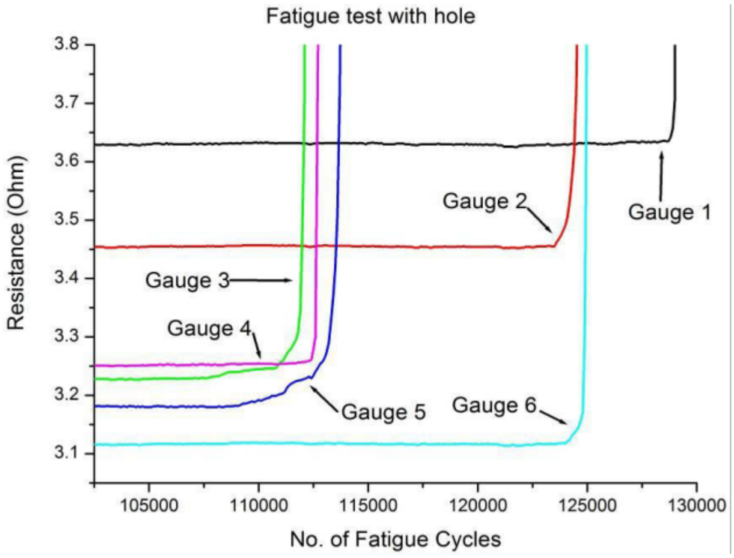

Figure 4 Fatigue-driven interruption of electrical resistance of all six embedded crack gauges on the aluminium alloy 2024-T3 plate. The stepwise change of signal is clearly visible.

The result can be seen in Figure 4, the occurrence of the cracks could be clearly identified. As such, crack propagation gauges appear the most promising concept in crack monitoring. However, a number of remarks need be mentioned. The first concern relates to the phenomenon of the so-called closed cracks, thus, to situations when the crack is under load and difficult to detect even with traditional NDT technologies. Here, crack gauges could also close again requiring to bring cracks under load for monitoring. However, own investigations showed that corrosion processes on the surface of crack gauges might cause a drop in conductivity that might help to overcome the closed-crack issue. Another issue is the self-testing capabilities of crack gauges. Imagine a situation when paint and the embedded painted-crack gauges are de-attached, the sensor might fail to detect underlying cracks. This issue is strongly related to the reluctance in aeronautics to accept bonded repair in repair operations, thus, if safety relies on adhesive bonding, glued crack gauges might raise related concerns. However, the all by all impression is that (painted) crack gauges remain one of the main candidates for structural health monitoring, also because of the simple wiring requirements and low power consumption when reading out the gauges.

2.2 Example using a lyotropic glass transition: Moisture monitoring in aircraft structures

The hygroscopic sensor material used in this study is made from the polymer polyvinyl alcohol (PVA) and the target solvent is H_2O. The electrically conductive, dispersed material is a ceramic powder made of titanium carbo-nitride (TiCN). After the ingress of water a percolation threshold in the range of RH=80% will trigger a huge change in the electrical conductivity far above so-called baseline variations [5] – in fact the resistivity increases by a factor of approximately 10^6. That percolation threshold is related to a so-called glass transition occurring in the PVA material that finally triggers water ingress in the sensing material and the required strong response function.

A working example designed by the authors is the monitoring of corrosive liquids present in diverse floor structures of various operational aircraft (Boeing 737-500, Boeing 747-400), in collaboration with Lufthansa Technik (Germany). Materials susceptible to corrosion are normally protected from the humid environment by insulations such as casings, coatings or seals. However, the intensive use of structures can damage these insulations, and aqueous liquids resulting from spills, condensation or rain can enter the confined spaces, such as floor structures or certain compartments in the fuselage of an aircraft. An interesting tool to detect underlying structural damage would be the detection of those hidden harmful liquids via appropriate sensor networks. In the case reported here, the water ingress following the structural damage/malfunction of sealings is detected by a change of the electrical resistance in dedicated sensing materials.

The detection of corrosive liquids gives interesting options for corrosion prevention already at early stages. In the present case, cable-sensors were embedded between floor panels under the galleys, the lavatories and the entrance areas, and the systems were in service up to seven years (between heavy maintenance). The read-out of sensing data was performed in an interval of appr. 100 flight hours using Ohmmeters; it has been proven that this sampling interval is sufficient for the maintenance operations considered.

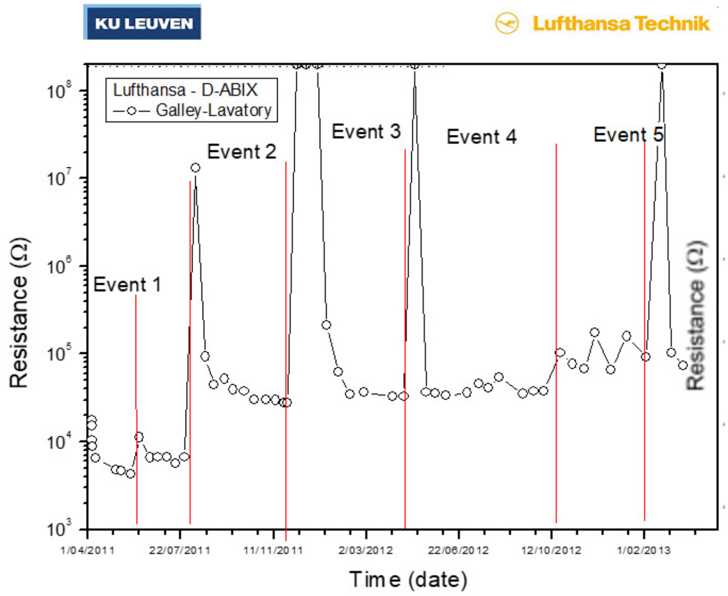

Figure 5 Wetting events in an operational airliner.

A typical response curve obtained in a Lufthansa aircraft over many month is provided in Figure 5. It clearly indicates “wetting events” in the floor structures under the galley of a Boeing 737-530 and similar data from two Boeing 747-430 are available, in all cases most likely caused by damaged seals [8]. A typical feature is that wetting events appear in the beginning temporally as “peaks”; and that the sections partially dry meanwhile. Moreover, the sensor is hygroscopic as such and operates also partially as a “water buffer”, visible by the fact that the baseline of the sensor increases gradually. The typical “peaks” in the plot give in any case a clear information to the maintenance teams to repair the respective sealings at the earliest possible maintenance. All by all, three operational airliners were equipped with the monitoring systems with an integral sensor length of more than 50 meters. In this way, a rich source of information is available to assess the water tightness of seals. Based on that, also new seal systems can be developed because the performance can be assessed very early.

The authors also developed a similar system for monitoring wetness in insulation blankets of aircraft. Insulation blankets are installed at the fuselage of aircraft to prevent that the passenger cabin and cargo area is exposed to the very low temperatures during flights at very high altitudes. This system operates fully wireless and reading-out occurs via RFID data transfer, so during flight no active electronics is present lowering in this way certification requirements. The following picture shows a wetting event in an insulation blanket model (lab based) transmitted by RFID technology (Farsens system, Figure 6).

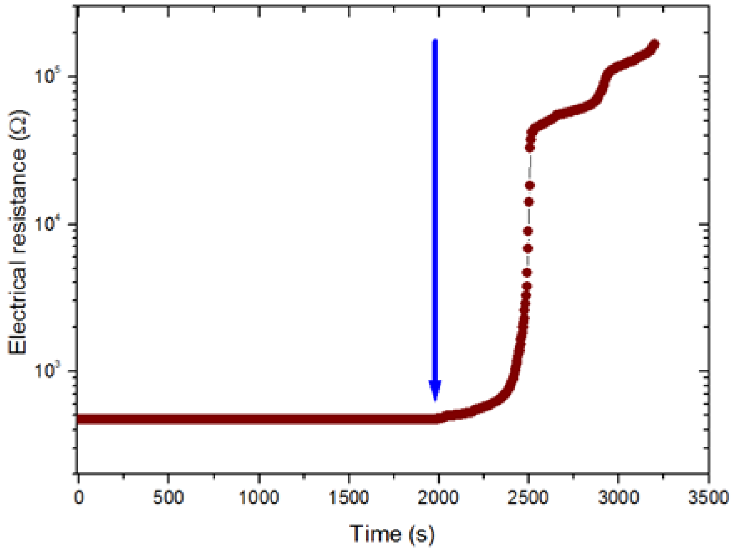

Figure 6 Wetting in a model-based insulation blanket transmitted by RFID technology.

2.3 Example using chemical solvation/absorption: Monitoring of phosphate-ester type of hydraulic liquids (Skydrol®) and kerosene

For that purpose, thus, to detect hydraulic liquids, sensor materials based on acrylics were selected. It is known from the "materials data sheet" of Skydrol® that they do not show any chemical resistance, i.e. all materials based on acrylics are essentially destroyed by that hydraulic liquid. A sensing material based on that material would thus have ideal properties for an appropriate detection mechanism. For developing a prototype, composites made on an acrylic matrix were chosen that were conductive due to the presence of metallic fillers, such as copper and nickel. The electrical resistance was monitored and the material was then exposed to Skydrol®.

From the operational point of view, leakage of hydraulic liquids does not only cause issues with the loss of hydraulic performance, these liquids are as mentioned above also harmful to different kinds of materials, including acrylics, e.g. Perspex. Moreover, these liquids establish a serious issue for humans since they can cause severe irritations when in contact with the skin and aspiration may cause respiratory irritation thus they create a hazard for mechanics and passengers in this way.

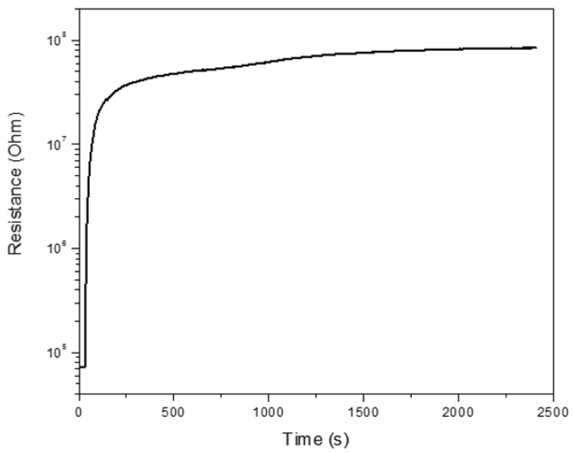

Figure 7 Response curve of sensor after deposition of Skydrol®.

To detect early leakage of hydraulic liquids in the neighbourhood of hydraulic pipes, a dedicated shroud system was developed in collaboration with Brussels Airlines [9] and later on with PFW Aerospace, that contains wire sensors with a sensitive coating only detecting the targeted phosphate-ester-type liquids. It is easy to install and not only liquid loss due to cracks, but also by lose fittings is detected. A typical response curve is presented in Figure 7.

2.4 Example using a thermal glass transition: Overheat detection in bleed air systems by optical fibre technology

Hot air leaking from bleed air systems is a serious damage case in aircraft because hot air will cause severe thermal damage to cable systems and other components. A monitoring technology based on the electrical conductivity of melted eutectic salt mixtures (Fenwal elements, see introduction) already exists. In the case of overheat, those salt mixtures start melting and electrical shortcuts between the electrodes are created enabling the pilot to shut-down the bleed air system in time. More recent developments even provide functionality towards localisation of the leakage for facilitating repair procedures, i.e. optical fibre systems based on Bragg gratings.

An alternative approach proposed by the authors is the use of polymer optical fibres (acrylic POF) that own an intrinsic glass transition at the desired target temperature developed in collaboration with PFW Aerospace (Germany) [10]. In the frame of an extended study, appropriate polymer optical fibres were selected that show their glass transition in the detection range which is in our case at appr. 125°C.

Due to the thermal glass transition, the total reflection capabilities in the polymer fibre is strongly disturbed at this point and a significant signal change can be determined. The almost total loss of signal can be determined by a single light electrode, but an interesting option is offered by time time-domain-reflectometry (TDR). A light pulse is launched into the fibre and an almost total reflection occurs at the position of the heat damage. In this way, the maintenance teams can easily identify the position of heat damage, which is highly important not to dismantle too large areas of an aircraft.

Although the sensor is “lost” after the glass transition melting, the financial efforts to implement new optical fibres sensors are negligible since the bleed air systems have to be repaired anyway and the polymer fibres used are relatively cheap, and last but not least, do not cause any electrical interferences.

2.5 Example using thermal phase transitions: Ice detection in fuel tanks for improving draining procedures

In daily flight operations, the accumulation of water in fuel tanks of aircraft due to condensation and contaminated fuel is unavoidable. While liquid water potentially leads to microbial corrosion and misreading of fuel gauges, frozen water can damage the aircraft's fuel system in the fuel tank, leading to potentially dangerous situations for passengers, crew and ground personnel. By draining the tank regularly, almost all the liquid water is removed from the bottom of the tank. However, this procedure only reduces the liquid water and not any remaining ice in the tank. Furthermore, neither the remaining amount of liquid water in the tank nor the amount of ice after or before the emptying process can be estimated. Finally, there are even reports of ice blocking the valve during draining, causing the fuel to flow out uncontrollably.

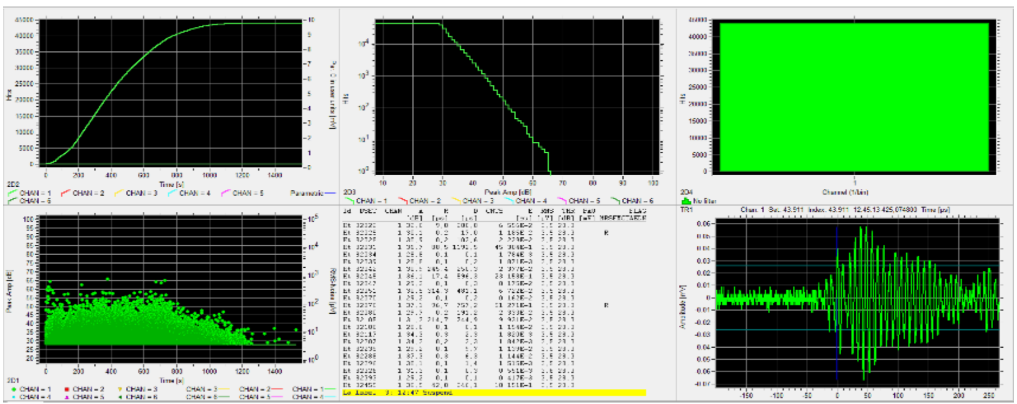

Figure 8 Acoustic signals from melting ice at a Al 2024-T3 fuselage panel. A typical waveform can be seen in the bottom right corner and the characteristic sigmoidal curve of accumulated hits is visible in the diagram in the upper left corner.

We developed a technology based on passive detection of melting ice (acoustic emission) whereby strong ultrasonic signals emerging from melting ice are recorded with the so called acoustic emission technique [11]. A typical acoustic waveform arising from ice-melting can be seen in Figure 8 in the bottom right corner. At the current stage, promising tests are performed on a realistic tank model as well first steps were taken for real aircraft.

It is since long a well-known fact that melting or freezing liquids are the source of characteristic acoustic signals that are usually within the ultrasonic range. Although the origin of the source is still not fully clarified, it has been proven to be a reliable means for detection of melting or freezing ice. In principle, it appears that the number of signals is related to the overall amount of melting or freezing ice but in practice of maintenance one cannot know when freezing and melting actually started, so one determines finally the “rate” of the signals. The disappearance of the signals arising from melting finally indicates the moment when the draining can start.

Figure 9 Detection of ultrasonic signals from, resp. “listening” to melting ice at a model tank at lab-scale as well as in future on fuel tanks to determine the moment water draining from fuel tanks can start.

The results show that such passive ultrasonic measurements are suitable for detecting the presence of ice in the tank based on a typical acoustic emission response curve (Figure 8). Furthermore, it was also shown that ice formation on aircraft surfaces can also be determined from the acoustic signals of freezing water [12]. Most interestingly is the behaviour of acoustic amplitudes and their distribution concerning “hits”. The occurrence of acoustic events follows the Gutenberg-Richter law which is originally known from describing the global statistics of earthquakes.

Last but not least, an example how the measurement would occur in practice is shown at Figure 9. Highly sensitive sensors are connected to an aircraft that has just landed and start recording at a relevant time after very noisy events, such as disembarkation and line maintenance, before draining operations begin.

3. Conclusions

This paper presents “sigmoidal responding sensing devices” for the health monitoring of structures and systems in diverse aircraft parts and components to essentially avoid problems arising from a too weak “contrast” between actual damage signals and interfering background variations. This finally leads to a clear enhancement of the probability of detection (PoD) for related inspections processes [13] and thus is a stimulation for implementation.

Although, the technologies are still limited to niche applications, they have the potential to provide solutions for very practical problems in daily maintenance operations of engineering structures towards Industry 4.0. The working examples of this paper indicate that with the involvement of partners in aeronautics the new concepts can be used as a complementary set of options for traditional SHM techniques.

4. Acknowledgements

Part of the research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n°212912 (Project: Aircraft Integrated Structural Health Assessment II - AISHA II), the “NDTonAIR” project (Training

Network in Non-Destructive Testing and Structural Health Monitoring of Aircraft structures) under the action: H2020-MSCA-ITN-2016- GRANT 722134 and the LuFo – the German Federal Aviation Research Programme LuFo “HiPPP: High Performance Pipe Production : hocheffiziente Rohrfertigung für die Luft- und Raumfahrt-Industrie : Abschlussbericht LuFo V-1”, 2017.

The authors also thank Brussels Airlines and Sirris for their cooperation on the topic of ice detection within the "NDTonAIR" and "Fighting Ice" projects. In addition, the authors are grateful to Daniel Backe of PFW Aerospace for the joint activities within the framework of the HiPP project.

5. Contact Author Email Address

mailto: helge.pfeiffer@kuleuven.be

References

[1] I. Pitropakis, Dedicated Solutions For Structural Health Monitoring Of Aircraft Components, MTM KU Leuven, Leuven, 2015, pp. 200.

[2] D. Roach, Real time crack detection using mountable comparative vacuum monitoring sensors, Smart Struct Syst 5 (2009) 317-328.

[3] D. De Baere, M. Strantza, M. Hinderdael, W. Devesse, P. Guillaume, Effective Structural Health Monitoring with Additive Manufacturing, in: V.a.M. Le Cam, Laurent and Schoefs, Franck (Ed.) 7th European Workshop on Structural Health MonitoringNantes, France, 2014.

[4] MaintenanceHandbook, Aviation Maintenance Technician Handbook Federal Aviation Administration2012.

[5] H. Pfeiffer, P. Heer, I. Pitropakis, G. Pyka, G. Kerckhofs, M. Patitsa, M. Wevers, Liquid detection in confined aircraft structures based on lyotropic percolation thresholds, Sensor Actuat B-Chem 161 (2012) 791-798.

[6] H. Pfeiffer, P. Heer, M. Winkelmans, W. Taza, I. Pitropakis, M. Wevers, Leakage monitoring using percolation sensors for revealing structural damage in engineering structures, Struct Control Hlth 21 (2014) 1030-1042.

[7] H. Pfeiffer, D. De Baere, F. Fransens, G. Van der Linden, M. Wevers, Structural Health Monitoring of Slat Tracks using transient ultrasonic waves, EU Project Meeting on Aircraft Integrated Structural Health Assessment (AISHA), www.ndt.net, Leuven, Belgium, 2008.

[8] H. Pfeiffer, Structural Health Monitoring makes sense, LHT Connection - The Lufthansa Technik Group Magazine (2012).

[9] H. Pfeiffer, M. Wevers, Sensor for detecting hydraulic liquids in aircraft, KU Leuven (University of Leuven), 2013.

[10] H. Pfeiffer, S. Sunechiieva, H. Sekler, D. Backe, M. Wevers, Monitoring of structures and systems of aircraft by highly non-linear sensing devices, 10th International Symposium on NDT in AerospaceDresden, 2018.

[11] M. Stamm, H. Pfeiffer, J. Reynaert, M. Wevers, Using Acoustic Emission Measurements for Ice-Melting Detection, Applied Sciences 9 (2019).

[12] M. Sohail, H. Pfeiffer, M. Wevers, Addressing Safety concerns in Hybrid Electric Aircrafts: In-Flight Icing Detection, Moisture Detection in Fuselage and Electrical Wiring and Interconnect System (EWIS), 11th EASN International ConferenceVirtual, 2021.

[13] H. Pfeiffer, J. Perremans, H. Sekler, M. Schoonacker, M. Wevers, The potential of highly non-linear sensing systems in engineering structures – operating applications in civil aircraft and chemical installations, 8th European Workshop on Structural Health MonitoringBilbao, 2016.

Copyright Statement