Structural Health Monitoring in an Operational Airliner: An Intermediate Report on Leakage Monitoring with Percolation Sensors

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ABSTRACT

Materials in aircraft that are prone to corrosion need to be protected from a wet environment. But as a result of the intensive use of aircraft, respective coatings and seals can be damaged and aqueous liquids arising from spillage, condensation or rain can enter the confined spaces causing heavy corrosion of the respective structures. The presented SHM solution is intended to predict and eventually prevent corrosion by indicating the presence of corrosive liquids in those respective confined spaces.

A sensor was developed and implemented in operational airliners for detecting aqueous liquids that is interrogated in time intervals of app. 100 flight hours. The functionality of the sensor is based on the collapse of the percolation conductivity in an organo-ceramic composite containing a conducting compound which is embedded in a hydrophilic matrix. A typical sharp increase of resistance due to the ingress of liquids can be monitored in different ways, and it is even possible to read out the data during line maintenance using a simple multimeter.

Since April 2011, three operational airliners from Lufthansa were equipped with those percolation sensor networks (Boeing 737-500, Boeing 747-400) protecting the floor structure below galley and service doors areas. Already now, results are so convincing that Lufthansa-Technik was able to adapt maintenance procedures for floor structures. Moreover, first results also indicate that those sensor networks could essentially help reducing the maintenance and repair costs.

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Even for the case that the fluid cannot be removed immediately, information on wetness provides a big added value to the maintenance operations, which leads to the possibility of an early allocation of repair resources – a realistic final target is the replacement of scheduled seal inspections.

In the meanwhile, the concept of the percolation sensor was extended to other liquids that are frequently used in an aircraft. An important application is e.g. the detection of hydraulic liquid or mineral oil-based lubricants and kerosene. For all those liquids, appropriate sensors were developed and implementation is partially under preparation. Finally, a small outlook will be given to the use of percolation sensors for crack detection as well.

Keywords: Structural Health Monitoring, leakage monitoring, percolation threshold, corrosion prevention.

INTRODUCTION

In a wet environment, special care is required to protect corrosion-susceptible materials. A typical example is the floor beam area in an aircraft. The floor structures are protected by coatings, and the space between floor panels is equipped with sealing systems including silicone, tapes and rubber mats. However, coatings and sealings can be damaged during aircraft operations and liquids arising from spillage (especially in the galley and lavatory area) or from passengers boarding at rainy weather conditions can penetrate the damaged areas causing corrosion in the underlying floor beams and seat tracks. As the maintenance of floor structures is scheduled within relatively long time intervals (D-check 5-7 years, C check 2-3 years), a starting corrosion problem remains undiscovered in most cases. An appropriate liquid sensor interrogated e.g. on a weekly base helps to avoid unnecessary maintenance costs.

The sensor presented is based on the collapse of percolation conductivity in electrically conducting composites [1]. Such composites contain conducting particles that are embedded in a liquid-absorbing matrix. Percolation means the inter-connectivity of conducting particles in certain lattice structures and a prominent example of such composites are conductive polymers, i.e. materials used for conducting glues or adhesives. Conducting composites are usually made of graphite or metal powders embedded in appropriate polymer matrices (epoxy and other compounds).

Figure 1 illustrates the conducting component, illustrated by spheres, within an insulating matrix (grey). When increasing the volume fraction of the conducting particles, the probability of having a conducting path (black line at the right picture) between electrodes is also increasing. In many cases, one finds a certain threshold of conductivity when the material turns from an isolator into a conductor (percolation threshold).

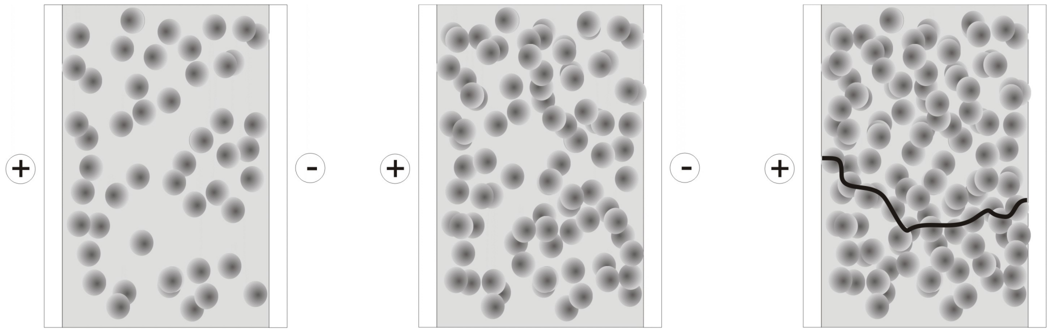

Figure 1. Simplified scheme of the creation of percolation conductivity.

The change in resistance at the percolation threshold can range up to 16 orders of magnitude [2]. As the conductivity strongly depends on the volume fraction, many physical quantities related to the volume fraction thus have an enormous influence on the conductivity. In this way, percolation offers interesting options for sensing applications.

DESIGN OF A PERCOLATION SENSOR FOR FLOOR STRUCTURES

Materials and methods

To obtain an appropriate floor structure sensor, a dedicated organo-ceramic composite was developed [3]. The use of conducting ceramic powders for that purpose is new and according to a literature review, no similar applications were found. Normally, conducting ceramic powders are used to create electrical conducting ceramics that can afterwards be machined by spark erosion. The main reason of using ceramic powders in our case is related to its chemical stability, such as fire and corrosion resistance.

As the liquid-absorbing matrix material, polyvinyl alcohol (PVA) was chosen [4]. It is a hygroscopic polymer that was selected because of its known swelling capacity, chemical compatibility and toxic harmlessness. The volume fraction of the conducting composite was chosen that the system is relatively far away from the percolation threshold so that variations of the baseline (humidity variations) do not have major influence on the resistance data.

Pictures of the conducting composite were obtained using Scanning Electron Microscopy (Figure 2). The average size of the ceramic particles is in the range of a few micrometers. Because of the preparation of the samples (polishing), it is possible that the distance between the particles is not completely the same than in the case of the conducting state.

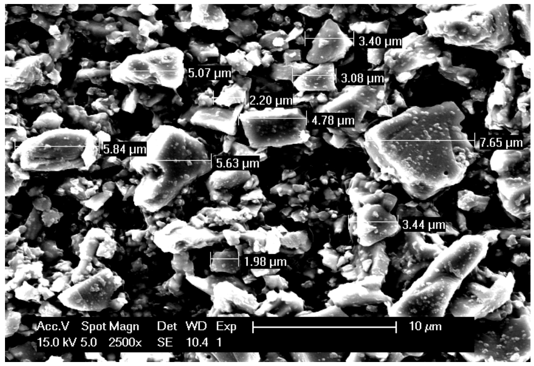

Figure 2. Scanning Electron Microscopy (SEM) picture showing details of the sensor material.

The sensor and its implementation in real aircraft

An important problem when embedding sensors in floor structures is the limited space that is available between floor panels or within seat tracks. In many cases, only grooves with a width of approximately 1 mm are available and sometimes sharp bends challenge the bending resistance of the sensor. Finally, the sensor needs to be extended with lengths reaching up to 4 m. It should be noted that for most applications, the exact position of the spilled liquid is not important. In the case of wetness removal, bigger floor segments would have to be opened anyway.

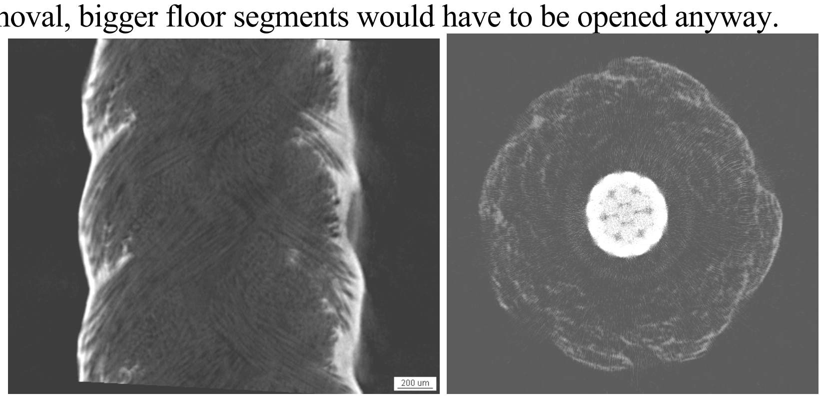

Figure 3. Microfocus X-ray imaging pictute of the sensor, the diameter is app. 1 mm. Left picture: The white gleam at the nylon cord represents the distributed conducting ceramic powder composite that turns into an isolator when in contact with water, Right picture: Feeding wire embedded in the core of the nylon cord.

Firstly, an isolated standard wire was embedded inside the core of a nylon cord. Then, the nylon surface was coated with the aqueous dispersion of the organo-ceramic composite. During drying, the sensor coating became conductive. Microfocus X-ray imaging (micro-CT) provided pictures from the interior of the sensor (Figure 3).

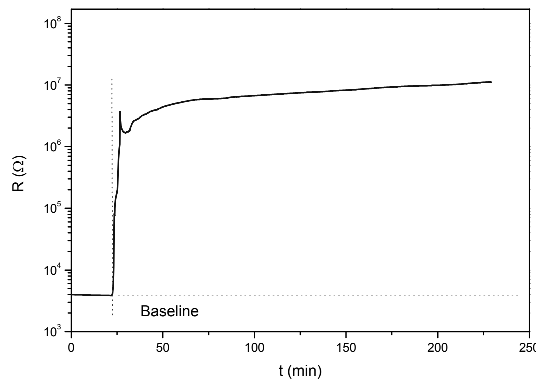

Figure 4. Electrical resistance after liquid spilling. Note that baseline variations in the logarithmic scale does not play any role with respect to the damage signal.

The sensor was deposited in a tube simulating the space inside floor structures and an electrical connection was established between sensor and a digital multimeter (Keithley 2000). Dedicated software was developed to record and analyze the resistance data. When e.g. 0,7 ml of a liquid spilled in an aircraft (cola) was deposited on the sensor, a characteristic response was measured such as shown in Figure 4.

The mechanism when the composite comes in contact with the liquid can be described using a schematic pseudo 3-component "phase" diagram (Figure 5) given conducting and non-conducting states as a function of the respective concentrations. When the liquid enters the composite having a TiCN concentration given by A (dry state), the local concentration of water gradually increases until point P is reached (see also the arrow describing water uptake). The sharp step in Figure 4 thus represents a time-depending, diffusion-driven percolation threshold.

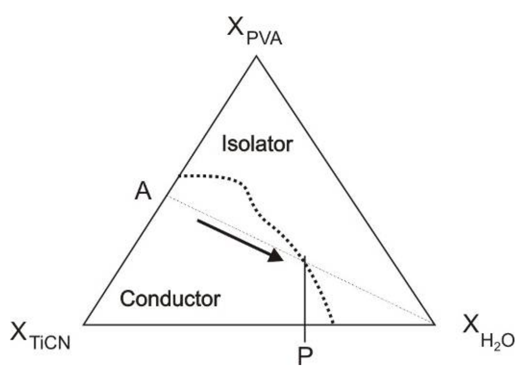

Figure 5. Idealised pseudo-3-component "phase" diagram showing conducting areas as a function of the respective concentrations. The dotted curve represents the percolation threshold.

After spreading, the liquid was absorbed by the sensor material. An important fact is that the liquid itself is also modestly conductive (ionic liquids). But it is obvious from Figure 4 that the remaining conductivity is much lower than the initial conductivity in the dry composite. Another interesting aspect of the sensor is its buffering capability, i.e. when absorbing spilled water, that water is partially no longer available for corrosion.

In the present case, the resistance increased by an approximate factor of 5000. This is a much higher value than the normal baseline variations of the resistance occurring at normal operational conditions. In this sense, the sensor avoids the big challenge related to many SHM sensor concepts, i.e. the problem to distinguish between baseline variations and damage-related signals.

A major advantage of the sensor material is that it keeps its state for a sufficiently long time, i.e. it is not required to bring additional electronics into the airplane. This reduces certification efforts. In practice, it is thus sufficient to measure the electrical resistance in certain time intervals during line maintenance using a low-end multimeter. The non-conductive state is quite stable because spilled liquids will remain in the respective floor structures, in this sense; the sensor represents a kind of a fuse. In a later stage of development, establishment of a data connection to the ARINC bus is intended so that information on wet floor structures is directly fed into the maintenance computer. Another option is the use of RFID facilities.

Figure 6. Part of the implementation area in a Boeing 737-500; left picture: the sensors (black wire) is placed between floor panels and right picture: partially re-sealed floor in the galley area with implemented sensor under the galley area and galley door.

The implementation in the operational airliners was carefully prepared, and all required certification steps were followed. Galley and lavatory areas as well as the space below the doorstep of the galley door were selected (Figure 6). The implementation was finally performed on a Boeing 737-500 as well as on two Boeing 747-400 from Lufthansa during the C resp. D-checks. The total length of the implemented sensors reaches up more than 40 m. Reading out resistance data is performed by a simple interface using a standard multimeter and data are collected and analyzed on a regular basis.

As an example, the resistance values for the galley area of a Boeing 737-500 are shown in Figure 7. At that position, multiple jump-like increases of resistances are observed indicating the presence of wetness. This can arise from direct leakage or even by condensation water. In any case, those signals should not be present when seals are still in good shape and corrosion might be expected for the case that the wetness cannot be removed at an early stage.

An interesting feature is the partial subsequent drying that is visible from the decaying resistance values after the wetness “events”. This is possible due to the drying capacity of the sensor itself (diffusion of water along the extended sensor) and by air circulations due to the micro-climate present in the floor structures. In any case, for real dry areas such events should not be present and the data obtained from Figure 7 show finally that inspections by opening floor structures could be avoided when no events are observed. This is because corrosion is the only fault mode occurring in those structures.

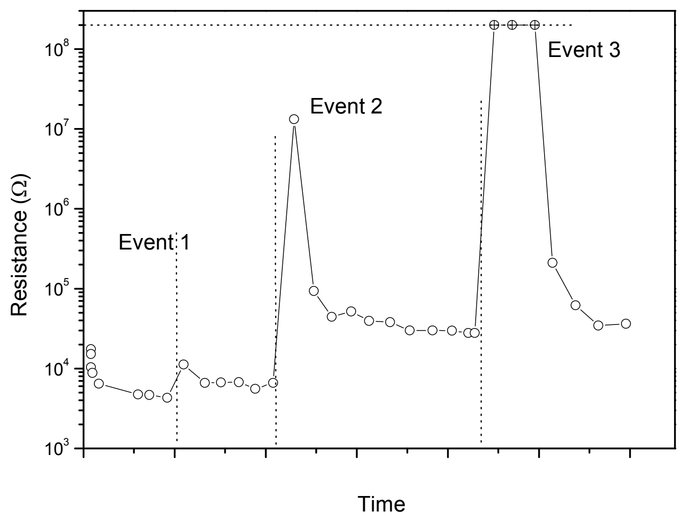

Figure 7. Electrical resistance data obtained from a sensor under a galley area. The time interval between the points represent approximately 100 flight hours.

The percolation sensor concept was in the meanwhile extended to further liquids frequently used in aircraft. An interesting application is e.g. the detection of the hydraulic liquid SKYDROL®, or mineral oils (e.g. to be applied in jet engines) and kerosene. For all these liquids, appropriate sensors were developed and implementation is partially under preparation. Another option arises from the use of painted percolation sensors for crack detection. Also here, the irreversible interruption of percolation conductivity by crack formation is used to detect cracks in an optimized way without using sophisticated sensor networks. In contrast to metal crack gauges, the added value of using percolation material arises from the possibility to tailor the matrix material in a way that an interruption of the conducting path is durable.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Community's Seventh Framework Program [FP 7/2007-2013] under grant agreement n°212912 (Project: Aircraft Integrated Structural Health Assessment II - AISHA II).

We also want to thank Gregory Pyka for performing the SEM analysis and Johan Vanhulst for establishing the data logging facilities. Furthermore, a special thank to Kim Vanmeensel and Wout Veulemans for the support with the ceramic powder technology.

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