# Monitoring of structures and systems of aircraft by highly non-linear sensing devices

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**Abstract.** Sensing systems, especially when used for interrogating the structural integrity of aircraft in traditional inspections, are frequently working in a quasi-linear mode. This approach however creates difficulties in some cases, especially when applications for structural health monitoring (SHM) are concerned. One of the major problems are base-line deviations interfering with damage-related signals that are in some cases moreover complicated due to interferences at complex aircraft structures creating major obstacles for a broad-scale implementation of SHM in aircraft. Advanced data processing and dedicated high-end hardware components are certainly capable of tackling part of these problems, but additional hardware requirements require extra power supply, together with advanced data transmission and processing facilities, also additional maintenance needs emerge.

In some cases, an interesting alternative is offered by highly non-linear sensing devices. They produce a sharp sensor response that ideally only depends on a certain damage-related outer parameter representing in this way a material-based threshold. Moreover, this sharp sensor response ideally ranges over many orders of magnitude above the baseline variations and in this manner, an ideal tool would be established to finally enormously increase the probability of detection, at least within the range of damage to detect.

After a short review on examples taken from the literature, that are in some cases successfully applied in operations, new developments are presented, such as water leakage sensors based on the percolation effect, dedicated optical sensors for reliably detecting damage in hydraulic pipes as well as defects in bleed air ducts. Most of them are able to cover bigger surfaces and are, when appropriate, also partially equipped with dedicated facilities for reliable damage localisation. Finally, a couple of examples are given that were already implemented in operational airliners, such as devices for the detection of corrosive liquids in aircraft (Boeing 737-500, Boeing 747-400).

# 1 Introduction

Highly non-linear sensing devices (HNSD) are here defined as sensing systems that show a clear sigmoidal, thus S-shaped response curve that is tailored to a pre-set damage range, or even only at a certain damage size, but with a large change in magnitude in contrast to diverse baseline variations [1]. In this way, they are in a certain sense an analogue to e.g. electrical fuses only providing information on a certain threshold-specific overcurrent without providing specifications on position or the actual amount of overcurrent.

An apparent limitation is the limited range of damage that is measured, but this drawback can be highly compensated by the partially high signal-to-noise ratio (SNR) that can even approach infinity providing new applications and options.

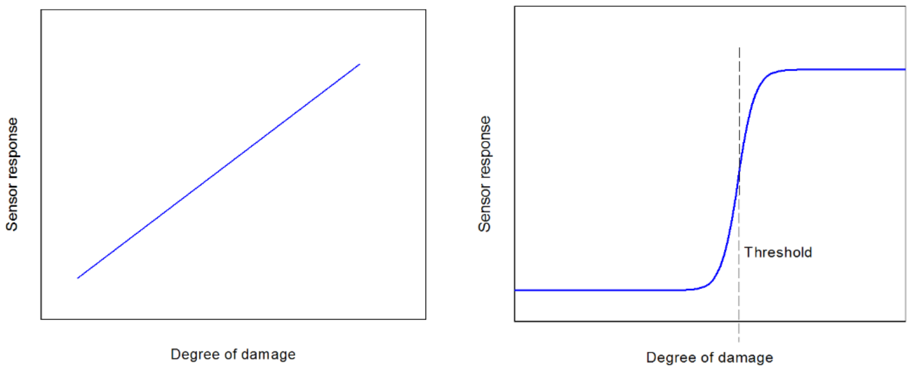


Fig. 1: Principal response of a quasi-linear and a highly non-linear sensing material [1].

Appropriate physical phenomena need to be selected show such S-shaped in essence, discontinuous behaviour as a function of the intended damage-related parameter to obtain a response curve such in Fig. 1. Those useful "large-effect" phenomena can be categorised into: i) mechanically-driven fracture, ii) phase transitions, iii) absorption and iv) chemical degradation. Related to that, the variation of the sensor data, i.e. the sensor response can ideally proceed over a big range of magnitude and therefore, the y-axis in the above figure, right can in some cases even be understood as a logarithmic scale.

A well-known, already commercialised example are crack propagation gauges that provide stepwise changes of an electrical signal as a function of a progressing fracture and their use for structural health monitoring in aircraft was also already proposed and reported.

Comparative vacuum monitoring (CVM) gauges [2] are a further typical example. Here, a propagating crack causes a loss of vacuum in fine capillaries that is monitored by appropriate flow gauges. Very recently, a similar approach was proposed when using pressure-medium-filled capillaries inside materials embedded via additive manufacturing [3]. In this case, not a flow-change, but a pressure drop will indicate the presence of a crack.

Highly interesting options are provided by phase transitions, such as the melting processes, solid state modifications or glass transitions. Already since many years the so-called Fenwal elements [4] are used in commercial aircraft applied for bleed air systems. These are "alarm wires" containing a salt mixture that melts at a certain target temperature range, establishing in this way an electrical conductivity leading to an intended shortcut between electrodes. Another example are appropriate solid state modifications in graphite material that is applied in PTC (positive temperature coefficient) [5] elements in order to protect electric circuits against overheat. A more recent application also implemented in aircraft refers to water absorption in hydrophilic polymers that trigger glass transitions to detect water leakage [6]. A similar concept is applied with for leakage detection of kerosene, in this case oil-absorbing elastomers are used to disrupt electrical percolation conductivity [6].

Chemical degradation offers further opportunities for monitoring, for instance when filaments or metallic wires are applied to detect corrosive conditions in engineering structures [7]. Also the detection of ester-type hydraulic liquids frequently applied in aviation is possible via the solvation of electrically conductive composites made of acrylics [6].

## 2 Probability of Detection (POD) of HNSD

It is a question of definition whether a distinct material feature is considered as a damage or just a particular variation of a material property, and this is also depending on the specific use of that material and its specifications. Nowadays, the performance of a certain NDT technology to find defects should ideally be characterized by the "probability of detection (POD)" where statistical functions modelling for given damage sizes the statistical probability to find this particular defect. To determine POD graphs, sufficient measurements of pre-defined damages need to be done and under ideal circumstances, related series of tests are performed on various test samples, by different operators that use different devices with the same specifications. Also the "background noise" needs to be taken into account when determining POD plots as they are part of the "false positives". In most of the cases, parallel to the POD value, an appropriate confidence interval is provided.

Two major approaches exist. In the case of the established hit/miss analysis, for every defect, tests are performed and a statistics is established for all "existing defects detected" versus "existing defect not detected". The other method is using real sensor data, called â (a-hat) that is analysed versus the real damage sizes, which is annotated by "a". Using the slope and the scattering of these data points, a non-binary POD curve is obtained using generalized linear regression methods (GLM) [8] that usually includes corresponding confidence intervals.

The POD analysis is well-developed for traditional non-destructive testing but still in an earlier phase for structural health monitoring [9]. Moreover, for obvious reasons, the highly non-linear sensing devices require a different approach for the "Probability of Detection" analysis as the most basic assumption for traditional NDT analysis is not fulfilled, which is the quasi-linearity of sensor response (in most cases log-linear sensor behaviour). Some thoughts about alternatives are presented in Pfeiffer et al. [10]. In essence, the probability of detection of a highly non-linear sensing device should be a normalised delta-function at the targeted damage size, thus it is approximately POD = 1 at the pre-set threshold and POD = 0 outside that range.

## 3 Crack detection via crack gauges

A perfect example for a HNSD are crack propagation gauges that are already widely commercially available (e.g. those provided by Vishay). Usually, they are adhesively attached to the potential crack area which might e.g. be situated around the crack initiation point during fatigue testing to follow the crack propagation [11]. They are made of a series of metallic wires leading to stepwise increase of the overall electrical resistance during successive wire breakage. The POD for crack propagation gauges is in this logic a series of small ranges with respective POD=1.

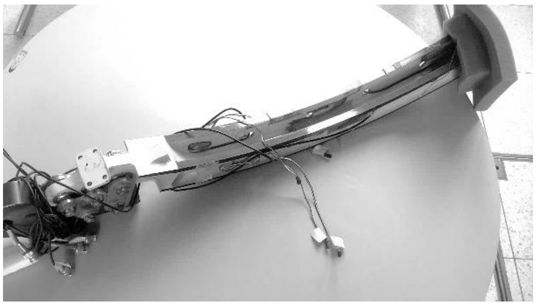

Fig. 2. Slat Track from Airbus A 320 with installed crack propagation of Vishay, partially overpainted.

A typical curve showing voltage development at the recording device obtained from crack gauges mounted on slat tracks of an Airbus A 320, Fig. 2 and Fig. 3.

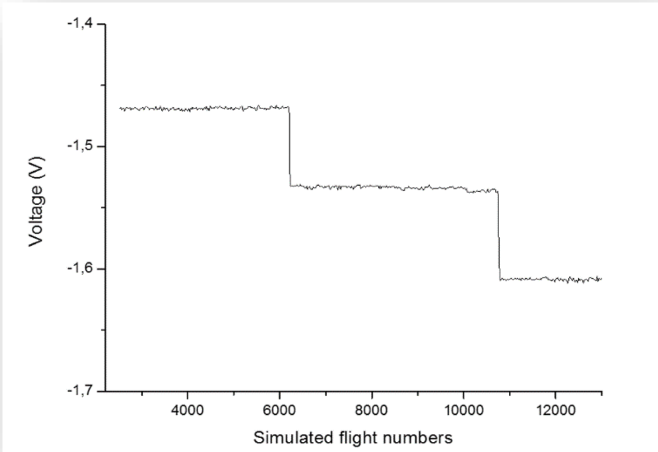


Fig. 3. Readings from crack propagation gauges, the distances between the “steps” represent 0,25 mm.

Between the periodic “steps”, crack gauges are more or less insensitive to crack propagation, thus, one can state that those systems establish a kind of “digitization” of material testing as only at the pre-set crack points, we have POD=1, in the other ranges it is POD=0.

## 4 Moisture monitoring for leakage detection

The leakage of water after structural damage/malfunction of sealings is reliably detectable by a change of the electrical conductivity of appropriate hygroscopic sensing materials. Also in this case, the sensing material tailored as HNSD is in a large humidity ranges quite insensitive to the liquid to be detected, but at the so-called percolation point the conductivity changes over many orders of magnitude [12].

In the example shortly presented here Fig. 4, the hygroscopic matrix material is made of polyvinyl alcohol (PVA) and the targeted solvent is water. The electrically conductive dispersed material is titanium carbo-nitride (TiCN). The percolation threshold related to humidity is approximately in the range of RH=80% and only at this point, a reliable detection of liquid is possible, but that signal is many orders of magnitude above baseline variations making this measuring principle very useful for practical applications.

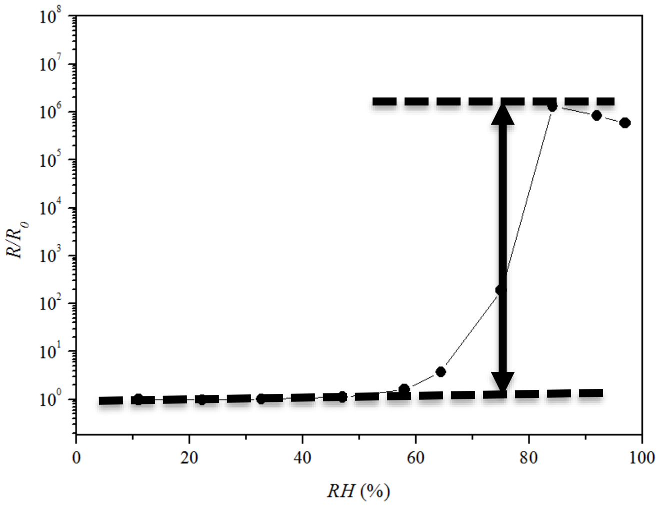


Fig. 4. Huge jump of electrical resistance of a water sensor at the percolation point RH=80% [12], note the logarithmic scale.

## 5 Monitoring of hydraulic liquids (Skydrol®) using conductive composites

Leakage of hydraulic liquids in aircraft does not only cause problems with potential loss of hydraulic performance, the leakage as such is harmful to different kinds of materials, including all acrylics, such as perplex glass [6]. Moreover, it is irritant for human beings creating in this way a hazard for mechanics and even passengers.

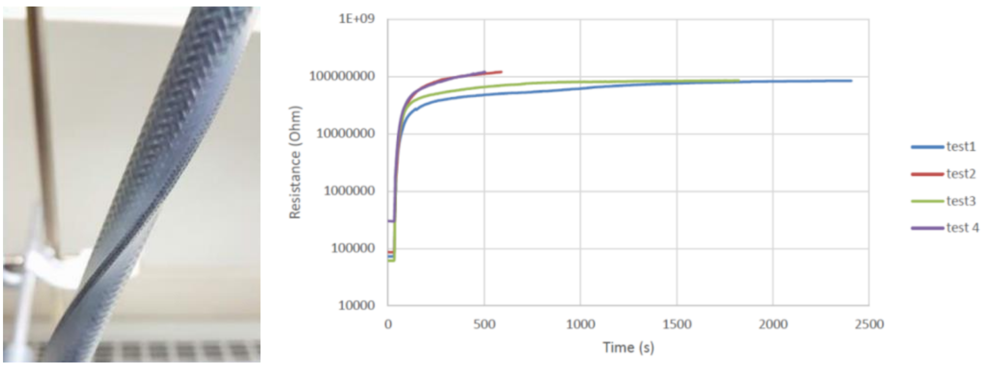


Fig. 5: Sensor wrapped around a hydraulic tube and sensor response recorded when exposed to tiny amounts of hydraulic liquids.

To detect early loss of hydraulic liquids in the corresponding tubes, a shroud system has been developed containing a wire sensor with a sensitive coating that is only detecting those kinds of phosphate-ester-type liquids. It can easily be installed and not only leakage due to cracks, but also caused by lose fittings will be detected. The implemented wire sensor and a typical response curve is shown in Fig. 5.

## 6 Monitoring of a bleed air system by optical fibre technology

Hot air escaping from bleed air systems is one of the most dangerous damage modes in aircraft as hot air is capable of causing severe thermal damage to cables and other components. To monitor such leakage, monitoring systems already exist that determine the conductivity of eutectic salt mixtures (Fenwal elements, see introduction). In the case of overheat, the salt mixtures melt and an electrical shortcut is established enabling the pilot to show-down the system early enough. Newer developments provide even functionality towards localisation of the leakage reducing inspection time during repair operations.

An alternative approach proposed here is the use of polymer optical fibres (acrylic POF) that have an intrinsic glass transition at the target temperature (Fig. 6 and Fig. 7).

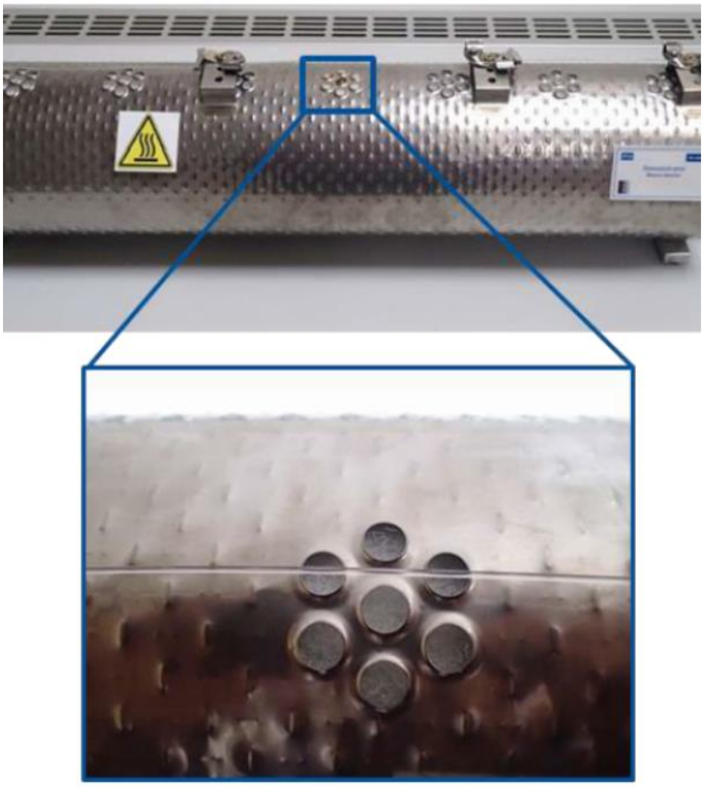

Fig. 6. Demonstrator for the detection of bleed air leakage. Above the pre-set “escape holes“ for hot air, a robust polymer optical fibre is installed undergoing glass transition at the target temperature, easily detectable by state-of-the-art optical time domain reflectometry (TDR).

a)

b)

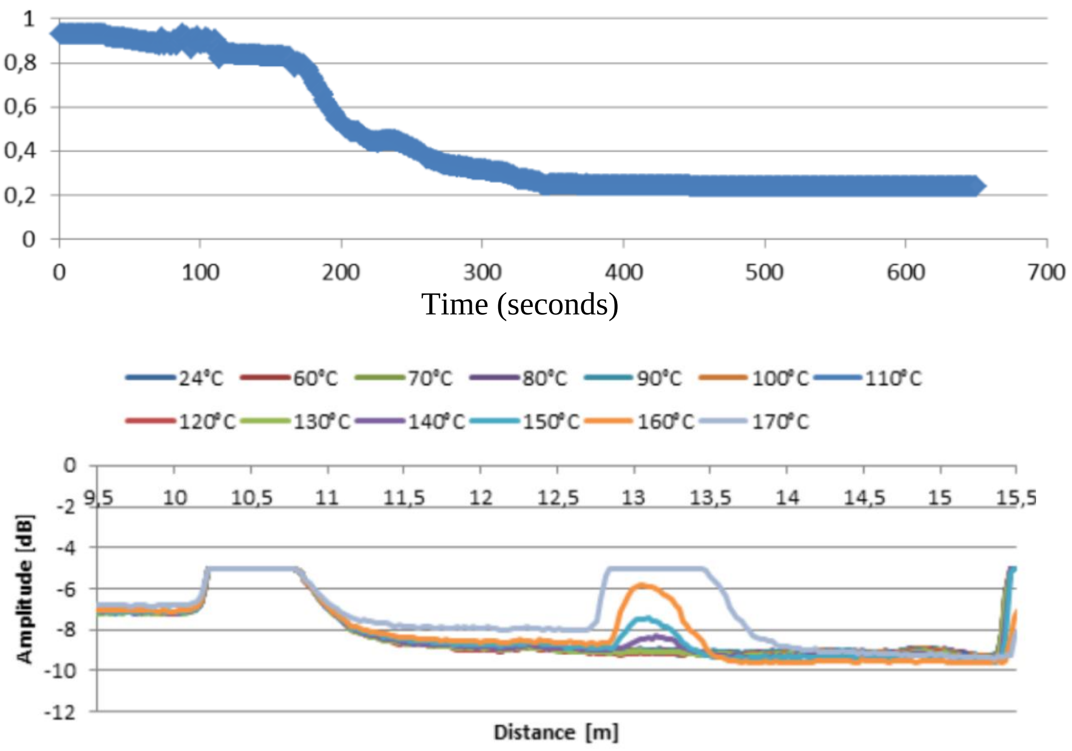


Fig. 7. Sigmoidal trend of light transmission through a polymer optical fibre a) when a target temperature of 135°C is reached, here after 180 seconds. The light transmission that has started at a plateau of almost 1 (100%) and falls down to a steady value of approximately 20%. The plot in time domain reflectometry is given by b), here the sensor starts at 10,5 meters and the defect is applied at 13 meters.

In this way, the optimised total reflection is lost at that area when heat damage occurs and this clear signal can even be determine by optical time domain reflectometry Fig. 7, b). Although the sensor is lost after melting, this is not a critical issue because the defect systems have to be repaired anyway and the cost for new optical fibres is negligible.

## 7 Example for moisture monitoring in operational aircraft

A working example developed by the authors is monitoring of corrosive liquids present in diverse floor structures of operational aircraft (Boeing 737-500, Boeing 747-400). The detection of those liquids provides interesting options for corrosion prevention already at very early stages [13]. Here, wire-sensors were embedded into between floor panels under galleys, lavatories and entrance areas, and the system are partially in service since 7 years now. The read-out of sensor data is performed after approximately 100 flight hours by use of simple ohmmeters and it has been proven that this sampling interval is highly sufficient.

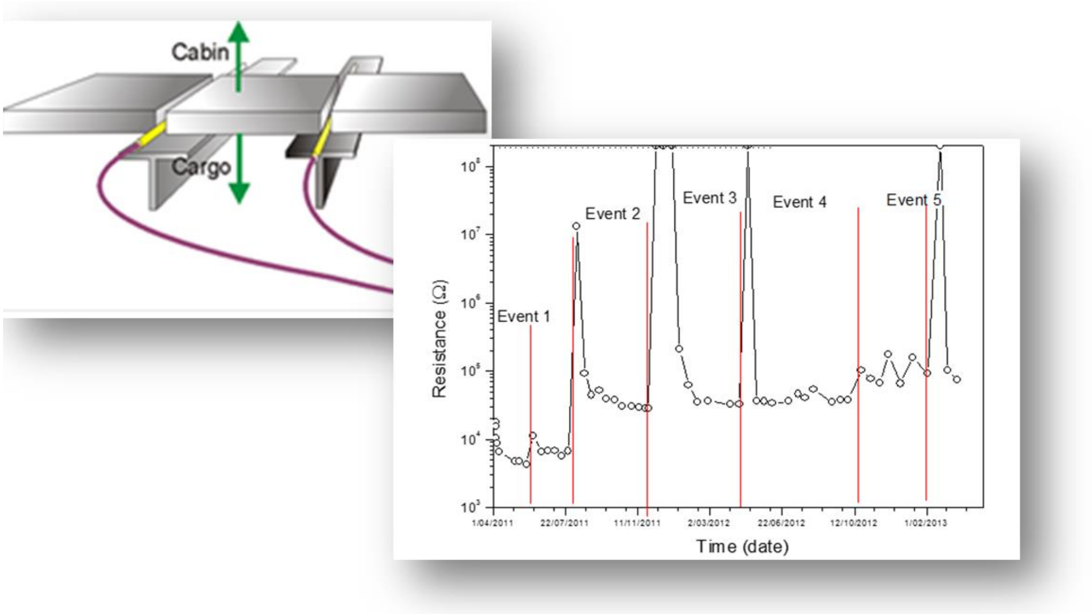


Fig. 8 Wire sensor for detecting "wetness events" in floor structures of a Boeing 737-530.

A characteristic response curve is shown in Fig. 8 that gives clear indications on "wetting events" in the floor under the galley area of a Boeing 737-530, most probably enabled by faulty isolations, please note the logarithmic scale suppressing non-relevant baseline variations. A typical feature is that wetness in the beginning appears just temporally as "peaks"; the area partially dries afterwards. The whole sensor is hygroscopic as such and works in this phase partially as a kind of water buffer, also visible by the fact that the baseline of the sensor as such increases gradually. These plots with this typical "peaks" give a clear information to the maintenance service teams to repair the respective sealings at the next occasion. Finally, currently, three operational airliners are equipped with these HNSD with an integral sensor length of app. 50 meters.

## 8 CONCLUSIONS

The intention of this paper is to present and encourage the implementation of "highly non-linear sensing devices" for health monitoring of structures and systems in aircraft to essentially avoiding problems arising from a weak "contrast" between damage data and background noise. Although, the application of this principle is still limited to certain niche applications, in some cases they enable easy to implement, straightforward solutions to practical problems in maintenance operations of engineering structures towards Industry 4.0. A few working examples are presented and further ideas will be developed to establish this concept as an alternative for traditional SHM techniques.

**Acknowledgements**

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