12th ECNDT
GOTHENBURG•SWEDEN•2018

Highly non-linear sensing devices in structural health monitoring

H. Pfeiffer[1*], S. Sunetchiieva[1], H. Sekler[2], M. Wevers[1]

1 KU Leuven, Department of Materials Engineering,
Kasteelpark Arenberg 44, Bus 2450, B-3001 Leuven, Belgium

2 Lufthansa Technik AG, Rhein Main Airport, 60546 Frankfurt/Main, Germany

Abstract

Sensors in traditional non-destructive testing (NDT) are usually working in a quasi-linear mode. However, this raises a number of difficulties when these sensing principles are applied to structural health monitoring (SHM). Base-line variations and complex sensor data due to diverse interferences with complex structures are one of the main obstacles for a broad-scale implementation of SHM in e.g. aircraft and civil structures. There were diverse solutions proposed to tackle these problems, such as advanced data processing and dedicated high-end hardware components. However, those excessive hardware requirements will in turn involve extra power supply and technologies for robust and extended data storage and processing. All these elements establish serious obstacles for a fast implementation of SHM in routine maintenance operations; not to forget the limited coverage inherent to some of those systems.

Besides the idea of focusing and limiting monitoring to selected hot-spots for avoiding large scale monitoring, an interesting alternative is offered by highly non-linear sensing devices. They are characterized by a sharp sensor response depending on an outer parameter that is related to a certain damage threshold. The highly non-linear behaviour is in this way an ideal tool to filter out baseline variations and thus, the probability of detection is superior with respect to many other technologies.

In the literature, there are a couple of highly non-linear sensing devices reported and even applied in operational practice, such as the alarm wires in bleed air systems for aircraft providing information on overheat, or crack gauges in fatigue testing. The presentation is intended as a small review on the different sensing principles applied for highly non-linear sensing devices. In general, the underlying physical principles for data reading our are in most cases electrical conductivity or optical transmission. Finally, a number of examples are presented that were already implemented, such as devices for the detection of corrosive liquids in aircraft (Boeing 737-500, Boeing 747-400) and chemical plants.

---

[*] Corresponding author: Kasteelpark Arenberg 44 bus 2450, B-3001 Leuven, Belgium,Tel.:0032/16/321232, Fax:0032/16/321990, helge.pfeiffer@mtm.kuleuven.be

1. Introduction and overview

Highly non-linear sensing devices (HNSD) are here defined as sensing systems that are only sensitive within a pre-set damage range, or even only at a certain damage size, but with a large change in magnitude with respect to diverse baseline variations. In this way, they are in a certain sense an analogue to for instance electrical fuses only providing information on a certain threshold-specific overcurrent without delivering more specifications on the actual degree of electricity that has caused that response.

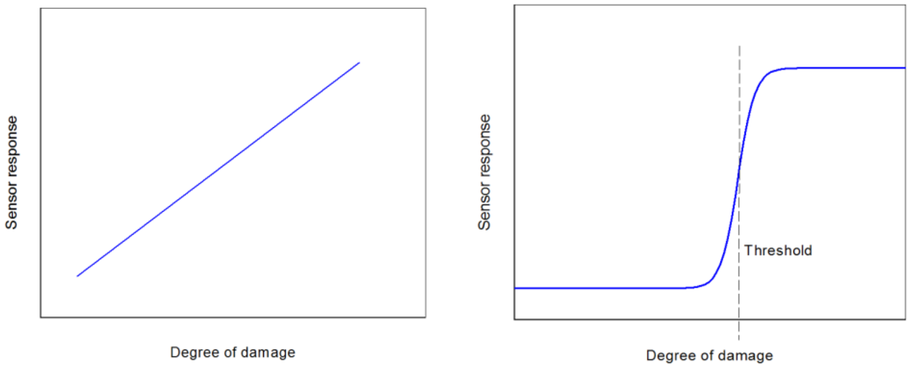

Figure 1: Principal response of a quasi-linear and a highly non-linear sensing material.

As mentioned above, a limitation is that those devices are only measuring within a certain range of damage. But this drawback is in specific applications highly compensated by the huge signal-to-noise ratio (SNR) that can even go to infinity in practical terms providing a number of interesting applications and options.

In order to design appropriate sensing systems one needs to select physical phenomena that show a typical discontinuous behaviour as a function of the intended damage-related parameter to obtain a response curve such in Figure 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 must proceed over a big range of magnitude and therefore, the y-axis in Figure 1, right can in this way be considered on a logarithmic scale.

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

A further typical example are the comparative vacuum monitoring (CVM) gauges [1]. Here, crack propagation causes a loss of vacuum that is monitored by appropriate pressure gauges. Very recently, a similar approach was proposed when using pressure-medium-filled capillaries inside materials embedded via additive manufacturing [2]. Also in this case, a pressure drop will indicate the presence of a crack.

Very interesting options are also provided by phase transitions, such as the melting processes, solid state modifications or glass transitions. Already since many years the so-called Fenwal elements [3] are used in practice that are applied for bleed air systems in aircraft. Those are a kind of alarm wires containing a salt mixture that exactly melts at a certain target temperature establishing 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) [4] elements in order to protect electric circuits against overheat. A more recent application refers to water absorption in hydrophilic polymers that trigger glass transitions to detect water leakage [5]. A similar principal is applied with for fuel leakage detection when oil-absorbing elastomers are used to disrupt electrical percolation conductivity [5].

Also chemical degradation processes offer interesting opportunities for monitoring, for instance when filaments or metallic wires are applied to monitor potentially corrosive conditions in diverse engineering structures [6]. Also the detection of certain ester-type hydraulic liquids frequently applied in aviation is possible via the solvation of electrically conductive composites made of acrylics [5].

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) [7] 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 [8]. 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. [9]. 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 [10]. 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.

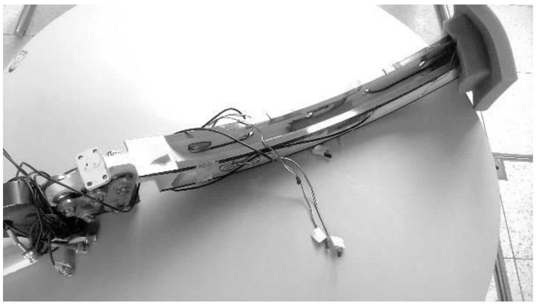

Figure 2: Slat Track from Airbus A 320 with installed crack propagation of Vishay, partially overpainted.

A typical curve showing voltage development at the recording device obtained from crack gauges mounted on slat tracks of an Airbus A 320 (Figure 2) under load test (Figure 3).

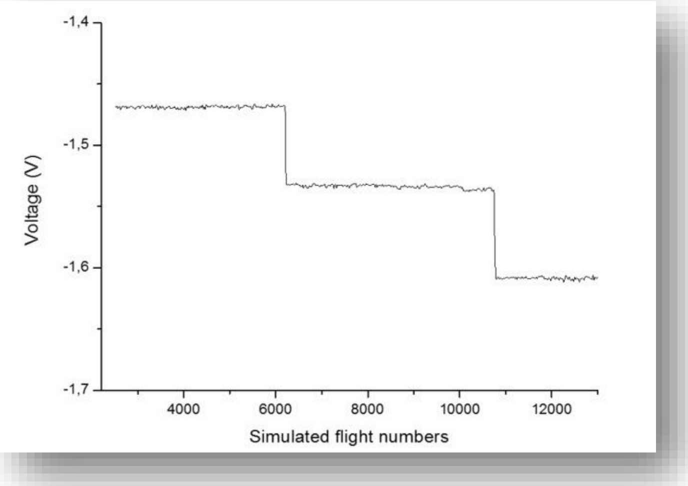

Figure 3: Readings from crack propagation gauges, the distances between the “steps” represent 0,25 mm.

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 [11].

In the example shortly presented here (Figure 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.

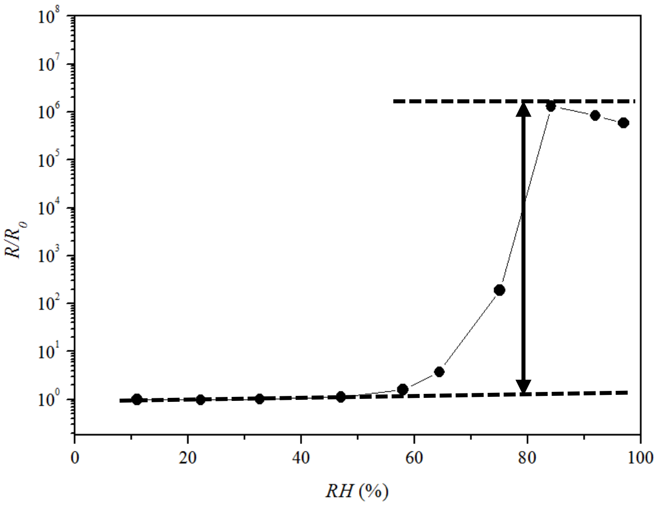

Figure 4: Huge jump of electrical resistance of a water sensor at the percolation point RH=80% [11], note the logarithmic scale.

5 Examples “in-service”

5.1 Moisture climate monitoring in aircraft

A typical working example developed by the authors is the monitoring of corrosive liquids present in the floor structures of operational aircraft (Boeing 737-500, Boeing 747-400). The detection of those harmful liquids provides interesting options for preventing corrosion already at very early stages [12]. In that specific example, elongated wire-sensors were embedded into diverse floor structures under galleys, lavatories and entrance areas, and the system is in service since 7 years now. The read out of sensor data is performed after approximately 100 flight hours by simple multimeters and is has been proven that this sampling interval is highly sufficient.

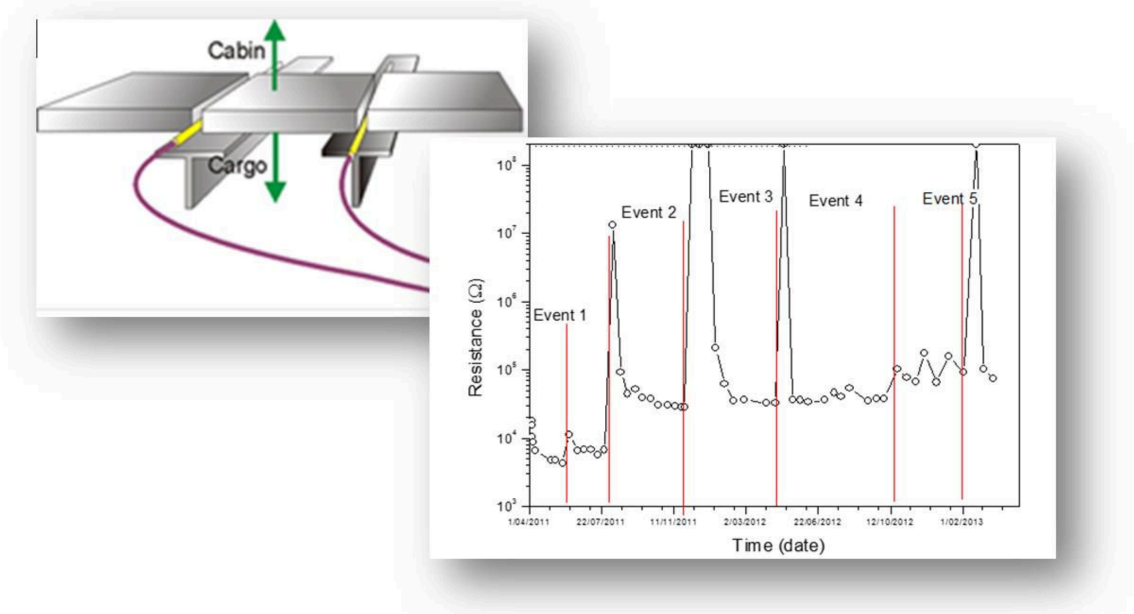

Figure 5: Wire sensor for detecting “wetness events” in floor structures of a Boeing 737-530.

A characteristic curve is shown in Figure 5 that gives clear indications on harmful “wetting events” in the floor under the galley area of a Boeing 737-530, most probably due to faulty isolations, please not the logarithmic scale that suppresses all other baseline variations. It is also a typical feature that the wetness in the beginning appears just temporally as “peaks” and 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.

5.2 Monitoring of moisture in outdoor-pipelines of a chemical plant

More elongated, extended sensing cables (25 meters) were installed for detecting enhanced moisture levels in pipeline insulations within a chemical plant to check upscaling that concept to very big industrial structures. For obvious reasons, the sensing material was quite similar to the examples described in the previous chapter applied in aviation. Here, to facilitate the data recording, the electrical resistance data was however measured and transmitted by wireless node transmitting the signal (ENV-Link-mini-LXRS, LORD MicroStrain) to a distant receiver (WSDA-Base-101-LXRS) and coupled into an internet connection (Figure 6). Currently, the sampling interval is set to 10 minutes and data are in principal analysed in a control unit 80 km far away from the pipeline. The system is also tested and partially running with a wireless mesh and RFID facilities to enable customisation according to maintenance needs.

Figure 6 Installation of percolation-based moisture gauges in pipeline isolations at BASF Antwerp and scheme of the data flow from the sensors to the remote host at the KU Leuven (University of Leuven).

Over several months, the sensor performance was tested and analysed versus local weather and climate information such as the amount of rain fall and humidity. In this way, faulty insulation were clearly identified as checked while re-opening the respective sections later on. A typical example for these wetness events is shown in Figure 7 presenting a sensor response as a function of time, also not the logarithmic scale that supresses baseline variations. Finally, after a couple of heavy rain events, the pipeline system became wet, after short periods of drying, another heavy weather events made that the sensors finally get “saturated” as the whole isolations was wet.

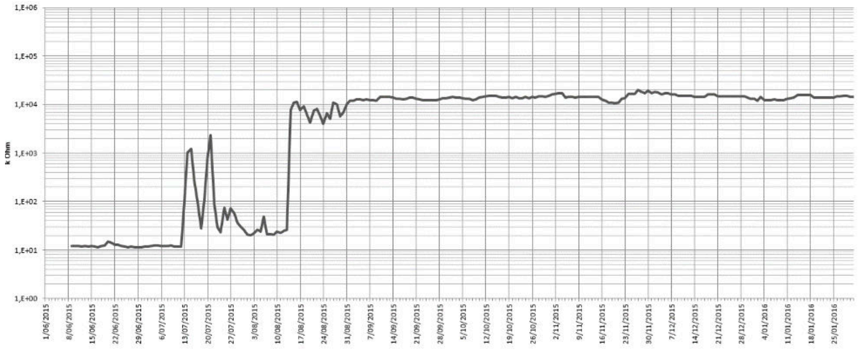

Figure 7: Typical data (logarithmic presentation of electrical resistance versus time) for wetted pipelines with problems in isolations.

6 CONCLUSIONS

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

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 and 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.

References:

[1] D. Roach, Real time crack detection using mountable comparative vacuum monitoring sensors, Smart Struct Syst 5 (2009) 317-328.
[2] 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.
[3] MaintenanceHandbook, Aviation Maintenance Technician Handbook Federal Aviation Administration2012.
[4] TycoElectronics, Fundamentals of PolySwitch Overcurrent and Overtemperature Devices - Polymeric PTC Technology, Advertisement Tyco Electronics (2015).
[5] 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.
[6] H. Budelmann, A. Holst, New Sensors for Rebar Corrosion Monitoring, Proceedings of the Fourth European Workshop on Structural Health Monitoring 2008 (2008) 211-218.
[7] Department of Defense - Handbook Nondestructive Evaluation System Reliability Assessment, MIL-HDBK-1823, USA, 2004.
[8] L.E. Pado, J.B. Ihn, J.P. Dunne, Understanding Probability of Detection (POD) in Structure Health Monitoring Systems, in: F.-K. Chang (Ed.) 9"‘ International Workshop on SHMUniversity of Stanford, 2013.
[9] 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.
[10] 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.
[11] 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.
[12] H. Pfeiffer, Structural Health Monitoring makes sense, LHT Connection - The Lufthansa Technik Group Magazine (2012).
[13] H. Pfeiffer, P. Heer, H. Sekler, M. Winkelmans, M. Wevers, Structural Health Monitoring Using Percolation Sensors-New User Cases from Operational Airliners and Chemical Plants, Structural Health Monitoring 2013, Vols 1 and 2 (2013) 2130-2137.