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LONG TERM MONITORING OF AN AIRCRAFT STRUCTURE DURING A FULL SCALE FATIGUE TEST.

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ABSTRACT

In the paper a technique for qualitative assessment of fatigue crack growth monitoring is presented, utilizing guided elastic waves generated by sparse PZT piezoelectric transducers network in the pitch catch configuration. The Damage Indices used for the inference carries marginal signal information content in order to decrease their sensitivity with respect to undesired non-controllable factors. The reason for that is to limit the false calls ratio which besides the damage detection capability of a system, plays a crucial role in applications. However even such simplified damage indices can be altered over a long term, leading to the misclassification problem. Considering single sensing path, it is very difficult to distinguish whether the resultant change of DIs is caused by a damage or due to such DIs decoherence. Therefore assessment approaches based on threshold levels fixed separately for DIs obtained on each of the sensing paths, would eventually lead to a false call. In order to decrease such misclassification risk a method to compensate the DIs drift is proposed utilizing the information from all of the network sensing paths. The proposed approach has been verified on a real structure during a Full Scale Fatigue Test (FSFT).

KEYWORDS : *SHM, fatigue cracks growth monitoring, long term structure monitoring, Damage Indices compensation.*

INTRODUCTION

The current methods of assuring integrity of structures used in the aerospace may become insufficient because of the safety as well as economic issues. The foundations of the most commonly adopted *damage tolerant* design philosophy relies on profound knowledge of fatigue durability and other material properties used in the aircraft manufacturing, an assumed load spectra of the structure and damage detection capabilities of non-destructive testing methods. However the way in which the particular aircraft is operated after it enters into the service doesn't necessarily fit to its statistical representation. The reliability of non destructive tests (NDT) is assessed in the so called PoD studies [1] under laboratory conditions, thus does not fully encompassing the human factor. Furthermore introduction of broad NDT programs as a necessary compound of the *damage tolerance* approach heavily affects the aircraft maintenance costs. Therefore conventional nondestructive testing techniques are nowadays supposed to be complemented by systems of structure integrated sensors continuously monitoring its health. Application of such methods would definitely increase safety, especially when considering hardly accessible 'hot-spots', but also it could save up to 50% of necessary inspections time depending on the aircraft type [2]. The figure 1 shows a survey of the aerospace industry needs [3] regarding Structural Health Monitoring (SHM) systems. Despite fracture mechanics is very well developed providing a tool to predict cracks evolution accurately, metallic structures are on the top of the demands list.

In the article an approach for the built of integrated monitoring system validated for the operational phase is presented. The aircraft used for it is PZL ORLIK TC II which is turbo propeller training aircraft for the armed forces. The main goal of the aircraft use is the military pilots training as

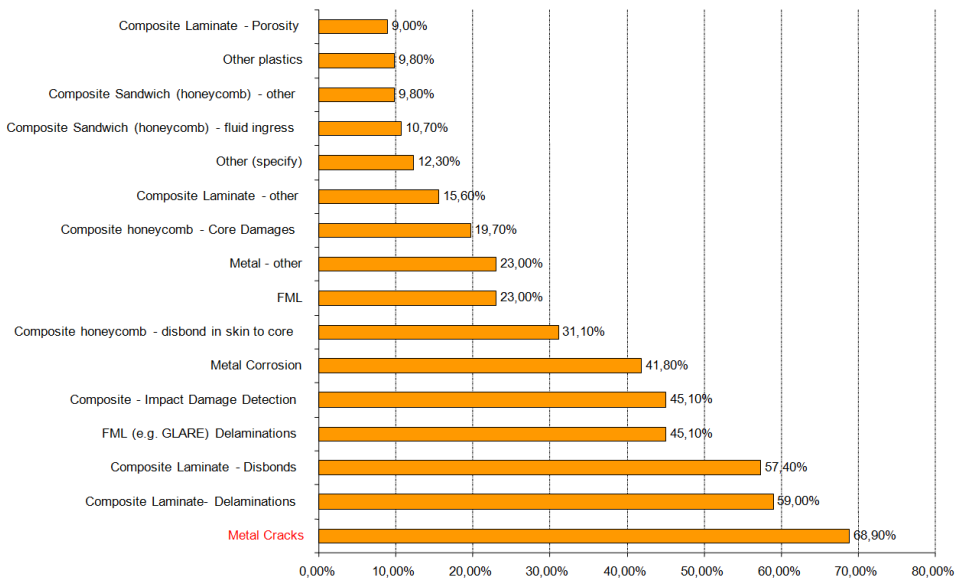


Figure 1 : Potential SHM applications with respect to the aerospace industry needs [3].

the preliminary training phase.). Due to the structure modification the aircraft undergoes the full scale fatigue test (FSFT). That test opened an opportunity for a SHM system installation at selected aircraft hot spot locations monitoring as well as early damage detection as an alternative approach which may support or in the future partially replace the scheduled NDI inspections. Beside PZT transducers a Comparative Vacuum Monitoring - CVM and Resistance Crack Gauges were applied. In some of the monitored aircraft hot spots those systems were hybridized to cross-check their findings.

SYSTEM SCHEME

A brief overview of a system for the aircraft structure monitoring is presented in the following section. The system building blocks are schematically presented on the figure 2.

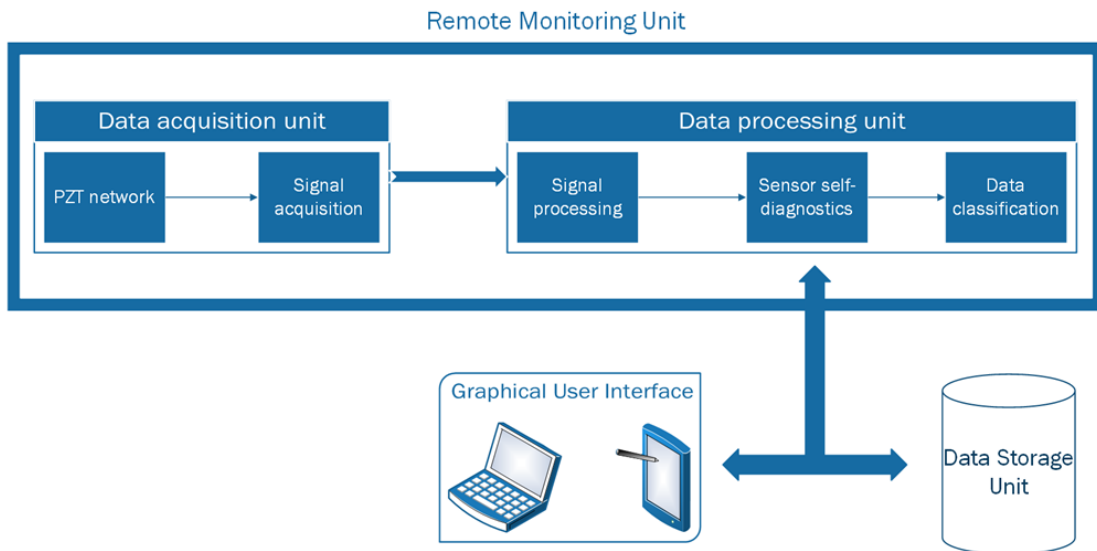


Figure 2 : The system block diagram.

These are:

- PZT transducers network divided into several measuring nodes;
- Remote Monitoring Unit (RMU) based on DSP architecture CPU;
- Data Storage Unit (DSU);
- Graphical User Interface (GUI).

The core of the RMU consists of four subsequent routines:

- signal collecting and its storage in DSU if indicated by sensor self-diagnostics component (Figure 1);
- signal processing based on several signal Damage Indices (DIs) correlated with the fatigue crack growth;
- sensor self-diagnostic component validating the PZT network, e.g. noise detection, sensors surface coupling strength, significant sensor working conditions changes detection;
- data classification methods for damage growth assessment.

One of the key issues in applying of piezoelectric transducers based monitoring systems to structures used in aerospace is to ensure sensor network durability in extremely varying environmental conditions. Thus a network self-diagnostic tools allowing for signal decoherence tracking in time is a vital component for any of such applications. Furthermore the most of data classification models are sensitive to outlying observations, therefore efficient sensor self-diagnostic prior to the structure evaluation is crucial for proper system working, e.g. false calls avoidance. In the proposed approach signals which do not pass sensor self-diagnostic check are stored in DSU for further expert assessment as depicted on the figure 1 in order to validate a sensor failure mode. Selected part of the aircraft structure hot-spots where measuring nodes of the network were deployed are presented on the figure 3.

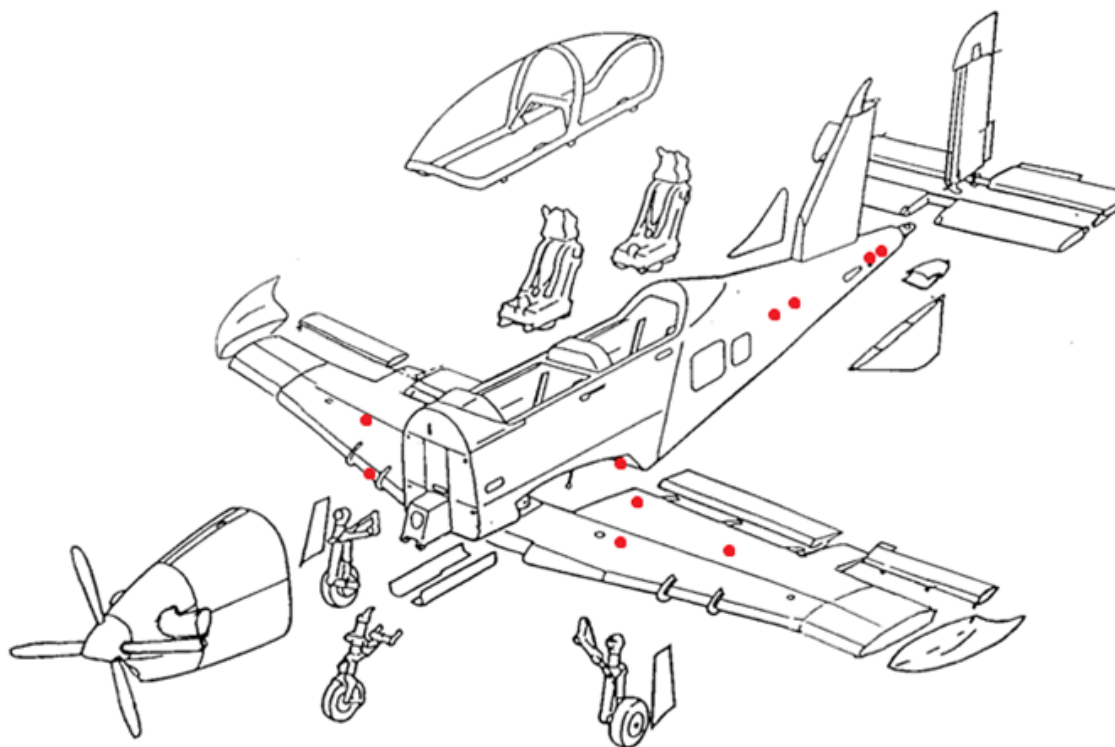


Figure 3 : Selected aircraft hot-spots.

SIGNAL ANALYSIS

One of the ideas for structural health monitoring systems built is based on the measuring of the mechanical properties of materials used for aircraft structural elements. The approach is based on analysis of small displacements propagation excited in the element by a network of PZT piezoelectric actuators [4, 5]. Solution for small deformation dynamics of the medium strongly depends on the boundary conditions, in particular the geometry of the object and its distortions caused by discontinuities and deformations. Structural damages can thus result in observable changes of the signal generated by the network sensors. The state of a monitored structure is assessed based on chosen signal characteristics called the Damage Indices (DIs). The acquired signals can be also influenced by factors other than damages thus posing a risk of false indications. Therefore DI's used for the structure assessment needs to be balanced between sensitivity to damages and stability under varying working conditions of transducers.

In the adopted approach the DI's carries marginal signal information content. Denoting as f_{gs}^{env} the envelope of a signal generated by the transducer g and received by the sensor s and as $f_{gs,b}^{env}$ the envelope of the corresponding baseline, i.e. the reference signal obtained for the initial state of the structure, the proposed Damage Indices are given as follows [6]:

$$DI_1(g, s) = 1 - cor(f_{gs}^{env}, f_{gs,b}^{env}), \quad DI_2(g, s) = \left| \frac{\int (f_{gs}^{env} - f_{gs,b}^{env})^2 dt}{\int (f_{gs,b}^{env})^2 dt} \right|, \quad (1)$$

where $cor(f_{gs}^{env}, f_{gs,b}^{env})$ stands for the sample correlation of the two signals. Both of the proposed DI's are correlated with the total energy received by a given sensor but also with its distribution in time during the measurement. Thus the DI's are sensitive to the two main modes of guided wave interaction with a fatigue crack, i.e. its transmission and reflection from a damage. However even such simplified damage indices can be altered over a long term, leading to the misclassification problem. Considering single sensing path, it is very difficult to distinguish whether the resultant change of DIs is caused by a damage or due to such DIs decoherence. Therefore assessment approaches based on threshold levels fixed separately for DIs obtained on each of the sensing paths, would eventually lead to a false call. An alternative approach is to compare changes of DIs for all of the sensing paths. A developing damage distort the signal only for sensing paths in its proximity. In order to decrease the misclassification risk a method to compensate such DIs drift is proposed. The method is based on the first order Taylor expansion formula and utilizes the information from all of the network sensing paths [7]. The proposed formula reads as follows:

$$DI_{comp}(g, s) = DI(g, s) - m - (m(g) - m) - (m(s) - m), \quad (2)$$

where:

$$m = \min_{\tilde{g}, \tilde{s}} DI(\tilde{g}, \tilde{s}) \quad (3)$$

is the minimum DIs change considering all of the network sensing paths;

$$m(t) = \min_{\tilde{s}} DI(t, \tilde{s}), \quad t = g, s \quad (4)$$

is the minimum DIs change for sensing paths originated from the transducer t .

The idea behind the formula (2) can be illustrated on the following example. Consider a 4-valent network as shown on the figure 4. Assume that unobservable drifts of DIs due to aging of single sensors are a and b and these are small enough that the drift on sensing path $g \rightarrow s$ is the sum of aging effects of transducers defining the path, eg. $a + b$ for the path $1 \rightarrow 3$. Direct check shows that

$$DI_{comp}(g, s) = 0$$

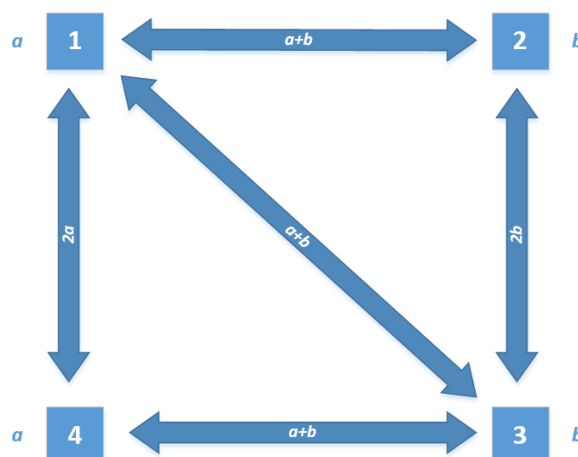


Figure 4 : The drift of Damage Indices for 4-valent network - a mechanism.

for all sensing paths of the network (Fig. 4). The first subtracted term - m in the formula (2) corresponds to homogeneous DIs flow cancelation whereas the last two terms suppress the signal decoherence inhomogeneities of the generator and the sensor.

The compensation formula is able to capture the drift inhomogeneities among the sensors of a network. However as it stands, it works only in a bounded interval of a given DI variability range - when its drift on a sensing path depends additively on aging of the transducers and it shouldn't be applied when this interval is exceeded. Thus simple and less volatile DIs are favoured in that context.

In order to collect the joint information from all of the paths the DIs are averaged:

$$ADI = \frac{1}{N(N-1)} \sum_{g,s} DI(g,s), \tag{5}$$

where N is the number of the network transducers.

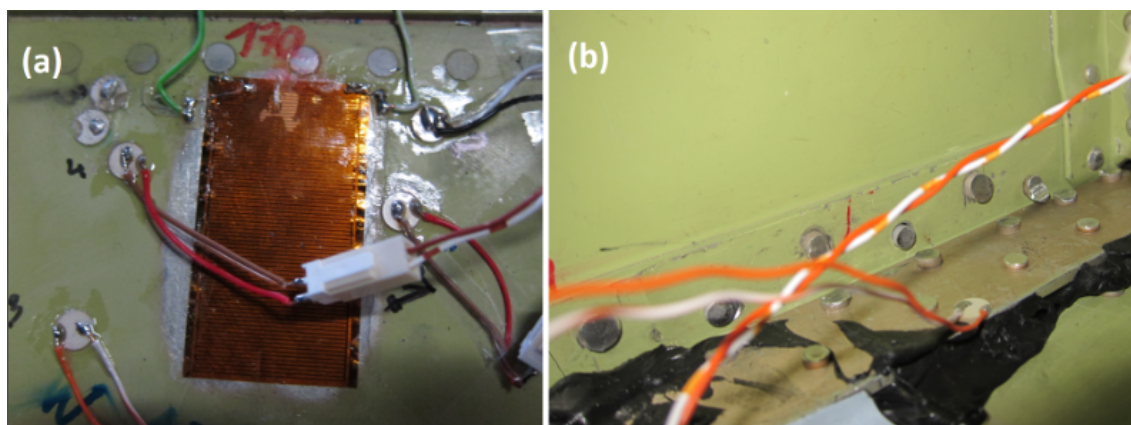


Figure 5 : Example of monitored hot-spots.

MONITORING RESULTS

In the following section damage detection capabilities of the system are discussed based on two chosen monitored hot-spots (Fig. 5). In both of the locations Resistance Crack Gauges (RCG) adapted to the

structure geometry were installed in order to verify the system indications. The crack was developing in the network shown on the Figure 5(b) and the other hot-spot (Fig. 5(b)) remained undamaged. One of the network node (Fig.5(b)) was installed on a structure containing riveted joints and other wave reflectors, the other structure (Fig. 5(a)) was of relatively simple geometry.

The Averaged Damage Indices for both of the nodes are presented on the figure 6. It was noticed that the number of well separated groups of data, corresponding to different extent of the crack agrees with the number of sensing paths crossed by the crack (Fig.6(b)). The data corresponding to subsequent periods of the monitoring of the undamaged structure are not separated (Fig. 6(a)).

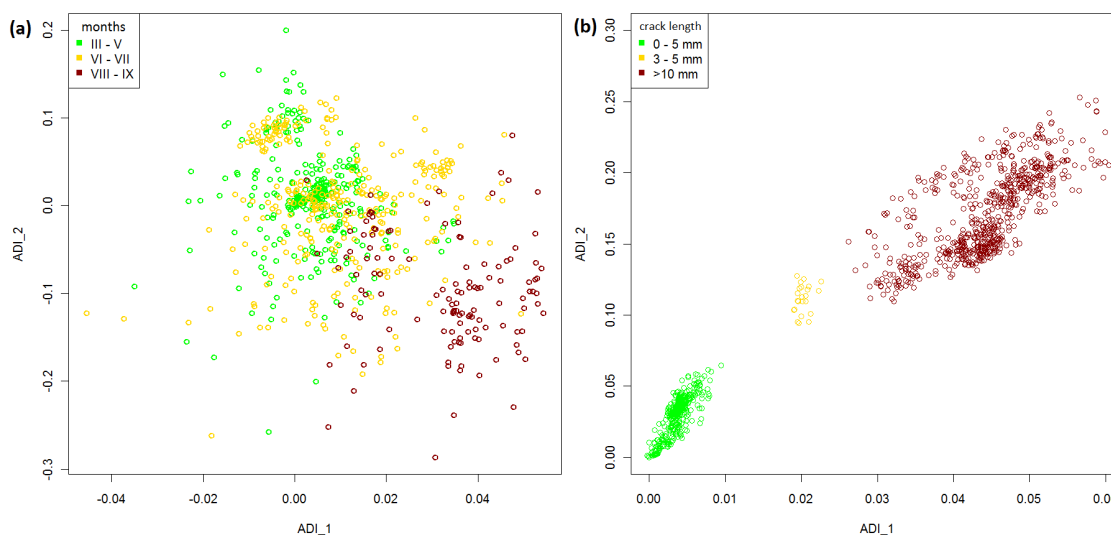


Figure 6 : Averaged Damage Indices for monitored hot-spots: (a) the undamaged structure and (b) the crack is developing within the network.

CONCLUSION

In the paper a method of monitoring fatigue crack growth by means of elastic guided waves was presented. The crack growth resolution of the approach is restricted to indicate if sensing paths of PZT sensor network were intersected by a developing crack. This is due to limited information content carried by the Damage Indices used. In return they exhibit small sensitivity to signal decoherence in time which allows to apply the proposed DIs drift compensation formula decreasing significantly false positive indications, which besides damage detection capability is one of the crucial factors in SHM applications. The approach was validated using a data collected during a Full Scale Fatigue Test of an aircraft.

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