Damage Detection in the Aircraft Structure with the Use of Integrated Sensors – SYMOST Project

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ABSTRACT

This paper presents approach for the damage growth monitoring and early damage detection in the aircraft structure based on the statistical models elaborated in the AFIT. Taking into the consideration the previous experience of the AFIT from the System of Health Monitoring (SHM) of the helicopter main rotor blades the array of the piezoelectric transducers (PZT) will be deployed in the structure of the PZL-130 Orlik TC II Aircraft. In the article approach for the monitoring of the aircraft hot – spots is presented with special attention on developed models which enables statistical inference about the damage presence and its growth. The results of the data collected from the subcomponents tests with the model description, correlation with the NDI results as well as approach for the aircraft SHM system design is delivered.

INTRODUCTION

The problem of monitoring the health of aircraft structures throughout the operational phase (operation and maintenance) are very complex and complicated. The spectrum of variable loads that affect the structure depends first and foremost on the way the aircraft is operated, hence, there is no possibility to precisely design the aircraft life before it enters the operational use. In the article the approach for the built of integrated monitoring system validated for the operational phase is presented. The aircraft presented it is PZL ORLIK TC II which is turbo propeller training aircraft for the armed forces. The aircraft was designed in Poland in the PZL WSK Warszawa Okecie and at present is manufactured at the PZL EADS Okecie in Warsaw. The main goal of the aircraft use is the military pilots training as the preliminary training phase.

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The aircraft have just started Full Scale Fatigue Test (FSFT) which will continue up to 2013. The FSFT of the structure is necessary in connection with the structure modification as well as with the change of the maintenance system (from the Safe – Life to Condition Based Maintenance). AFIT delivered to the FSFT the NDI programme as well as the health monitoring techniques and the know - how. In particular as an alternative approach which may support or in future partially replace the scheduled inspections the SHM system for that aircraft based on PZT sensors will be designed and verified during FSFT.

The SHM system should follow the international standards for such systems and named as the SHM paradigm [1] which means the system is organized in hierarchical structure:

- damage identification and localization;
- damage classification and size quantification;
- residual life estimation.

In the project multiple tasks are oriented to achieve as high as possible technical readiness of the system (in the operational way of thinking). However there are still few challenges associated with the SHM system design such as [2]:

- utilizing formal methods for designing sensing and data processing systems;
- correlating damage indications with remaining structural capabilities;
- minimizing false calls in spite of benign changes in operation and boundary conditions;
- addressing durability of on-board hardware.

In the article only selected applications of such system included in the SHM paradigm and associated with the quantification of the damage size will be presented. The statistical approach based on the so called averaged damage indices and supervised learning (SL) techniques will be highlighted. Article presents the approach for classification of the damage indices from the time of flight signals from the PZT sensors of the guided waves propagation. That includes: damage indices selection, classification models, self diagnosis application and SL techniques.

STRUCTURAL HEALTH MONITORING

The issue of damage monitoring with use of elastic waves excitation in a given medium undergoes a rapid development [3–7]. Elastic waves depending on their source and the geometry of the structure under consideration can propagate over significant distance. They are also sensitive to local structure discontinuities and deformations providing a tool to detect local damage of large aerospace structures. One of the major obstacle in direct application of this method is complexity of signals excited in real structures. Reliable SHM systems should therefore provide different type of damage assessment which would allow for cross-validated evaluation of the structure:

- qualitative data - damage presence in a given network cell, its kind and the degree of criticality;

- quantitative data - exact location and size of a damage.

Basic information concerning the health of the structure can be provided by the so called Damage Indices (DI's). Denoting as f_{gs} the signal generated in transducer g and received in sensor s and as $f_{gs,b}$ signal baseline, some basic DI's can be defined using the following simple signal characteristics:

L^1 symmetric characteristic – $DI_1(g,s) = \frac{\left|\int (|f_{gs}| - |f_{gs,b}|) dt\right|}{\int |f_{gs,b}| dt}$, (1)

L^2 symmetric characteristic – $DI_2(g,s) = \frac{\left|\int \left(f_{gs}\right)^2 - \left(f_{gs,b}\right)^2 dt\right|}{\int \left(f_{gs,b}\right)^2 dt}$,

correlation with the baseline – $DI_3(g,s) = cor(g,s)$.

Similar DI's can be obtained using Fourier filtered signals or other signal transformations. These simple signal characteristics can be useful for qualitative assessment due to their small volatility which should also improve false calls ratio.

Damage Growth Monitoring

Reliable damage size assessment needs to develop methods independent or adjusted to the damage location. Therefore for a given damage index $DI_j(g,s)$ (1) the averaged damage index can be defined [8, 9]:

$$ADI_j = \frac{1}{n(n-1)} \sum_{\substack{g,s: \\ g \neq s}} DI_j(g,s), \quad (2)$$

where n is the number of transducers in the sensor network cell. Proposed DI's have positive sign irrespectively of the amount of energy received by the given sensor, which is important property when averaging. Averaged Damage Indices (ADI's) are less dependent on the damage localization, i.e. they are invariant with respect to sensors permutation, which makes them better suited for damage size estimation. They contain joint information from all sensing paths which should improve possibility of small damage detection. Moreover these indices can be also defined in case of improper functioning of several transducers in the network.

Using ADI's based on different signal characteristics the efficient Averaged Damage Indices (eADI's) [9] can be derived by dimensional reduction methods, e.g. Principal Component Analysis (PCA), Linear Discriminant Analysis (LDA) or multidimensional scaling [10, 11]. These indices can be further used as independent variables in damage classification or regression models.

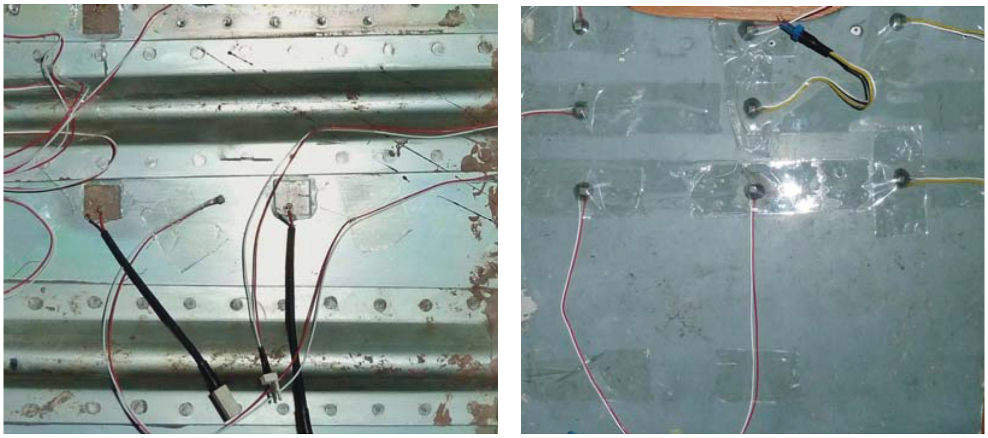

Figure 1. Bottom side of a specimen and retrofitted sensor network.

Testing the Model

Averaged Damage Indices and their efficient counterparts introduced in the previous section was verified on the aircraft structure specimens containing fasteners joint, substructure and other wave reflectors. Two specimens of a chosen type were prepared and retrofitted with network consists of 8 sensors. One of the specimen is presented on the figure above (Fig. 1). Two cracks at different locations were simulated for each specimen. Elastic waves of different frequencies and modulation windows were excited.

Correlated damage indices can be used as a sensors self diagnostic tool. Observations distorted by noise or originated from faulty sensors resulting in particular in different spectrum of the received signal are outlying from the correlation line and should be dropped out before averaging. Resulting ADI's were normalized for each frequency by shifting on the mean for undamaged specimens and divided by standard deviation.

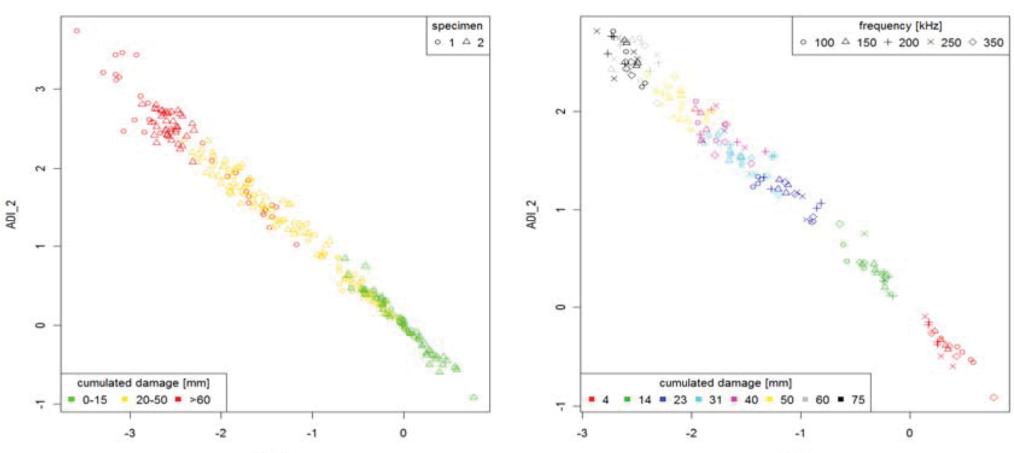

Figure 2. Correlated ADI's for overall data and chosen specimen.

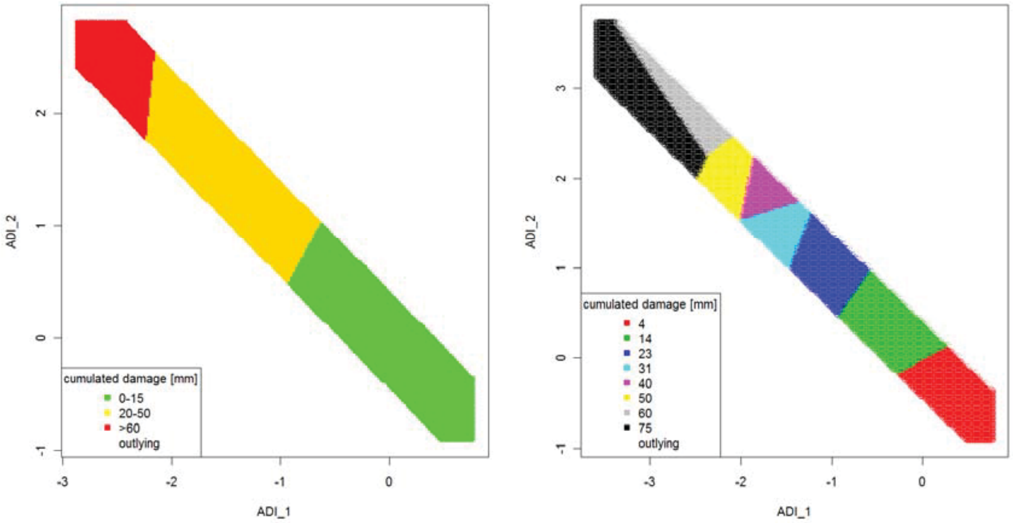

Figure 3. LDA boundaries for overall data and chosen specimen.

Two correlated ADI's denoted as ADI_1, ADI_2 with the best group separation property are presented on the following plot (Fig. 2). Data are classified with respect to cumulated damage, i.e. total cracks length for each specimen and plotted for both specimens and selected one separately. LDA classification regions based on them are shown on Fig. 3.

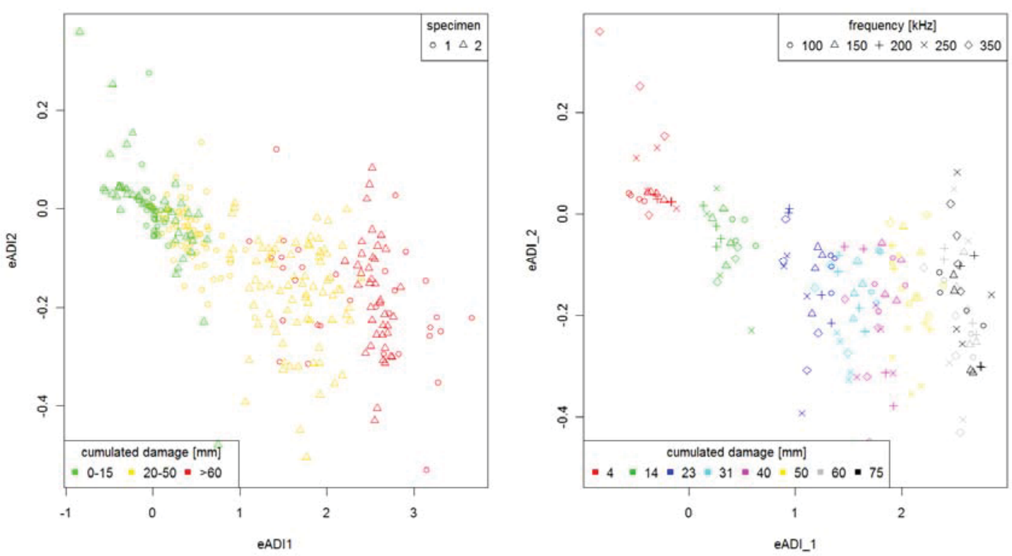

Figure 4. PCA based efficient ADI's for overall data and a chosen specimen.

The following charts (Fig. 4) shows two the most efficient ADI's obtained by PCA method both for overall data and for a chosen specimen. These eADI's were used further to provide two k nearest neighbor (k-nn) models [10] for damage size estimation. Classification regions in this method are obtained by determining the most

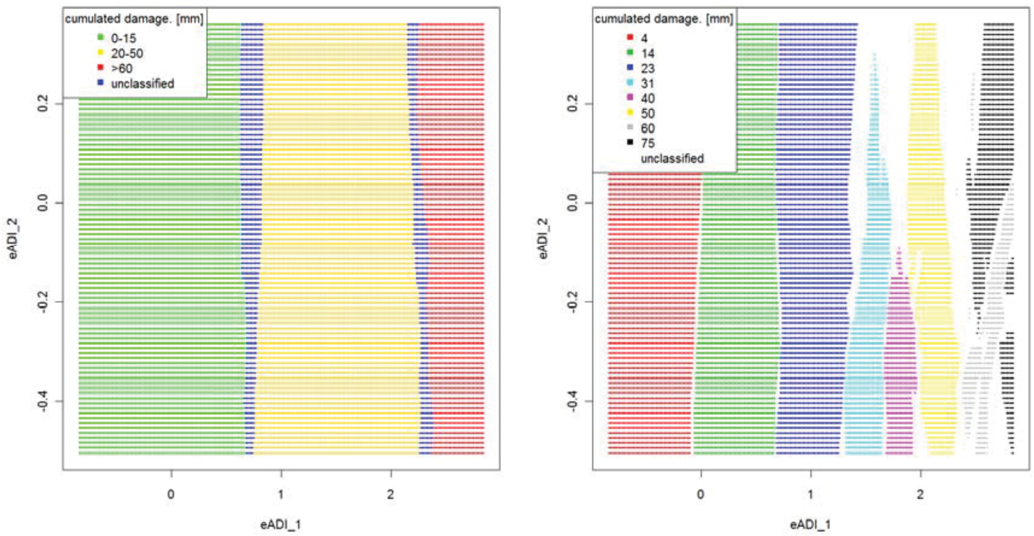

Figure 5. Nearest neighbor classification regions.

frequent class of *k* samples from the training dataset which are the nearest to a given region point. Classification regions for 15-nn and 8-nn model based on training dataset for both specimens and selected one are presented on the plot (Fig. 5).

The 15 nearest neighbor model was verified with use of 5-fold crossvalidation technique [10] obtaining group classification probabilities for each magnitude of cumulated damage (Tab. 1). Since classification regions of undamaged (0−15 [mm]) and seriously damaged (> 60 [mm]) specimens for this model are separated (Fig. 4) there is no risk of type II misclassification.

		Group classification probability		
		0 – 15 mm	20 – 50 mm	above 60 mm
Group	0 – 15 mm	1	0	0
	20 – 50 mm	0	0.98-1	0-0.02
	above 60 mm	0	0-0.07	0.93-1

Table 1. Cross-validation results of 15-nn model.

SUMMARY

In the article an approach for aircraft structural health monitoring system was delivered. The main goal of the built such system was to create an early detection system for the damage presence in the aircraft structure. In the paper a SHM statistical model meeting certain requirements of SHM paradigm was presented and verified on real aircraft structures. A proposal for the signal analysis and damage presence is delivered as the damage indices. The main challenge before turning system into operational phase is to assure its durability and reliability, e.g. the possibility of replacement of faulty PZT transducers in the sensor network. This will demand to develop *quasi baseline free* methods of inference, which is meant here as no necessity of calibrating the functioning of the given network cell after sensor replacement but still training dataset is needed on the system design phase. The proposed signal characteristics should be robust enough to provide such quantitative structural health assessment after signal denoising and other signal transformation. Another issue is the inference about the damage presence and the damage growth. Article presents elaborated and verified on the signal collected from the trials statistical techniques. The next step in that project is to monitor the damage growth in the aircraft during the FSFT. There was designed and deployed the sensors network system as well as the monitoring system.

ACKNOWLEDGMENTS

I would like to thank very much the **NCBIR** for the supporting of the work which has to be realized under the LIDER project LIDER/25/43/L-2/10/NCBiR/2011 based on the agreement from the 09.08.2011 r.

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