Lamb-wave-based monitoring of the aircraft during full-scale fatigue experiment - results and conclusions

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Abstract

In scope of the SYMOST project a turbo-prop military aircraft, monitored by a net of piezoelectric transducers, was subjected to a long-term full-scale fatigue experiment. Lamb waves excited by the sensor net were used for the detection and localization of fatigue damage. Several algorithms for Lamb wave signal processing and interpretation were implemented and tested in the project. This paper presents selected results of the full-scale fatigue experiment of the PZL-130 Orlik TC II Aircraft, including: four methods of temperature compensation for Lamb waves and diagnose obtained by ensembles of neural networks operating on groups of damage indices. Results of aircraft monitoring by means of different SHM methods over a period of one year are presented and commented. Different approaches to damage detection are compared in terms of their reliability and their limitations for practical applications.

Keywords: Guided waves, Condition monitoring, Aerospace, Neural network, Aircraft, ANN Ensembles, Temperature compensation

1. INTRODUCTION

Current methods of assuring integrity of structures used in the aerospace industry may soon become insufficient both because of safety as well as economic issues. The foundations of the most commonly adopted damage tolerant design philosophy rely on profound knowledge of fatigue durability and other material properties used in 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 does not necessarily fit to its statistical representation. The reliability of non-destructive tests (NDT) is assessed in so-called Probability of Detection studies under laboratory conditions, thus not fully encompassing the human factor. Furthermore, introduction of broad NDT programs as a necessary component of the damage tolerance approach heavily affects the aircraft maintenance costs. However, such NDT inspections have to be carried out at specific time intervals, which means an aircraft has to be removed from service for that time. It is thus
highly desirable to complement nondestructive testing techniques with SHM systems of structure-integrated sensors continuously monitoring the state of the host composite. Application of such methods would definitely increase safety, especially when considering hard to access hot-spots, and could save up necessary inspections time depending on the aircraft type.

These motivations have driven the SYMOST project, which main purpose was to develop Lamb-wave-based SHM system for the load-carrying structure of the PZL Orlik TC II turbo prop aircraft. To this end the aircraft was subjected to fatigue experiment. Throughout the experiment the state of the aircraft was monitored with sparsely located net of piezoelectric transducers (PZT), which were used for generation and acquisition of Lamb-wave signals.

This paper is devoted to presentation of selected results of that full-scale fatigue test (FSFT) obtained with signal state assessment algorithms based on soft-computing approaches. The authors present results obtained with ensemble of ANNs and outcomes of algorithms aimed at compensation of temperature and environmental changes present during acquisition of Lamb-wave signals. Differences of these approaches as well as their application potential are discussed.

The paper is organized as follows: section 2 introduces data classification with ensembles of ANNs and methods for compensation of temperature influence for LW signals, section 3 briefly describes experimental procedures and implementation of the methods in particular problem, finally, section 4 concludes and summarizes the paper.

2. METHODS’ DESCRIPTION

2.1. Ensembles of ANNs

Multimodal and dispersive nature of Lamb waves result in very complicated signals acquired during monitoring. A common way of interpretation of these signals requires calculation of several damage-sensitive metrics and their assessment with multidimensional data classifiers – e.g. Artificial Neural Networks (ANNs). Although many papers were proposed in this scope [1 - 4] none of them uses state-of-the-art solutions in the area of multidimensional classification. A classical approach to data classification with neural nets uses a single network, usually a multilayered perceptron, which is tailored to specific task using trial-and-error approach. On the other hand, ensemble approach requires many networks of different structures to be trained on similar data. A subset of these networks forms the ensemble, which is then used in classification of new samples (See fig. 1). Responses of all the ensemble members are averaged. Although ensemble approach is proven to provide better results than using single network [5 - 7] it is rarely used in SHM. Here, the ensemble approach is used for the purpose of fatigue damage detection. Damage-sensitive features calculated from LW signals are arranged in vectors that are passed to ensembles of ANNs to obtain structural state in proximity of particular sensor pairs. In order to provide diversity of ensemble members authors provide structural variability of ANNs. Multilayered perceptron networks, radial basis function networks and self-organizing maps of different sizes are all included in initial pool of classifiers that are trained on random subsets of training data. Performance of these candidate electors on the testing subset of data is used to arrange them in order of rising efficiency; 10 best classifiers are used as final ensemble.
2.2. Decision fusion temperature compensation for LWs

Temperature changes significantly affect results of LW-based monitoring. This influence manifests itself mainly in stretch of the signal in time domain and changes of signal amplitudes. There are many methods of temperature-influence compensation for LW measurements. They can roughly be divided into the baseline signal stretch (BSS) [8, 14] methods that aim to modify baseline signal to adjust it to signals acquired under different temperatures, the novelty detection (ND) approach, that uses database of signals acquired under different temperature conditions and then choses the one that fits best currently acquired signal [9], and other approaches that are based on cointegration of signals [10], decomposition [11,12] or group measurement (GM) approach [13]. Recently, a fusion of BSS, ND and GM methods was proposed and tested in LW-based fatigue damage detection [13].

Operation principle of the temperature compensation decision fusion (TCDF) algorithm includes three algorithms operating on different stages of signal processing:

- The BSS method for comparison of signals – in form of a D1IP temperature-resistant damage index [14].
- The ND method for definition of the normal range of signal changes – in form of optimal baseline selection (OBS) algorithm [13].
- Assessment of sub-level decisions performed with above methods with use of group measurement approach [13].

Obtained values are compared with threshold in order to decide whether the damage is present in the structure. The threshold is selected as mean of indications in initial phase of monitoring plus three times its standard deviation.
3. EXPERIMENTAL EVALUATION

3.1. Subcomponent-scale database preparation

An important part of the R&D work within the SYMOST project were fatigue tests of selected structures of PZL-130 Orlik aircraft structure. Two independent PZT networks, containing 4 sensors each were deployed on a specimen containing multiple rivet joints (Fig. 2) and a widespread fatigue damage was developed. During the test, the signals at different stages of damage development, from two of the independent PZT networks were acquired using the following parameters:

- excitation frequency: 100 kHz
- modulating window: Hanning
- length of excitation: 8 periods.

Signals were obtained under three different structure loads at each level of the damage development, that is: free end, medium and maximum stress of fatigue cycles.

3.2. Full-scale fatigue test description

The ultimate goal of the SYMOST project was the development of health monitoring technology for PZL-130 Orlik aircraft. The aircraft underwent a Full Scale Fatigue Test (FSFT). That test opened an opportunity for a SHM system installation for selected aircraft ‘hot spot’ locations monitoring as well as early damage detection.

The structure is loaded in a specially designed test rig by means of twenty actuators, which apply forces to the wing, fuselage, empennage and landing gear [15]. The whole test was contracted for 36000 simulated flight hours (SFH). One of the most important elements of each fatigue test is the load sequence. In case of a full-scale fatigue test when multiple actuators and constrains are applied simultaneously most care must be taken in order to create conditions identical with reality and thus giving credible results. Load sequence for fatigue
test of PZL-130 Orlik TC-II was based on operational load monitoring program carried out with an aircraft instrumented with foil strain gauges. Total of 86 measurement points were installed in 13 sections measuring 27 different loads. Final sequence, representing 200 Simulated Flight Hours, consisting of over 26 000 load lines was used during the test. Four main types of operational loads were used: flight loads, buffeting loads, landings and taxing.

The system building blocks are schematically presented in the figure (Fig. 3). These are:
- PZT network divided into several measuring nodes;
- Remote Monitoring Unit (RMU) – based on DSP architecture CPU;
- Data Storage Unit (DSU);
- Graphical User Interface (GUI).

Selected parts of the aircraft structure in the form of ‘hot-spots’ where measuring nodes were deployed are presented on the figure (Fig. 4).
In order to evaluate the methods described in subsections 2.1 and 2.2 authors have chosen four hot-spots, which are described in the table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Number of measurements, period of signal acquisition</th>
<th>State at the end of the FSFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1837, 5 months</td>
<td>Intact</td>
</tr>
<tr>
<td>#2</td>
<td>1481, 5 months</td>
<td>Intact</td>
</tr>
<tr>
<td>#3</td>
<td>1804, 5 months</td>
<td>Intact, unstable</td>
</tr>
<tr>
<td>#4</td>
<td>242, 2 months</td>
<td>Damaged</td>
</tr>
</tbody>
</table>

3.3. Signal processing for the purpose of ANN-based diagnose

Experiment described in sec. 3.1 was used as source of data for ensemble classifier training. For that reason, data were pre-labeled using knowledge of actual size of fatigue crack at given time moment. That data, containing 312 samples were fed to ensemble training algorithm that was designed according to procedure described in section 2.1. Next, trained ensembles were used for state assessment of four hot-spots selected out of all monitored areas during FSFT. No further actions, including outlier removal, were taken.
3.4. Signal processing for the purpose of temperature influence compensation

Data described in sec. 3.2 were fed to the TCDF algorithm according to procedure described in sec. 2.2: most representative datasets were built separately for each sensor pair, using temperature-resistant damage index DI_IP. Diagnoses obtained for each sensing path were merged using GM approach. Then, using data acquired at initial stage of monitoring, a threshold equal to median of indications plus three times their standard deviation was chosen. Values exceeding this threshold were treated as premises of damage, while others were treated as representing intact state.

3.5. Results

Results obtained with using all the methods are displayed in fig. 5. It is seen, that both approaches provide very good results for monitoring of hot-spots #1, #2 and #4. Both the efficiency of the damage detection and amount of false positives are at acceptable levels. The methods’ performance differs, however, for the case of hot-spot #3. High level of noise caused the ensemble of ANNs to assess the hot-spot state as damaged. It was a result of two facts. Firstly, damage indices fed to the network have no ability to distinguish damage from other factors that may influence signal processing, as they are merely measures of a similarity between two signals. Secondly, detection thresholds are set up during the training phase of ANNs and thus they are influenced only by data available at training stage. If the training dataset does not cover for all situations possible in monitoring phase, it is vulnerable to this kind of errors. Temperature-compensation approach is, on the other hand, immune to such errors as thresholds are determined in initial phase of monitoring on the basis of data acquired in particular hot-spot.

![Figure 5 - Results of monitoring for four hot-spots using ensembles of ANNs and fusion of temperature compensation methods](image-url)
4. SUMMARY AND CONCLUSIONS

The results obtained during the FSFT allow for conclusion that the test was prepared according to standards and credible fatigue damages have been developed within the structure. Investigation of the detected damages and their origin allowed for drawing valuable conclusions. The FSFT took totally 2.5 years, during this period multiple NDI inspections were delivered simultaneously to SHM system operation. More than 800 damages were found and these observed by means of the SHM system were confirmed by the NDI inspection. After the FSFT final teardown inspection was performed, which further confirmed existence of the damage and damage size was correlated with the indications of the SHM system used as applied NDI techniques.

In this paper selected results of that investigations are shown. It was found, that both temperature compensation methods and ensemble ANN approach provide good results. There are, however, issues that require attention during the methods' set-up. Firstly, usage of the methods that involve learning from data requires training dataset with similar data distribution. In this case training data were of relatively good quality. Data obtained during FSFT were, however, noisy and characterized by high standard deviation of features acquired for the same structural state. As a result, some of the intact hot-spots under investigation were wrongly classified as damaged. That disadvantage can be compensated by methods that involve threshold setup based on data acquired in initial stage of condition monitoring. This approach was employed in temperature-compensation technique that resulted in good state assessment also for noisy hot spots.

REFERENCES


