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Damage detection in aluminum and composite elements using neural networks for Lamb waves signal processing

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ABSTRACT

One of the important factors in the structural health monitoring systems is the amount of data that need to be analysed in real time. This study investigated the use of artificially deteriorated signals of Lamb waves in training the novelty detection (ND) system for the early damage detection. In this system Auto-associative Neural Networks were trained using principal components calculated on the basis of experimentally measured signals. The specimens studied relate to two different materials commonly used in the aerospace industry, i.e. aluminium and glass fibre reinforced polymer. Lamb waves measured in these specimens are a good example that the ND algorithm works correctly in case of simple as well as complex signals. Furthermore, it was found that the designed ND system remained sensitive and robust even when it used raw signals with a relatively low sampling rate, on a fairly narrow time window and even noised signals.

1. Introduction

Much research in recent years has focused on the development of sensitive and reliable Structural Health Monitoring (SHM) systems. One of the commonly developed non-destructive measurement techniques, which is widely used in SHM, is based on the phenomenon of elastic wave propagation [1,2]. This approach assumes that an anomaly appearing in the structure (fault condition) can be detected and identified on the basis of measured signal analysis. The analysis of elastic wave signals consists in general of quantitative and qualitative description of their changes (e.g. attenuation, distortion, reflection) caused by a damage appearance and growth. Since the reflections and dispersion effects may produce pretty complex signals, therefore the determination of parameters suitable for damage detection requires the application of advanced signal processing techniques [3]. For this purpose an approach of novelty detection [4] was proposed in this paper. The idea is to use a data set of signal parameters obtained from a reference structure (e.g. undamaged structure, numerical models, laboratory tests) and use soft computing methods in order to warn about the damage appearance. In such a way neural networks (NNs) can be trained to perform the automatic analysis of the structure diagnosis process and then implemented in SHM system as an electronic circuit.

SHM is also a technology which can provide cost effective maintenance of advanced composite structures. However, there is still a need to reduce the overall cost of applying health monitoring to large structures. Data acquisition hardware typically consumes most of the investment in a structural monitoring system [5]. This is largely related to the amount of data that need to be processed. For this reason, various methods are used to compress signals [6,7,4] or adjust the parameters of signal measured [8]. Therefore the present study is an attempt to reduce the dimensionality of measurement data set by signal deterioration, which

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involved mainly its decimation and windowing. The shorter the length of the signal the smaller computation effort and computation time required. This can have a direct impact on reducing the requirements of measuring equipment and costs of dedicated SHM systems. At the same time, an additional aspect of research has become the sensitivity and reliability of the SHM system developed and this issue is also taken into account in this paper.

Elastic waves propagating in the monitored structure can be captured using non contact measurement (Laser Doppler Vibrometers) as well as piezoelectric sensor integrated into the test structure. However, regardless of the measuring technology, visual interpretation of the received signals can be simple or complex. In some cases there are clear reflections in signals associated with the appearance of damage. It is much more difficult to interpret signals in which such a phenomenon does not exist and the only noticeable change is negligible attenuation of amplitude or phase shift. This may be due to the selected parameters of excitation signal (i.e. its operating frequency), type of the sensor used or multiple overlapping reflections (e.g. from the edge of the specimen). In the present study both simple and complex cases were investigated, using the results of laboratory measurements carried out on an aluminium and Glass Fibre Reinforced Polymer (GFRP) specimens. In addition, these models take into account the existence of two types of discontinuities: an opening and a thermal damage.

2. Methodology

2.1. Damage detection system

Successful preliminary research findings encourage the authors to further investigate the damage detection system proposed [7]. Their purpose is to discuss the sensitivity and reliability for simple and complex signals with reduced quality.

In this work the results of previous laboratory experiments were used [9,10], where measurements were performed on two samples of aluminium strips. In order to actuate and to sense the elastic wave signals a surface-mounted piezoelectric transducers were used. An anomaly (damage) was modelled by drilling holes of different diameters. The structure responses recorded by digital oscilloscope were then subjected to a procedure of signal processing (decimation, windowing, etc.) and feature extraction (Principal Components Analysis, PCA) as described in [7]. Input vectors have been created based on the selected number of principal components obtained from the measured time signals. In addition, it was assumed in this study, that the input vectors are of the same length and consist of 16 consecutive principal components. This number allows the signals reconstruction with error $<0.5\%$ and enables a significant compression of time signals. Unfortunately, the disadvantage is the computation time, when the signals are composed of a large number of samples.

A defined pattern database was then used to train Auto-associative Neural Network (AaNN) for the purpose of novelty detection. An output vector of this neural network is the same as the input vector. Thus, when such a trained AaNN is fed with the inputs obtained from a damage state of the system, the novelty index $NI = \|\mathbf{x} - \mathbf{x}\sim\|$, which measures the distance between the known input and output of the AaNN, will increase [4,7]. In this study, feedforward neural networks with one hidden layer were used and they were trained using Levenberg–Marquardt algorithm.

Signal processing as well as neural networks simulations was performed in Matlab environment [11]. Each time the AaNN training was repeated 50 times, and depending on the value of the calculated index *NI* the binary classification of structure (undamaged, damaged) was made. One indicator of the suitability assessment was the number of *properly trained classifiers* (PTC). It shows how many classifiers were trained flawlessly in each series of simulations. If even one particular pattern has been incorrectly classified, the classifier is considered to be acting in an improper manner. For example, if the total number of AaNN trained is 50 and one of them incorrectly classifies any patterns, then the PTC is 49 out of all 50 trials. This number can be expressed as a percentage value (98%) and it provides information on how easily the properly functioning classifier can be trained. A small number of PTC may indicate instability of the diagnosis system that occurs when the damage introduced have a little effect on the measured signals or the parameters used for training. In such a situation, the final results of ANN training are usually dependent on the initial values of randomly selected weights and obtaining the PTC becomes more difficult.

Another indicators that were used to measure the classifiers' usefulness and its accuracy are a *true positive rate* (TPR) and a *true negative rate* (TNR). They measure how often the classification is correct when the specimen is really damaged or undamaged. These two values, complemented by a *false positives rate* (FPR) and a *false negatives rate* (FNR) are the components of a table known as a confusion matrix. However, because these indicators are mutually dependent (i.e. $FPR = 1 - TPR$, $FNR = 1 - TNR$) only TPR and TNR were provided in this article and expressed as a percentage. Moreover, they were calculated not for a single classifier, but for the total number of classifiers trained, especially when some of them are not the PTC. In such a way the TPR and TNR give information of how many patterns are correctly classified as damaged and undamaged. In an extreme case, this means that when one or a few patterns are misclassified by all the 50 classifiers trained, then the $PTC = 0$, but sensitivity indicated by the TPR and TNR may still remain at the high level of 98%.

2.2. Description of cases studied

2.2.1. Simple and complex signals

The specimens studied relate to two different materials commonly used in the aerospace industry, i.e. aluminum and GFRP. Their choice is not accidental, because they are an excellent example of two qualitatively different cases of signals registered. The first analysed samples are sufficiently long and narrow to recognize in the signal an incident wave and its subsequent reflection from both the strip ends and the growing damage.

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