A Sensor Fault Detection Methodology applied to Piezoelectric Active Systems in Structural Health Monitoring Applications

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Abstract Damage detection is the basis of the damage identification task in Structural Health Monitoring. A good damage detection process can ensure the adequate work of a SHM System because allows to know early information about the presence of a damage in a structure under evaluation. However this process is based on the premise that all sensors are well installed and they are working properly, however, it is not true all the time. Problems such as debonding, cuts and the use of the sensors under different environmental and operational conditions result in changes in the vibrational response and a bad functioning in the SHM system. As a contribution to evaluate the state of the sensors in a SHM system, this paper describes a methodology for sensor fault detection in a piezoelectric active system. The methodology involves the use of PCA for multivariate analysis and some damage indices as pattern recognition technique and is tested in a blade from a wind turbine where different scenarios are evaluated including sensor cuts and debonding.

1. Introduction

Structural Health Monitoring (SHM) is an imperative need in the damage identification process. The use of a good SHM system allows to improve the inspection process and optimise the performance over uncertain conditions to ensure the security of the in-service structure in its continuous operation, through regular inspection for malfunctioning or damaging [1]. Damage diagnosis is often classified in different levels starting with the damage detection, where the existence of abnormalities gives information about the presence of damages to the SHM system [2]. In this sense, the reliability of the systems plays an essential role, and given the nature of some approaches, a fault in the sensor sub-system, results in a false-positive damage detection which produces that structure can be incorrectly classified [3]. Different sensors can be used in the inspection process, some of the most popular are the PZT sensors due to its versatility since they can work as sensors or as actuators producing and collecting different kind of

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waves which are propagated trough the structure. Specifically, in data-driven algorithms which use pattern recognition techniques, the health of the piezoelectric transducers can be consider as a critical factor in the inspection process [4],[5],[6]. Common damages in PZT transducers include sensor debonding, piezoelectric fractures, bad connections which are produced even from the installation of the monitoring system or produced during life-time of the structure [7].

Previous work by the authors included the use of multivariate statistical methods to detect [8], localize [7] and classify [10] structural damages using PCA and some bio-inspired methodologies such as Self-Organizing Maps and Artificial Immune Systems [11]. In this paper, a fault detection methodology which is based on Principal Component Analysis and some damage indices is proposed and applied to an active piezoelectric system which acts in different actuation phases. To validate the methodology, sensor debonding, incremental cuts and crystal removals are studied, results show a good performance in the identification of the different scenarios. This paper is organized as follows: Section 2 includes a brief description of the Fault detection methodology and the experimental setup used for the validation, Section 3 presents the Results and finally some conclusions are discussed in last section.

2. **Fault Detection Methodology and Experimental Setup**

For the experimental setup a blade from a vertical axis wind generator ALEKO WGV75W was equipped with four piezoelectric sensors which were distributed over the two external faces, (see figure 1). The inspection process is performed by the PZTs working in different actuation phases as in [8], this active system uses each sensor acting as receiver and as actuator in the four different phases of the experiment. The excitation input was a 50 cycles and 100 KHz burst signal with 8 V of amplitude, data were collected at a 20 MHz sample rate, and organized by sensor actuation phases as in [10]. The signal generation and acquisition program were developed in MatLab®.
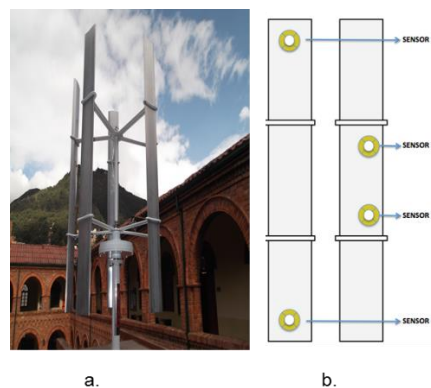

Figure 1. a) Vertical axis wind generator ALEKO WGV75W
[9]. b) Distribution of the piezoelectric transducers.

The data from the structure in all the actuation phases are organized in different unfolded matrices when sensors are known as healthy and pre-processed using group-scaling [11]. These data are used to define the pattern by each actuation phases. After that, a PCA model is obtained by each actuation phase and the number of scores are defined according to the retained variance. Subsequently, with the structure and the sensors in different states are obtained, organized and pre-processed to be projected into the PCA-model by each actuation-phase. These projections are plotted and used to calculate the Q and T^2-

index [8][12]. The former is based on analysing the residual data matrix to represent the variability of the data projection within the residual subspace.

Eight damages were induced over one sensor, they are described in Table 1 and their appearance is shown in figure 2. Five of the eight damages are related to the piezoelectric crystal with cuts and removal of a certain area, the other three are related to the debonding of the metal plate of the sensor. Both, crystal removing and debonding damages are supposed to be critical in the actuation mode, since these can change the signal applied to the structure. In the same way, in the data acquisition, these damages can affect the data reliability since the mechanical transduction to the electrical field which is going to be corrupted for the cracks in the crystal and to the incomplete energy received (case of debonding).

Table 1. Sensor Induced Damages

Type	Used area	Brief description
Cut [a]	-	Cut to the middle of the crystal at 25% line
Cut [a]	-	Complete cut of the crystal at 25% line
Crystal removal	25%	Removal of the 25% area of the crystal
Crystal removal	50%	Removal of the 50% area of the crystal
Crystal removal	75%	Removal of the 75% area of the crystal
Sensor Debonding [b]	25%	Adherent in the 75% of the sensor's plate
Sensor Debonding [b]	50%	Adherent in the 50% of the sensor's plate
Sensor Debonding [b]	75%	Adherent in the 25% of the sensor's plate

[a] The damage doesn't compromise any area type of the sensor

[b] The damage compromises the sensor metallic plate area

Those damage were physically induced in the sensor 1, the other piezoelectric transducers and the wind blade structure were in a healthy state. Figure 3 presents a description of the percentage of debonding.
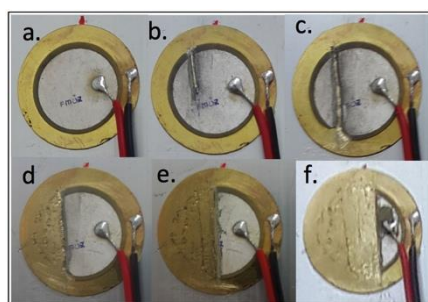

Figure 2. a) Undamaged sensor. b) Crystal middle cut at 25% line. c) Crystal complete cut at 25% line. d) Crystal 25% removal. e). Crystal 50% removal f) Crystal 75% removal.
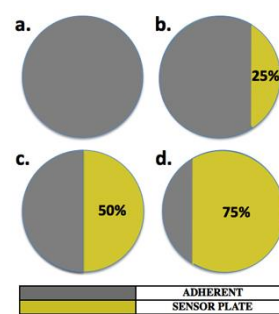

Figure 3. Debonding damage illustration, a) undamage. b) debonding 25%. c) debonding 50%. d) debonding 75%.

To show the influence of the damaged sensors in the damage detection process, 2 simulated damages which consists of magnets attached to the structure in order to change the mechanical impedance were introduced as in Figure 4.
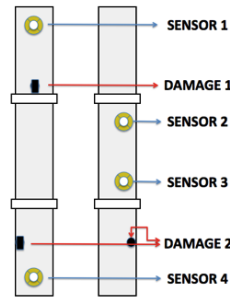

Figure 4. Two impedance damages over the wind blade structure, each damage is composed by magnets to represent a load in the structure, and which can be recognized by mechanical behaviour of the sensing devices.

3. **Results**

The use of the methodology previously introduced allows to obtain two different results. First, when the first two projections (scores) to the principal components are used, the score plots are obtained. Second, when the measurements T^2 and Q are used, the damage indices plots are obtained. These plots are calculated by each actuation phase and analysed with all the faults and structural conditions including to the healthy state.

As first outcome, Figure 5 shows the score and damage index plots using data from undamaged sensor, crystal cuts and removals were organized to evidence if each sensor fault could to be recognized by comparing with the baseline. By a simple comparison, can be concluded that in this case, score plot with just two components is not able to discern the presence of faults, however the use of the damage indices allow to determine the presence of all damages and some differences between them. Similar results are obtained in each actuation phase.
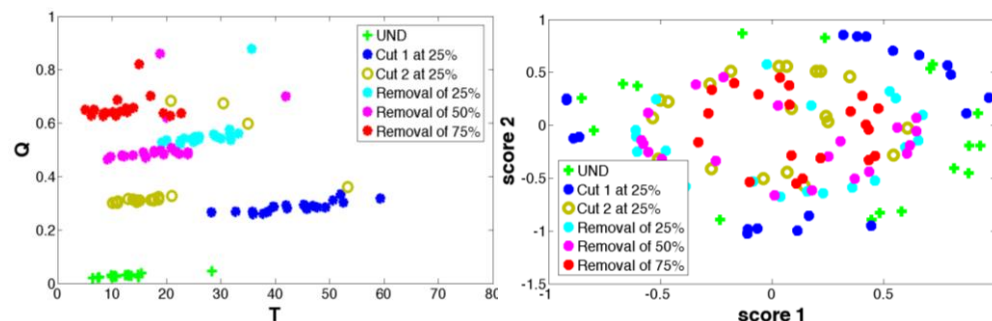

Figure 5. T-Q PCA indices and Scores 1-2 for the 5 damages induced over the piezoelectric crystal. (actuation phase 2)

Damages over the sensing system maybe critical, but in some cases it is not possible to replace or repair the sensors immediately. Considering this situation, the second test was performed by including simulated damages to the structure when one of the sensor is known as with a fault. Figure 6 shows the results in the use of the damage indices, as it is shown both damages can be separated from undamaged, however it is necessary to highlight that baselines were built with the sensor in the different fault conditions, this result allow to confirm that the pattern recognition approach allows to determine the presence of damages in spite of the faults in a sensor.
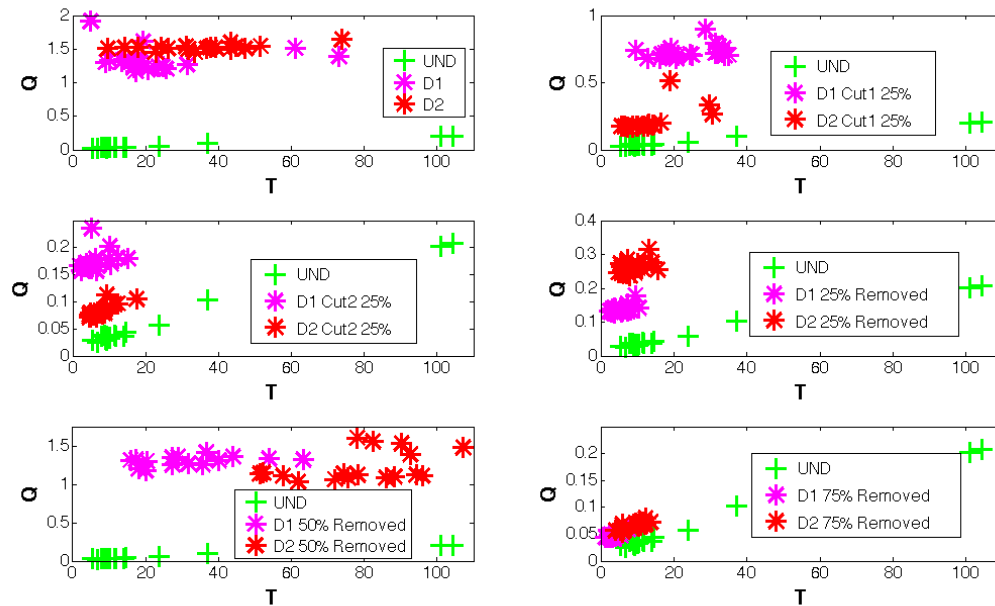

Figure 6. T-Q PCA indices for the 2 impedance damages over the structure in a. undamaged sensors b. fault the damages are measured from the 5 faults induced over the piezoelectric crystal (actuation phase 1)

Evaluating the rest of the actuation phases, similar results are obtained, although for the Phase 1 which includes the fault sensor at 75% crystal removal case, the damages seem to be close enough from each other, is the only case where they behave like this (figure 7).
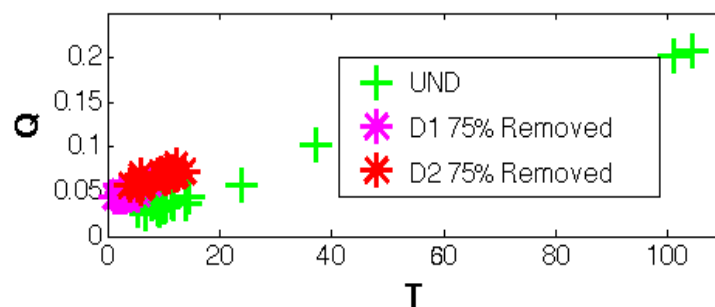

Figure 7. T-Q PCA indices for the 2 impedance damages over the structure, damages are measured from the 75% crystal over the piezoelectric.

As third experimental validation, the detection of debonding was performed. Figure 8 presents the results when an incremental debonding is studied in two actuation phases. As it is possible to observe, the undamaged state is separated from the different faults.
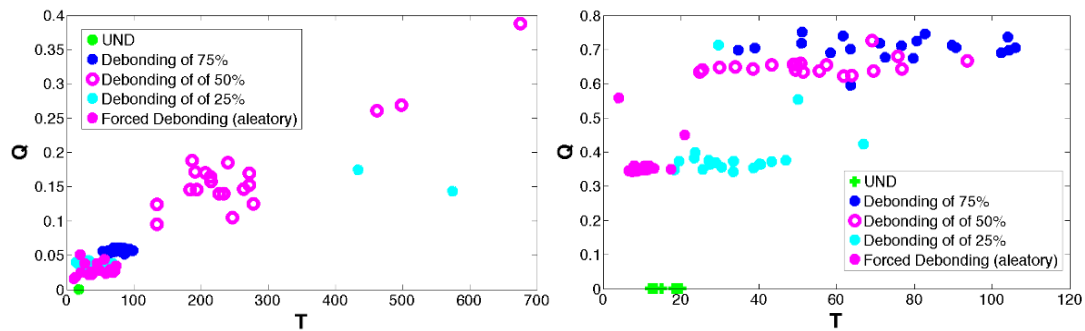

Figure 8. T-Q PCA indices for the debonding damages over the structure. For the actuation phases 1 and 2.

Conclusions

The PCA and Damage Indices based methodology allow to detect all the faults in spite of the differences between crystal cuts, crystal removal and debonding. Better results were obtained with the use of the damage indices, this is because two components are not sufficient to discriminate differences between the different scenarios. One of the disadvantage in the methodology is the big quantity of plots to analyse, in this case two plots by each actuation phase, however this paper shows that damage indices plots can be evaluated without the use of the score plots. This pattern recognition approach has the advantage of the baseline comparison, which can be related not only to the structure damage but also with the performance of the active sensor through its nominal behaviour. The methodology shows advantages for implementation in a SHM system, since it can be used as a first method to detect the current state of the sensors previously to the application of damage identification in a structure. Since multivariate analysis is needed, the pre-processing can be used to detect damages in the structure and faults in the sensors. In addition, since the methodology is based on a pattern recognition which can be applied to the analysis of data from sensors attached to the structures different to the PZTs used in this work.

Acknowledgments

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