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Sensor fault detection in a damage detection approach based on piezo-diagnostics

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Abstract
Online monitoring systems demand an adequate operation of sensor system used to acquire structural state measurements. If a damaged sensor record is incorporated in the diagnosis algorithm, it could be generate uncertainties and generate unsuitable alarms. Thus, appropriate operation of sensor system is a critical requirement in order to obtain a high reliability for structural damage diagnosis algorithms. In this work a data-driven procedure is studied in order to mitigate the faulty sensor effect in a monitoring system. The studied method takes advantage of piezo-diagnostics approach, where piezoelectric devices are attached to the surface of the monitored structure to produce guided waves. Thus, piezoelectric measurements are analyzed by applying principal component analysis and cross-correlation, in order to detect abnormal behaviors. In this sense, the squared prediction error Q and Hotelling squared statistical indices are used to observe a typical behaviour caused by sensor problems or structural damages. The methodology is validated on a lab carbon steel pipe section by using scenarios that include electric power failures, disconnecting power cords as well as mass adding. As concluding remark, in this work was possible to separate structural damage and fault sensor states at different clusters.

1 INTRODUCTION

Structural condition monitoring is of high interest for industrial applications since risks associated with early operating failures detection can be minimized and maintenance cost can be reduced **[1]**. In this sense, structural health monitoring methods based on guided waves have demonstrated to be effective for monitoring of structures such as pipe loops and beams, among others **[2]**, **[3]**. In particular, damage assessment by processing measurements from piezoelectric devices (PZT) generating guided waves has been discussed with promising results **[4]**, **[5]**. It also has been reported the need of including algorithms capable of validating a sensors network in order to avoid false alarms **[6]**. Thus, it is required to implement sensor fault evaluation algorithms in order to obtain reliable diagnostics.

In this paper, a methodology for evaluating PZT failures by means of principal component analysis is studied. It is performed through piezo-diagnostics approach, where guided waves generated by piezoelectric devices are analyzed. Therefore, if a sensor failure occurs, changes in the piezoelectric response are identified by comparing statistical indices respect to a reference undamaged state. The methodology is validated by using experimental data from a carbon steel pipe section, where scenarios included correspond to electric power failures and disconnecting power cords regarding to sensor faults, and mass adding in the pipe surface as structural damage. The experimental results show that damages can be distinguished from normal operation and it is possible to group some types of damage cases into well-differentiated clusters.

2 METHODS AND PROCEDURE

Structural Health Monitoring (SHM) refers to the implementation of online global strategies for damage identification of civil, mechanical and aeronautical structures. The objective of SHM is to diagnose a structure as a whole or its constitutive components in order to improve safety and reliability **[7]**.

An important issue in SHM is the identification of faulty sensors, due to their limited life expectation, that can degrade the performance of the assessment system **[8]**. This research topic has been studied during last years, where high sensitivity to connectivity, bias, complete failure, drifting and precision degradation have been found. Also, environmental variables influence greatly on a proper response of sensors, including PZT based architectures **[9].**

This paper is focused on methods and procedures used to manage possible malfunction due to degradation of intrinsic device properties and wrong manipulation. In this sense, a piezoelectric active-sensor diagnostics and validation using instantaneous baseline data is described in Overly et.al **[10]**. Also, Zhang and Gao **[11]** studies fractural behavior of piezoelectric by using principal component analysis as alternative to evaluate sensor cuts and debonding in a piezoelectric active system **[12]**. Thus, the methodology used in this paper is based on piezo-diagnostics approach and Principal Component Analysis (PCA), which is summarized in **Figure 1**.

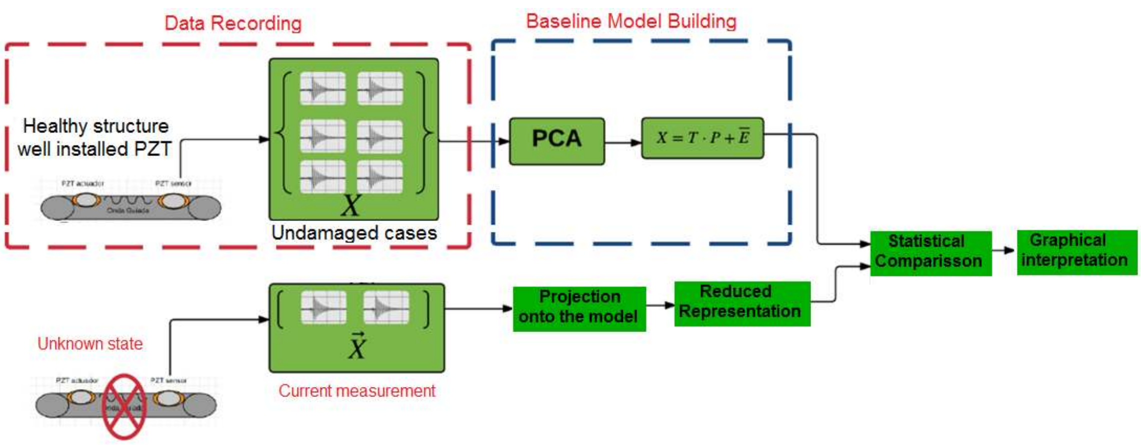

Figure 1: Diagram of the studied methodology

According to **Figure 1**, the diagnosis is achieved by processing piezoelectric measurements using principal component analysis. Several PZT devices are properly attached along the surface of the structure, where one of them operates as actuator and the remaining ones as sensors. Then, an unknown state is detected by comparing a reduced representation of current PZT measurements with previously built baseline model that is obtained by recording repeated structural measurements of the pristine structure. Thus, the methodology consists of two stages: 1.) Baseline Model Building and 2.) Monitoring. Both stages include a preprocessing stage that consists of a cros-correlation of actuation and sensing signals and a normalization procedure [13].

The main result of the first stage is a reduced representation of the pristine structure through a statistical model (eq. (1)).

$$T = \hat{X}P + E, \tag{1}$$

where, P belongs to the principal components or the projection matrix, E to the residual error, $\hat{X}$ is the normalized undamaged matrix (computed by using GroupScalling method), and T is the resulting reduced representation of undamaged matrix after applying PCA, which consists of scores with minimal variance.

For the second stage, statistical indices are used to detect deviation of current piezoelectric measurements respect to the baseline model. Therefore, new PZT records are projected to the principal components space by means of the projection matrix P obtained in the stage 1. Then, the statistical indices squared prediction error Q and t-squared T^2 are computed as measurement of abnormal behaviors (eq. (2) and (3)).

$$Q = \sum_k (e_k)^2, \tag{2}$$

where, e_k is the residual error estimated with k principal components.

$$T^2 = T^T \lambda^{-1} T\ , \tag{3}$$

where λ is the statistical model variance. As a result, differences between baseline and current state indices values are associated to a structural damages or PZT failures.

3 EXPERIMENTAL SETUP

Experimental tests were conducted in a lab carbon steel pipe loop, which includes an air compressor to maintain pressured the specimen at 80 PSI, a monometer as indicator of operation pressure and an aluminum frame with facilities to produce temperature variations in the environment through high power lamps. Also, the structural lab specimen is provided with a piezo-active system to generate guided wave, which includes amplifiers, data recorders and signal conditioners. A photo of the specimen is presented in **Figure 2.**

Figure 2: Test structure photo

On other hand, the pipe loop consists of five 100 x 2.54 x 0.3 cm bridled sections instrumented with a PZT actuator located at the middle point and two PZT sensors at the ends. In order to evaluate the system performance, one type of structural damage was included (mass adding) and several experiments including PZT faults were achieved to environmental temperature around 27ºC.

3.1 PZT FAULT SCENARIOS

Two types of sensor faults were studied: debonding and wiring losses. The first one corresponds to degrade adherent properties, while in the second one electric power failures or unexpected power cords disconnections are recreated. PZT failures are physically induced over one of the PZT sensors installed on the third section of pipe loop and they are supposed to be critical for acquisition purposes. **Figure 3** presents an appearance of PZTs with bonding damages. It is remarked that the other PZTs were used in a healthy state.

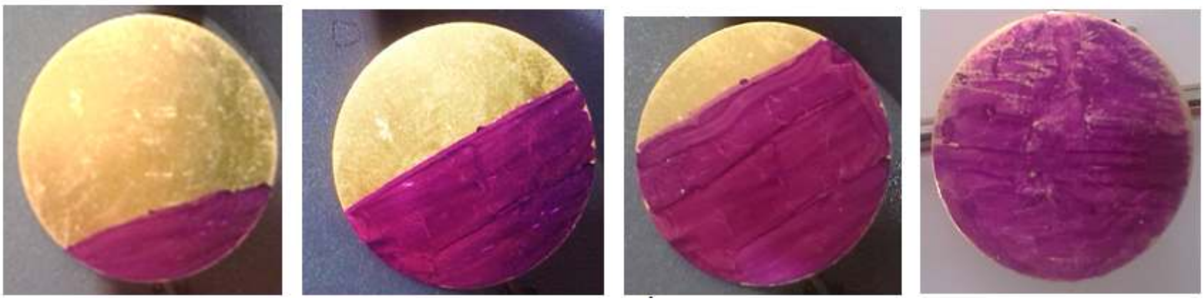

Figure 3: Debonding PZT areas

As it is shown in **Figure 3**, PZT bonding damage cases consider the absence of coupling layer, which is shown as the shaded area. Specifically, adhesive cyanoacrylate serves as interface between piezoelectric device and structure surface (coupling material). The diameter of PZT devices used in this study is approximately 2 cm and decoupling areas are configured to be 0.5cm (25%), 1.0cm (50%), 1.5cm (75%) and 2.0cm (100%), which produce 4 scenarios from incipient failures and to full debonding. On the other hand, the induced wiring faults are shown in **Figure 4**, where two additional PZT failure scenarios (ground loss and full disconnection) were recreated to analyze the influence of wiring losses. These experiments affect the data reliability due to an isolated condition of PZT sensor from the acquisition system, which produces corrupted information in the recording process with a high probability of false alarm in the diagnosis stage.

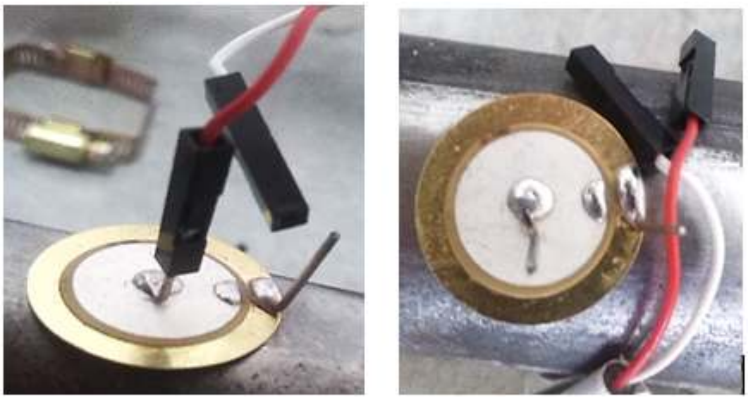

Figure 4: Wiring PZT failures. Left: Ground loss. Right: Full disconnection.

3.2 STRUCTURAL DAMAGE

In order to differentiate the variation of the used statistical indices between structural damage and sensor faults, a special shaped accessory was added to the surface pipe section between the PZT's sensor-actuator path (see **Figure 5**). Thus, the equivalent mass of the structure is modified and an alteration of the guided waves traveling through structural surface is produce by appearance of a new discontinuity.

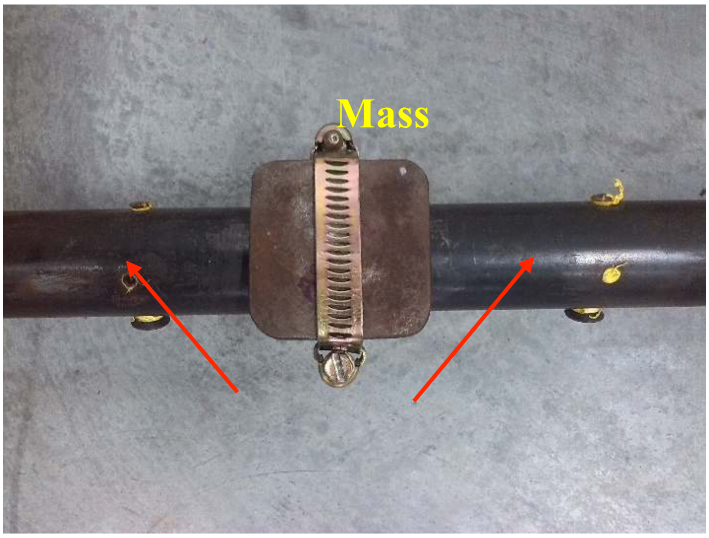

Figure 5: structural damage.

Although, as it is illustrated in **Figure 5** the test bench structure has the possibility of inducing leaks (see arrows), this type of damages was not considered in this study. However, bolts and other elements used to recreate this kind of leak damages are included in the nominal state of the structure and consequently in the statistical baseline model.

4 RESULTS AND DISCUSSION

The combination of different types of damages described on previous sections allows studying if it is possible to distinguish between structural damages and sensor faults. For each condition described previously, 100 experiment repetitions were conducted in order to evaluate the methodology introduced in this paper. Also, guided waves are induced with a 5 cycles Burst type pulse, which is then amplified to +-10V in order to excite the PZT actuators around resonance frequency (80 [KHz]).

As first result, the T-squared and Q-statistic plots are obtained for the case of healthy sensors and mass adding (see **Figure 6**). A clear differentiation of the structural damage is obtained when all sensors are well installed and they are properly working. It is highlighted a great difference of statistical indices values which produces compact clusters with low variability. Then, in order to analyze the influence of sensor faults, the scatter plot of statistical indices is obtained for the wiring losses case (see **Figure 7**). An additional experiment was conducted by acquiring data without actuation signal. This last condition corresponds to process only noise signals since PZT actuator was not excited.

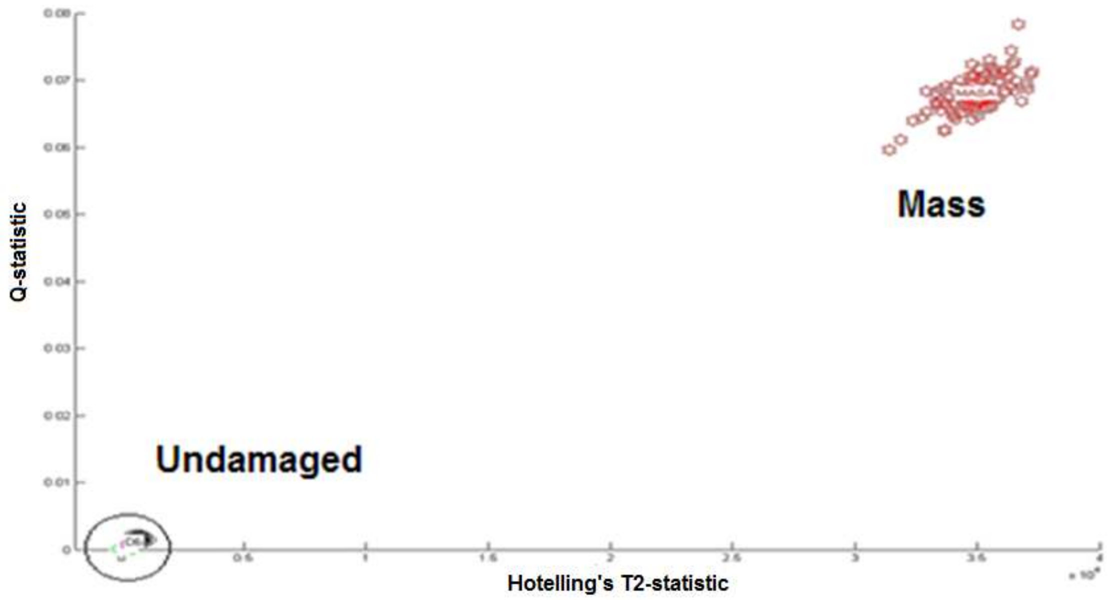

Figure 6: Statistical indexes for structural damage.

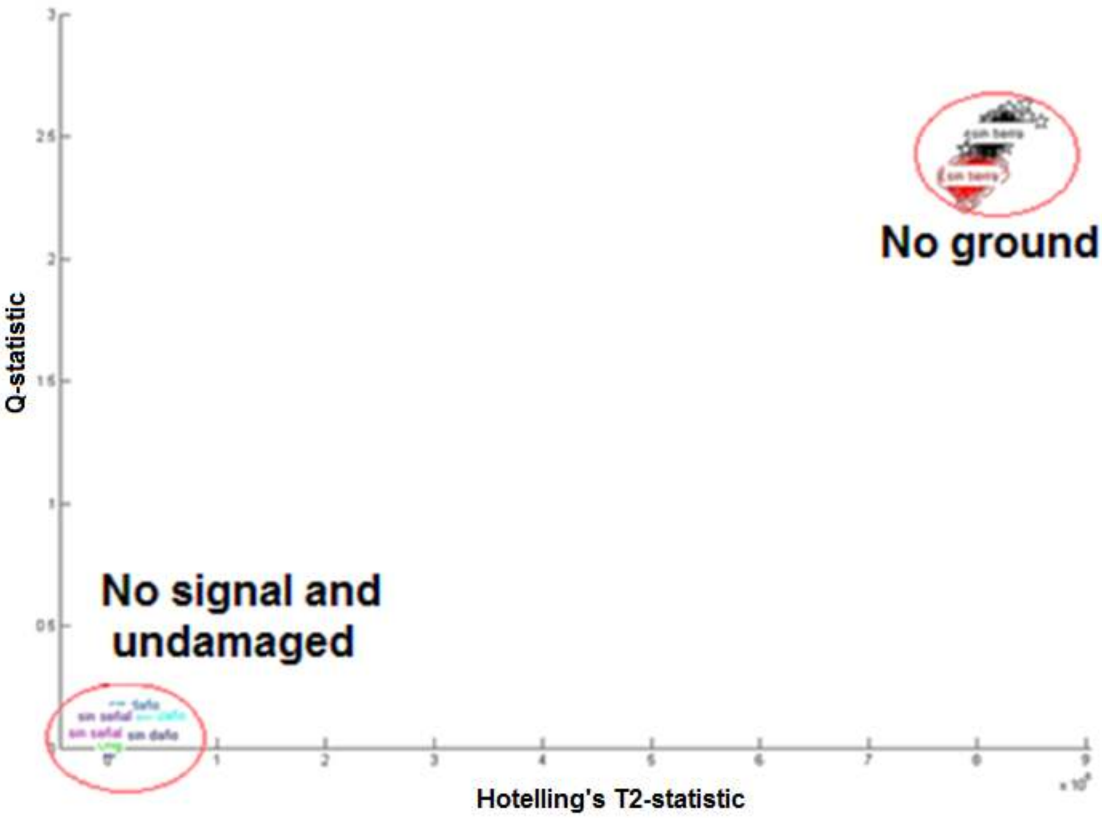

Figure 7: Statistical indexes for faulted sensors.

The scatter plot of **Figure 7** shows an evident data separation for PZT sensor ground wiring losses condition. However, data regarding to undamaged state (no sensor faults and no structural damages) show an apparent overlapping. **Figure 8** presents a zoom detail of how values are distributed.

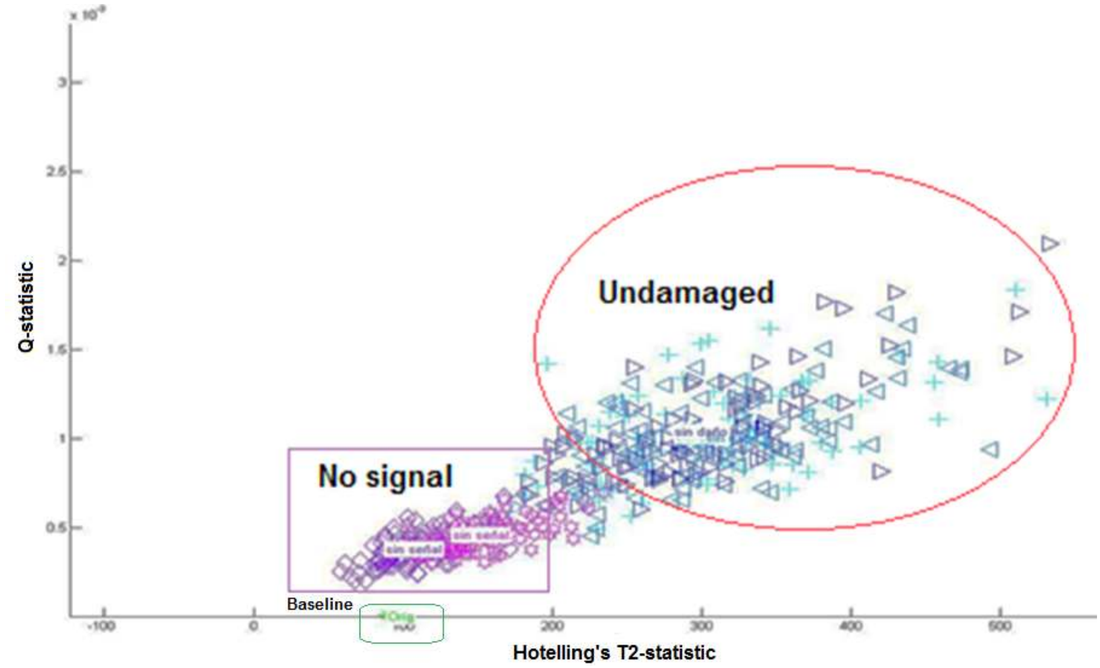

Figure 8: Zoom for faulted sensor condition.

Results in **Figure 8** indicate that behavior without actuation signal is located below undamaged state. Also, it is noted that exists a small difference between index values used to build the baseline model and those computed for undamaged conditions. As final outcome, damage index plot using data from debonding sensor condition is shown in **Figure 9**.

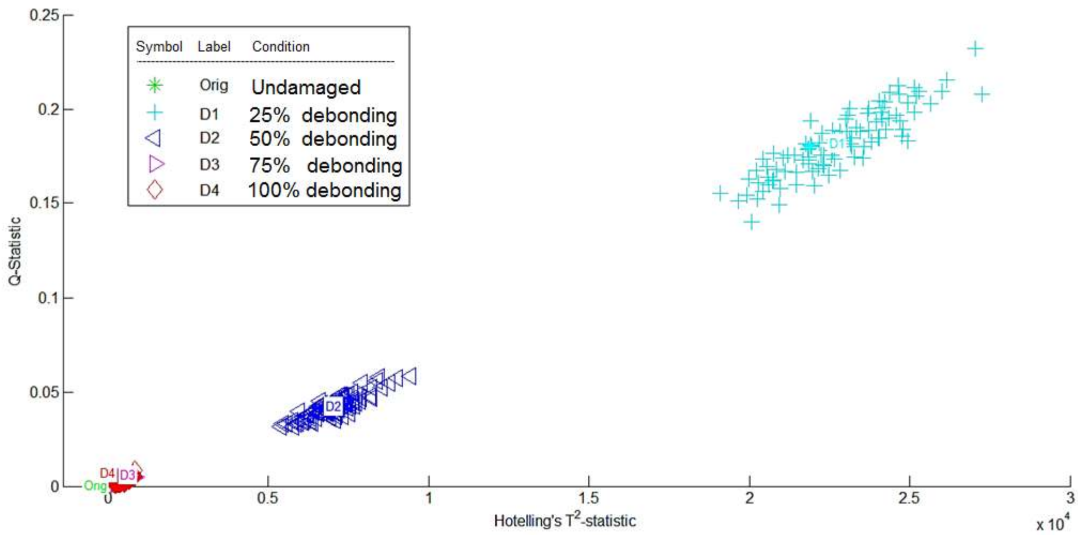

Figure 9: Statistical indexes for debonding PZT faults.

According to results of **Figure 9**, a bigger difference is obtained when debonding is greater than 25% probably since small energy of acquired signals. In addition, the index values are sorted in a decreasing way, which helps to define identification zones in the scatter plot. However, in contrast to wiring scenarios, debonding fault type is hard to distinguish from other cases (wiring failures and structural damages) since statistical indices values present some degree of confusion.

In summary, the methodology discussed in this paper has the capability of differentiating sensor fault conditions and structural damages. Moreover, each damage type are grouped in different ranges and organized in separated clusters, which facilitates decision-making process through thresholds or classification learning algorithms.

5 CONCLUSION

In this paper experimental results were conducted in order to validate the efficacy of a methodology to detect fault sensors and structural damages by using principal component analysis and piezo-diagnostics approach. It was demonstrated that statistical index from sensor fault cases result in values greater or lesser than those corresponding to mass adding structural damage case. Thus, sensor failure condition corresponds to atypical performance in the diagnosis response and high indices out or bellow from common values can be associated to failures in connection system. Therefore, the methodology is suitable to solve condition monitoring tasks with a reduced probability of false alarms. Future research is required to analyze different structural damage types as leaks or corrosion. Besides, it is suggested to study another kind of PZT degradation, for example crystal deterioration, plate cuts and stressing. It is highlighted that normalization method used in pre-processing stage, before applying principal component analysis, influences and modifies the results. So, it is suggested to carry out sensitivity analysis of this issue.

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