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OUTLIER IDENTIFICATION IN IMPEDANCE-BASED SHM

Bruno Pereira Barella
Federal University of Goiás, IMTec, Catalão-GO, Brazil
brunobarella@hotmail.com

Stanley Washington Ferreira de Rezende
Federal University of Goiás, IMTec, Catalão-GO, Brazil
stanley-washington@hotmail.com

João Paulo Moreira Bento
Federal University of Goiás, IMTec, Catalão-GO, Brazil
joaopaulo.moreira.bento@gmail.com

José dos Reis Vieira de Moura Júnior
Federal University of Goiás, IMTec, Catalão-GO, Brazil
zereis@ufg.br

Abstract. *Impedance-based structural health monitoring method is one of the most prominent predictive methods applied nowadays to detect small damages in structures. However, some noise aspects can make difficult the application of the technique in real structures. These noisy sources can be from electrical/connectors or even mechanical disturbances aspects, generating signatures sometimes identified as false positives. In this contribution one aluminum beam was monitored and three conditions of damages (light, medium and heavy) and some noisy conditions was evaluated. By the use of the GESD (Generalized Extreme Studentized Deviate) test a procedure was proposed to evaluate and remove these outliers. Concluding, the test and procedure were able to detect and eliminate the noisy samples from the total set with success and can be a useful tool to work with other recent developments in the online monitoring systems.*

Keywords: *Outliers, GESD test, Impedance-based Structural Health Monitoring.*

1. INTRODUCTION

A bad choice in the maintenance planning can result in catastrophic effects. The incident in the flight Aloha Airlines 243, a catastrophic error occurred in a Boeing 737-297 due to an explosive decompression. Figure 1 shows the aircraft structure (Afshari, 2012; Hendricks, 1991).

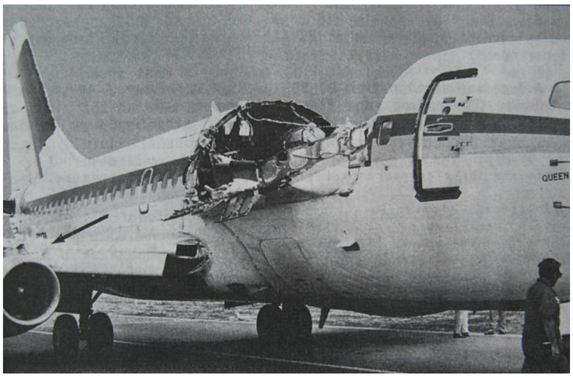

Figure 1. Flight Aloha Airlines 243 incident.

This historic case could be avoided if the modern structural health monitoring techniques were used to prevent incipient damages (Afshari, 2012).

The SHM (Structural Health Monitoring) evaluates continuously the integrity of the mechanical systems along its useful life, allowing the minimal human intervention and reducing costs (Park *et al*, 2005). For this purpose, damage is considered as a structural change caused by external sources, causing different performances of the structure before and after the damage (Freitas *et al.*, 2016; Inman et al., 2005). This performance variation corresponds to a dynamic response change, i.e., the mass, stiffness and/or damping changes. Then, the impedance-based SHM compares the electromechanical impedance signatures of the pristine and damaged structures.

Environment conditions such as extreme temperatures or external vibrations can change significantly the monitored impedance signature (Rabelo, 2014). Thus, it is necessary to take into account a procedure to remove outliers from the data sets, avoiding false positives or indicating a presence of damage where it is not happening.

Based on this context, this contribution proposes an approach of outlier removal techniques by the use of statistical tools. Then, the purpose of this approach is to make the impedance-based SHM technique more robust to remove false signatures and propitiate a better result in stand-alone applications.

2. ELECTROMECHANIC IMPEDANCE-BASED METHOD

The impedance-based SHM method uses a sensor/actuator bonded on the structure in order to obtain the pristine signature of the system (baseline data). Piezoelectric transducers are bonded in the structure not changing the dynamic behavior of the system (Moura Júnior, 2008).

Piezoelectric patches are dielectric materials that generate electric fields when subjected to strain in specific directions. On the other hand, they can produce displacements if an electric field is applied. Thus, this material can be used as sensor (direct effect) as well as actuator (inverse effect) in only one component (Pereira, 2010).

The main piezoelectric materials are: PZT (Lead Zirconate Titanate) and the PVDF (polyvinylidene fluoride) (Pereira, 2010).

Equations (1) and (2) were developed by Voigt in 1910, representing the direct and inverse effects (Banks, 1996).

$$D = d\sigma + \varepsilon E_1 \tag{1}$$

$$S = s\sigma + dE_1 , \tag{2}$$

where D is the displacement vector (N/m), E_1 is the electric field vector (V/m), S strain vector (N/m²), σ tension vector (N/m²), d is the piezoelectric tensor (m/V), ε dielectric tensor e s is the elastic property.

The impedance-based method uses simultaneously the direct and inverse effects. By this way, to perform the data acquisition is necessary to apply an alternate current sweeping along the desired frequency to receive the dynamic response of the structure. This dynamic response is gathered by the sensor and converted in electrical current measuring the electrical resistance of the PZT patch (Park et al., 2005).

The electromechanical impedance can be expressed by the ratio of the electrical voltage applied to the PZT patch by the electrical current obtained due to the dynamic response of the system. Equation (3) defines the admittance as a correlation of the electrical impedance of the patch to the mechanical impedance of the structure (Liang et al., 1997).

$$Y(\omega) = i\omega a(\overset{-T}{\varepsilon_{33}}(1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) - Z_a(\omega)} d_{3x}^2 \overset{E}{Y_{xx}}) , \tag{3}$$

where Y(ω) is the electrical admittance, $Z_a(\omega)$ is the mechanical impedance of the PZT patch, $Z_s(\omega)$ is the mechanical impedance of the structure, $\hat{Y}^E_{xx}$ is the complex Young modulus of the PZT patch with electrical field equals to zero, d^2_{3x} is the PZT coupling constant in the x direction with strain equals to zero, ε^{-T}_{33} is the dielectric constant with strain equals to zero, δ is the PZT dielectric constant, α is the PZT geometry.

Also, it is suggested to use the technique in a higher frequency range (30-200kHz) (Moura Júnior, 2008). The most appropriate range of monitoring must have some peaks (resonances) because they change more in case of damages. Some statistical methods can be applied to find the best frequency range and it is highly recommended for complex structures (Moura et al., 2004, Bento et al., 2016).

The damaged and baseline impedance signatures are compared for a qualitative analysis (structure is damaged or not). However, for a better understanding it is necessary to have a quantitative analysis in order to find the severity of the damage. The RMSD (Root Mean Squared Deviation) is used in this contribution and described by the Eq. (4) (Palomino, 2008).

$$RMSD = \sum_{i=1}^{n} \sqrt{\frac{[\mathrm{Re}_{i,1} - \mathrm{Re}_{i,2}]^2}{[\mathrm{Re}_{i,1}]^2}} , \tag{4}$$

where $Re_{i,1}$ represents the measured signature of the pristine structure, $Re_{i,2}$ represents the measured signature of the damaged structure for the frequency *i*, and *n* represents the frequency points evaluated. Then, RMSD index is proportional to the damage severity of the structure.

3. GESD METHOD

An outlier is defined as a value in a non-normal distance of the data set (Rohlf, 1975). The existence of them can promote incorrect evaluation about the data set, as such as the false positives. This condition points to an inexistent problem. Then, the outlier identification is very important to a proper data evaluation.

The GESD (Generalized Extreme Studentized Deviated) method detects potential outliers in a dataset that follows a normal distribution (condition). This method uses a generalization of the test of the extreme deviation of the T Student distribution (Rosner, 1983).

The test needs only a superior limit *k* to locate the outliers in a data amount. Then, the test will conduct *k* iterations, to locate one outlier, test to locate two outliers following to *k* outliers.

Initially, it is calculated the extreme deviation of the T Student Distribution for a sample with normal distribution, according to the Eq. (5).

$$R_i = \max \left\{ \frac{|x_i - \bar{x}|}{s} \right\}, \tag{5}$$

where $\bar{x}$ is the average, *s* the standard deviation and x_i the value of the sample with $i=1, 2, 3, \ldots, k$. These last values are calculated one by one and then compared to the critical value of λ obtained by the Eq. (6).

$$\lambda_i = \frac{(n-i)t_{n-i-1,p}}{\sqrt{(n-i-1+t^2{}_{n-i-1,p})(n-i+1)}}, \tag{6}$$

where $t_{n-i-1,p}$ is the percentual point from the 100_p of the T Student distribution with $n-1-i$ degrees of freedom and the *p* value is obtained by the Eq. (7).

$$p = 1 - \left[\frac{\alpha}{2(n-i+1)} \right], \tag{7}$$

with α as the significance level for the general test. The critical value λ represents the cut value to identify it as an outlier (Yu et al., 2004).

GESD compares the R_i e λ_i values. If $R_i \leq \lambda_i$ is declared the inexistence of outliers in the sample, but if $R_i > \lambda_i$ is defined the existence of the outlier and it is identified as x_i. One Matlab® code was implemented following this description in order to automate the process.

4. EXPERIMENTAL PROCEDURE

In order to evaluate the GESD method, it was used an I profile structure (260x70x100 mm) with a PZT patch bonded at the middle and at 10mm of the tip Fig. (2).

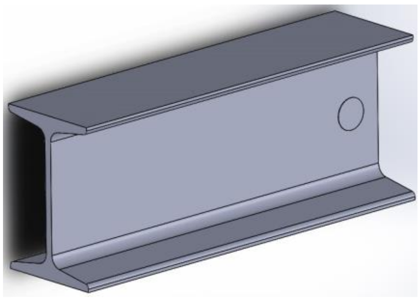

Figure 2. I profile structure used in the experiment

It was applied three different places of damage (added mass). First level was considered at 200 mm far from the PZT patch; second level was 150 mm and third at 100 mm far from the PZT patch. Figure 3 illustrates the three levels of damages.

Figure 3. Damage 1 - Damage 2 - Damage 3

It was gathered 30 impedance signatures for each level (baseline, damage 1, damage 2 and damage 3) by the use of the Analog Devices card EVAL-AD5933EBZ (Devices, 2007) represented in the Fig. 4. Also, it was used the RMSD as the metric to quantify the proposed damages.

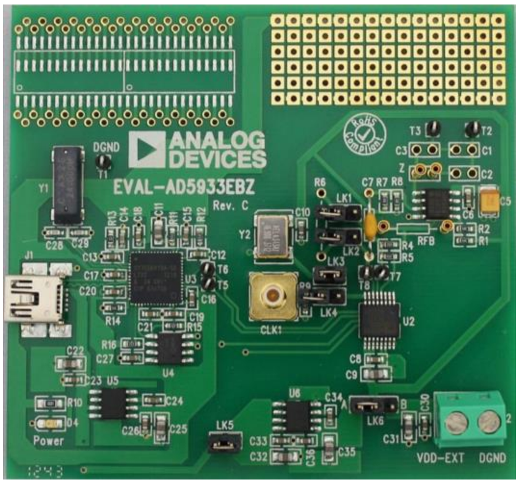

Figure 4. Data acquisition card

It was developed a Matlab® code in order to simulate 3 outliers for each data set from the 30 sampled data gathered for each group. The procedure identifies the average of the signatures and finds the maximum amplitude. Then, select randomly 50 points (10% of the sample amount) from 511 for each group and randomly change them, generating 3 samples for each group.

After generating the outliers, it was applied the K-means method to classify each level of damage proposed, separating the samples in groups. Then, the four groups were checked to be normal by the Shapiro-Wilk test, a condition to apply the GESD method that will remove the outliers from the data sets (Torman et al., 2012).

5. RESULTS AND DISCUSSIONS

The experiment was measured in a frequency range from 27 to 32 kHz obtained by trial and error method with a sampling of 511 points. It was used only the real part of the electromechanical impedance signature due to the fact that it is imaginary component is more sensitive to temperature changes and real part is associated to the mechanical impedance (Raju, 1997). The impedance signatures of each group are represented in the Fig. 5. Each signature illustrated is the average of the 30 samples.

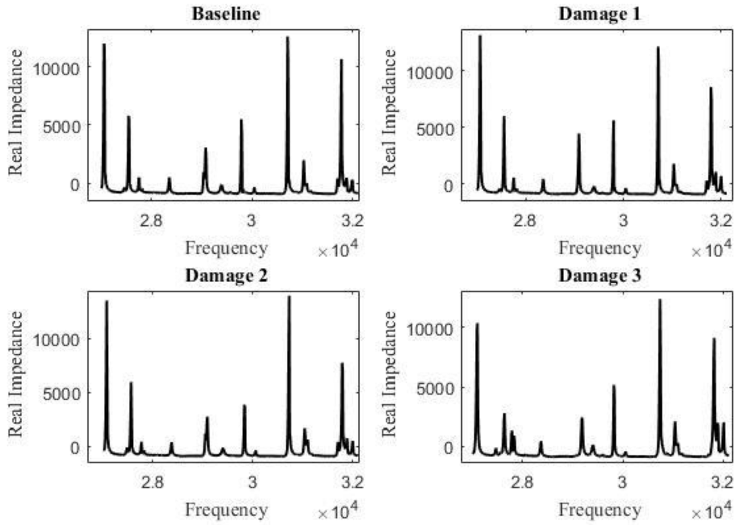

Figure 5. Impedance signatures for each group (averages).

Figure 6 illustrates the noise inserted in the baseline signature. It was changed 50 out of 511 points of the sample.

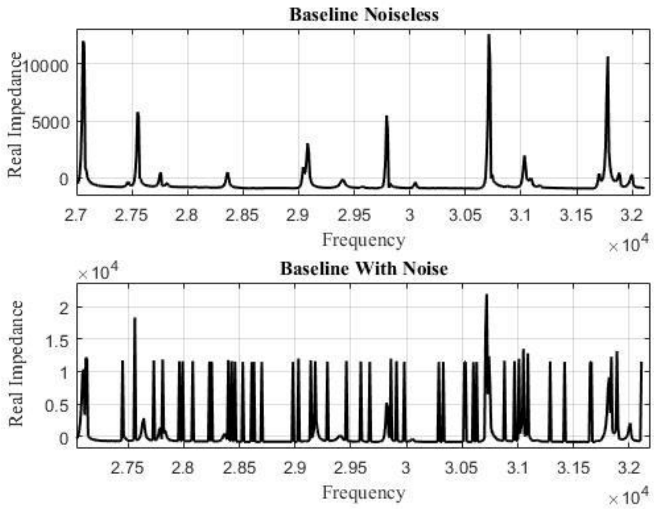

Figure 6. Baseline with noise and noiseless

After the inclusion of the noise, the sample sets are classified by the K-means method. This classification aims to separate the four groups of damages. Figure 6 (a) illustrates the groups with the correspondents outliers inserted into each level.

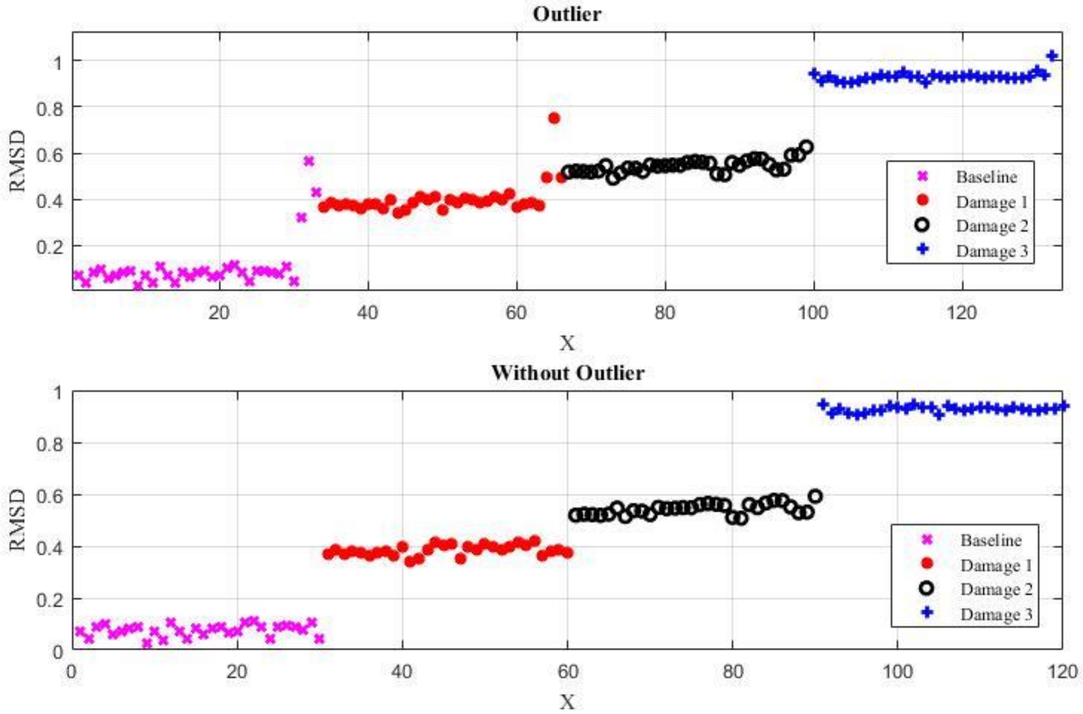

Figure 7. Outlier removal from the samples

It was applied the Shapiro-Wilk test with 95% of confidence to check the normal distribution and then it is possible to apply the proposed GESD method for outlier removal. Figure 6 (b) illustrates the result of the GESD method removing 3 outliers from both baseline and Damage 1 data sets, but only 2 out of 3 outliers from the Damage 2 and 3 data sets.

6. CONCLUSION

Regarding online damage detection systems, it is very important to remember the false positive aspects and effects in effective responses. In this contribution was presented a robust method with a simple to implement approach (GESD), creating a functional procedure to evaluate and remove false positive samples in SHM systems.

Although the presented method was not able to remove all outliers from the samples, the proposed approach illustrates good results identifying approximately 83% of the outliers.

In this contribution it was identified that the GESD method is more difficult to find outliers as much greater is the damage severity. In further works should be investigated alternative approaches to find a better result in such conditions.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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