Proceedings of COBEM 2009

DAMAGE METRICS ASSOCIATED WITH ELECTROMECHANICAL IMPEDANCE TECHNIQUE FOR SHM APPLIED TO A RIVETED STRUCTURE

Lizeth Vargas Palomino, lvpalomino@mecanica.ufu.br
Valder Steffen, Jr, vsteffen@mecanica.ufu.br
Federal University of Uberlândia – School of Mechanical Engineering – Campus Santa Mônica, Av. João Naves de Avila 2121, Bloco 1M – Uberlândia - Brazil

Abstract. *The basic concept of impedance-based structure health monitoring is measuring the variation of the electromechanical impedance of the structure caused by the presence of damage, by using patches of piezoelectric material bonded on the surface of the structure (or embedded). Through these piezoceramic sensor-actuators, the electromechanical impedance, which is directly related to the mechanical impedance of the structure, is obtained. Based on the variation of the impedance signals, the presence of damage can be detected. To quantify the damage, a particular damage metric is set to assign a characteristic scalar value to the damage. The impedance-based structure health monitoring technique can be potentially used to monitor riveted components as those found in a number of engineering applications, such as automotive, aeronautical, and civil engineering structures. The objective of this work is to evaluate nine different damage metrics proposed by the literature that are tested in an aircraft structure and to calculate the damage as characterized by rivet losses. The results show that some matrices are more sensitive than the others for the particular application studied.*

Keywords*: Structure health monitoring, Damage metrics, Riveted structure.*

1. INTRODUCTION

Failures occurring in industrial equipment and structures in general are associated to friction, fatigue, impact, and crack's growth or to other reasons. For an appropriate functioning of the system, the failure should be located and repaired timely. In general terms, the problem of damage monitoring consists in locating and measuring the fault and estimating the remaining life of the system. One of the most important ambitions of modern engineering is to perform structural health monitoring in real time in components of high cost and considerable responsibility. Thus, the creation or improvement of techniques that enhance the accuracy and reliability of the tracking process is highly desirable and is the subject of several studies both in industry and academic environments (Farrar *et al.,* 2005).

There are several techniques for monitoring the occurrence and propagation of structural damage. One of these techniques is the so-called impedance-based structural health monitoring (Park and Inman, 2005). This technique is based on the electromechanical coupling that results from a piezoelectric transducer installed on the monitored structure. Then, by measuring the electrical impedance, which depends on both the electrical characteristics of the transducer and the physical or mechanical characteristics of the structure (Liang *et al.,* 1994), incipient damage can be detected. For this purpose, the variations found in the impedance curves are analyzed. For quantification purposes specific damage metrics are proposed. These damage metrics are calculated from the measurement comparisons between the pristine condition and the damaged structure, by using numerical and statistical tools as described in the literature (Palomino, 2008).

In this context, this paper presents a study of different damage metrics found in the literature, all used to monitor the electromechanical impedance in order to determine which of them are more sensitive to incipient damage such as the loss of rivets in a riveted structure.

1.1. Impedance-based structural health monitoring

The technique known as impedance-based structural health monitoring uses the piezoelectric properties of the PZT patch that is installed in the structure being tested and is considered as a non-destructive damage evaluation method (Park *et al.,* 2003). The basic idea behind this technique is to monitor the changes in the structure's mechanical impedance caused by the presence of damage. Since the direct measurement of the structure's mechanical impedance is a difficult task, the method uses piezoelectric materials (PZT) bonded to or incorporated into the structure, allowing the measurement of the electrical impedance. This measurement is related to the structure's mechanical impedance, which is affected by the presence of damage. Evidently, it is considered that the piezoelectric sensor-actuator used in the monitoring procedure remains intact along the test.

The impedance-based SHM technique was first proposed by Liang *et al.* (1994) and subsequently the method was extended by Chaudhry *et al.* (1995, 1996), Sun *et al*. (1995), Park *et al.* (1999, 2000, 2001, 2003), Giurgiutiu and Zagrai (2000), Soh *et al.* (2000), Bhalla *et al.* (2002), Giurgiutiu *et al.* (2002, 2003), Moura and Steffen (2004), Peairs (2006) and Moura (2008). As previously mentioned, this health monitoring technique utilizes impedance sensors to monitor changes in the structural stiffness, damping and mass. The impedance sensors consist of small piezoelectric patches, usually smaller than 25x25x0.1mm, which are used to measure directly the local dynamic response.

The piezoelectric material acts directly producing an electric voltage when a mechanical stress is applied on the material. Conversely, a mechanical stress is produced when an electric field is applied. The impedance-based monitoring method uses simultaneously both versions, direct and inverse, of the piezoelectric effect (Park *et al.,* 2003).

When the PZT patch is bonded to the structure and a very low electric voltage is applied, generally 1V (Raju, 1997), a strain is produced in the PZT patch. Using a high frequency of excitation (in terms of typical modal analysis testing), the dynamic response of the structure represents only the local area of the sensor and is not affected by the boundary conditions. Then, the response of the mechanical vibrations is transmitted to the sensor in the form of an electrical response. When an incipient damage leads to changes in the dynamic response (given by the impedance signal), this is observed in the electric response of the PZT.

The electromechanical model that quantifies and describes the measurement process is illustrated in Fig. 1 for a single-degree-of-freedom system.

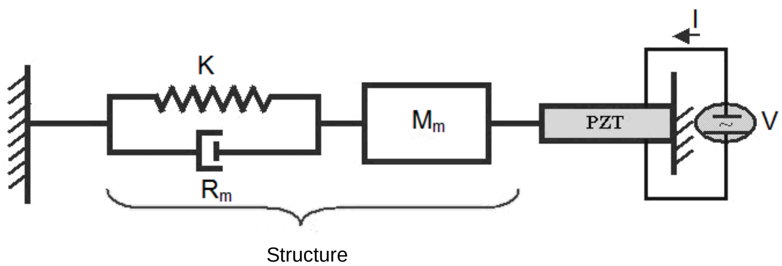


Figure 1. Model used to represent a PZT-driven dynamic structural system

For this system, Liang *et al.* (1994) demonstrated that the admittance Y (ω) of the PZT patch can be written as a function of the combined actuator PZT's and structure's mechanical impedance, as given by Eq. (1):

$$Y(\omega) = i\omega a\left(\bar{\varepsilon}_{33}{}^{T}\left(1 - i\delta\right) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}{}^{2}\hat{Y}_{xx}^{E}\right) \tag{1}$$

where $Y(\omega)$ is the electrical admittance (inverse of the impedance), $Z_a(\omega)$ and $Z_s(\omega)$ are the PZT material's and the structure's mechanical impedances, respectively. $\hat{Y}_{xx}^{E}$ is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero electric field, $\bar{\varepsilon}_{33}^{T}$ is the dielectric constant at zero stress, δ is the dielectric loss tangent of the PZT, and a is a geometric constant of the PZT. Assuming that the mechanical properties of PZT do not vary over time, Eq. (1) shows that the electrical impedance of the PZT patch is directly related to the structure's impedance. Damage causes changes in the structure's mechanical impedance thus changing local dynamics features. Hence, the electrical impedance is used to monitor the structure health as represented by the structure's mechanical impedance.

The sensitivity of the technique to detect structural damage is related to the frequency range selected. A very small damage in the structure does not cause significant changes in the structure's stiffness, mass and damping properties. Therefore, it is necessary for the excitation wavelength to be smaller than the characteristic length of the damage to be detected. According to the literature, the frequency range typically used in the impedance-based method is 30 kHz to 250 kHz. The range for a given structure is determined by trial and error methods. However, Moura and Steffen (2004) presented a statistical procedure that can be used to obtain the best settings for tests of electromechanical impedance. In the impedance-based method frequency ranges that contain 20 to 30 peaks are usually chosen, because the number of peaks provides a better dynamic response over the frequency range. A band around a high frequency (150 kHz) is favorable to detect the location, while a lower range, around 70 kHz, covers larger areas where damage could be located (Sun *et al.,* 1995).

As for the sensitive region to identify changes, *Park et al.* (2003) states that for a simple PZT damage located at a radial distance of up to 0.4 m can be identified in composite materials and up to 2 meters in bars consisting of a single metal.

The curve that represents the impedance response provides a qualitative assessment of the damage. For a quantitative assessment of the failure a damage metric is used (Palomino, 2008). In the literature there are different damage metrics and the most important of them are addressed in the present contribution.

To establish a methodology able to quantify structural changes, a reference to the damage metric (baseline) should be defined, corresponding to the structure without damage. Thus, comparisons can be made involving the metric values of the pristine conditions and the damaged structure. These comparisons should be able to indicate the presence of damage in the structure.

The most used statistical model in the literature is the root mean square deviation (RMSD); its formal definition is given by Eq. (2)

$$RMSD = \sqrt{\sum_{i=1}^{n}\left(\frac{\left(\mathrm{Re}\left(Z_{1,i}\right)-\mathrm{Re}\left(Z_{2,i}\right)\right)^2}{n}\right)} \tag{2}$$

where $\mathrm{Re}\left(Z_{1,i}\right)$ is the impedance of the PZT measured under healthy condition, and $\mathrm{Re}\left(Z_{2,i}\right)$ is the impedance for the comparison with the baseline measurement at frequency interval i , and n is the total number of frequency points used in the comparison. This calculation is done within a predefined frequency range. As a first alternative for this metrics, it is proposed to replace the denominator by the impedance measured under healthy condition (baseline) (Grisso, 2004; Peairs, 2006)

$$RMSD1 = \sqrt{\sum_{i=1}^{n}\left(\frac{\left(\mathrm{Re}\left(Z_{1,i}\right)-\mathrm{Re}\left(Z_{2,i}\right)\right)^2}{\mathrm{Re}\left(Z_{1,i}\right)^2}\right)} \tag{3}$$

The root mean square deviation defined by Eq. (3) is called RMSD1. In this case, the level of impedance measurement does not affect qualitatively the damage metrics, although the result obtained is changed by the points taken in the comparison.

Another definition of the root mean square deviation, RMSD2, is described by Giurgiutiu and Rogers (1998). In, Eq.(4), it is possible to observe that the sum is made independently in the numerator and the denominator.

$$RMSD2 = \sqrt{\frac{\sum_{i=1}^{n}\left(\mathrm{Re}\left(Z_{1,i}\right)-\mathrm{Re}\left(Z_{2,i}\right)\right)^2}{\sum_{i=1}^{n}\mathrm{Re}\left(Z_{1,i}\right)^2}} \tag{4}$$

The damage metric described by Eq. (4) was used in other studies where comparisons were made between different metrics (Tseng and Naidu, 2002; Giurgiutiu and Zagrai, 2005).

Another possibility to use the root mean square deviation, RMSD3, is provided by Park *et al.* (2003).

$$RMSD3 = \sum_{i=1}^{n}\sqrt{\frac{\left(\mathrm{Re}\left(Z_{1,i}\right)-\mathrm{Re}\left(Z_{2,i}\right)\right)^2}{\mathrm{Re}\left(Z_{1,i}\right)^2}} \tag{5}$$

In Eq. (5) the sum is outside the root, unlike the definitions previously given.

Peairs (2006) presents yet another change in the root mean square deviation, RMSD4, as it is shown by the following equation:

$$RMSD4 = \sqrt{\sum_{i=1}^{n}\left(\frac{\left(\left(\mathrm{Re}\left(Z_{1,i}\right)-\mathrm{Re}\left(\overline{Z}_1\right)\right)-\left(\mathrm{Re}\left(Z_{2,i}\right)-\mathrm{Re}\left(\overline{Z}_2\right)\right)\right)^2}{n}\right)} \tag{6}$$

where $\mathrm{Re}\left(\overline{Z}_1\right)$ and $\mathrm{Re}\left(\overline{Z}_2\right)$ are the averages of measurements for the two conditions analyzed. These averages are included in Eq. (6) to minimize the effect of small variations on the metric value, resulting from possible changes in temperature or electrical resistance of the cables connecting the sensor to the impedance analyzer, as shown in Fig. 2, where measurements are illustrated by an aluminum-made beam, while maintaining the same conditions (without damage).

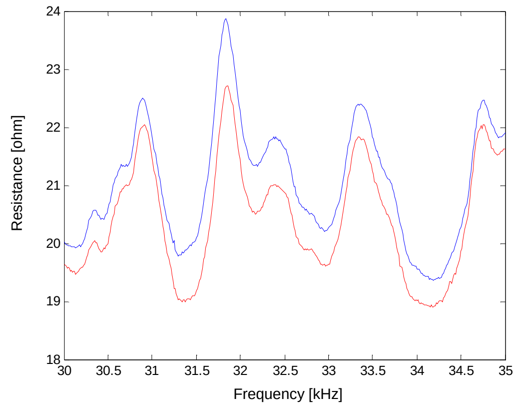


Figure 2. Example of the magnitude variation between two impedance measurements for the structure under pristine condition

The variations shown in Fig.2 appear quite frequently. Then, to determine the baseline, the average of several measurements for the structure in healthy state should be used. With the mean value and the standard deviation calculated for each point, Peairs (2006) presents Eq. (7) as a new definition of the root mean square deviation:

$$RMSD5 = \sqrt{\sum_{i=1}^{n}\left(\frac{\left(\frac{\mathrm{Re}(\bar{Z}_{1,i}) - \mathrm{Re}(Z_{2,i})}{S_{Z_1,i}}\right)^2}{n}\right)} \tag{7}$$

where the standard deviation of each point of the baseline is included, $S_{Z_1,i}$,is included in order to make the metric less sensitive to changes in the impedance signal due to changes in the environment (not linked to any damage in the structure).

Another alternative is the correlation coefficient deviation damage metric, which is used to quantify and interpret information from two data sets. The mathematical formulation, Eq. (8), involves the difference between 1 and the correlation coefficient between the measurement and the reference (Giurgiutiu and Zagrai, 2005).

$$CCD = 1 - CC \tag{8}$$

where CCD is the correlation coefficient deviation and the CC is correlation coefficient that it is given by Eq. (9).

$$CC = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(\mathrm{Re}(Z_{1,i}) - \mathrm{Re}(\bar{Z}_1)\right)\left(\mathrm{Re}(Z_{2,i}) - \mathrm{Re}(\bar{Z}_2)\right)}{S_{Z_1}S_{Z_2}} \tag{9}$$

where S_{Z_1} is the standard deviation of the baseline and S_{Z_2} is the standard deviation of the impedance signal to be compared. When the correlation coefficient is equal to 1, it means that the signals are fully correlated. When the difference between the signals is large the CC value is small. The CC value is also used to compare and quantify the admittance signals (Naidu and Soh, 2003).

The average square difference is another metric used by the electromechanical impedance method to quantify the damage (Raju, 1997), and its mathematical formulation is given by Eq. (10):

$$ASD = \sum_{i=1}^{n}\left[\mathrm{Re}(Z_{1,i}) - \left(\mathrm{Re}(Z_{2,i}) - \delta\right)\right]^2 \tag{10}$$

where δ is the difference of the averages of each signal, as represented by Eq. (11)

$$\delta = \mathrm{Re}\left(\overline{Z}_1\right) - \mathrm{Re}\left(\overline{Z}_2\right) \tag{11}$$

This damage metric is also used to remove the effect of variations in the amplitude due to changes in the environment.

Another metric used by the electromechanical impedance method is the mean absolute percentage deviation (Tseng and Naidu, 2002):

$$MAPD = \sum_{i=1}^{n} \left| \frac{\left(\mathrm{Re}\left(Z_{1,i}\right) - \mathrm{Re}\left(Z_{2,i}\right)\right)}{\mathrm{Re}\left(Z_{1,i}\right)} \right| \tag{12}$$

It is observed that the MAPD, Eq. (12), is similar to the root mean square deviation defined by RMSD3, (Eq. (5)).

Finally, this paper includes also the metric given by the simple sum of the average difference between the signals (Peairs, 2002). This damage metric does not use any relation between the values considered and is calculated as shown by Eq. (13):

$$M = \sum_{i=1}^{n} \left(\mathrm{Re}\left(Z_{1,i}\right) - \mathrm{Re}\left(Z_{2,i}\right)\right)^2 \tag{13}$$

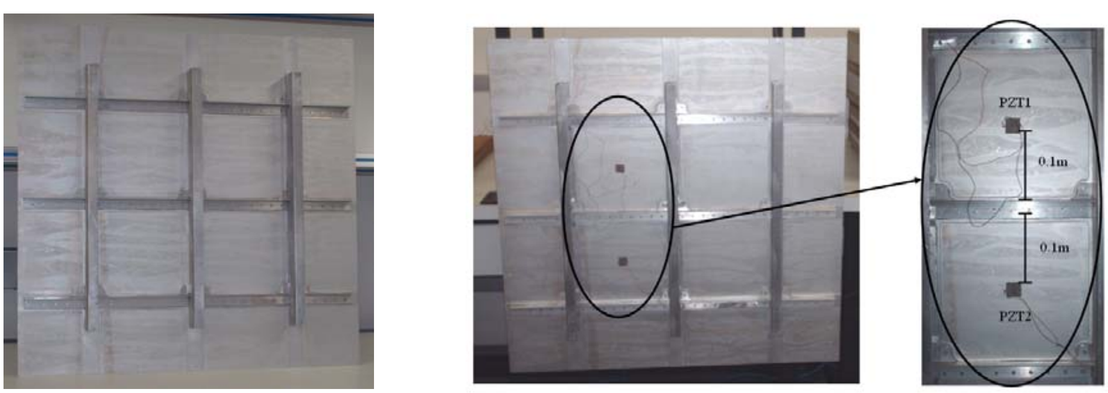
2. METHODOLOGY

One of the most commented unexpected damage news occurred on 28 April 1988 with the Aloha Airlines aircraft, Boeing 737-297 model. The flight left the airport of Halo heading to the Honolulu International Airport with 86 passengers and six crew members. During the flight, a fuselage part separated from the aircraft structure (see Fig.3), causing an emergency landing.

Figure 3. Fuselage separation of the Aloha Airline aircraft in 1988 (Farrar *et al.,* 2005).

A damage that may affect the plane fuselage, leading to consequences such as those mentioned above, is the loss of rivets due to fatigue loading. In order to evaluate the metrics used in the Impedance-based structural health monitoring method in real cases, an aircraft fuselage part was used to simulate the loss of a rivet.

The structure used can be seen in Fig. 4(a), with dimensions of 0.81x0.81 m. Two 0.02 x 0.02 m PZT patches (PZT1 and PZT2) were symmetrically bonded to the panel 0.1m apart from a line of rivets in the structure (Fig. 4(b)).



(a) fuselage component

(b) PZT patches bonded to the structure

Figure 4. Aircraft fuselage component.

The structure was suspended by nylon cords to characterize free-free boundary conditions.

To create an incipient damage in the fuselage, one of the rivets was removed, as shown in Fig. 5.

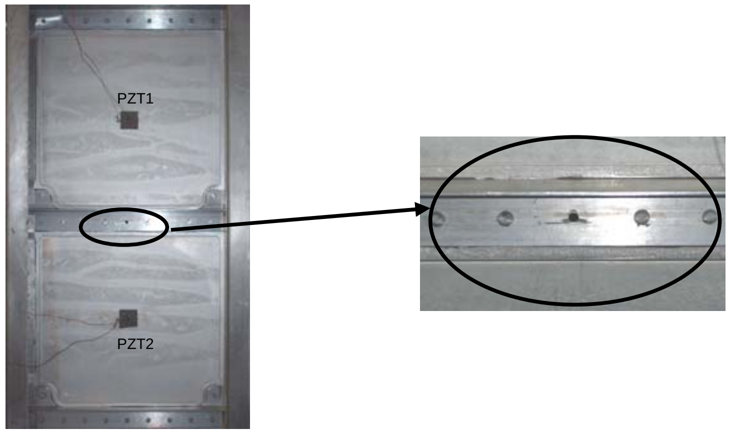


Figure 5. Damage inserted in the structure (rivet removed).

The impedance signal was acquired with the HP4194A impedance analyzer for each of the states of the structure (with and without damage). To the state without damage, three measurements were made on different days to follow the behavior of the signals on the structure without damage. Then, the collected data were processed and analyzed according to various metrics as previously described for analyzing which of them was more sensitive to incipient damage.

3. RESULTS

During the test, the copper tape used to polarize PZT2 collapsed; therefore the PZT2 results are not presented in this work, since the changes observed in the resulting impedance signal could be due to the detachment of the tape and not properly to the damage inserted in the test. It is very important to ensure that the conditions of the PZT patches do not vary during the test. Evidently, if there is any variation in the PZT patches (debonding, for example), the results can not be taken into account.

As mentioned previously for the pristine condition, three measurements were performed on different days. The frequency range used for the tests was 36.5 kHz to 41.5 kHz. Every day six measurements were taken and the average of the signals was obtained for each day as shown in Fig.6.

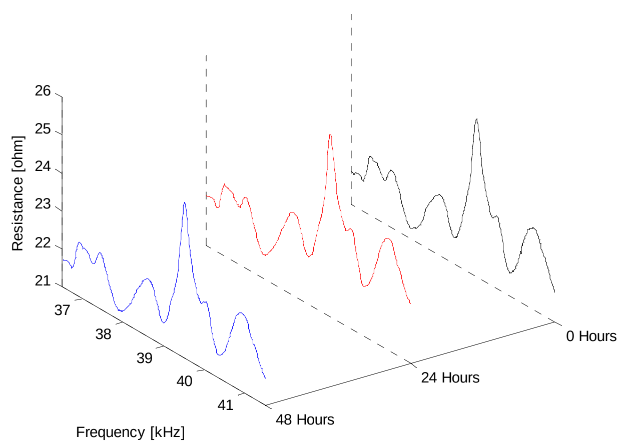


Figure 6. Impedance signals of the fuselage component measured on different days (pristine condition).

Figure 6 shows that the impedance signals had no variations in their form; however, when the damage metrics was calculated the values corresponding to each day exhibited small differences as depicted in Table 1, where the damage metrics obtained for each day are shown.

Table 1. Damage metrics average for three different days (pristine condition).

	0 HOURS	24 HOURS	48 HOURS
RMSD	0.1013	0.6012	0.4183
RMSD1	0.0897	0.5345	0.3715
RMSD2	0.0045	0.0268	0.0187
RMSD3	1.4478	9.9077	6.6089
RMSD4	0.1330	1.1322	0.7267
RMSD5	0.0213	0.0532	0.0476
CCD	0.0073	0.0375	0.0426
ASD	1.6900	4.5891	4.3252
MAPD	1.4478	9.9077	6.6089
M	5.1704	146.6882	76.1743

Figure 7 presents the impedance signals for each state of structure (baseline and structure without rivet). The variation of the signals for the two states can be observed.

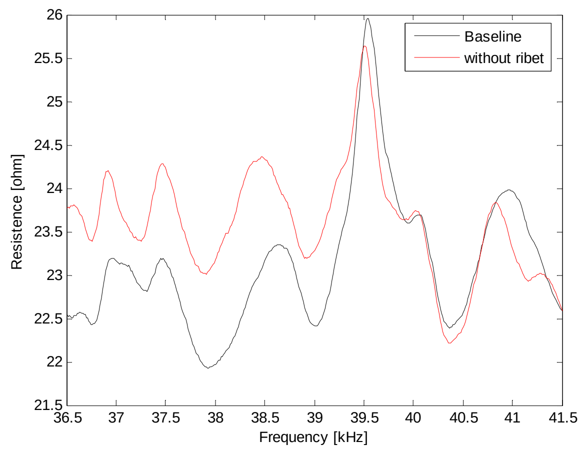
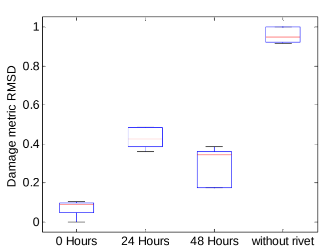
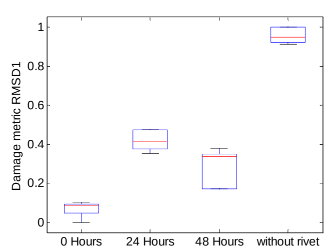


Figure 7. Impedance signals measured in the fuselage (PZT1).

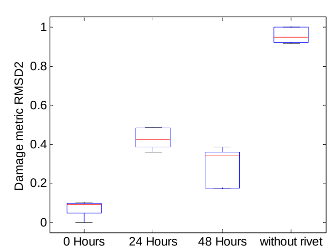
The values of the damage metrics were normalized with respect to the maximum value found. The different damage metrics are illustrated in the Fig. 8. The first three boxes in each graph represent the metrics measurements for the structure without damage and the remaining boxes show the measurements corresponding to the damaged structure as caused by the loss of a rivet. The standard deviation for each state can also be observed in the figure.



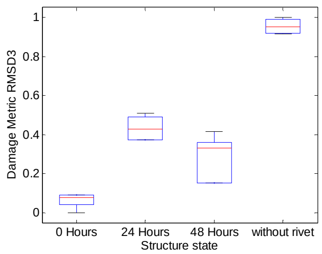
(a) Mean and standard deviation (RMSD)



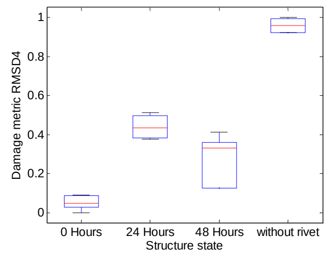
(b) Mean and standard deviation (RMSD1)



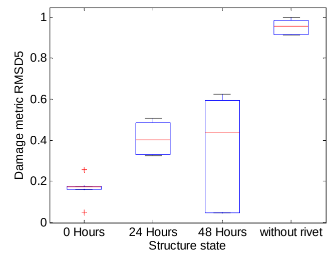
(c) Mean and standard deviation (RMSD2)



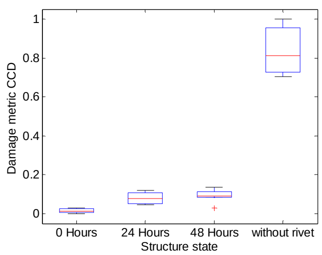
(d) Mean and standard deviation (RMSD3)



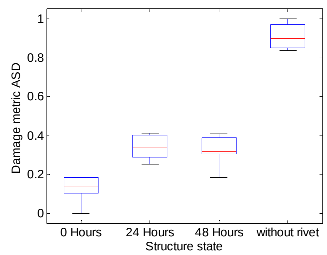
(e) Mean and standard deviation (RMSD4)



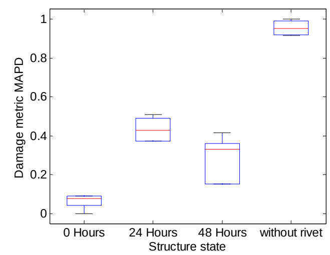
(f) Mean and standard deviation (RMSD5)



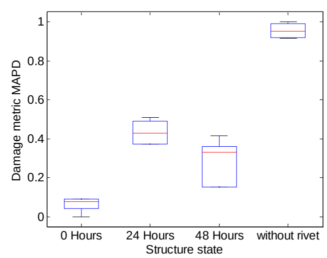
(g) Mean and standard deviation (CCD)



(h) Mean and standard deviation (ASD)



(i) Mean and standard deviation (MAPD)



(j) Mean and standard deviation (M)

Figure 8. Damage metrics comparison.

3.1. Statistical Testing

This section is dedicated to the verification, from the statistical point of view, if the average of 18 measurements without damage is or is not different from the average of six measurements made with the structure without the rivets for the three damage metrics that exhibited better performance, namely the correlation coefficient deviation, CCD – Eq. (8); the average square difference, ASD – Eq. (10); and the sum of squared difference, M – Eq. (13). Obviously, if the average values are equal, then the damage metrics calculated are not able to represent the difference between the baseline and the structure without rivet, accordingly. However, if the test of null hypothesis is rejected and the average values are different, then the damage metrics values associated with PZT1 are able to recognize the damage (structure without rivet). Thus, the hypothesis test is as follows:

H_0: *the mean values of the damage metrics for the structure without damage and with damage are equal;*
H_1: *the mean values of the damage metrics for the structure without damage and with damage are different.*

The ANOVA for the three hypothesis tests are shown in Tab.2, Tab.3, and Tab.4.

Table 2. ANOVA for the damage metric CCD for PZT1.

SOURCE	SS	DF	MS	F	P-LEVEL
Columns	2.68625	1	2.68625	567.20	0.000
Error	0.10419	22	0.00474		
Total	2.79044	23			
		R^2=96.10%			

Table 3. ANOVA for the damage metric ASD for PZT1.

SOURCE	SS	DF	MS	F	P-LEVEL
Columns	1.8845	1	1.8845	153.16	0.000
Error	0.2707	22	0.0123		
Total	2.1552	23			
		R^2=86.87			

Table 4. ANOVA for the damage metric M for PZT1.

SOURCE	SS	DF	MS	F	P-LEVEL
Columns	3.00636	1	3.00636	461.36	0.000
Error	0.14336	22	0.0652		
Total	3.14971	23			
		R^2=95.24%			

The significance level considered in the present work was 0.05 and for the three cases the value of the p-level is below this value, which rejects the null hypothesis. Therefore, the average values between the states with and without damage are different. Consequently, the technique can be possibly considered for damage detection purposes and further studies can be performed.

4. CONCLUSION

It can be observed that the signals considered for the healthy structure do not show significant variations among them since they were all obtained for the same structure, over three days. When the damage metrics was calculated, small variations were found. However, for damaged structures the variations that appear in the signals are much larger as compared to those obtained from the pristine condition. As the authors are interested on incipient damage this behavior seems to be quite interesting for real world applications.

It can be concluded that all damage metrics considered exhibited good sensitivity to the loss of a rivet. This is because the difference in the damage metric values between the states without and with damage is quite evident. The best damage metrics for the present case study were the following: a) correlation coefficient deviation (CCD), b) average square difference (ASD), c) simple sum (M). This is due to major differences obtained by these metrics when comparing the states of the structure for the cases without damage and with damage. Other tests are required for different types of structures for which all the metrics should be tested. It is worth mentioning that hypothesis tests were performed to demonstrate that the damage metrics, selected as the most sensitive ones, were able to adequately recognize the loss of rivet in the panel studied.

5. ACKNOWLEDGEMENTS

The first author is thankful to CNPQ for her MSc scholarship. Both authors are grateful to FAPEMIG and CNPq for partially funding this research work through (INCT-EIE).

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