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Non-parametric Inference Applied to Damage Detection in the Electromechanical Impedance-based Health Monitoring

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Abstract**—** *The electromechanical impedance-based structural health monitoring is a non-traditional vibration technique that compares a pristine signature to a damaged one. However, in order to compare a complete frequency response function to another, it is necessary to create a virtual index called damage metric, which indicates how far the investigated structure states from the initial condition. The most used index is the RMSD (Root Mean Square Deviation) to have a quantitative measurement of the monitored structures but CCD (Correlation Coefficient Deviation) is more robust to temperature changes. Thus, this contribution focuses on thisCCD damage metric for simulated damages (mass addition) of Al beams in a 2x5 factorial design. The first factor considered was the pristine or damage condition. The second factor was the environmental temperature of the specimen, during the signature gathering, for five levels: -10 ºC, 0 ºC, 10 ºC, 20 ºC and 30 ºC. According to the references, temperature is a very important aspect to be considered because some changes in the signature can be promoted, and for this purpose a temperature chamber was used in the study. Several statistical evaluations were performed and this contribution illustrates the median of the damage metrics are greater than the baseline ones. Also, although the temperature level creates shifts of the damage metrics, this not caused false positives, enabling the technique to differentiate the damage to the pristine conditions.*
Keywords**— *Impedance-based SHM, Non-parametric inference, False positive removal.***

I. INTRODUCTION

The maintenance function is one of the most important aspects of production management today due to the straight effects in repair costs, spare parts and production losses.Then, maintenance has replaced the corrective maintenance of critical items for predictive maintenance. In this development, new supervision mechanisms have emerged, such as SHM (Structural Health Monitoring).The electromechanical ISHM (impedance-based SHM) method is one of the most promising approaches, presenting several research contributions over the last three decades [6-7, 11, 13-17, 19].

ISHM is a methodology that allows damage detection by comparing a pristine condition, related to a baseline signature,to a new condition under investigation. This impedance signature is gathered from a PZT patch bonded on the surface of the structure under investigation and an impedance analyzer store this information. The real part of the impedance is considered for the monitoring purposes due to its relation to structural features while the imaginary part, related to the PZT patch, it is not used in this study[11, 13-14].

Impedance signatures are measured over a frequency range (domain) and structural changes in stiffness and mass due to incipient damage cause changes in shape and peaks of the function.Thus, it is necessary to create a quantitative approach for evaluating the changes that occurred in the signature throughout the monitoring process.This summary is made using damage metrics that make it possible to verify the damage hypothesis in relation to the initial condition (baseline).

However, in addition to structural changes, environmental temperature is a factor that can affect damage metric because it has an important effect on impedance signature [16-17]. Thus, this variable must be

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considered in the monitoring process in order to avoid mistakes.

There are several damage metric definitions due to the ability of some specifics to be more robust to interference such as temperature itself, even though it cannot completely eliminate its influence.In this contribution, it is used the most appropriate metric for the damage detection with temperature changes through statistical tests such as Kruskal-Wallis and Wilcoxon-Mann-Whitney [1-5, 8-10, 12, 18].

First most used metric in ISHM is the RMSD (Root Mean Square Deviation) and is described in Eq. (1)[13-14].

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

(1)where $Re(Z_{1,i})$ is the real part of the baseline impedance measurement at frequency i, $Re(Z_{2,i})$ is the real part of the impedance measurement under investigation at a frequency i, and n is the total number of frequency points.

However, the damage metric most robust and considered in this contribution is the CCD (Correlation Coefficient Deviation) described by Eq. (2) [7, 17].

$$CCD = 1 - CC \quad (2)$$

where CCD is the deviation from the correlation coefficient and CC is the correlation coefficient given by Eq. (3).

$$CC = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(Re(Z_{1,i})-Re(\bar{Z}_1)\right)\left(Re(Z_{2,i})-Re(\bar{Z}_2)\right)}{S_{Z_1}S_{Z_2}} \quad (3)$$

where S_{Z1} is the standard deviation of the baseline signature and S_{Z2} is the standard deviation of the impedance signature under investigation. Correlation coefficient 1 means 100% both signatures are fully correlated. The greater the difference between signatures, the lower the CC value. The CC value is also used to compare and quantify admittance signals [17]. On the other hand, the greater the difference between them, the greater the CCD value.

Regarding the statistical tests used, the Wilcoxon-Mann-Whitney Test is applied in the comparison of two independent groups in order to verify whether the samples provide enough evidence to support the hypothesis that both belong to the same population.It is an alternative to the t-test, a parametric test for equality of means, since it does not require any hypothesis about population distributions.

The Kruskal-Wallis test is an extremely useful test to decide if *k* independent samples ($k>2$) come from the same population. This test is applied for small samples or if assumptions required to perform the analysis of variance are seriously compromised. This test is an extension of the Wilcoxon-Mann-Whitney test, and therefore uses ranks assigned to the observed values.The test also determines that the variable under analysis is measured on a scale at least ordinal and, therefore, applies to the damage metrics determined from the electromechanical impedance.

In this study and for applied purposes, it is very important the analysis of the damage detection based on comparison of the baseline with cases under investigation. However, there is a paramount importance in the use of the values of the metrics for classification in true positive or true negative events.

The false positive classification can lead to the mobilization of teams and financial resources to repair the false damage.On the other hand,a false negative rating can lead to serious safety problems and subsequently high maintenance and compensation values.

A proposed methodology for classifying the values of the metrics is based on statistical quality control in which the threshold for the decision rule is determined by Eq. (4).

$$PZT_{threshold} = \mu_{max} + 3\sigma_{max} \quad (4)$$

where$\mu_{max}$and σ_{max} are respectively the upper limits of the confidence intervals for the mean and for the standard deviation in the baseline [17].

II. EXPERIMENTAL PROCEDURE

In this case study, two aluminum beams of 500x38x3.2 mm were used. In each one a 1 mm thick and 20 mm diameter PZT(Lead Zirconate Titanate) patch was glued to 100 mm from one end.

Five levels for environmental temperatures and two levels of damage were considered.

Baseline measurements were made without adding mass while other damage levels were caused by addition of concentrated mass at the opposite end of the sensor in the structure: B = baseline, D = 0.6g. Fig. 1 illustrates both specimen during the measurements in a bi-supported condition inside the chamber.

Fig.1: Two beams with PZT patches and mass additions.

A climate and temperature control chamber (Platinous EPL-4H series) was used to control the temperature effect. It was considered five environmental temperature levels: -10 ºC, 0 ºC, 10 ºC, 20 ºC e 30 ºC.This chamber is installed in the Structural Mechanics Laboratory (LMEst) of the School of Mechanical Engineering (FEMEC) at the Federal University of Uberlandia (UFU).

III. RESULTS AND DISCUSSION

In this contribution the Kruskal-Wallis test is justified to compare the temperature/damage levels since the assumptions of normality of residues and homogeneity of variances, necessary for the correct application of parametric tests, were not satisfied according to Table 1.

Table 1: p-values of Shapiro-Wilk and Levene Tests for CCD damage metric.

PZT Patch	*p-value*	
	Shapiro-Wilk	*Levene*
1	1.1×10^{-18}	8.5×10^{-18}
2	5.3×10^{-21}	1.2×10^{-13}

As presented in Table 1, this finding is verified through the p-values of the Shapiro-Wilk and Levene tests, which were less than 0.05 for both PZT patches. It should be noted that if only one of the assumptions is not met, the use of parametric analysis of variance is incorrect. In this case, both normality of residues and homogeneity of variances assumptions were not met. Therefore, the Kruskall-Wallis test is a good alternative. Due to the lack of a test for homogeneity of variance in experiments with more than one factor, the temperature and damage levels were arranged, thus forming a single factor composed of 10 levels.

Also, according to Table 2, the comparison of the combined levels of temperature and damage using the Kruskal-Wallis test, show that despite the temperature effect, the test is sensitive to the detection of damage regardless of which PZT patch is. In all metrics, the first five groups (levels) differ from the last five, in other words, the baselines (B) at any of the temperatures differ from conditions with damage (D) at any temperature level.

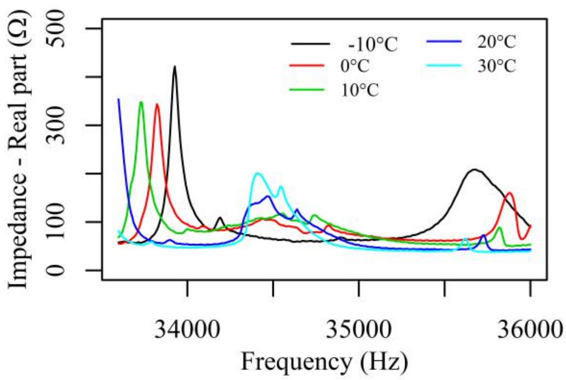
Table 2: Median and comparison of CCDs by Kruskal-Wallis test.

Temp/Damage	*PZT patch 1*	*PZT patch 2*
-10ºC - B	*0.0016 a*	*0.0009 a*
0ºC - B	*0.0016 b*	*0.0006 b*
10ºC - B	*0.0006 c*	*0.0006 c*
20ºC - B	*0.0005 d*	*0.0006 d*
30ºC - B	*0.0005 e*	*0.001 d*
-10ºC - D	*0.8492 f*	*0.8439 e*
0ºC - D	*0.8617 g*	*0.8651 e*
10ºC - D	*0.8565 h*	*0.8763 f*
20ºC - D	*0.831 hi*	*0.8873 fg*
30ºC - D	*0.818 i*	*0.8439 g*

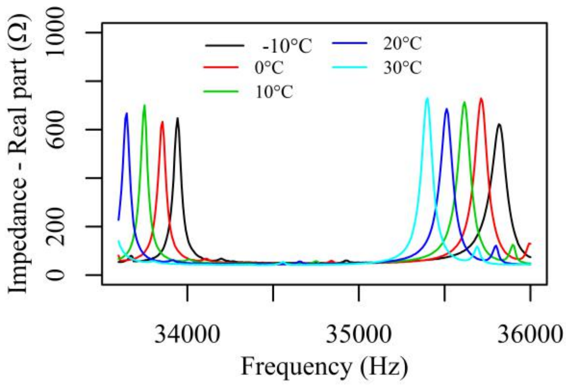
B: Baseline; D: Damage.

On the other hand, blocking the baseline (B) or the damaged (D) cases, there are differences between the temperatures, which confirms the temperature effect in the metrics.

A pattern of the temperature effect can be observed, in which all temperatures differ in groups of two in the baseline versus the damaged condition. Regarding damage at temperatures 10 and 20ºC and likewise at 20 and 30ºC, there was no significant difference (p-value> 0.05) with the other pairs being significantly different (p-value <0.05). Thus, it is observed that the temperature effect influences the impedance signature since the signals should coincide at the different temperature values and this does not occur. This fact is observed in the baselines of the PZT patch 1 (Fig.2a) as well as in PZT patch 2 (Fig.2c). The same occurs in both cases with damage for the two PZT patches (Figs.2b and 2d). As the damage is the same by changing only the temperature parameter, then the impedance values should match. This observation must be made by specific PZT patch since each sensor has its particularities and, therefore, there will be a variation from patch to patch. Consequently, it was decided to present in each plot (Fig.2), the average impedance for the 30 impedance signatures, by temperature, due to the variations between signatures or repetitions. Only part of the frequency range is shown here to visually demonstrate the temperature effect on the impedance.



a) PZT patch 1 – Baseline



b) PZT patch 1 – Damage

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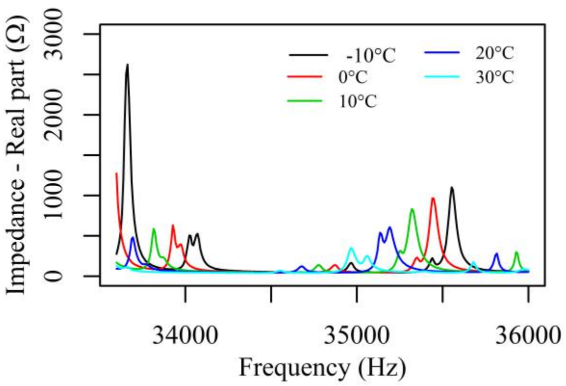
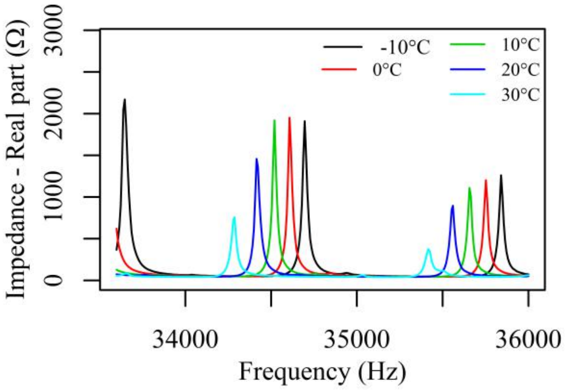


c) PZT patch 2 – Baseline

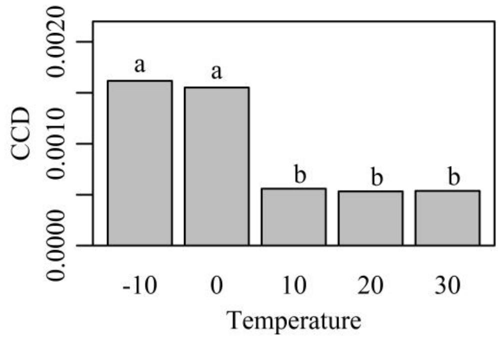


d) PZT patch 2 – Damage

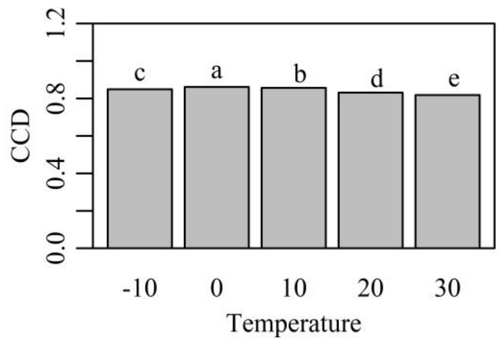
Fig.2: Avg impedance signatures vs Temperature levels

According to the method's premises, the impedance signature is expected to be significantly different in the damaged condition compared to the baseline in some frequency range. The impedance signatures obtained in the two conditions may not differ in all frequency points, but, if there is damage, the difference between their values will be noticeable in some frequency sub-range. Thus, it is not convenient to observe or directly compare the impedance values across the monitored frequency range. The large number of frequency points that are not sensitive to damage could lead to mistaken decisions about the presence or absence of damage. To consider this aspect, damage metrics are used, which aim to summarize all information of the impedance signature in a single quantitative scalar value. In general, this damage metric illustrates how different the baseline signatures are from the supposed damaged condition.

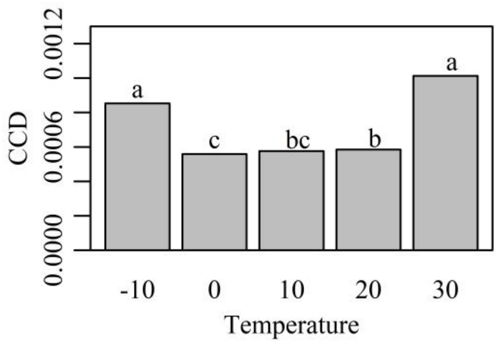
ISHM has developed several damage metrics. Some of them are addressed to minimize impacts as such as temperature effects. However, it is observed as shown in Fig.3 that the temperature effect also significantly affects the damage metric.Results of the effect of temperature on the CCD damage metric are shown in Fig.3.



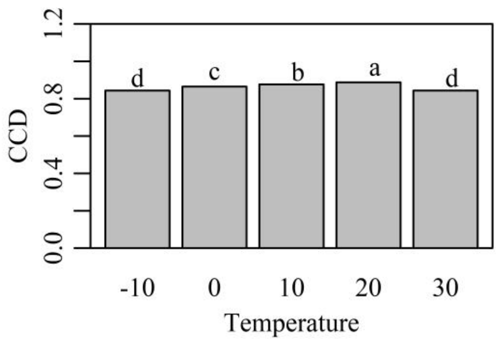
a) PZT patch 1 – Baseline



b) PZT patch 1 – Damage



c) PZT patch 2 – Baseline



d) PZT patch 2 – Baseline

Fig. 3: Comparison of temperatures by the use of Kruskal-Wallis test (both specimens, median of the CCD damage metric – baseline and damage).

In each figure, temperatures with same letter at the top of the column indicate that they do not differ significantly according to the Kruskall-Wallis test (p-value> 0.05).It is observed in Figs.3a-d that there are differences in all cases. The patterns of differences in both PZT patches are not the same in both pristine and damage cases indicating that temperature changes on the damage metric depends on the case.For the CCD damage metric of the pristine conditions in PZT patch 1, the temperatures -10ºC and 0ºC do not differ as well as the temperatures 10ºC and 20ºC, but -10ºC differs from 10ºC and 20ºC from 30ºC. In the damage condition of the same PZT patch,all temperatures differ.

Considering the possibility of a distinguished effect of temperature on the CCD damage metric for pristine and damage conditions, in each PZT patch, as observed descriptively in Fig.3, it is acceptable to compare the two states, with damage and baseline, by temperature.

Since the temperature parameter affects the impedance signature, each case was compared with a baseline under same temperature. Results of the Wilcoxon-Mann-Whitney test presented in Table 3 indicate the efficiency of this test in the damage detection for this specific experiment. For all temperature levels and PZT patches, the test was highly significant with p-values lower than 10^{-10}indicating that the damage was detected.It should be noted that the application of the Wilcoxon-Mann-Whitney test is conducted by use of thedata ranks and the median, which is the most suitable indicator to summarize the set.

The Wilcoxon-Mann-Whitney test's lack of sensitivity to extreme values is an advantage because it reduces the possibility of detecting a damage when it does not existor the non-detection of the damage in the opposite condition.These two possibilities are called false positive and false negative, respectively.

Table 3: Wilcoxon-Mann-Whitney test for damage detection at each temperature and PZT using the CCD metric.

PZT Patch	Temp. (ºC)	Condition (median)		p-value
		Baseline	Damage	
1	-10	0.00161727	0.84915706	3.016×10^{-11}
	0	0.00155151	0.86167958	1.691×10^{-17}
	10	0.00055904	0.85650092	3.016×10^{-11}
	20	0.00053254	0.83104712	1.691×10^{-17}
	30	0.00053703	0.81802007	1.691×10^{-17}
2	-10	0.00085333	0.84387215	3.018×10^{-11}
	0	0.00055869	0.86514823	1.691×10^{-17}
	10	0.0005758	0.87634048	3.018×10^{-11}
	20	0.00058458	0.88732282	1.691×10^{-17}
	30	0.00101233	0.84387215	1.691×10^{-17}

Despite the difference of effects of temperature for both conditions, damage and baseline (Fig.3), it is desirable that the methodology is able to identify the damage regardless the temperature. Tables 2 and 3 show the results of comparisons of all possible cases considering temperature and damage (D / B) in which codes D and B reference to the condition with damage and baseline, respectively. The damaged condition differs from the baseline signature in any temperature level. This fact shows that in this experiment, in spite of the temperature effect, the methodology was robust to detect the damage.

Table 4 presents the temperature-independent results for damage detection for the CCD metric. It can be remarked that, regardless of the temperature, damage condition was identified (p-values> 0.001).

Table 4. Temperature-independent Wilcoxon-Mann-Whitney test for damage detection for both PZT patches (Medians).

PZT Patch	Baseline	Damage	p-value
1	0.0006	0.8492	1.08×10^{-50}
2	0.000602	0.865148	1.08×10^{-50}

Tables 5 and 6 show the proportions of false negatives and false positives identifications for both PZT patches by the use of CCD metrics. It is considered in this experiment, a baseline for each temperature and each PZT patch.

A threshold for each specific PZT patch was determined from the baseline, considering each temperature. For a such measurement, a damage metric value below the threshold is classified as false negatives and adamage metric value above the threshold is defined as false positive.

The hypothesis of data normality for the CCD damage metric was not achieved. Bootstrap methodology is applied for building confidence intervals becauseit is more general than the parametric approach. This feature is because there is no need for normality and then can be used in this specific case study. Thus, the confidence intervals were chosen via Bootstrap technique.

Tables 5 and 6 show the existence of false positives in the CCD damage metric, since the occurrence of the damage metrics above the threshold should be zero for values obtained from the baselines. On the other hand, there are no values classified as false negatives. This number of false positives can be caused due to the existence of discrepancy points inside the damage metrics.

Table 5. Proportions of false negatives for the CCD damage metric in PZT patches 1 and 2.

PZT Patch	Thres.(B)	False Negative (D)				
		-10ºC	0ºC	10ºC	20ºC	30ºC
1	-10ºC	0	0	0	0	0
	0ºC	0	0	0	0	0
	10ºC	0	0	0	0	0

	20ºC	*0*	*0*	*0*	*0*	*0*
	30ºC	*0*	*0*	*0*	*0*	*0*
2	*-10ºC*	*0*	*0*	*0*	*0*	*0*
	0ºC	*0*	*0*	*0*	*0*	*0*
	10ºC	*0*	*0*	*0*	*0*	*0*
	20ºC	*0*	*0*	*0*	*0*	*0*
	30ºC	*0*	*0*	*0*	*0*	*0*

Table 6. Proportions of false positives for the CCD damage metric in PZT patches 1 and 2.

PZT	*Thres.(B)*	*False Positives (D)*				
		-10ºC	*0ºC*	*10ºC*	*20ºC*	*30ºC*
1	*-10ºC*	*0*	*0*	*0*	*0*	*0*
	0ºC	*0.133*	*0*	*0*	*0*	*0*
	10ºC	*0.733*	*0.6*	*0*	*0*	*0*
	20ºC	*0.8*	*0.7*	*0*	*0*	*0*
	30ºC	*0.766*	*0.7*	*0*	*0*	*0*
2	*-10ºC*	*0*	*0*	*0*	*0.066*	*0.166*
	0ºC	*0*	*0*	*0*	*0.066*	*0.166*
	10ºC	*0.066*	*0.033*	*0*	*0.066*	*0.166*
	20ºC	*0*	*0*	*0*	*0*	*0*
	30ºC	*0*	*0*	*0*	*0*	*0*

IV. CONCLUSIONS

Damage detection using non-parametric tests as Kruskal-Wallis and Wilcoxon-Mann-Whitney is a suitable approach for damage detection in SHM methods since they do not need to satisfy statistical assumptions compared to parametric techniques. In this contribution, both tests were efficient for detecting damage but it is important to remark that each experiment and case study can have different impedance signature patterns.

Nonparametric tests were also effective for detecting damage even in temperature-dependent conditions as the electromechanical impedance-based SHM.

Nonparametric tests were also more efficient in damage detection in relation to the threshold technique since there were no false positive problems.

However, the temperature effect can induce false positives, detecting damages in absence of them. Based on this finding it suggests new studies considering a smaller difference between the temperature levels in order to investigate false positives. If such false positives do not happen at smaller temperatures, any measured condition along the monitoring can be compared to the baseline signature.

Other damage severities are also a suggestion for future contributions since this parameter is temperature-dependent. The hypothesis of interest in this case would be to investigate the boundaries which temperature would interfere in the damage detection.

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