

UNIVERSIDADE FEDERAL DE UBERLÂNDIA
FACULDADE DE ENGENHARIA AERONÁUTICA

VICTOR HUGO ALVES BORGES

**Damage Detection Using the Impedance-based SHM Approach Under
Dynamic and Static Loads**

UBERLÂNDIA

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Abstract

The Structural Health Monitoring (SHM) methods are used to inspect and detect structural damage. And one of the methods that is showing promising results is the Structural Health Monitoring based on Electromechanical Impedance (Impedance-based Structural Health Monitoring - ISHM). This tool stands out as a versatile technique, which can be easily applied in complex structures due to the portability of instruments, ease and agility in data processing, generating real-time information about the structure. This method is based on the principle of Electromechanical Impedance (EMI), which uses the interaction between the mechanical and electrical properties of a piezoelectric transducer, coupled or incorporated in a structure, to measure impedance signatures. With these signatures, it is possible to qualitatively evaluate the presence of the damage. And to quantify changes in impedance signatures, it is used mathematical functions called damage metrics. Despite the advantages of the impedance method, this technique still has some disadvantages, such as influence on temperature variation, static and dynamic loads, causing false positives in the damage detection. This article focuses on the application of the Impedance based SHM method, performing two experiments on structures under external vibrations, static loads and temperature variations to analyze their influence on impedance signatures. For this, an aluminum beam was made with a piezoelectric transducer bonded on its surface. In addition, to evaluate the damage detection of the technique under various boundary conditions, a damage was simulated in the structure, which nut and bolt were removed from the beam.

Key Words: Non-destructive evaluation, Structural Health Monitoring, Electromechanical impedance method, Damage detection, External vibrations, Structural Strain

Resumo

Os métodos de monitoramento de integridade estrutural (Structural Health Monitoring - SHM) são utilizados para inspecionar e detectar danos em estruturas.. E um dos métodos que está mostrando resultados promissores é o de monitoramento de integridade estrutural baseado em Impedância eletromecânica (Impedance-based Structural Health Monitoring - ISHM). Esta ferramenta destaca-se como uma técnica versátil, que pode ser facilmente aplicada em estruturas complexas devido à portabilidade dos instrumentos, facilidade e agilidade no processamento de dados, gerando informações em tempo real sobre a estrutura. Este método baseia-se no princípio da impedância eletromecânica (EMI), que utiliza a interação entre as propriedades mecânicas e elétricas de um transdutor piezoelétrico acoplado ou incorporado em uma estrutura para medir as assinaturas de impedância. Com essas assinaturas, é possível avaliar qualitativamente a presença do dano. E para quantificar as mudanças nas assinaturas de impedância, são utilizadas funções matemáticas chamada métricas de danos. Apesar das vantagens do método de impedância, esta técnica ainda apresenta algumas desvantagens, como influência nas medições da variação de temperatura, de cargas estáticas e dinâmicas, provocando falsos positivos na detecção de dano. Com isso, este artigo se concentra na aplicação do método SHM baseado em Impedância, realizando dois experimentos em estruturas sob vibrações externas, cargas estáticas e variações de temperatura para analisar sua influência nas assinaturas de impedância. Para isso, foi feito uma viga de alumínio com um transdutor piezoelétrico. Além disso, para avaliar a detecção de danos da técnica sob várias condições de contorno, foi simulado um dano na estrutura , no caso, foi removido a porca e o parafuso da viga.

Palavras-chave: avaliação não-destrutiva; monitoramento de integridade estrutural; método de impedância eletromecânica; detecção de danos; vibrações externas; tensão mecânica.

SUMMARY

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1. INTRODUCTION

Nondestructive testing is extremely important, can prevent machines from stop working or collapsing, leading to a production line interruption and economic losses. There are many nondestructive techniques available today, such as ultrasonic, liquid penetrant, visual inspection, remote visual inspection and many others. Impedance-Based Structural Health Monitoring (ISHM) is a nondestructive technique based on the use of piezoelectric transducers to detect changes in a structure. This structure is analyzed prior to any condition change, in order to obtain a baseline Frequency Response Function (FRF) of the PZT (lead zirconate titanate) patch impedance. The obtained baseline is compared to an analysis after a condition change. Using mathematical manipulations to filter bad collected data and the application of certain compensations, the denominated damage metrics can give us an evaluation of the current state of the structure, being able to identify and quantify damages. Damage is defined as changes introduced to the system, including changes in the boundary conditions.

The ISHM has many advantages, such as the implementation in real-time health monitoring, easy application on complex structures and better accessibility due to its small-sized sensors-actuators. However, previous studies (Palomino et al., 2012) has shown that the impedance cannot be significantly influenced by magnetic fields and ionic environment (if the sensor is properly shielded), while the temperature has a significant change in the impedance signature. Another study (Stancalie et al., 2015) shows that when an additional mass is hanged in a beam (thus generating strain), the electromechanical signature of this beam changes. The temperature influence can be corrected using compensations.

Therefore, in order to make the ISHM analysis more versatile and enabling the use of EMI method on structures subjected to vibrations and loads variations, this study aims to quantify and analyses the influence of mechanical vibrations during the impedance measurement of a system, studying if the monitoring can occur even on a system under these circumstances.

An earlier study showed that when the system is under low-frequency excitation, the variation of real impedance is not significant (Bastani, Amindavar, Shamshirzaz, & Sepehry, 2012). Another significant study has shown that the effect of external excitation the admittance, consequently the impedance, cannot be neglected if the vibration frequency and the piezoelectric (a PZT was used) actuation frequency are comparable (Yang & Miao, 2008). It is also known that a system is susceptible to the contamination of ambient vibrational noise, which happens to be in

the low frequency range, typically less than 100 Hz (Bhalla & Soh, 2004). An increase in tensile load can generate a progressive rightward shift of the peaks (Lim & Soh, 2012).

This work has as main objective to verify the existence of the relation between the vibration and the electromechanical impedance and, if so, to quantify and study a compensation for this relation.

There are several factors that raise interest in the prognosis of failure and the monitoring of structural integrity, especially in applications related to aerospace systems. Among these factors are the safety responsibility and the economic expenditure. If an efficient monitoring system is in constant operation on all aircraft, the persons responsible for its maintenance could take the necessary steps to minimize the number of failures and provide a substantial saving in aircraft maintenance.

Thus, with the efforts of researchers in both academia and industry, several techniques of Structural Integrity Monitoring are being developed. Each has advantages and disadvantages, which results in the inexistence of a technique that is applicable to all existing monitoring conditions.

This way, the choice of this theme is justified by the technological importance of improving the level of maturation of ISHM techniques considering basic factors regarding pre-evaluation and Validation of EMI signatures in order to guarantee the correlation with the structure being monitored.

The present work is structured in 4 chapters, besides the introduction and final considerations. In the Introduction, an initial approach of the problem was made, also showing the objectives of the work and the justification of the choice of the theme. The first chapter presents the concept of electromechanical impedance method. In the second chapter presents the determination of the statistical limits as well as the temperature compensation with optimization procedure. The third chapter presents the process of vibration, the experimental configurations and the discussion of the results found. Finally, the fourth chapter presents the experimental results together with a discussion of the results. Conclusion about the work is made in the final considerations.

2. ELECTROMECHANICAL IMPEDANCE METHOD

The Impedance-Based SHM is based on the coupled electromechanical behavior. Piezoelectric materials are capable of converting electrical energy into mechanical energy, this is known as direct effect. Under mechanical deformation, those materials are capable of generating electrical energy, which is known as the reverse effect. Therefore, piezoelectric materials can be used as actuator and as a sensor simultaneously, this way the complexity and associated cost of this method is significantly reduced.

As the piezoelectric material patch is bonded or embed to the structure, when a low voltage is applied, usually 1V (Raju, 1997), at high frequency, the vibration of the patch will induce the system to vibrate as well. The dynamic response of the system will be transmitted back to the patch, which act like a sensor, sending electric signals to the data acquisition system. Theoretically, the electromechanical impedance method was first proposed developed by Liang et al. (Liang, Sun , & Rogers, 1994) and it is continuously developed by many others until nowadays.

The electromechanical model that quantifies and describes the measurement process is illustrated in Figure 1 for a single degree of freedom system (mass m , stiffness k , and damping c ; V and I are the voltage and current, respectively) (Steffen Jr, Cavalini Jr, & Finzi Neto, 2014).

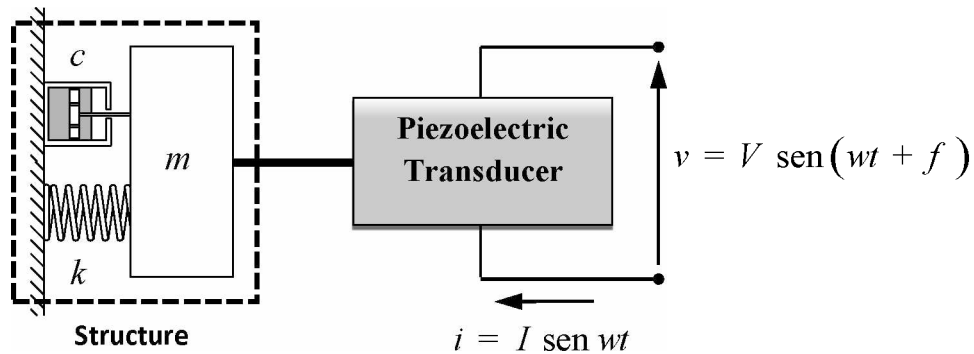


Figure 1 - Electromechanical model that describes the process of measuring the impedance signature. Source: (Steffen Jr, Cavalini Jr, Finzi Neto, 2014)

For this one-dimensional system, the admittance $Y_a(\omega)$, the inverse of the impedance, can be written as a function of the combined PZT actuator and structure mechanical impedance, as shown in Equation (1):

$$Y_a(\omega) = I(\omega)\omega a \left\{ \varepsilon_{33}^T [1 - I(\omega)\delta] - \frac{Z_{ma}(\omega)}{Z_{ma}(\omega) - Z_{me}(\omega)} d_{3x}^2 \hat{Y}_{xx}^E \right\} \quad (1)$$

where $\hat{Y}_{xx}^E$ is the complex Young's modulus of the PZT patch with zero electric field, d_{3x} is the piezoelectric coupling constant in arbitrary x direction at zero electric field, ε_{33}^T is the dielectric constant at zero stress, δ is the dielectric loss tangent to the PZT patch, a is a geometric constant of the PZT patch, and is ω the frequency. Assuming that the mechanical properties of the PZT patch are constant through the monitored time, equation (1) **Error! Reference source not found.** shows that the electrical impedance of the PZT patch is directly related to the structure's impedance.

This model neglects the physical influence of the bonding between the PZT patch and the host structure. Xu and Liu (Xu & Liu, 2002) proposed a two degrees-of-freedom system to better describe this case. With the decrease in bonding quality, a PZT-driven system would show increase in resonant frequencies (Xu & Liu, 2002).

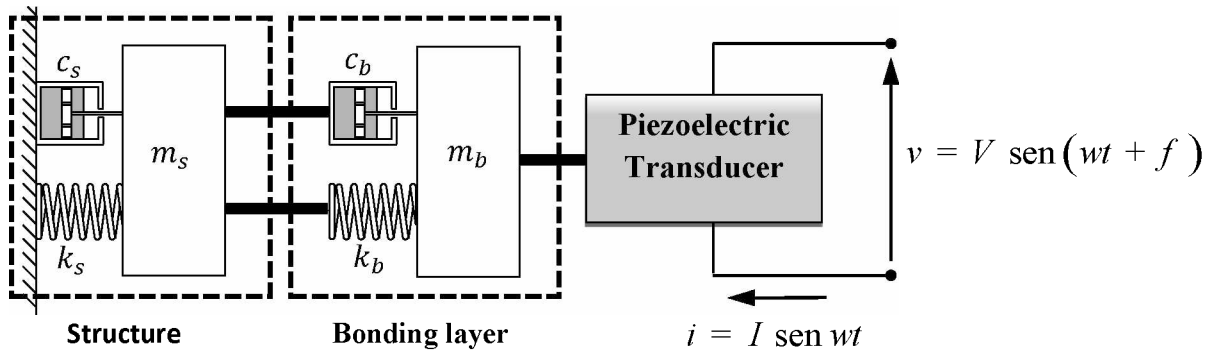


Figure 2 - One-dimensional electromechanical model considering the bonding layer.

The EMI method is used in high frequency excitation process (30-1000 kHz) (Lim & Soh, 2016). The analyzed frequency range is chosen by trial-and-error, where the areas with the most peaks (20 to 30 peaks) are the best ones to be chosen, it has a more accurate sensitivity to incipient damage due to the good level of details along the frequency range (Moura Jr & Steffen Jr, 2004). 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 F. P., Chaudhry, Liang, & Rogers, 1995).

The technique is based on the detection of damages comparing the impedance readings before (using a baseline) and after an event. In order to quantify the structural changes (damages), a methodology of damage metrics should be defined.

The most used statistical measurement in EMI based SHM is the root mean square deviation (RMSD), which is defined by equation **Error! Reference source not found.**. This metric is not qualitatively affected when applied in impedance signatures obtained from different PZT patches (different amplitude levels).

$$RMSD = \left\{ \sum_{i=1}^n \frac{[\text{Re}(Z_{1,i}) - \text{Re}(Z_{2,i})]^2}{\text{Re}(Z_{1,i})^2} \right\}^{1/2} \quad (2)$$

where $\text{Re}(Z_{1,i})$ is the real part of the impedance signature of the PZT measured at baseline condition (reference), $\text{Re}(Z_{2,i})$ is the real part of the impedance for comparison at the frequency interval i , and n is the number of points of the impedance signal representing the frequency vector ($i = 1, 2, \dots, n$).

The deviation of the correlation coefficient (CCD) is used to measure and interpret the information found in both data sets considered. The mathematical formulation of this metric is given by the difference between the first scale and the correlation coefficient CC of the signatures obtained from any measurement and its reference (Giurgiutiu & Zagari, 2005). The greater the correlation coefficient, CC, the smaller will be the deviation CCD and smaller are the changes caused by the damage in the system

$$CCD = 1 - CC = -\frac{1}{n} \sum_{i=1}^n \frac{[\text{Re}(Z_{1,i}) - \text{Re}(\bar{Z}_{1,i})][\text{Re}(Z_{2,i}) - \text{Re}(\bar{Z}_{2,i})]}{S_{Z1}S_{Z2}} \quad (3)$$

where $Z_{1,i}$ is the impedance signature of the PZT of the baseline condition and $Z_{2,i}$ is the impedance signature for comparison at the frequency interval i . The symbols $\bar{Z}_{1,i}$ and $\bar{Z}_{2,i}$ represent mean values, while S_{Z1} and S_{Z2} represent standard deviations (Steffen Jr, Cavalini Jr, & Finzi Neto, 2014).

Among all these damage metrics, in this study the RMSD was used due to its good sensitivity (Palomino, 2008).

3. STATISTICAL THRESHOLD DETERMINATION

A reliable SHM system should be able to provide diagnosis with a pre-configured level of confidence based on the pristine conditions of the host structure (Rabelo et al., 2015).

A meaningful procedure for estimating parameters of random variables involves the estimation of an interval, as opposed to a single point value, which will include the parameter being estimated with a known degree of uncertainty. A confidence interval can be established for the mean value μ_x and variance σ_x^2 based on the sample mean $\bar{x}$ and standard deviation, for a sample of size N , according to equation (3) and (4) (Rabelo, Steffen Jr, Finzi Neto, Lacerda, 2016):

$$\left[\bar{x} - \frac{st_{v;\alpha/2}}{\sqrt{N}} \leq \mu_x < \bar{x} + \frac{st_{v;\alpha/2}}{\sqrt{N}} \right], v = N - 1 \quad (3)$$

$$\left[\frac{vs^2}{X_{v;\alpha/2}^2} \leq \sigma_x^2 < \frac{vs^2}{X_{v;1-\alpha/2}^2} \right], v = N - 1 \quad (4)$$

where s^2 is the sample variance, $t_{v;\alpha/2}$ is a student t variable of v DOF, and $X_{v;\alpha/2}^2$ is a chi-square variable with v DOF.

Therefore, those intervals were obtained, and the threshold was determined according to equation (5):

$$PZT_{threshold} = \mu_{x_{max}} + 3\sigma_{x_{max}} \quad (5)$$

where $\mu_{x_{max}}$ is the upper limit for the population mean and $\sigma_{x_{max}}$ is the upper limit for the population standard deviation, both obtained choosing a significance level $\alpha = 95\%$ applied to equations (3) and (4). It should be noted that the choice of the decision threshold influences both the detectable size and the probability of a false positive (Rabelo, Steffen Jr, Finzi Neto, & Lacerda, 2016).

This assumption is was made due to the normal distribution of the PZT samples, which was tested in this research using the Lilliefors (Lilliefors, 1969) test for normal distribution at a significance level of 0.5%.

As previously noted, the impedance signatures are subject to temperature influence. The temperature is known to cause a vertical and horizontal shift in the impedance signature (Bastani, Amindavar, Shamshirzaz, & Sepehry, 2012). As the climate chamber have an uncertainty of 1°C, it was used a derivative-free (Hybrid Optimization Algorithm (Rabelo et al., 2015)) based compensation technique on the impedance signature to compensate the temperature.

4. EXPERIMENTAL RESULTS

4.1 First Experiment

In the first experiment, a $0.3 \times 0.038 \times 0.003$ m aluminum beam (Aluminum Alloy 2024) was instrumented with one piezoelectric transducer and one accelerometer. The size of the PZT patch is $0.03 \text{ } \varnothing \times 0.002$ m. The sensitivity of the used accelerometer (352C22) was 1.070 mV/m/s^2 . Both the PZT patch and the accelerometer were bonded on the surface of the beam as shown in the

Figure 4Error! Reference source not found..

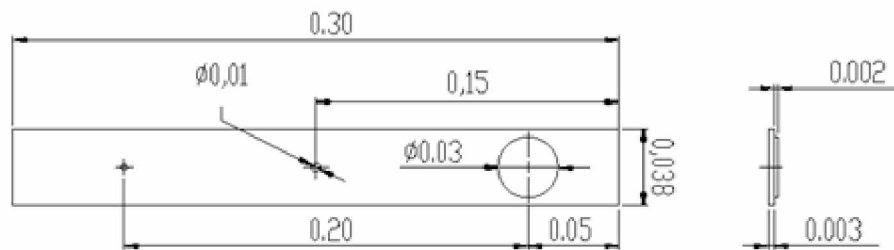


Figure 3 – Beam dimensions

The beam was placed inside a thermal chamber, supported by a Mini SmartShaker™ (K2007E01). The PZT was plugged in a portable electromechanical receiver. The join of the shaker and the beam is on the exact half of the beam, and as it is not the center of mass of the beam, it will be allowed to have the second vibration mode of the structure. For the damage condition, a bolt and a nut was screwed in a hole 200 mm away from the center of the PZT patch, the damage introduced was by removing this bolt and nut. The weight of this introduced bolt and nut is 1.21g, the weight of the analyzed beam is 117.56g. Details are presented in Figure 4.



(a)



(b)



(c)

Figure 4: (a) Environmental test chamber; (b) portable impedance meter device (SySHM impedance meter); (c) experiment setup.

It was acquired 15 impedance signatures samples of each state at each temperature. For each sample, 10000 points were acquired, with 6400 mean numbers, from 30kHz to 200kHz. When changing the temperature, an one hour gap wait was respected between the experiments for the temperature equilibrium of the system.

A random white noise signal, of 400 mV and 800 mV, was generated by the signal generator and sent to the Mini SmartShaker™. The range of the generated signal was 10Hz to 51.21kHz, which is the maximum supported by the signal generator. It was acquired 250 averages of the accelerometer response signal, which had the same range as the signal generator of the dynamic signal analyzer. Table 1 details the experiment.

Table 1- Detailed Vibration analysis Experiment

<i>Run</i>	<i>Voltage (Random Noise Signal)</i>	<i>Temperature</i>	<i>Damage</i>
1	None	10°C	None
2	400 mV	10°C	None
3	800 mV	10°C	None
4	None	10°C	<i>Removed screw</i>
5	400 mV	10°C	<i>Removed screw</i>
6	800 mV	10°C	<i>Removed screw</i>
7	None	25°C	None
8	400 mV	25°C	None
9	800 mV	25°C	None
10	None	25°C	<i>Removed screw</i>
11	400 mV	25°C	<i>Removed screw</i>
12	800 mV	25°C	<i>Removed screw</i>
13	None	35°C	None
14	400 mV	35°C	None
15	800 mV	35°C	None
16	None	35°C	<i>Removed screw</i>
17	400 mV	35°C	<i>Removed screw</i>
18	800 mV	35°C	<i>Removed screw</i>

Figure 5 shows the impedance signatures measured in the system considering different conditions.

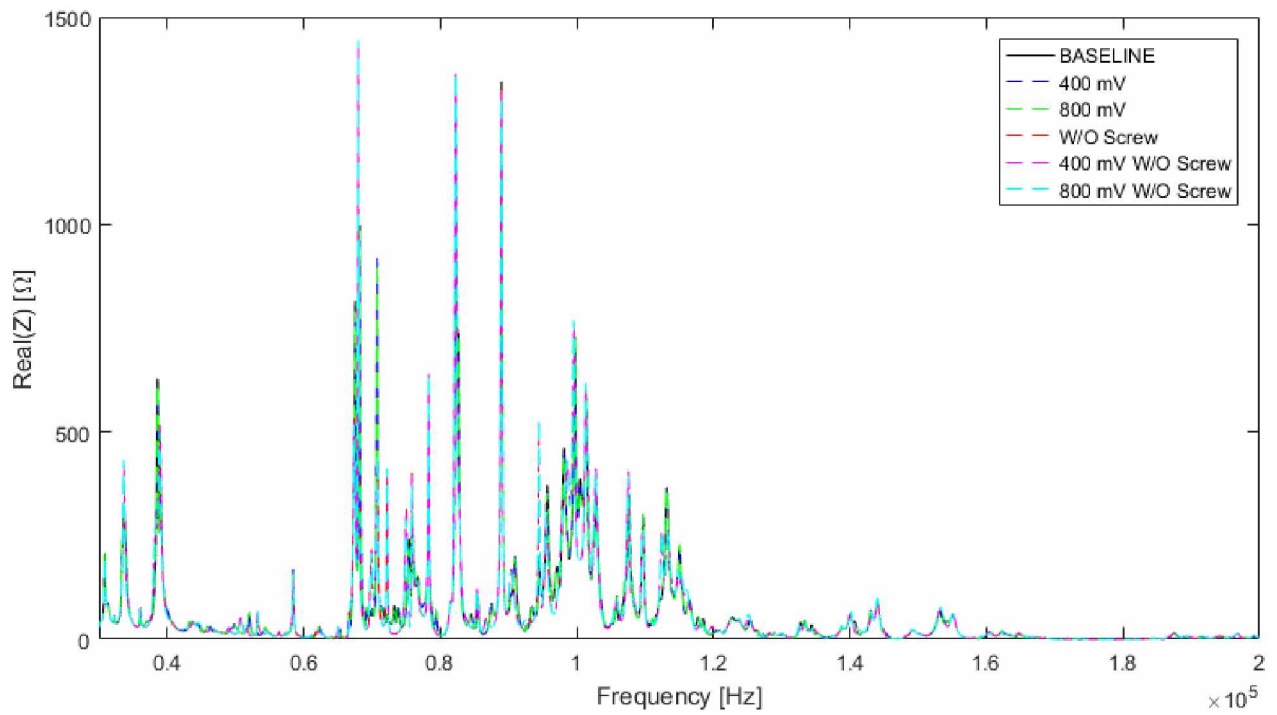


Figure 5 - Complete impedance signatures measured at 10° C (35-200) kHz

It is noticeable that after the 125kHz and before the 65kHz frequency, the impedance signature is not well defined. Thus, it is only analyzed the range from 65kHz to 125kHz.

The damage metric obtained with and without the temperature compensation, along with their respective impedance signatures are presented in the following figures.

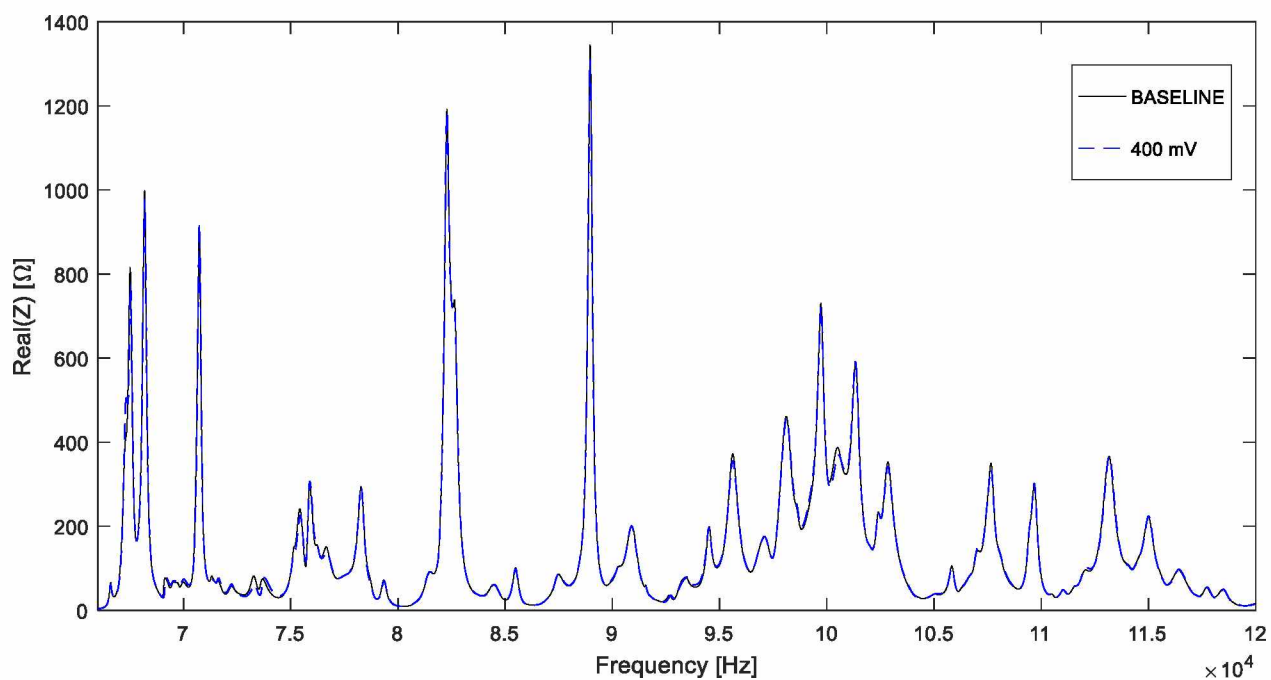


Figure 6 - Impedance signatures of Baseline and 400 mV conditions measured at 10° C (65-120) kHz.

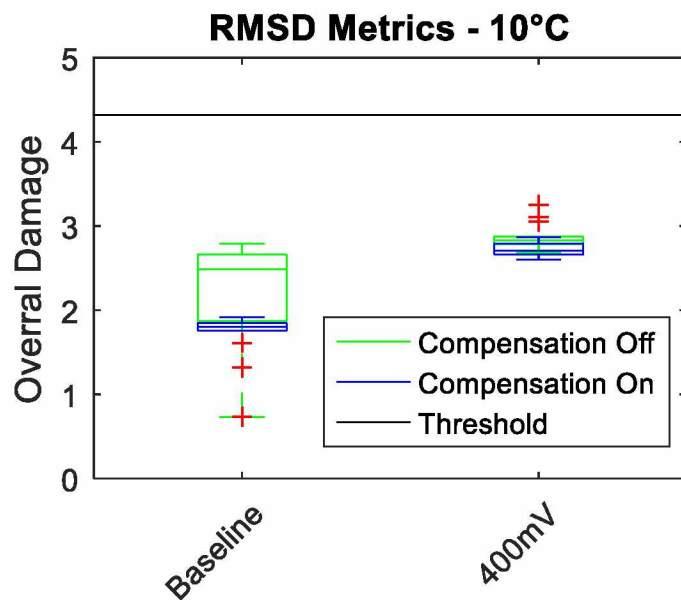


Figure 7 - RMSD of Baseline and 400 mV conditions measured at 10°.

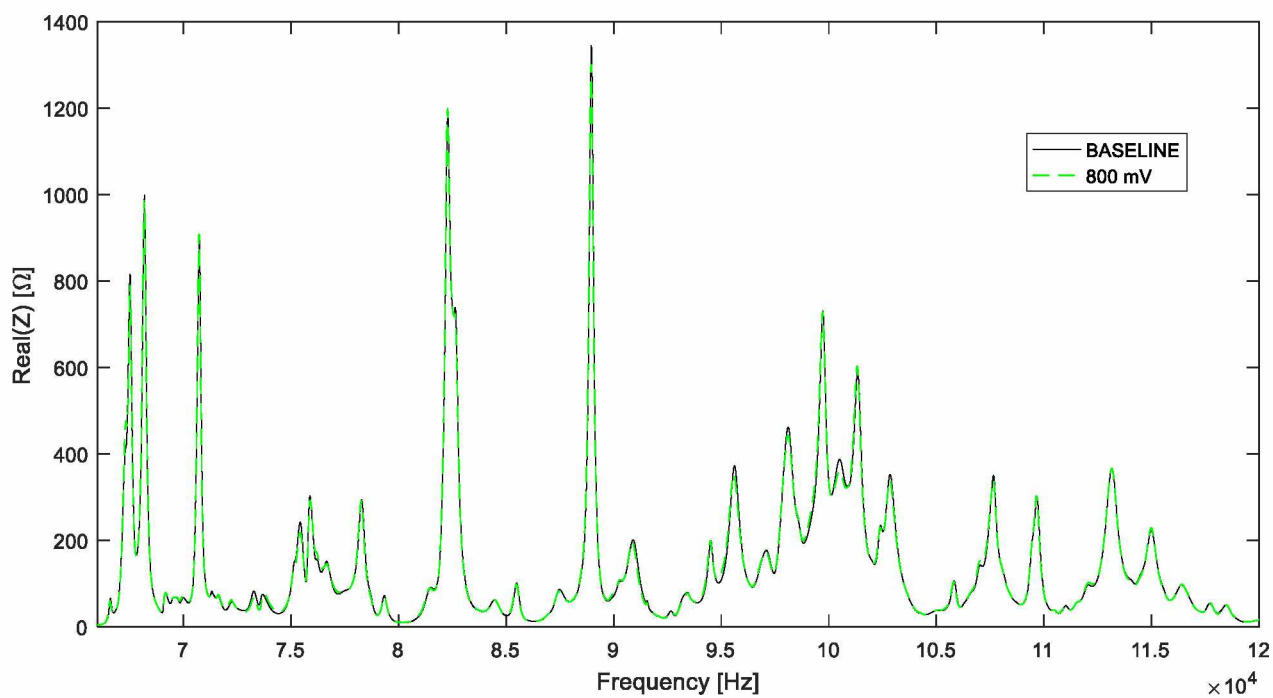


Figure 8 - Impedance signatures of Baseline and 800 mV conditions measured at 10° C (65-120) kHz.

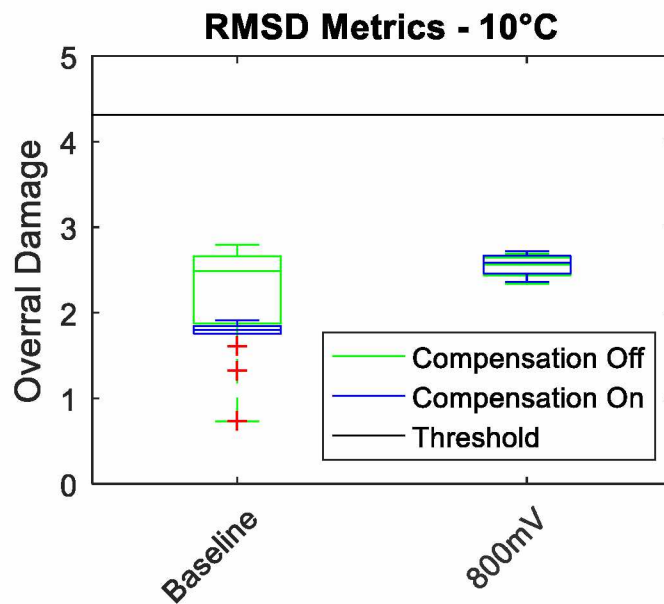


Figure 9 - RMSD of Baseline and 800 mV conditions measured at 10°.

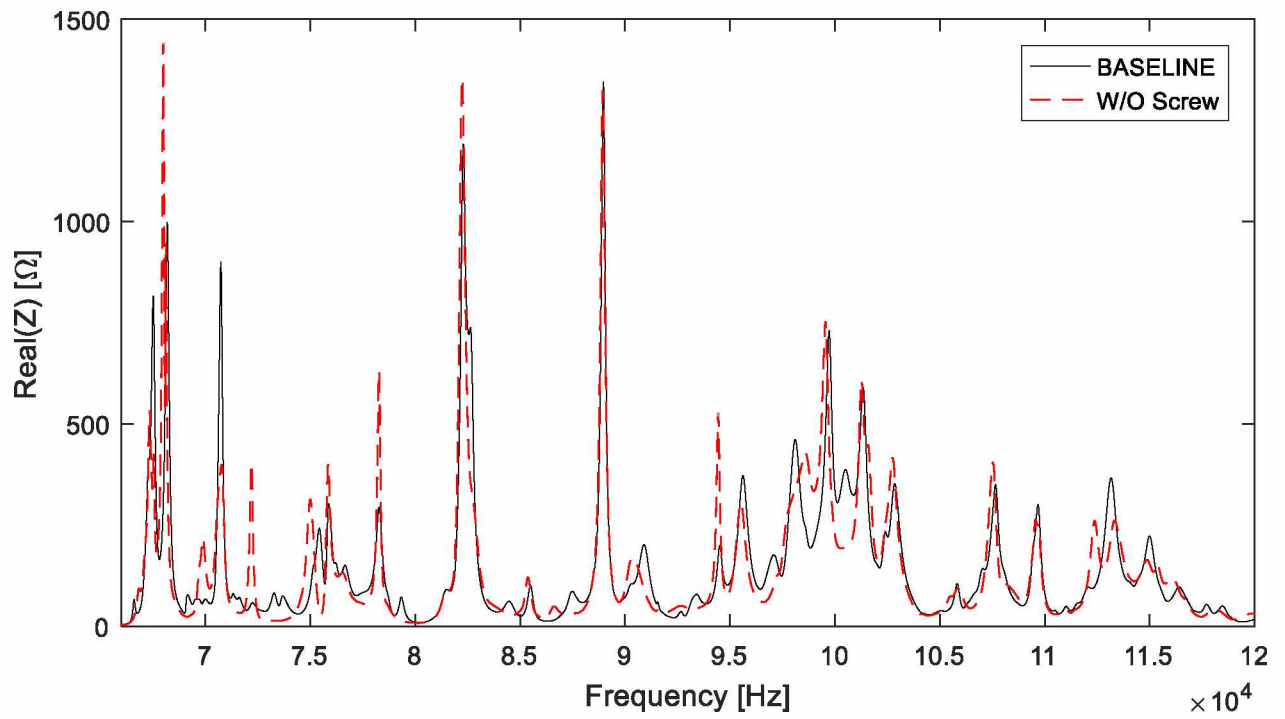


Figure 10 - Impedance signatures of Baseline and W/O Screw conditions measured at 10° C (65-120) kHz.

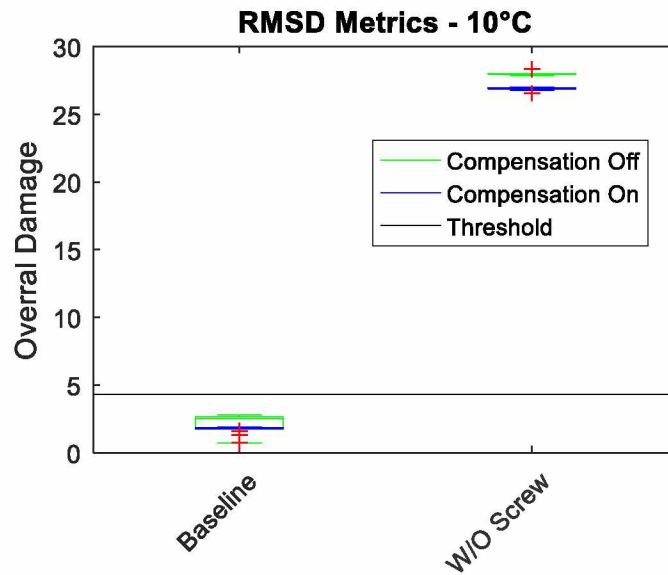


Figure 11 - RMSD of Baseline and W/O Screw conditions measured at 10°.

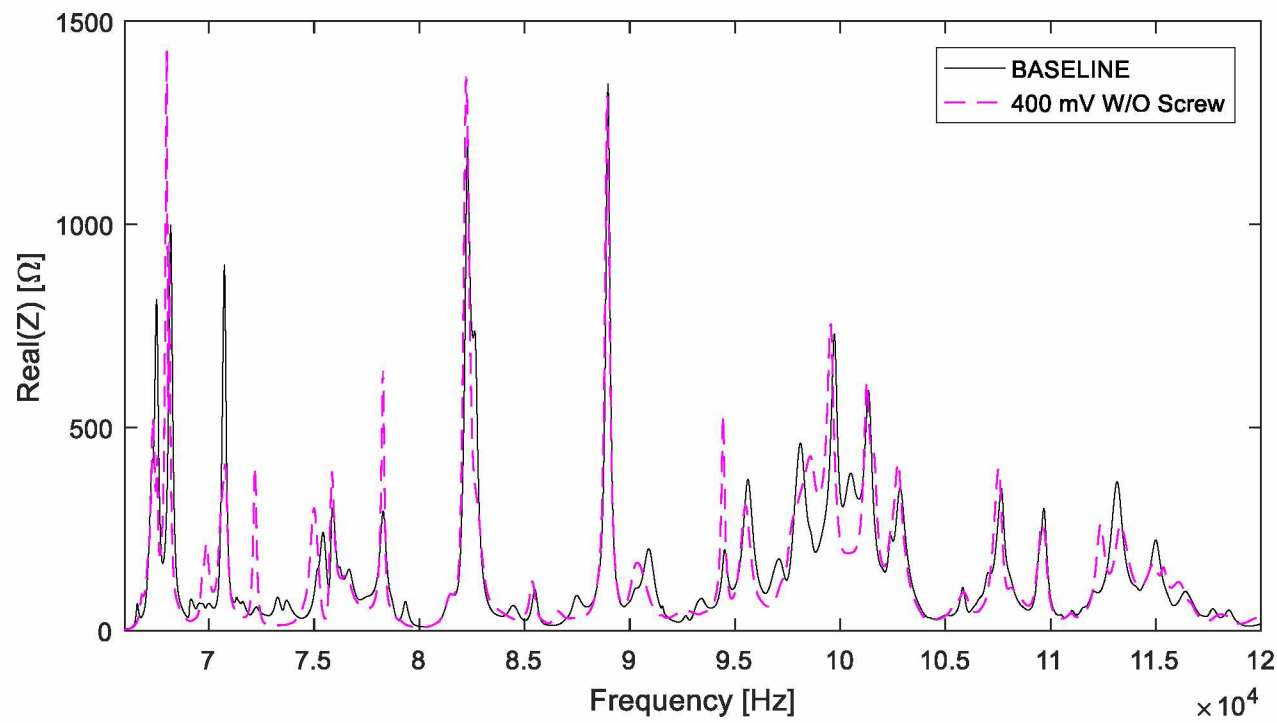


Figure 12 - Impedance signatures of Baseline and 400 mV W/O Screw conditions measured at 10° C (65-120) kHz.

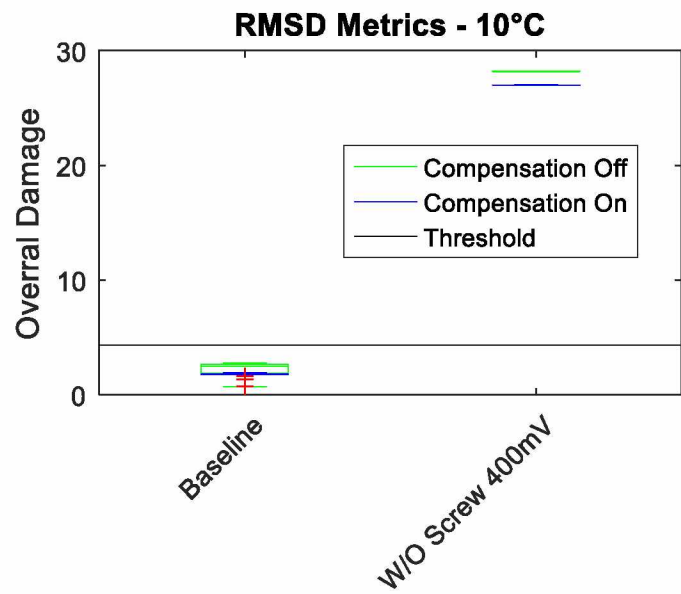


Figure 13 - RMSD of Baseline and 400mV W/O Screw conditions measured at 10°.

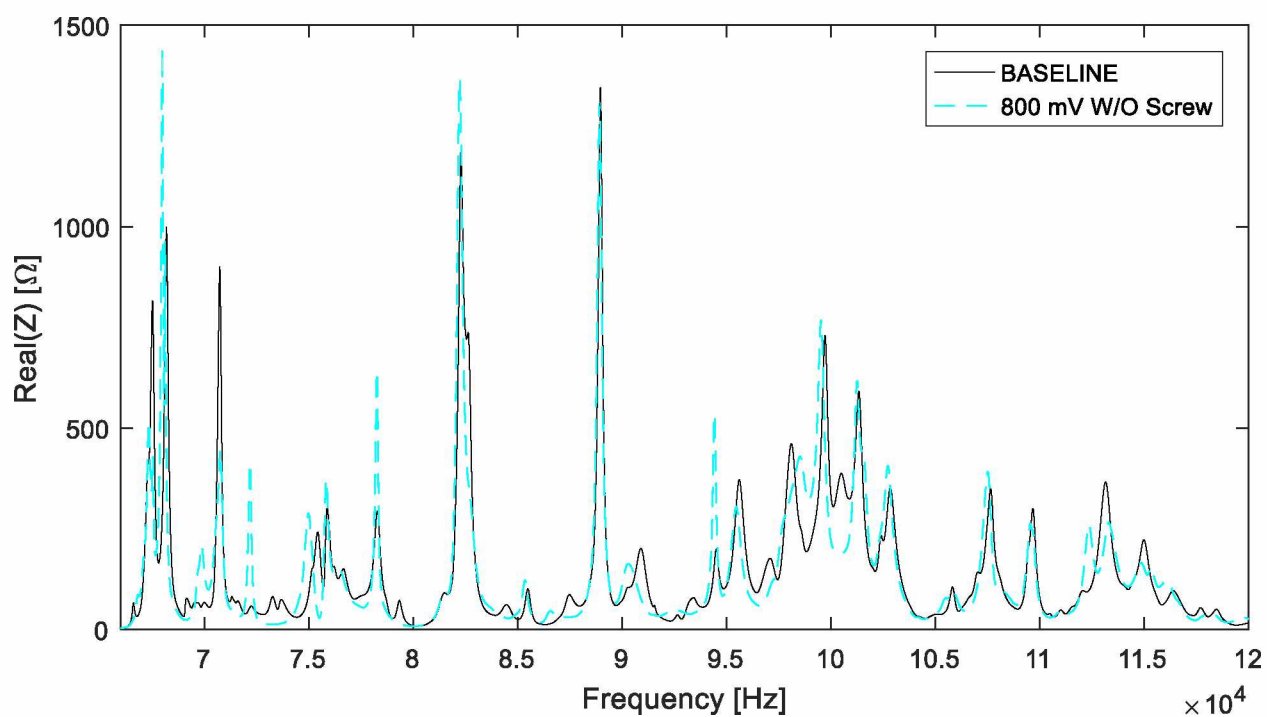


Figure 14 - Impedance signatures of Baseline and 800 mV W/O Screw conditions measured at 10° C (65-120) kHz.

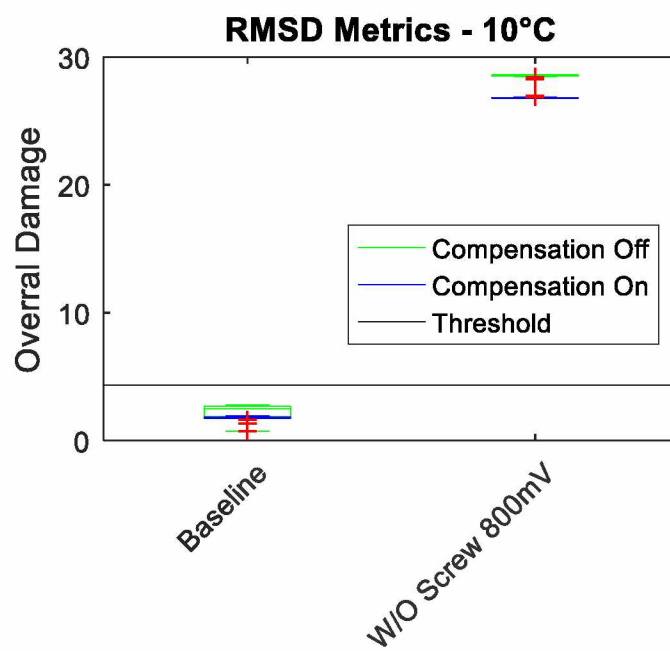


Figure 15 - RMSD of Baseline and 800mV W/O Screw conditions measured at 10°C.

The impedance signatures and the RMSD Metrics for the 25° C and 35° C conditions showed similar behaviour, as presented in the Figure 16 and Figure 17.

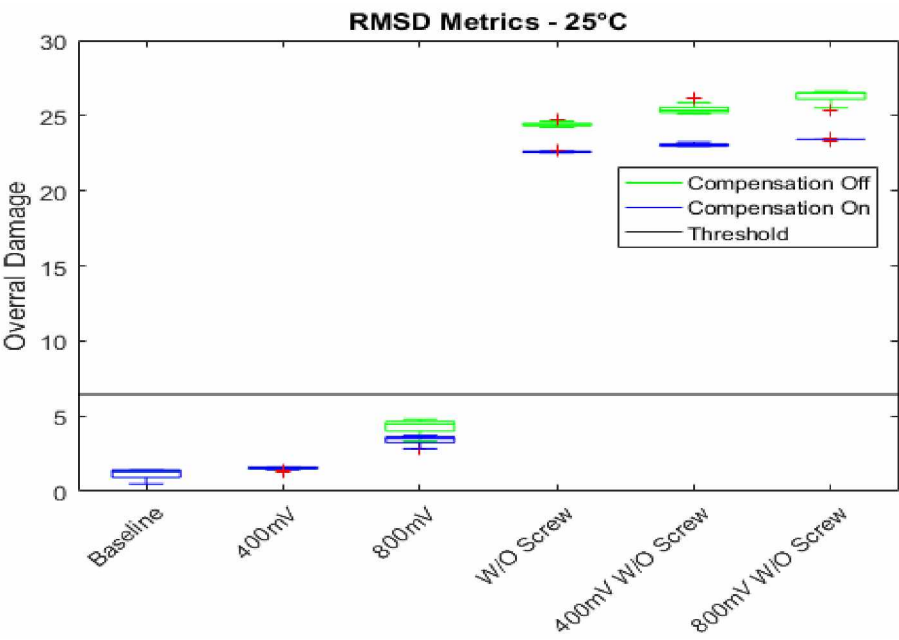


Figure 16 - RMSD metrics obtained at 25° C

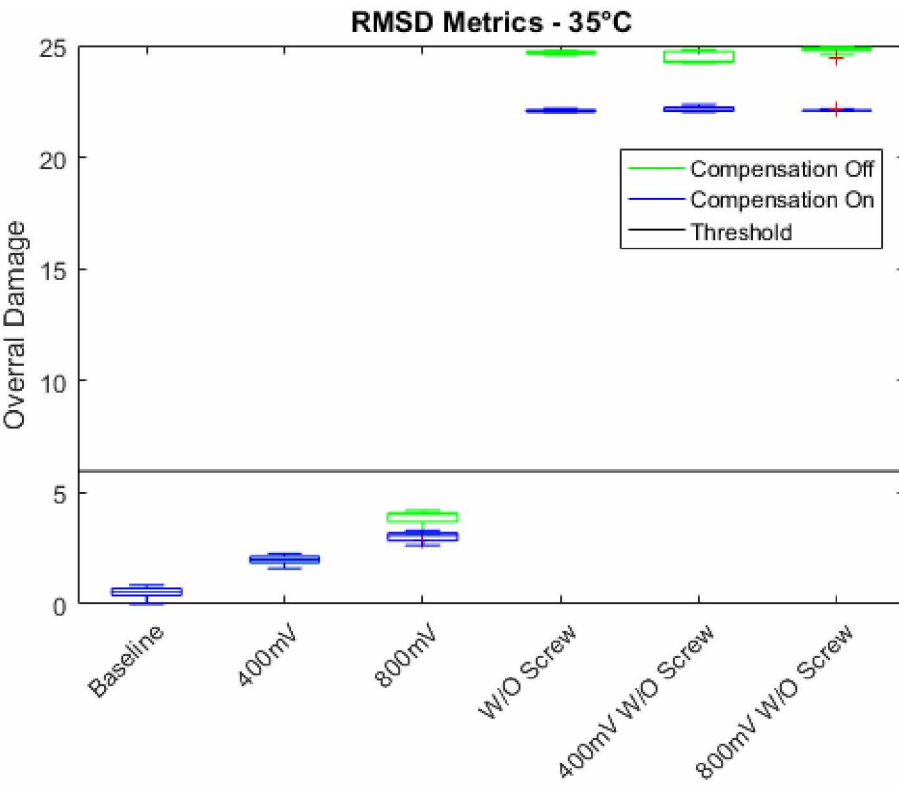


Figure 17 - RMSD metrics obtained at 35° C

Note that the load variation is able to change the damage metric values, however, the damage conditions were correctly identified.

The influence of the external vibration is relatively small compared with the introduced damage, but it cannot be neglected. The damage can be easily detected by the damage metrics and the analysis of the impedance signature. But if the damage was smaller, the variation induced by the dynamic load could have been greater than the damage itself.

The electromechanical admittance (inverse of impedance) amplitudes were compared with the accelerometer amplitudes in the range that both signals were acquired. They show no significant correlation (see Figure 18). This result was expected due to the different nature of both amplitudes, and, the previous analysis results.

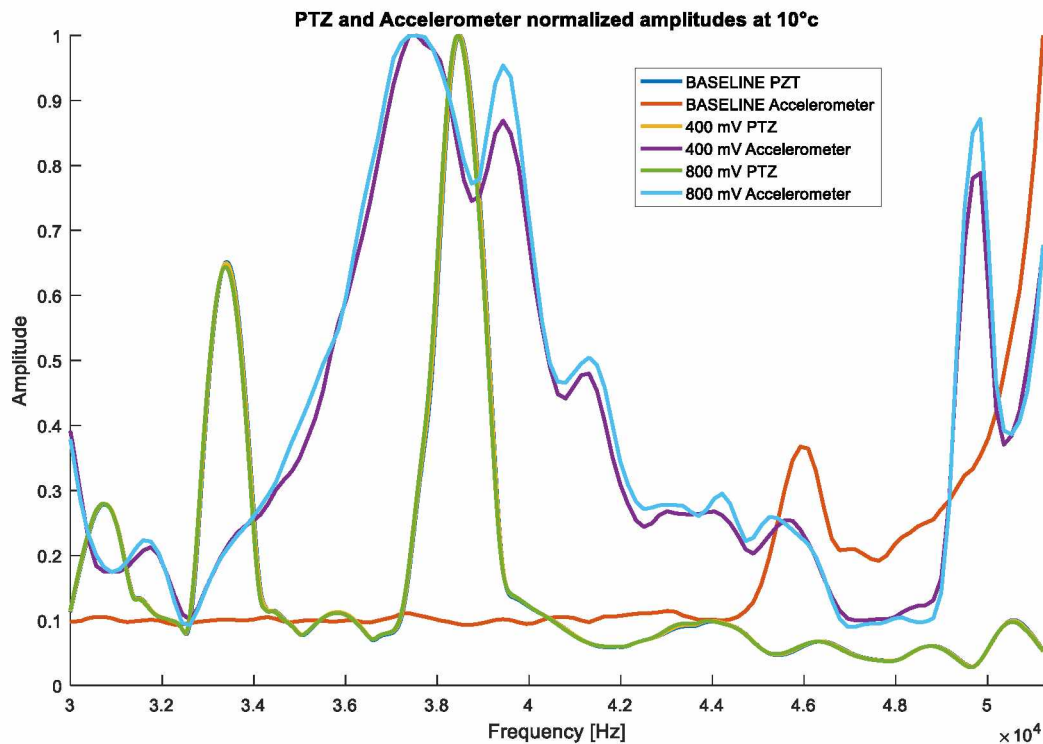


Figure 18 - PTZ and Accelerometer with normalized amplitudes

4.2 Second Experiment

The influence of a static load condition was also investigated in this work. In this experiment, the same model of beam as the vibration analysis experiment was used, except for the hole in the center of the beam for the Shaker support (see Figure 19). It was set in a fixed base



Figure 19 - Clamped beam with the masses 1 + 2 + 3 hanged in the marking (the mark is 152mm away from the PZT)

placed in a thermal chamber at a constant temperature of 25°C to avoid influence of temperature variation in the electromechanical signature while the experiment is performed. The PZT was plugged in a portable electromechanical receiver. The tests (impedance signature scans of PZT) were given in Tables 2 and 3.

Table 2 - Detailed static load experiment

<i>State</i>	<i>Condition</i>	<i>Temperature</i>
Baseline	Clamped beam	25°C
1	Clamped beam, tighter screws at the base	25°C
2	Clamped beam with the mass 1 hanged at the marking	25°C
3	Clamped beam with the masses 1+2 hanged at the marking	25°C
4	Clamped beam with the masses 1+ 2 + 3 hanged at the marking	25°C

Table 3 - Masses's details

Mass ID	Weight
1	88.49 g
2	112.22 g
3	81.25 g

As the masses were hung on the beam, a tension load was created. The influence of this static load and the extra strain created at the crimping on the PZT signature is what is analyzed in this article. It were acquired 30 impedance signatures samples of each state. Each sample has 10000 points, with 512 mean numbers, ranging from 30kHz to 200kHz. Figure 13 show the impedance signature associated with the baseline and state 1 conditions.

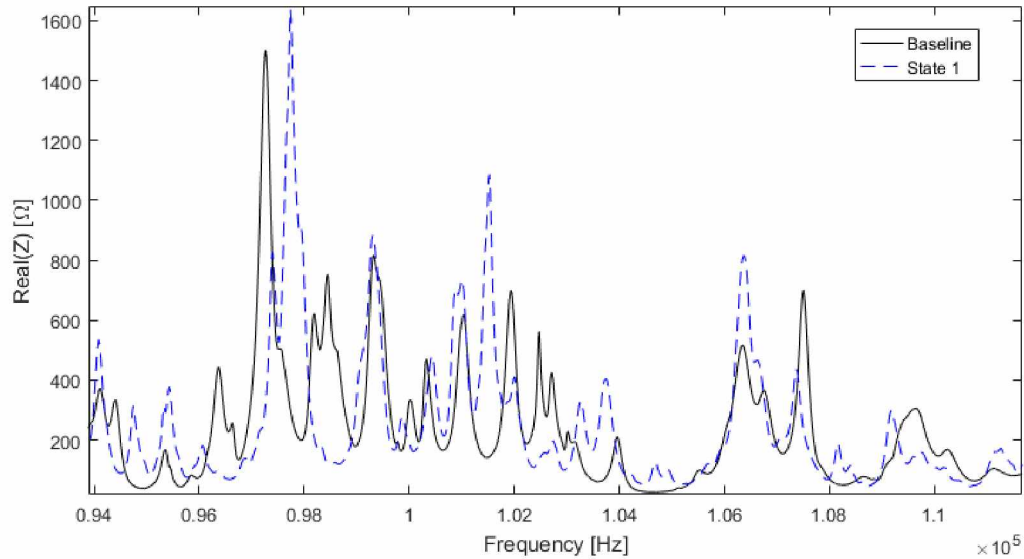


Figure 20 - Impedance signatures considering the baseline and state 1 conditions

Looking into the impedance signature itself, we can see that when the screw is tightened (when the boundary conditions where changed), different signature peaks appeared (see Figure 20).

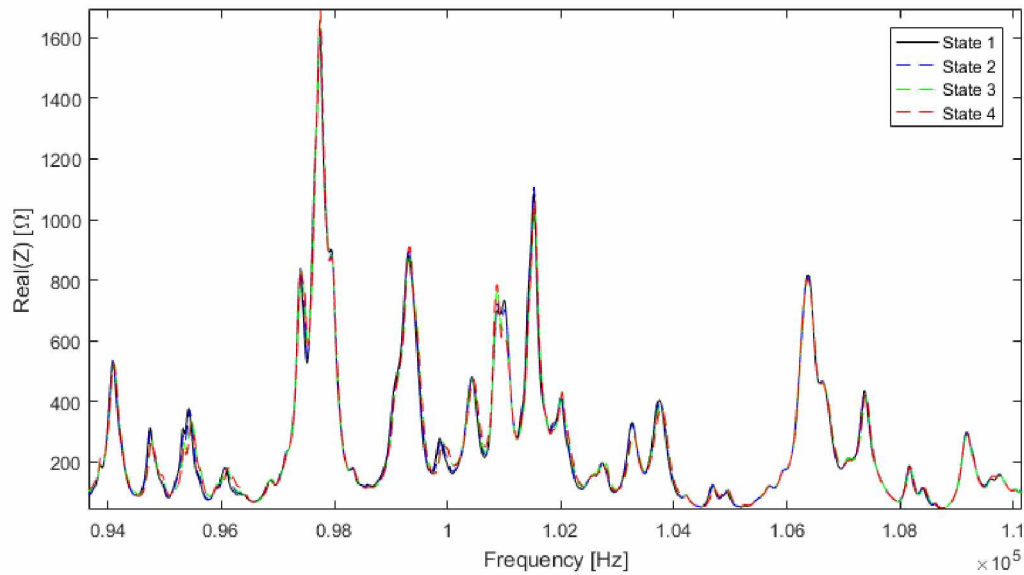


Figure 21 - Signature peaks at 25°C

Figure 21 shows that the load application on the structure has much lower influence than the change in the boundary conditions.

Just like in the first experiment, it was used a derivative-free based compensation technique on the impedance signature. The damage metrics with and without this compensation are presented in Figure 23.

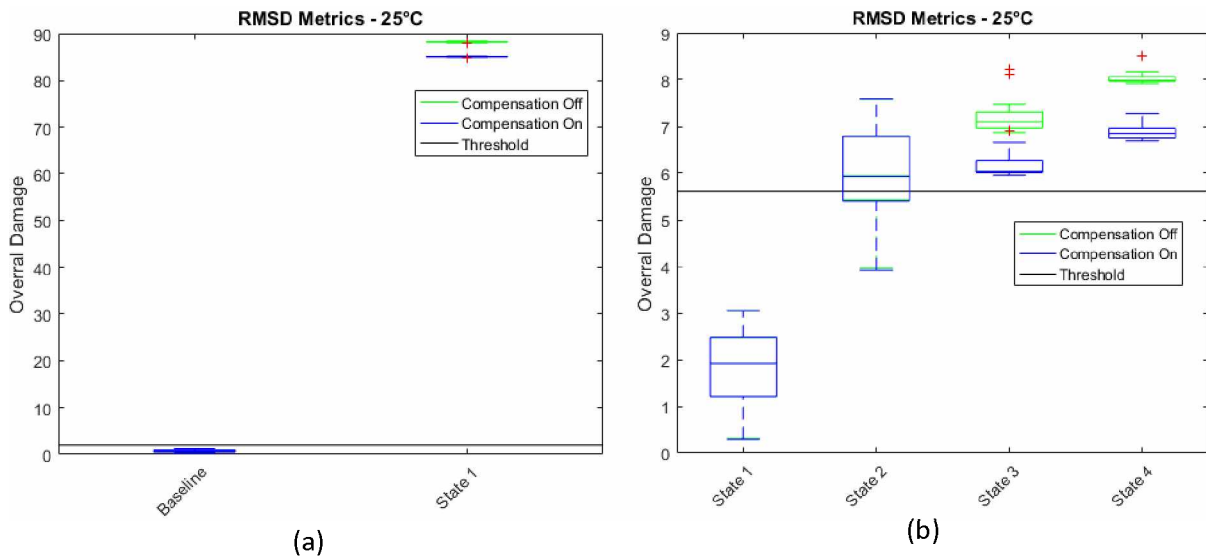


Figure 22: (a) RMSD comparing the baseline and state 1 conditions; (b) RMSD comparing the damage conditions

As visible in the Figure 22 (a), it is clear that the change in the clamp condition, when screws were tightened, significantly interfered the impedance signature. For better analysis of the other states, the second run was used as baseline. It still visible in Figure 22 (b) the change in the impedance signature in each state.

5. FINAL CONSIDERATIONS

In this paper, the damage metrics and the impedance signature analysis was used to evaluate the influence of dynamic and static load on the Impedance-Based Structural Health Monitoring. Two experiments were carried out: *i)* the influence on the impedance signature of the dynamic load using a shaker to excite mechanical vibration in the structure and *ii)* the influence on the impedance signature of static load and the boundary conditions tightening the clamp and hanging weights on the end of the analyzed structure. The RMSD Metrics showed a very good definition and accuracy when the conditions were changed, showing that this metric is an excellent tool even for detecting small changes. The vibration has a small but noticeable influence on the impedance signature in every temperature condition. The change in the clamp condition changed significantly the impedance signature, which could be easily detected by the damage metrics. The static load, just like the dynamic, has a small but noticeable influence on the impedance signature. Moreover, these influences could not be precisely determined, which makes the compensation impractical. Consequently, this study demonstrates the relevance of analyzing the loads conditions on the use of the ISHM. Further studies will encompass a compensation methodology in the ISHM for the change in the boundary condition of an analyzed structure, besides the best acquisition time for the electromechanical impedance analysis under dynamic loads.

REFERENCES

- Adams, D. (2007). *Health Monitoring of Structural Materials and Components* (Vol. 1). West Sussex, England: John Wiley & Sons Ltd.
- Baptista, F., Filho, J., & Inman, D. (2011, March). Real-time multi-sensors measurement system with temperature effects compensation for impedance-based structural health monitoring. *Structural Health Monitoring*, 11(2), pp. 173-186.
- Bastani, A., Amindavar, H., Shamshirzaz, M., & Sepehry, N. (2012, December 14). Identification of temperature variation and vibration disturbance in impedance-based structural health monitoring using piezoelectric sensor array method. *Structural Health Monitoring*, 11(3), 305–314.
- Beard, S., Kumar, A., Qing, X., Chan, H., Zhang, C., & Ooi, T. (2005, March 06). Practical issues in real-world implementation of structural health monitoring systems. *Smart Structures and Materials*.
- Bhalla, S., & Soh, C. K. (2004). High frequency piezoelectric signatures for diagnosis of seismic/blast induced structural damages. *NDT & E International*, 37(1), 23-33.
- Bhalla, S., Naidu, A., Ong, C., Soh, C. (2002, December). Practical Issues in the Implementation of Electromechanical Impedance Technique for NDE. In *Proceedings of the SPIE International Symposium on Smart Materials, Nano and Micro-Smart System*.
- Chaudhry, Z., Joseph, T., Sun, F., & Rogers, C. (1995). Local-Area Health Monitoring of Aircraft via Piezoelectric Actuator/Sensor Patches. *Smart Structures and Integrated Systems*, 2443.
- Chaudhry, Z., Lalande, F., Ganino, A., & Rogers, C. (1996). Monitoring the Integrity of Composite Patch Structural Repair via Piezoelectric Actuators/Sensors. *AIAA*, 1074-CP.
- Doebeling, S., Farrar, C., Prime, M. (1998). A summary review of vibration-based damage identification methods. (T. Oaks, Ed.) *Shock and Vibration Digest*, pp. 91-105.
- Farrar, H., Hemes, D., Stinemates, S., Nadler, B., & Czarnecki, J. (2004). *A Review of Structural Health Monitoring Literature from 1996-2001*. LA-13976, Los Alamos National Laboratory.
- Finzi Neto, R., Steffen Jr., V., Rade, D., & Gallo, C. a. (2011). A low-cost electromechanical impedance-based SHM architecture for multiplexed piezoceramic actuators. *Structural Health Monitoring*, 4, pp. 391-401.
- Giurgiutiu, V., & Zagrai, A. (2005). Damage detection in thin plates and aerospace structures with the electro-mechanical impedance method. *Structural Health Monitoring*, 4, 99-118.
- Giurgiutiu, V., Zagrai, A., Bao, J., Redmond, J., Roach, D., & Rackow, K. (2003). Active Sensors for Health Monitoring of Aging Aerospace Structures. *International Journal of The Condition Monitoring and Diagnostic Engineering Management*, pp. 3-21.

- H., L., Y., Y., & Annamdas, V. (2010). Parallel Interrogation of Piezoceramic Transducer in Electromechanical Impedance Technique for Quick Damage Detection. *Materials and Manufacturing Processes*, 5(4), 249-254.
- Inman, D. (2001). Damage prognosis for aerospace, civil and mechanical systems. *Brazilian Congress of Mechanical Engineering*.
- Inman, D., Farrar, C., Lopes Jr., V., & Steffen Jr., V. (2005). *Damage Prognosis for Aerospace, Civil and Mechanical Systems* (Vol. 1). John Wiley & Sons Ltd.
- Koo, K.-Y., cPark, S., Lee, J.-J., Yun, C.-B., & Inman, D. (2007). Impedance-based structural health monitoring considering temperature effects. *Health Monitoring of Structural and Biological Systems*, 6532, p. 65320C.
- Krishnamurthy, K., Lalande, F., & Rogers, C. (1996). Effects of temperature on electrical impedance of piezoelectric sensors. *Smart Structures and Materials*.
- Leo, D. (2007). *Engineering Analysis of Smart Material Systems* (Vol. 1). New Jersey: John Wiley & Sons, Inc.
- Liang, C., Sun, F., Rogers, C. (1994). Coupled Electromechanical Analysis of Adaptive Material Systems – Determination of the Actuator Power Consumption and System Energy Transfer. *Journal of Intelligent Material Systems and Structures*, 5(1), 15-20.
- Liang, C., Sun, F., Rogers, C. (1994). Coupled Electromechanical Analysis of Adaptive Material Systems - Determination of The Actuator Power Consumption and System Energy Transfer. *Journal of Intelligent Material Systems and Structures*, 5, pp. 12-20.
- Lilliefors, H. W. (1969). On the Kolmogorov-Smirnov test for the exponential distribution with mean unknown. *Journal of the American Statistical Association*, 387–389.
- Lim, Y. Y., & Soh, C. K. (2016). Fatigue damage diagnosis and prognosis using EMI technique. In *Structural Health Monitoring (SHM) in Aerospace Structures* (p. Chapter 15). Philadelphia: Elsevier Woodhead Publishing.
- Lim, Y., & Soh, C. (2012). Effect of varying axial load under fixed boundary condition on admittance signatures of electromechanical impedance technique. *Journal of Intelligent Material Systems and Structures*, 23(7), 815-826.
- Moura Jr, J. R. (2008). *Uma Contribuição aos Sistemas de Monitoramento de Integridade Estrutural Aplicada a Estruturas Aeronáuticas e Espaciais*. Uberlândia: Universidade Federal de Uberlândia.
- Moura Jr, J., & Steffen Jr, V. (2004). Impedance-Based Health Monitoring: Frequency Band Evaluation. IMAC. Dearborn, MI, USA.

- Moura, J. J. (2006). Impedance-Based Health Monitoring for Aeronautic Structures using Statistical Metamodeling. *Journal of Intelligent Material Systems and Structures*, 17, pp. 1023-1036.
- Palomino, L. (2008). *Análise das Métricas de Dano Associadas à Técnica da Impedância Eletromecânica para o Monitoramento de Integridade Estrutural*. Uberlândia: Universidade Federal de Uberlândia.
- Palomino, L., Tsuruta, K., Moura, J. J., Rade, D., Steffen, J. V., & Inman, D. (2012). Evaluation of the Influence of Sensor Geometry and Physical Parameters on Impedance-Based Structural Health Monitoring. *Shock and Vibration*, 19(5).
- Park, G. S., & Farrar, C. e. (2003). Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward. *The Shock and Vibration Digest*, pp. 451-463.
- Park, G., Kabeya, K., Cudney, H. H., & Inman, D. J. (1999). Impedance-Based Structural Health Monitoring for Temperature Varying Applications. *JSME International Journal*.
- Peairs, D. (2006). *High Frequency Modeling and Experimental Analysis for Implementation of Impedance-based Structural Health Monitoring*. Virginia Polytechnic Institute and State University, Virginia.
- Rabelo, D. d., Steffen Jr, V., Finzi Neto, R., & Lacerda, H. (2016). Impedance-based structural health monitoring and statistical method for threshold-level determination applied to 2024-T3 aluminum panels under varying temperature. *Structural Health Monitoring*, 1(1), 1-17.
- Rabelo, D. S., Tsuruta, D. D., de Oliveira, D. D., Cavalini Jr, A. A., Finzi Neto, R. M., & Steffen Jr, V. (2015, November). Fault detection in a rotating shaft by using the electromechanical impedance method and a temperature compensation approach. *Proceedings of the XXXVI Ibero-Latin American congress on computational methods in engineering (CILAMCE 2015)*, pp. 22-25.
- Raju, V. (1997). *Implementing impedance-based health monitoring*. Blacksburg, VA: PhD Thesis, Virginia Polytechnic Institute and State University.
- Rytter, A. (1993). *Vibrational Inspection of Civil Engineering Structures*. Aalborg University.
- Soh, C., Tseng, K., & Bhalla, S. G. (2000). Performance of Smart Piezoceramic Patches in Health Monitoring of a RC Bridge. *Smart Materials and Structures*, 9, 533-542.
- Stancalie, A., Sporea, D., Malinowski, P., Mieloszyk, M., Opoka, S., Wandowski, T., & Ostachowicz, W. (2015). Influence of support conditions and temperature on the EMI characteristics. *Journal of Physics: Conference Series*, 628(1), 012112.
- Steffen Jr, V., Cavalini Jr, A., & Finzi Neto, R. (2014). Impedance-based fault detection methodology for rotating machines. *Structural Health Monitoring*, 14(3), 228-240.
- Sun, F. P., Chaudhry, Z., Liang, C., & Rogers, C. A. (1995). Truss structure integrity identification using PZT sensor-actuator. *Journal of Intelligent Material Systems and Structures*, 6, 134-139.

- Sun, F. P., Chaudhry, Z., Rogers, C., Majmundar, M., & Liang, C. (1995-a). Automated real-time structure health monitoring via signature pattern recognition. *2443*, 236-247.
- Sun, F., Chaudhry, Z., Liang, C., & Rogers, C. (1995-b). Truss Structure Integrity Identification Using PZT Sensor-Actuator. *Journal of Intelligent Material Systems and Structures*, *6*, pp. 134-139.
- Xu, Y., & Liu, G. (2002). A modified electro-mechanical impedance model of piezoelectric actuator-sensors for debonding detection of composite sensors. *Journal of Intelligent Material Systems and Structures*, *13*(6), 389-396.
- Yang, Y., & Miao, A. (2008). Effect of External Vibration on PZT Impedance Signature. *Sensor Algorithms*, *8*(11), 6846-6859.
- Zhang, Y., F., X., J., C., Wu, C., & D., W. (2011). Electromechanical Impedance Response of a Cracked Timoshenko Beam. *Sensors*, *11*, 7285-7301.
- Zhou, D., Kim, J., Ha, D., Quesenberry, J., & Inman, D. (2009). A system approach for temperature dependency of impedance-based structural health monitoring. *Smart Sensor Phenomena, Technology, Networks, and Systems*, *7293*, pp. 72930U-72930U-10.