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IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING INCORPORATING COMPENSATION OF TEMPERATURE VARIATION EFFECTS

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Abstract. *The ongoing development of Structural Health Monitoring (SHM) systems has been showing to be a potential tool for reducing maintenance costs, improving life and increasing performance of engineering structures. Impedance-based SHM (ISHM) utilizes the electromechanical behavior of piezoelectric materials to detect adverse changes due to material or mechanical failures of structures. Environmental conditions such as temperature present a challenge in providing reliable diagnostics capable of distinguishing between structural damage and temperature effects. In the present study, an effective frequency shift method was implemented by using correlation analysis and experimental work both on an aluminum panel and an aircraft panel under conditions with temperature variation in order to show the performance of the ISHM method. In order to reduce temperature effects in impedance signatures, this study investigates the possibility of using several baselines to perform a more accurate diagnostic for structural integrity even under temperature variation applications by using statistical tools for determining damage metrics threshold levels. Results have shown that with this strategy, for a certain level of confidence, reliable diagnostics can be obtained with ISHM systems.*

Keywords: *Structural Health Monitoring, SHM, Impedance, Temperature Compensation.*

1. INTRODUCTION

SHM is referred as the process of implementing a strategy for damage detection and characterization of engineering structures. In this context, damage is defined as changes in dynamic properties of the structure, including changes in boundary conditions, which may affect the system's performance. Thus, damage can be associated to several factors, such as friction, fatigue, impact, stress concentration, crack growth, corrosion, among others. For a proper functioning of the SHM system, the failure should be located and opportunely repaired. Nowadays, one of the most ambitious challenges in engineering is to implement SHM in real time of components of high cost or huge responsibility for the system being considered.

This process of SHM involves the observation of a system using dynamic response measurements periodically sampled through a sensors network. From the signals obtained, damage-sensitive features must be extracted and, afterwards, a statistical analysis of these features must be made in order to determine the structure's current condition. The main goal of SHM is to obtain, at the end of the process, periodically updated information regarding the structure's ability to perform its intended design function, considering factors such as aging and wear resultants from operational or environmental conditions.

Among the SHM techniques, the method based on the electromechanical impedance (EMI) is considered to be one of the most promising. It is a nondestructive method that explores the electro-mechanical coupling property of piezoelectric materials to monitor the occurrence and evolution of structural damage. By using the same piezoelectric element as both sensor and actuator, a small number of components and cables are necessary (Park, *et al.*, 2003). For the monitoring success of this technique, the system must be robust to environmental variations from different sources (Moura and Steffen, 2006). Otherwise, environmental changes could influence the measurements, undermining the reliability of the procedure. Moreover, the process of monitoring the structural integrity can identify a situation of false positive during the evaluation of a given structure. Particularly, temperature variations present a common undesired effect as frequency shifts and change in peak amplitudes of impedance signatures (Palomino, *et al.*, 2011). In order to obtain a reliable diagnostic regarding the structure's integrity, a temperature compensation procedure based on correlation analysis was implemented as proposed by (Park, *et al.*, 1999). As a way of obtaining better compensation in a wide temperature range, this work investigates the possibility of using several baselines to perform a more accurate diagnostic even under temperature variation applications.

1.1 Impedance-Based Structural Health Monitoring

The basic idea behind this technique is to monitor the changes in the structure's mechanical impedance caused by the presence of damage. Since direct measurement of the mechanical impedance of the structure is a difficult task, the method uses piezoelectric materials bonded to or incorporated into the structure, allowing the measurement of the electrical impedance. This measurement is related to the mechanical impedance of the structure, 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 ISHM technique was first proposed by Liang, *et al.* (1994), and subsequently the method was extended by Sun, *et al.* (1995), Chaudhry, *et al.* (1996), Park, *et al.* (1999, 2003), Soh, *et al.* (2000), Giurgiutiu, *et al.* (2003), Moura and Steffen (2006), Peairs (2006), Moura (2008), Liu, *et al.* (2009), Finzi Neto, *et al.* (2011), and Palomino, *et al.* (2011).

The ISHM method uses simultaneously both versions, direct and inverse, of the piezoelectric effect. 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 patch. The electromechanical model that quantifies and describes the measurement process is illustrated in Fig. 1 for a single-degree-of-freedom system (1 DOF).

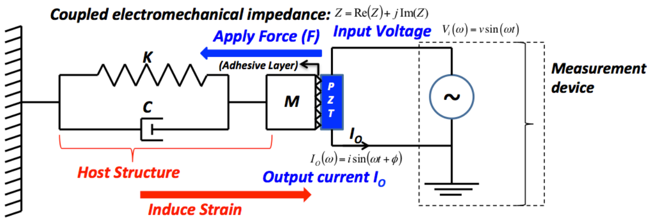


Figure 1. Mechatronic 1 DOF model of the Impedance-Based Structural Health Monitoring method

It has been shown that the admittance $Y(\omega)$, inverse of the impedance, of the PZT patch can be written as a function of the combined PZT actuator and structure mechanical impedance, as given by Eq. (1), Liang, *et al.*, (1994):

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

where $Z_a(\omega)$ 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, $\bar{\varepsilon}_{33}^{T}$ 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 the PZT patch do not vary over the time used for monitoring, Eq. (1) shows that the electrical impedance of the PZT patch is directly related to the structure's impedance.

It is necessary for the excitation wavelength to be smaller than the characteristic length of the damage to be detected. According to the literature (Park, *et al.*, 2003), the frequency range typically used in the impedance-based method is from 30 kHz to 250 kHz. The effective range for a given structure is determined by trial and error methods or by optimization procedures (Moura, *et al.*, 2008). As for the sensitive region to detect changes, Park, *et al.*, (2003) claim that for a simple PZT a damage located at a radial distance of up to 0.4 m can be identified in composite materials and up to 2 m 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 previously defined Damage Metric (DM), or Damage Index (DI) is used (Palomino and Steffen, 2009). In the present contribution, the main damage metric used is the correlation coefficient deviation (CCD). This DM use two signals, where the first corresponds to the *baseline* and the second is the test measurement. The CCD is given by Eq. (2):

$$CCD = 1 - \frac{1}{n}\sum_{i=1}^{n}\left\{\frac{\left[\mathrm{Re}(Z_{1,i}) - \mathrm{Re}(\overline{Z_1})\right]\left[\mathrm{Re}(Z_{2,i}) - \mathrm{Re}(\overline{Z_2})\right]}{S_{Z_1}S_{Z_2}}\right\} \tag{2}$$

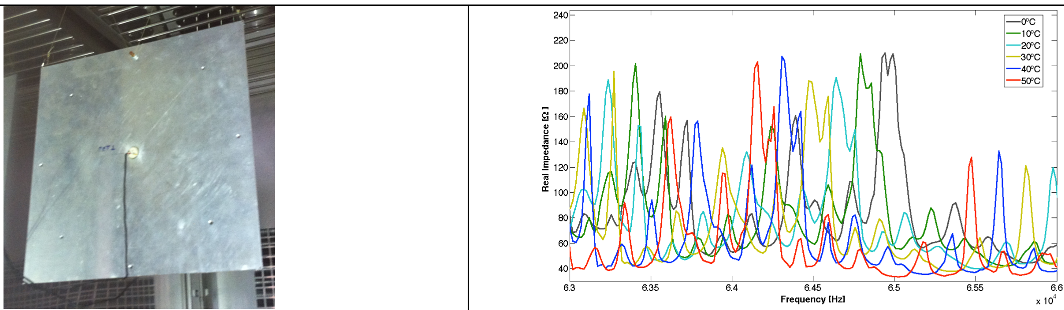
where $\mathrm{Re}(Z_{1,i})$ and $\mathrm{Re}(Z_{2,i})$ are the real part of the impedance from the *baseline* and test measurement at frequency *i*, respectively; *n* is the number of frequency points, $\mathrm{Re}(\overline{Z_1})$ and $\mathrm{Re}(\overline{Z_2})$ are the average of the *baseline* and test measurement, respectively; S_{Z_1} and S_{Z_2} are the standard deviations of the *baseline* and test measurements, respectively.

The next section discusses the effects caused on ISHM systems by temperature variations.

2. TEMPERATURE VARIATION EFFECTS

In engineering applications, issues such as operational and environmental variability are often present. Such events can cause changes in the impedance signatures obtained from the SHM system. In this section, the effect of the temperature variation is illustrated in order to show the changes caused in the impedance signatures. Figure 2(a) shows an aluminum plate of dimensions 305 mm x 305 mm x 3 mm, instrumented with a PZT patch type 5H with 15 mm diameter x 1 mm thickness attached on a central position. Figure 2(b) shows the effect of the temperature variations in the impedance signatures. The tests in this study were performed inside the environmental chamber ESPEC model EPL-4H, whose temperature resolution is of 0.5ºC after 30 minutes of settling time to stabilize the internal temperature. The temperature range utilized was from 0ºC to 50ºC in steps of 10ºC. Each impedance signature was measured with 600 points and the frequency range was from 63 kHz to 66 kHz.

By analyzing Fig. 2(b), the effects of the temperature can be seen predominantly as horizontal shifts due to changes in the resonance frequencies of the system. Vertical shifts can also be seen due to the change in the capacitance of the sensor, as well as a change in some peak amplitudes. It is imperative that the SHM process can distinguish changes in sensor reading caused by damage from changes caused by varying operational and environmental conditions, because without such discrimination, the SHM process will produce false-positive indications of damage. In this study, a compensation procedure was implemented based on the effective frequency shift through correlation analysis. This technique was inspired on the method firstly proposed by Sun *et al.*, (1995), Park *et al.*, (1999) and extended by Koo *et al.*, (2008). The advantages and drawbacks of these techniques will be discussed later on.



(a) (b)

Figure 2. Temperature variation effects on an *Al* plate for a temperature range of 0ºC to 50ºC.

2.1 Temperature Compensation Procedure – Effective frequency shift through correlation analysis

The shifts caused by temperature variations may be considered uniform for a determined and limited frequency band. Conversely, the changes caused due to a structural damage do not follow the same trend. This feature allows us to mitigate temperature variation effects with a data normalization procedure (Rabelo, 2014).

Initially, the vertical shift Δ_v can be applied by compensating the difference in overall average value of the *baseline* and the test measurement patterns according to Eq. 4:

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

In the next step, the correlation coefficient $CC_{Z_1Z_2}$ is utilized in order to determine the extension of the frequency shift. The $CC_{Z_1Z_2}$ is obtained according to Eq. 5, which is part of the CCD damage index:

$$CC_{Z_1Z_2} = \frac{1}{n}\sum_{i=1}^{n}\left\{\frac{\left[\mathrm{Re}\left(Z_{1,i}\right)-\mathrm{Re}\left(\overline{Z_1}\right)\right]\left[\mathrm{Re}\left(Z_{2,i}\right)-\mathrm{Re}\left(\overline{Z_2}\right)\right]}{S_{Z_1}S_{Z_2}}\right\} \tag{5}$$

If the test measurement Z_2 is shifted of n frequency points from a *baseline* Z_1, then its correlation coefficient will be maximized when the impedance signature of Z_2 is shifted by n points. After this procedure, both signatures should be fully correlated, except for the portion caused by damage if it is present. Thus, an optimization procedure is performed, searching for the maximum correlation coefficient as a function of the frequency shift of n data points delayed, or advanced. Therefore this technique searches for the optimum frequency shift Δf and the corrected impedance signature is given according to Eq. 6:

$$\mathrm{Re}\left(Z_{corr,i}\right) = \mathrm{Re}\left(Z_{2,i\pm\Delta_f}\right) + \Delta_v \tag{6}$$

where $\mathrm{Re}\left(Z_{corr,i}\right)$ is the real part of the impedance corrected at frequency i, $\mathrm{Re}\left(Z_{2,i\pm\Delta_f}\right)$ is the real part of the test measurement shifted by Δf data points at frequency $i \pm \Delta_f$. In the frequency axis, the shift will be applied to the right if the test measurement's temperature is greater than the *baseline*'s temperature, otherwise the shift will be oriented to the left. Therefore it is of the upmost importance to have temperature readings for all measurements performed as close as possible to the sensors in the structure being monitored by an ISHM system.

In the end of the process, the damage metrics are updated with the corrected impedance signature. As an illustration, the aluminum plate form Fig. 2(a) was tested under a large temperature range in order to check the performance of this temperature compensation method. Figures 3(a) and 3(b) show the comparison with the previous measurements performed in the Al plate for the same temperature range. In this case, only one *baseline* was acquired at -30ºC, and each signature was measured with 600 data points, after 30 minutes of settling time for temperature stabilization.

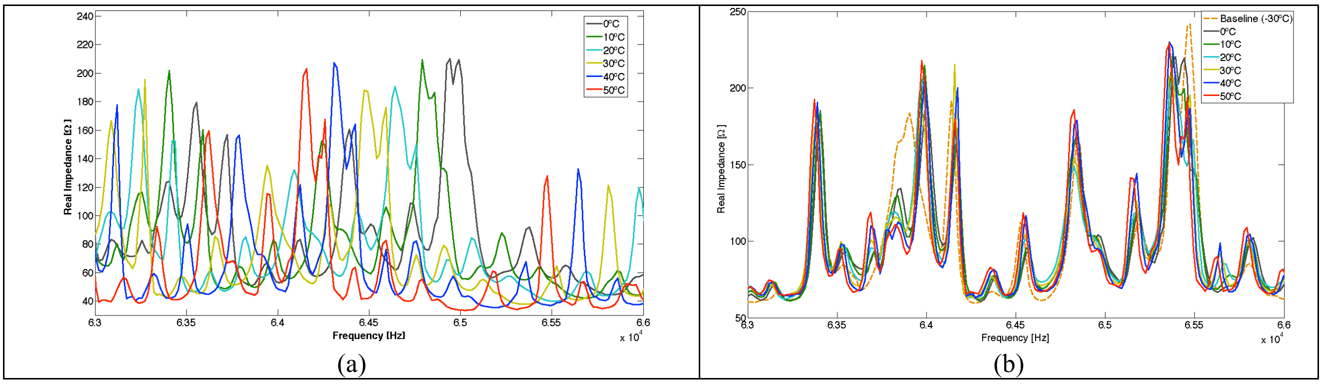


Figure 3. Temperature compensation procedure on an Al plate for a temperature range of 0ºC to 50ºC. (a) – Impedance signatures without compensation; (b) – Impedance signatures with compensation.

Overall, it can be noted that the temperature compensation procedure provides good agreement among the impedance signatures in a wide temperature range. However, since there's some variation in peak amplitudes, a perfect match in practical application will rarely occur, as can be noted in the resonance peak close to 64 kHz in Fig. 3(b).

Despite a good agreement can be obtained with the temperature compensation techniques, there are limitations regarding the frequency band. This is also true when the desired temperature range is extremely large, which could implicate in poor matching in the signatures when the temperature gradient is very large (Rabelo, 2014). Therefore, for a structure being designed to work under a determined temperature range, the ISHM system would require more than only one *baseline* in order to provide a more reliable diagnostic, since the temperature compensation would become more effective. In the following sections, the ISHM system will be tested under two structures: a fastened aluminum beam and an aircraft aluminum panel.

3. EXPERIMENTAL CASE STUDY #1 – FASTENED ALUMINUM BEAM

The goal of the first experiment is to investigate and obtain a better understanding of practical issues when dealing with an ISHM system subject to variation of external conditions, such as temperature and boundary conditions. Although this temperature compensation technique has been extensively used in the literature, one drawback that is worth mentioning about it is that the frequency bandwidth used in the monitoring process is limited in order to obtain an optimum correlation coefficient for the frequency shift. Figure 5 shows a fastened aluminum beam, which was used to evaluate this effect:

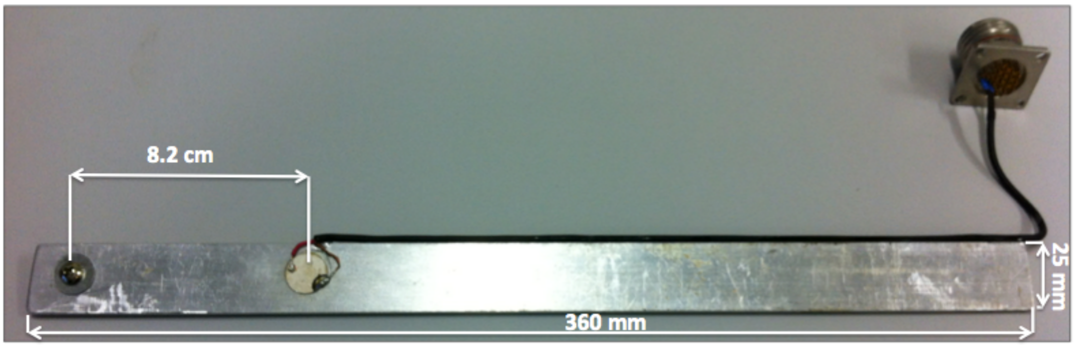


Figure 5. Experimental setup of a fastened aluminum beam with a PZT patch type 5H.

Two different frequency ranges were selected for this beam: a narrow one from 101 kHz to 116 kHz and a wide range from 20 kHz to 200 kHz. Both frequency ranges were measured twice, but in different temperatures: the *baseline* was acquired at 0 ºC and another measurement for the pristine condition was made at 30 ºC. Figure 6 shows the results without and with the temperature compensation procedure for each frequency range.

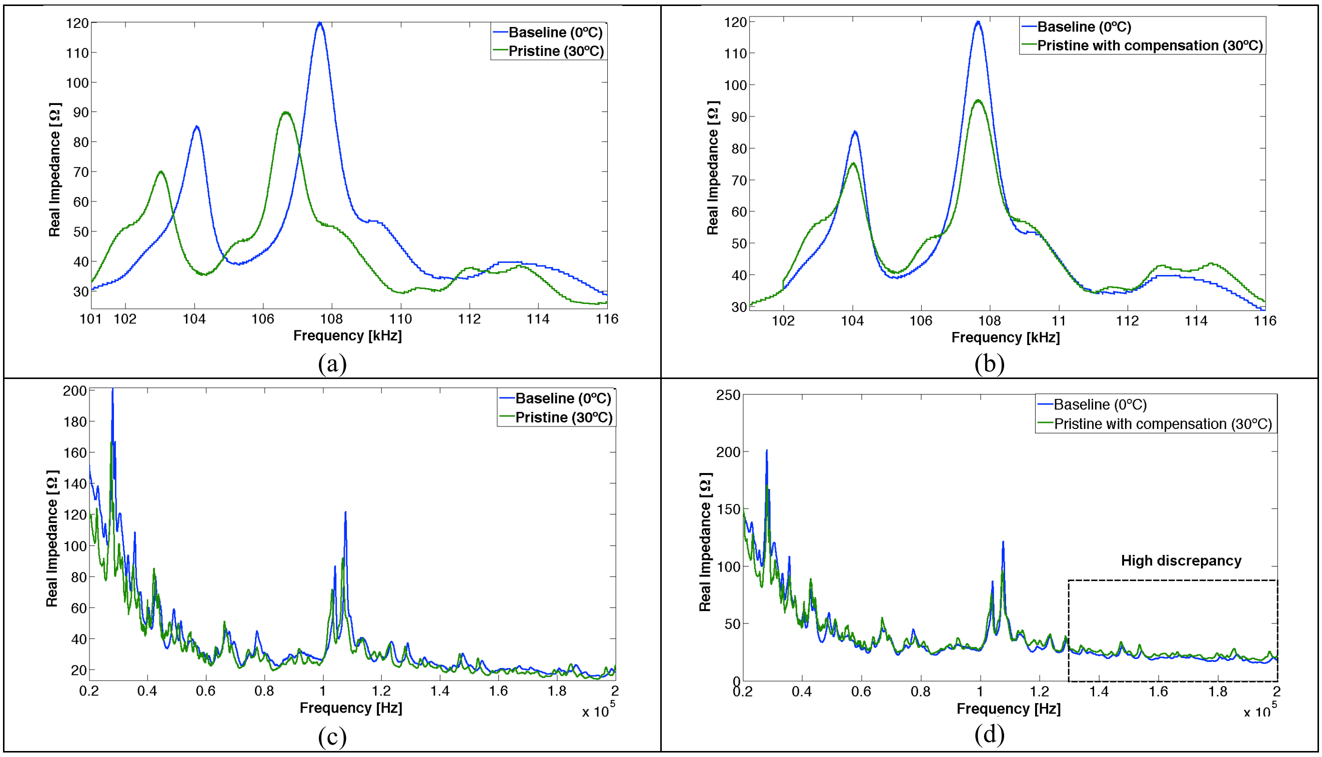


Figure 6. Impedance signatures: Narrow frequency range - (a) without compensation, (b) with compensation; Wide frequency range – (c) without compensation, (d) with compensation.

Figure 6(b) shows a good correlation of the impedance signatures when the temperature compensation method is applied to the narrow frequency band considered. However, there is a high discrepancy between the signatures shown in Fig. 6(d) when the temperature compensation method is applied to the wide frequency band. This occurs because the frequency shift due to the temperature drifts does not follow a linear trend along the frequency axis. Instead, the frequency shift increases for higher frequencies (Baptista *et al.*, 2014), (Rabelo, 2014).

Hence, both the temperature variation and the frequency bandwidth chosen for the monitoring process are parameters that may affect the performance of an ISHM system for a correct diagnosis. It is important to note that if a PZT transducer's impedance signature comprises several resonance peaks, it means the sensor has high sensitivity.

This result shows that the frequency bandwidth used should be both narrow, so that a good temperature compensation is established, and with a high density of resonance peaks in its impedance signature, thus indicating a good electromechanical coupling for that frequency region. Next, damage was introduced in the aluminum beam by loosening the fastener by 1/8 of a turn, causing a loss of stiffness in that region. For this test, two methodologies were tested: Methodology 1 was to acquire a baseline at 0ºC, and perform measurements at the temperature range of 10 ºC to 50 ºC in steps of 10 ºC. After the damage was introduced, it was measured at the temperature of 30ºC. Methodology 2 consists of using a baseline in the temperature of 20 ºC, thus reducing the temperature gradient, and finally measuring the structure at 30 ºC at conditions pristine, and with damage. Figure 7 depicts the damage metrics results:

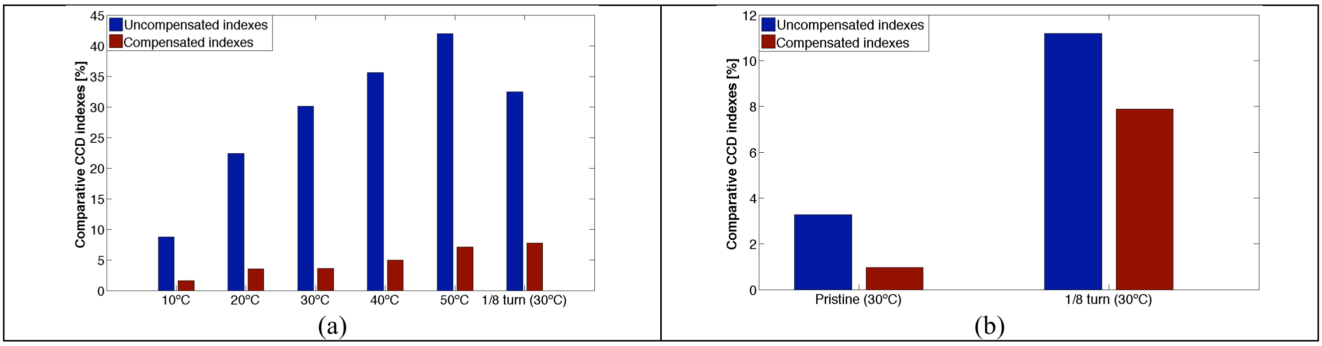


Figure 7. CCD damage indexes – (a) Methodology 1 with *baseline* acquired at 0ºC; (b) Methodology 2 with *baseline* acquired at 20ºC.

Figure 7(a) shows the CCD values for the cases without damage at temperatures ranging from 10 ºC to 50 ºC without damage, and the final pair of values corresponds to the damage case measured at 30 ºC. Figure 7(b) shows the CCD values of the structure without damage at 30 ºC and with the damage case measured at 30ºC. These results show that although it could be possible to draw a line of threshold separating the healthy conditions to the damaged condition up to the temperature range of 0 ºC to 30 ºC with a certain confidence level. A much more reliable procedure would be to use the data with a *baseline* which was acquired at a closer temperature from the test measurement – in this case the methodology 2, where the compensated damage indexes from Fig. 7(b) varied from 3.6% in a healthy state to 7.75% in the damaged state. These results show that it is extremely recommended to acquire as many *baselines* as possible at different temperatures when setting an ISHM system to perform a predictive maintenance for an engineering structure.

4. EXPERIMENTAL CASE STUDY #2 – AICRAFT ALUMINUM PANEL

When an engineering structure is monitored, the complexity of the compensation procedure can be significantly increased. Factors such as temperature distribution, thermal stresses and boundary condition effects can play a larger role in the ISHM system as compared to simple structures such as beams and plates. In this section, an aircraft aluminum panel was instrumented in order to test the performance of the current ISHM system. A total of 7 PZT patches type 5H, and one temperature sensor, designated as STEMP, were installed on the aircraft aluminum panel as shown in Fig. 8(a), whose dimensions are of 810 mm x 810 mm x 3mm. In order to simulate damage and check the system's ability to detect it, two masses were attached with beeswax. Mass 1 has 0.2 g and mass 2 has 39.6 g were added, one at a time. Mass 1 was placed close to the PZT 3 on a beam region, and mass 2 was placed close to PZT 1 on a panel region, as shown in Fig. 8(b). The structure was installed inside the environmental chamber and the frequency range selected for the PZTs was of 20 kHz to 35 kHz for all sensors, with 300 frequency points. In this experiment, Damage 1 corresponds to the removal of mass 1, Damage 2 corresponds to the removal of mass 2. The masses were removed sequentially.

Figure 8. Aeronautical panel instrumented with 7 PZT patches. (a) General view; (b) – Position of simulated damages.

The *baselines* were recorded at temperatures of 0 ºC, 10 ºC, 20 ºC, 30 ºC, 40 ºC and 50 ºC. Next, undamaged cases were recorded at temperatures of 31 ºC and 43 ºC, and finally Damage 1 was recorded at temperature of 31 ºC and 43 ºC. In order to perform the diagnosis, two methodologies were verified:

- Methodology 1: The only *baseline* available was recorded at 0 ºC.
- Methodology 2: All measurements of *baselines* from 0 ºC to 50 ºC in steps of 10 ºC were recorded and the signature utilized for temperature compensation was the closest one in terms of temperature gradient.

For concision, results of uncompensated and compensated CCD values for PZTs 1 and 3 are shown in Fig. 9.

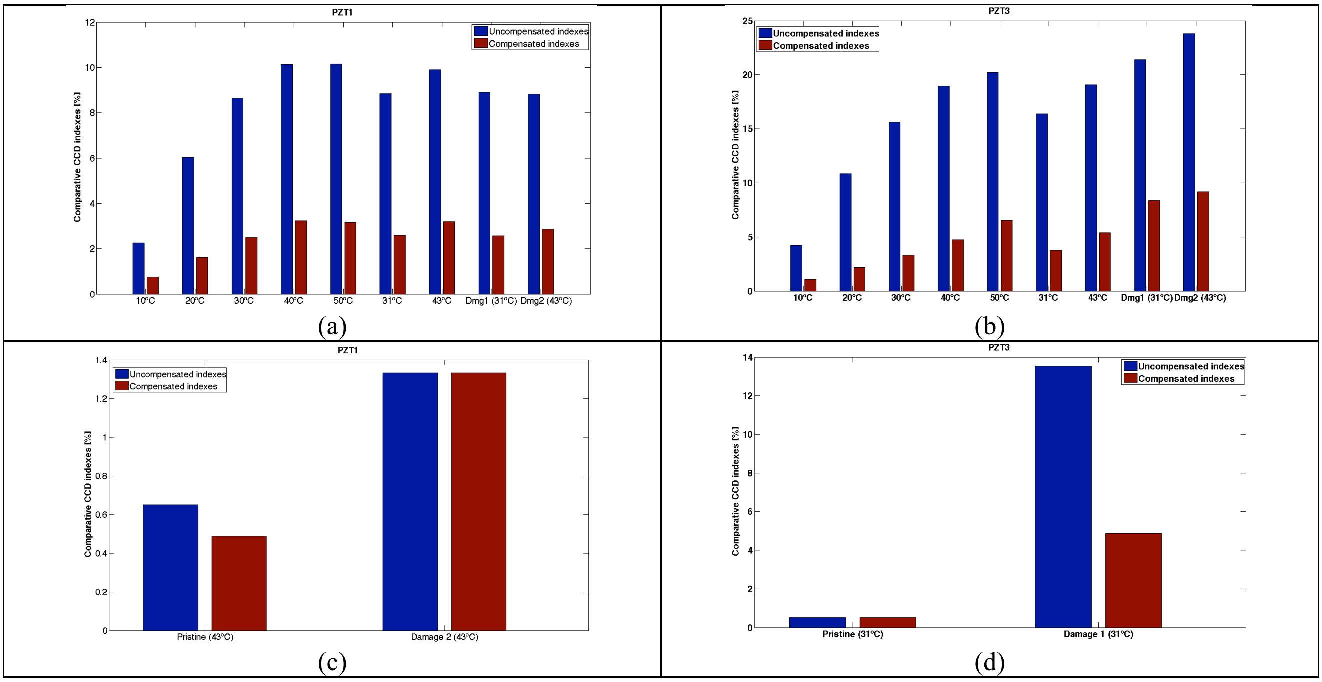


Figure 9. Damage indexes. (a) – Methodology 1, PZT1; (b) Methodology 1, PZT3; (c) Methodology 2, PZT1; (d) Methodology 2, PZT3.

Figures 9(a) and 9(b) show that the first 7 indexes correspond to undamaged cases, however as the temperature gradient rises, the temperature compensation procedure degrades, as it provides higher indexes. The final two values corresponds to the damage cases 1 and 2, respectively where the masses were removed. These results show that although there is a significant reduction in the damage indexes after the compensation method, by only using a single *baseline*, which in Methodology 1 was obtained at temperature 0ºC, the CCD values were not considerably high enough in damage cases as compared to the pristine conditions. However, Methodology 2, which utilizes the closest *baseline* in terms of temperature gradient, has shown significant discrepancy between the pristine case and the damage case for both cases in PZT1 and PZT3. Table 1 summarizes the cases of undamaged and damaged conditions for both methodologies:

Table 1. Diagnostics results for PZTs 1 and 3 with both methodologies.

	PZT1		PZT3	
	CCD - Pristine	CCD – Damage 2	CCD - Pristine	CCD – Damage 1
Methodology 1	3.2%	2.87%	3.79%	8.35%
Methodology 2	0.487%	1.33%	0.524%	4.87%

One can notice that the changes in the damage indexes are significantly more pronounced with the use of Methodology 2, i.e., using a *baseline* closer in terms of temperature gradient for the compensation procedure. Additionally, with statistical techniques, a threshold level could be determined for the system to indicate that a change has been detected on the monitored structure.

5. CONCLUSION

In this study, the ISHM technique was investigated considering the effects of temperature variation. It was experimentally verified that a change in temperature could severely compromise the system's capability of performing a correct diagnosis. The temperature variation causes frequency shifts as well as some vertical shifts in some resonance peaks. However, damage produces a more local and abrupt change in the signature. The frequency shift compensation through correlation analysis was successfully implemented. A literature review was presented as well. The experimental section of this study presented case studies involving an aluminum beam, as well as an aluminum panel. Although the temperature compensation procedure has reduced the damage indexes, a more substantial diagnosis was obtained by using a single *baseline* in a narrower temperature range. Overall, the frequency shift compensation through the correlation analysis technique produces good matches for an ISHM system; however, limitations such as temperature range and frequency bandwidth should be chosen as narrow as possible, since the procedure reduces its performance for wider frequency bands due to frequency shifts that follow a non-linear trend. As future perspective, further investigation will be made in order to obtain a more robust compensation technique procedure for ISHM systems.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Baptista, F.G., Budoya, D.E., Almeida, V.A. and Ulson, J.A.C., 2014. “An experimental study on the effect of temperature on piezoelectric sensors for impedance-based structural health monitoring”. *Sensors*, Vol. 14, p.1208.

Chaudhry, Z., Lalande, F., Ganino, A. and Rogers, C., 1996. “Monitoring the integrity of composite patch structural repair via piezoelectric actuators/sensors. AIAA-1996-1074-CP.

Finzi Neto, R.M.F., Steffen, V., Rade, D.A., Gallo, C.A. and Palomino, L.V., 2011. “A low-cost electromechanical impedance-based SHM architecture for multiplexed piezoceramic actuators”. *Structural Health Monitoring*, Vol. 10, p. 391.

Giurgiutiu, V.I., Zagrai, A. and Bao, J.J., 2003. “Active sensors for health monitoring of aging aerospace structures”. *International Journal o the Condition Monitoring and Diagnostic Engineering Management.* Vol. 6, p. 3.

Koo, K.Y., Park, S., Lee, J.J. and Yun, C.B., 2008. “Automated impedance-based structural health monitoring incorporating effective frequency shift for compensating temperature effects”. *Journal of Intelligent Material Systems and Structures.* Vol. 00-2008.

Liang, C., Sun, F.P. and Rogers, C.A., 1994. “Coupled electromechanical analysis of adaptative material systems – determination of the actuator power consumption and system energy transfer”. *Journal of Intelligent Material Systems and Structures*. Vol. 5, p. 740.

Liu, X. and Paurobally, R., 2009. “Robust damage metric in terms of magnitude and phase for impedance-based structural health monitoring”. *Structural Health Monitoring.* Vol. 8, p. 303.

Moura Jr., J.R.V., 2008. “*A contribution to structural health monitoring systems applied to aeronautic and space structures*”. Ph.D. thesis, Federal University of Uberlandia, Brazil.

Moura Jr., J.R.V. and Steffen Jr., V., 2006. “Impedance-based health monitoring for aeronautic structures using statistical meta-modeling”. *Journal of Intelligent Material Systems and Structures.* Vol. 17, p. 1023.

Palomino, L.V. and Steffen Jr., V., 2009. “Damage metrics associated with electromechanical impedance technique for SHM applied to a riveted structure”. In *Proceedings of the 20th International Congress of Mechanical Engineering – COBEM2009.* Porto Alegre, Brazil.

Palomino, L.V., Moura Jr., J.R.V., Tsuruta, K.M., Rade, D.A. and Steffen Jr., V., 2011. “Impedance-based health monitoring and mechanical testing of structures”. *Smart Structures and Systems*, Vol. 7, p.15.

Park, G., Cudney, H. and Inman, D.J., 1999. “Impedance-based structural health monioring for temperature varying applications”. *JSME International Journal*. Vol. 42, p. 249.

Park, G., Sohn, H., Farrar, C.R. and Inman, D.J., 2003. “Overview of Piezoelectric impedance-based health monitoring and path-forward”. *The Shock and Vibration Digest*. Vol. 35, p. 85.

Peairs, D.M. 2006. “High frequency modeling and experimental analysis for implementation of impedance-based structural health monitoring”. Ph.D. thesis, Virginia Polytechnic Institute and State University, Virginia, USA.

Rabelo, D.S. 2014. “Impedance-based structural health monitoring incorporating compensation of the temperature variation effect”. M.S. dissertation, Federal University of Uberlandia, Brazil.

Soh, C.K., Tseng, K., Bhalla, S. and Gupta, A., 2000. “Performance of smart piezoceramic patches in health monitoring of a RC bridge”. *Smart Materials and Structures.* Vol. 9 p. 533.

Sun, F.P., Chaudhry, Z., Liang, C. and Rogers, C.A., 1995. “Truss structure integrity identification using PZT sensor-actuator”. *Journal of Intelligent Material Systems and Structures.* Vol. 6 p. 134.

8. RESPONSIBILITY NOTICE

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