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Proceeding Paper

Irregular Temperature Variation Effects on Damage Detection Based on Impedance Measurement from Piezoelectric Transducers †

Felipe Augusto Barnabé and Fabricio Guimarães Baptista *

Laboratory of Transducers and Data Acquisition, Department of Electrical Engineering, School of Engineering, São Paulo State University (UNESP), Bauru 17033-360, Brazil
* Correspondence: f.baptista@unesp.br; Tel.: +55-14-3103-6764

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Abstract: Piezoelectric transducers have been extensively investigated for the development of non-destructive techniques in structural health monitoring systems. Among the various techniques that have been proposed, the electromechanical impedance technique stands out for its simplicity of installation, where a piezoelectric transducer operates simultaneously as a sensor and an actuator, establishing a relationship between the electrical impedance of the transducer and the integrity of the structure. Although many studies have reported the feasibility of this technique, some practical challenges have hampered its effective application in real structures, where one of the most critical problems has been the temperature variation. In order to mitigate the temperature effects, damage indices and compensation methods have been proposed in recent years and satisfactory results have been obtained. However, these compensation methods are typically tested in laboratories using small structures with uniform temperature variation. On the other hand, large structures in real applications may be subject to irregular temperature variation. Therefore, this study aims to investigate the effects of irregular temperature variation on the impedance signatures of piezoelectric transducers and, consequently, on the feasibility of detecting structural damage. Experimental tests were performed on an aluminum plate with multiple piezoelectric transducers installed under different temperature conditions, and the impedance signatures were qualitatively and quantitatively analyzed using damage indices. The results indicate that the irregular temperature variation can make some damage indices and compensation techniques unfeasible in real applications with large structures.

Keywords: piezoelectric transducers; impedance; temperature; damage detection; monitoring; nondestructive testing

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1. Introduction

Monitoring different engineering structures is of vital importance to reduce maintenance costs and increase user safety. Over time, deterioration processes of different types can occur, such as corrosion, cracks, and reduction of resistance, which can produce serious accidents. Therefore, structures need to be evaluated using structural health monitoring (SHM) systems based on non-destructive testing (NDT) techniques [1], which reduce maintenance costs, increase reliability, and can be performed remotely.

Several NDT techniques exist, such as Lamb waves [2], acoustic emission [3], and eddy current tests [4]. Among the various techniques, electromechanical impedance (EMI) stands out for presenting several advantages, such as low cost of implantation and easy installation, consisting only of a PZT (lead zirconate titanate) patch fastened to the host structure [5,6]. Due to the piezoelectric effect, a relationship is established between the electrical impedance of the transducer and the mechanical impedance of the structure which is affected by structural damage. Damage detection is obtained by comparing two impedance signatures, one of which is obtained when the structure is in a condition considered healthy. This comparison is performed using damage indices such as root mean square deviation (RMSD) and correlation coefficient deviation metric (CCDM) [7].

Despite many comprehensive studies on the application of EMI techniques, there are still many challenges without a definitive solution, one of the most critical being the effects of temperature. Different authors have sought to correct the effects of temperature variation on EMI by proposing different techniques. The most common effects highlighted in EMI signatures are shifts in frequency and magnitude [8,9]. To compensate for the shifts in frequency, the effective frequency shift (EFS) method based on the correlation coefficient maximization has been used [10,11]. However, the studies reported on the EFS method are based on small structures with uniform temperature distribution. On the other hand, in real applications, structures are typically large and may have an uneven temperature distribution.

Therefore, this article aims to present an initial study on the effects of irregular temperature distribution on the EMI technique and on the effectiveness of compensation using the EFS method. This article is organized as follows: the principle of the EMI technique is presented in Section 2; the experimental procedure is presented in Section 3; the results are presented and discussed in Section 4; and conclusions are presented in Section 5, followed by the list of references.

2. SHM Based on EMI Technique

The basic principle of the EMI technique is presented in Figure 1, in which a piezoelectric transducer is fixed, by means of a high stiffness adhesive, on the structure to be monitored with mechanical impedance $Z_S(\omega)$, and has its electrical impedance $Z_E(\omega)$ measured by a system with angular frequency (ω) which varies within an appropriate range, which is normally above 30 kHz to minimize the effects of external vibrations.

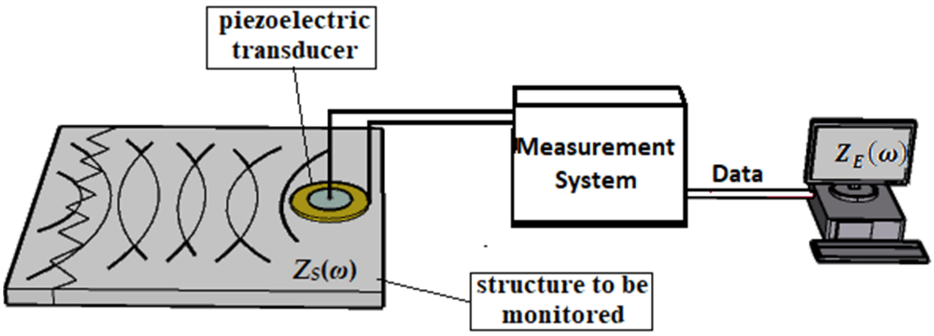


Figure 1. Application of the EMI method.

Due to the piezoelectric effect, a relation is established between the mechanical impedance $Z_S(\omega)$ of the structure and the electrical impedance $Z_E(\omega)$ of the transducer. For a simplified analysis, a one-dimensional electromechanical model [12] can be developed to relate these two quantities:

$$Z_E(\omega) = \frac{1}{j\omega C}\left(1 - \frac{d_{31}^2}{s_{11}\varepsilon_{33}} \frac{Z_s(\omega)}{Z_s(\omega) + Z_p(\omega)}\right)^{-1} \quad (1)$$

where $Z_E(\omega)$ and $Z_S(\omega)$ are the electrical impedance of the transducer and the mechanical impedance of the monitored structure, respectively, $Z_P(\omega)$ is the mechanical impedance of the transducer, ω is the angular the frequency, C is the transducer capacitance, j is the imaginary unit, and d_{31}, s_{11}, ε_{33} are the piezoelectric, elasticity and dielectric constants, respectively. Subscripts 1 and 3 indicate the tensor component for a one-dimensional assumption.

According to Equation (1), there is a relationship between the electrical impedance of the transducer and the mechanical impedance of the structure. Therefore, any change in the mechanical properties of the structure caused by damage implies a corresponding change in the electrical impedance of the transducer. As mentioned before, damage detection is achieved by comparing two impedance signatures using damage indices. In this study, the CCDM index was used to analyze the effects of temperature and is calculated as follows:

$$CCDM = 1 - C_C, \quad (2)$$

where C_C is the correlation coefficient given by:

$$C_C = \frac{cov[Z_{E,H}(\omega),\ Z_{E,D}(\omega)]}{\sigma_1 \sigma_2}, \quad (3)$$

in which "cov" is the covariance of the two impedance signatures, $Z_{E,H}(\omega)$ and $Z_{E,D}(\omega)$ are the signatures obtained for the structure in healthy and damaged conditions, respectively, and σ_1 and σ_2 are the corresponding standard deviations of each signature. The impedance signatures are complex, and the real part was used in this study to calculate the CCDM index.

The experimental setup is presented in the next section.

3. Experimental Setup

Experimental tests were carried out to analyze the effects of temperature in uniform and irregular distribution in different points of the host structure using a 450 mm × 450 mm × 1 mm aluminum plate. To produce heating, a thermal blower was used, which is a tool that has already been successfully applied in other works and can heat the structure with temperature ranging from 25 °C to 120 °C. To perform the temperature measurement, a FLIR C2-X thermal camera connected to a laptop was used, which made it possible to accurately measure and control the uniform and irregular temperature distribution.

Eight piezoelectric diaphragms were placed in the aluminum structure using cyanoacrylate adhesive, forming a network of transducers. Figure 2a,b show the experimental arrangement in the laboratory and the placement of the piezoelectric transducers on the aluminum plate, respectively.

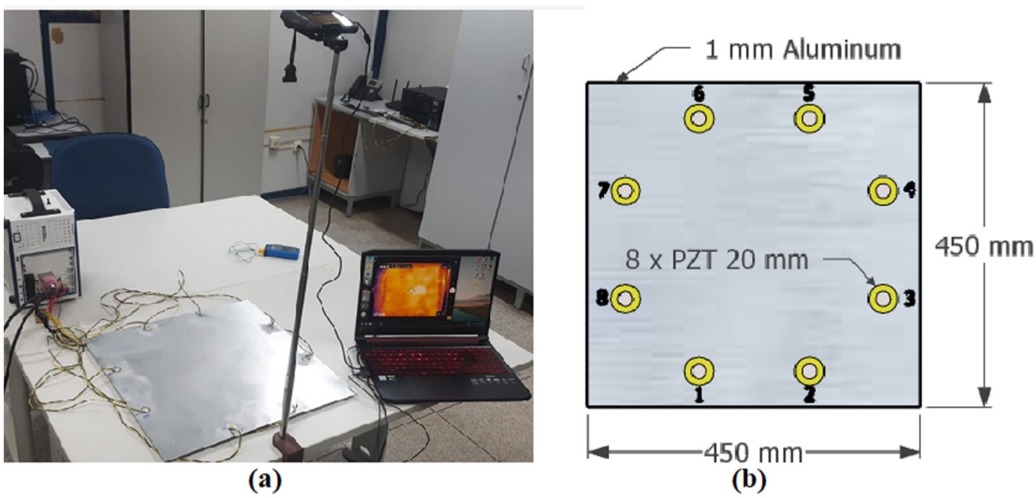


Figure 2. (**a**) Experimental setup. (**b**) Structure and position of the piezoelectric transducers.

To measure the electrical impedance of the transducers was used a multifunctional data acquisition (DAQ) device that generates a chirp signal with adjustable amplitude, step and frequency range to excite the transducers and simultaneously samples the response signals. The DAQ device is based on the NI-PXIe-1071 chassis with PXIE-5413 arbitrary waveform generator and PXIE-5105 8-channel oscilloscope. Control of the DAQ device, as well as signal processing, were performed using LabVIEW software.

The aluminum plate was heated with uniform and irregular temperature distribution. For different conditions, the CCDM index, as well as the EFS compensation method, were computed to analyze the temperature effects. The results are presented and discussed in the next section.

4. Results

The measurement system was set with amplitude of 10 V and sampling rate of 4 MHz, with a frequency step of 1 Hz to collect the impedance signatures in the frequency range from 1 Hz to 200 kHz. In a first test, the structure was heated evenly over its entire surface. In the following tests, the plate was heated irregularly. Baseline data were collected with the temperature in the laboratory at approximately 17 °C.

Figure 3a shows the thermal image of the plate uniformly heated to a temperature of 45 °C. The CCDM indices calculated for the eight sensors in relation to the baseline signature in 10 kHz sub-bands are shown in Figure 3b.

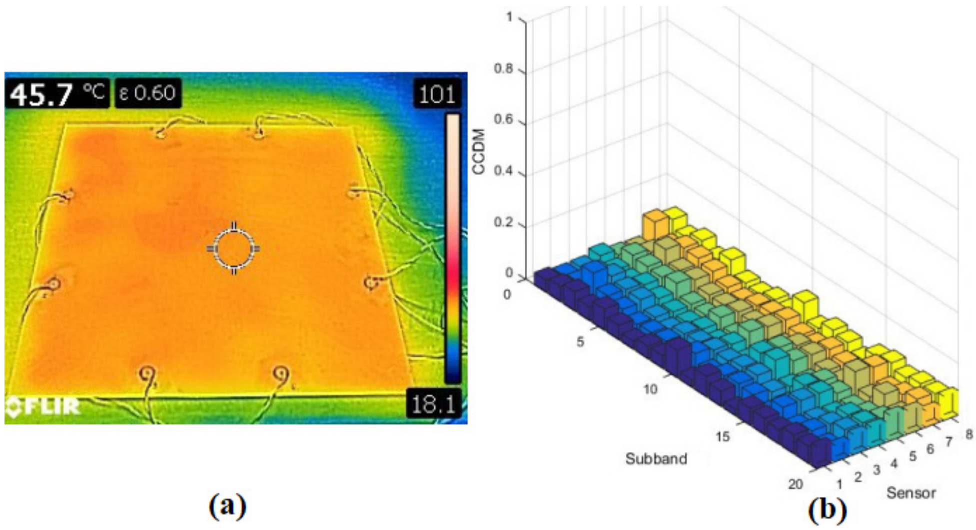
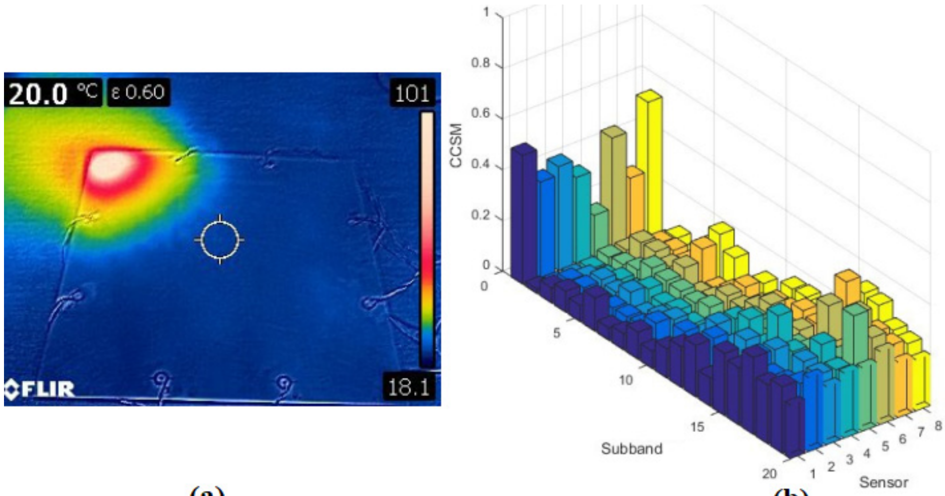


Figure 3. (**a**) Thermal image of the uniformly heated structure; (**b**) CCDM indices calculated after compensation with the EFS method.

It is important to note that CCDM indices were calculated after compensating the impedance signatures using the EFS algorithm. According to the results, despite the temperature variation, the CCDM indices were low for all eight transducers, remaining below 0.2. Although the temperature variation is significant, the heating is uniform throughout the structure. Consequently, the frequency and amplitude shifts in the impedance signatures are uniform, not causing changes in their shapes. Therefore, the EFS algorithm is effective in compensating the effects of temperature variation, making CCDM indices low and avoiding a false positive diagnosis of the monitored structure.

On the other hand, in practical applications, the heating of the structure may be irregular; that is, some parts may be hotter than others. In order to analyze the effects of the irregular temperature distribution, the plate was heated only in one of the corners between Sensors 6 and 7, according to the diagram shown in Figure 2b. The thermal image and CCDM indices obtained in this condition are shown in Figure 4a,b, respectively.



(a) (b)

Figure 4. (**a**) Thermal image of the heated plate in one of the corners between Sensors 6 and 7; (**b**) CCDM indices calculated after compensation with the EFS method.

As can be seen in Figure 4b, unlike the previous result, the CCDM indices obtained in the condition of irregular temperature distribution were significantly higher. The high CCDM indices are explained by changes in the shape of the impedance signatures due to irregular heating. As a consequence, variations in impedance signatures are similar to those caused by structural damage, making the EFS compensation method inefficient.

This situation can be critical in real applications, especially in the monitoring of large structures, where the structure can present parts with different temperatures. In this condition, the EFS compensation algorithm may not be feasible, leading to a false positive diagnosis.

5. Conclusions

In this paper, the effects of temperature on impedance-based structural health monitoring were experimentally investigated using an aluminum plate with eight piezoelectric diaphragms. Changes in amplitude and frequency of the impedance signatures were evaluated by heating the structure with significant temperature variation.

The experimental results showed that the variations in the frequency of the impedance signatures were successfully compensated in the aluminum plate whose temperature was applied uniformly over the entire structure. As expected, the compensation based on the frequency shift adjustment algorithm corrected the impedance signatures and showed damage indices very close to their baselines.

However, when the temperature was irregularly distributed throughout the structure, for example, heating only in one of its corners, the damage indices were significantly higher, even after applying the compensation algorithm. This result is due to changes in the shape of the signatures caused by irregular heating, making the compensation algorithm based on frequency shift inefficient.

The results presented in this article indicate that the effects of temperature variation is still a critical practical problem in the detection of structural damage based on the EMI method, especially when the monitored structure is irregularly heated. Therefore, new compensation techniques need to be investigated and proposed.

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