An Experimental Assessment of PZT Patches for Impedance-Based SHM Applications

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Abstract—In this paper, we present an alternative method for assessing the sensitivity of lead zirconate titanate (PZT) piezoceramics for damage detection in structural health monitoring (SHM) systems based on the electromechanical impedance (EMI) principle. An assessment of the sensitivity is obtained experimentally using the pencil lead break (PLB) method, which is frequently used in acoustic emission (AE) systems. Tests were carried out on an aluminum beam, and the results show a clear relationship between the damage indices obtained from the electrical impedance signatures of the PZT patch bonded to the monitored structure and the power spectral density (PSD) obtained using the PLB method.

Keywords: piezoceramics; PZT; structural health monitoring; SHM; pencil lead break; PLB; electromechanical impedance; EMI

I. INTRODUCTION

Recently, piezoelectric transducers have been studied for use in structural health monitoring (SHM) applications. The purpose of SHM systems [1] is to monitor a certain structure and detect damage at an early stage, increasing the efficiency of predictive maintenance and increasing user safety.

Damage detection should be based on the non-destructive testing (NDT) method for minimal invasiveness of the monitored structure and should not significantly alter the mechanical properties of the structure. The electromechanical impedance (EMI) technique is considered one of the most promising non-destructive methods mainly because it is simple and inexpensive. This method has been studied for decades, and several studies confirm its effectiveness in complex and lab-sized structures. SHM systems based on the EMI principle have the advantage of using low-cost, small and lightweight piezoelectric transducers. These devices are similar to adhesives attached to the monitored structure and are minimally invasive.

As with other methods for detecting damage, the piezoelectric transducers used in the EMI technique should be properly characterized to improve their sensitivity and reliability. An assessment method widely used in acoustic emission (AE) applications is the pencil lead break (PLB) method or pencil lead fracture (PLF) method. This work was supported by the São Paulo Research Foundation (FAPESP) grants 2012/10825-4, 2013/16434-0 and by PROPe-UNESP.

The experimental results show that there is a clear relationship between the PSD and damage indices, indicating that the PLB method can be a useful tool for experimentally assessing the sensitivity of the PZT patches for damage detection based on the EMI principle. The necessary background for the EMI and PLB methods is presented in the next sections.

II. EMI PRINCIPLE

The EMI technique is a very common and promising method used for damage detection in SHM applications for various types of structures [3]. This method uses the sensitivity capability of smart PZT materials and performs an inspection that will not destroy or compromise the mechanical properties of the monitored structure.

The EMI technique is essentially a vibration technique in which the piezoelectric transducer is excited, typically in the frequency range of 30-400 kHz. The basic principle is based on the electromechanical interaction between the mechanical impedance of the structure that will be monitored and the electrical impedance of the piezoelectric transducer that is
bonded to the structure [4]. The basic configuration is shown in Fig. 1.

In Fig. 1, the PZT patch is attached to the structure to be monitored. The patch is connected to a measurement system that provides its electric impedance ($Z_E(\omega)$) at a frequency $\omega$, which should vary within an appropriate frequency range. Thus, the measurement system should excite the PZT patch in a certain frequency range using an excitation signal, which can be, for example, a chirp signal (this type of signal performs a sweep from a low frequency to a high frequency). Therefore, in the EMI technique, the PZT patch operates both as an actuator and as a sensor and due to the piezoelectric effect, occurs an interaction between the electrical impedance of the patch and the mechanical impedance of the structure.

In the past, the electrical impedance measurements were performed using commercial impedance analyzers, including the 4192A and 4194A analyzers made by Agilent Technologies (Santa Clara, CA, USA) and Hewlett Packard (Palo Alto, CA, USA), respectively. These instruments provided high measurement accuracy. However, they are very expensive and have several functionalities that are not required in the EMI technique. Therefore, in the recent years, new measurement systems that are low cost and more accessible have been proposed.

A. Damage Detection and Quantification

The transducer in the EMI technique acts as both a sensor and as an actuator. Thus, many researchers have proposed models to study the relationship between the electrical impedance of the transducer and the mechanical impedance of the monitored structure. One of the most popular models was proposed by Liang et al. [5]. In this model, the electrical impedance of the transducer is given by:

$$Z_E(\omega) = \frac{1}{j\omega} \left( \varepsilon_{33} \tau - \frac{Z_a(\omega)}{Z_a(\omega) + Z_p(\omega)} d_{33}^2 E \right)^{-1}$$

where $Z_E(\omega)$ is the electrical impedance, $Z_a(\omega)$ is the mechanical impedance of the structure to be monitored, $Z_p(\omega)$ is the mechanical impedance of the transducer, $\omega$ is the frequency, $\tau$ is a geometric constant, $\varepsilon_{33}$ is the dielectric constant for a constant mechanical tension $T$, $\varepsilon_{xx}^p$ is the Young’s modulus for a constant electric field $E$, $d_{33}$ is the piezoelectric constant, and $j$ is the unit imaginary number.

According to (1), there is a relationship between the electrical impedance ($Z_E(\omega)$) of the transducer and the mechanical impedance ($Z_a(\omega)$) of the monitored structure. Therefore, any change in the mechanical impedance of the structure caused by damage, such as cracks or corrosion, implies a corresponding variation in the electrical impedance of the transducer, which is obtained using the appropriate measurement system.

The detection of structural damage is obtained from the two electrical impedance signatures of the transducer because one of the signatures is obtained when the structure is in a healthy condition. The analysis is performed using the appropriate indices. The damage index most widely used is the root mean square deviation (RMSD), which is given by:

$$RMSD = \sum_{k=\omega_i}^{\omega_f} \left[ \frac{Z_{E,D}(k)-Z_{E,H}(k)}{Z_{E,H}(k)} \right]^2$$

where $Z_{E,H}(k)$ and $Z_{E,D}(k)$ are the real part of the electrical impedance signatures acquired from the measurement system for the structure under healthy and damaged conditions, respectively, and are measured at a frequency $k$ that ranges from $\omega_i$ (the initial frequency) to $\omega_f$ (the final frequency). We used the real part of the impedance because it is known as the most sensitive part for detecting damage.

III. PENCIL LEAD BREAK METHOD

Generally, sensors have many obstacles and problems that influence the results. According to [6], the three main problems are the effect of the mounting conditions on sensitivity, the sensitivity of the sensor, and the degradation of the sensitivity and its method of evaluation. Thus, these factors result in measurement changes in the peak voltage and duration time of the signals acquired from the sensors.

The principle of the PLB method consists of breaking a pencil lead against the structure to be analyzed or against the rod where the sensor is installed. Breaking the pencil lead releases an impulsive stress and an elastic wave within a wide frequency spectrum. Thus, the PLB method is a simple and reliable way to obtain a wideband signal source, which is commonly used in AE applications to estimate the sensitivity of piezoelectric sensors and to perform their calibration. The basic experimental configuration is shown in Fig. 2.

The procedure consists of acquiring the voltage signal from the sensor using an appropriate instrument or data acquisition (DAQ) device while the pencil lead is broken. Then, the acquired signal is properly processed for analysis. The analysis is usually performed in the frequency domain. In this study, we performed the analysis in the frequency domain using the PSD. Because the stress released by breaking the pencil lead is impulsive and generates a wideband signal, it is necessary to use an antialiasing filter. For other applications, it may also be necessary to use amplifiers.

The lead length, lead diameter, and angle of the lead relative to the structure change the rupture force and

![Figure 1. Basic configuration of the EMI method.](image)

![Figure 2. Basic configuration of the PLB method.](image)
consequently the results [7]. Therefore, these factors should be taken into account to ensure a good reproducibility of the results. Because of its simple implementation and its popularity in laboratories, the American Society for Testing and Materials (ASTM) has adopted the PLB method as a standard E976 [8]. In this study, we looked for a relationship between the PLB method and the EMI technique for structural health monitoring systems. The experimental procedure is presented in the next section.

IV. EXPERIMENTAL SETUP

To confirm our conjecture, tests were performed on an aluminum beam with a length of 500 mm, a thickness of 3.18 mm, and a width of 38.10 mm. A square PZT ceramic patch of type 5H and a size of 15 mm x 15 mm x 0.267 mm was bonded at a distance of 20 mm from the end of the beam using cyanoacrylate glue.

Structural damage was induced by placing a nut on the beam at a distance of 100 mm from the PZT patch. We used a nut, representing the damage, with dimensions of 8 mm x 4 mm and a mass of 0.988 g, resulting in a mass load of 0.55%. The aluminum beam with the 5H PZT patch and the nut that we used to simulate the structural damage are shown in Fig. 3.

The electrical impedance of the PZT patch was measured using the system developed in [9], which uses a DAQ device with a sampling rate of 2 mega-samples/second (MS/s) and a personal computer. The PZT patch was excited using a chirp signal with an amplitude of 1 V. The measurement system was adjusted to provide electrical impedance signatures in the frequency range of 0-250 kHz with a step of 2 Hz.

The PLB method was performed using a mechanical pencil lead with a diameter of 0.5 mm and a length of 3 mm, and the contact angle between the lead and the specimens was 40° for all tests. The lead was broken at a distance of 100 mm from the PZT patch, which is the same distance as the nut placement for inducing structural damage. According to the E976 standard [8], a ring guide made of Teflon should be placed on the tip of the mechanical pencil to aid in breaking the lead consistently. However, in this study, we substituted the ring with a rubber hose. Fig. 4 illustrates this idea.

The results show that this configuration for the mechanical pencil provides consistent and reproducible signals. The voltage signals obtained with the PLB method were acquired using the DAQ device described above at a sampling rate of 2 MS/s. We used a passive antialiasing filter with a cutoff frequency of 584 kHz. This configuration provided reproducible and reliable data up to 250 kHz. All measurements were obtained for the specimens on a table with foam blocks and at room temperature.

The effectiveness of the PLB method to assess the sensitivity of the PZT patches to detect structural damage was analyzed by comparing the PSD obtained using the PLB method and the electrical impedance signatures using the RMSD index. The experimental results are presented in the next section.

V. RESULTS AND DISCUSSION

A. Signals Obtained Using the PLB Method

The voltage signal in the time domain acquired from the PZT patch using the PLB method is shown in Fig. 5. The analysis of the voltage signal was performed in the frequency domain by computing its PSD. The PSD was computed using the Welch method with a Hanning window of size 256 and an overlap of 50%. The corresponding PSD signal is shown in Fig. 6.
According to Fig. 6, the PSD is significantly higher for lower frequencies and decreases as the frequency increases. Furthermore, the PSD has maximum and minimum points throughout the frequency range analyzed.

B. Effectiveness of the PLB Method for the EMI Technique

In this work, we look for an experimental estimate of the sensitivity of the piezoelectric transducer to detect structural damage based on the EMI principle using the PLB test.

An effective way to evaluate the effectiveness of the PLB method for the EMI technique is by comparing the PSD with the RMSD index. The damage index was calculated using the real part of the electrical impedance signatures. Thus, Fig. 7 shows the impedance signatures acquired from the PZT patch that is bonded to the healthy (without the nut) and damaged (with the nut) aluminum beam.

From Fig. 7, we can infer that the damage causes changes in the electrical impedance, which are detected and quantified by the damage indices. To evaluate the variation of the indices with respect to the frequency, the RMSD index was calculated using (2) in sub-bands of 10 kHz and with an initial frequency ($\omega_1$) ranging from 0 to 240 kHz.

The RMSD indices are shown in Fig. 8. According to the results, there is a relationship between the PSD obtained from the PLB method shown in Fig. 6 and the damage indices obtained from the electrical impedance signatures shown in Fig. 8. The RMSD indices are significantly higher for low frequencies and are lower for frequencies above approximately 100 kHz. For frequencies above 200 kHz, the values are significantly lower. Therefore, the damage indices decrease as the frequency increases similarly as with the PSD, indicating that the PLB method may be a useful tool for assessing the PZT patches in SHM systems based on the EMI technique.

A more extensive study with additional theoretical and experimental results has been presented in [10].

VI. CONCLUSIONS

In this study, we propose an experimental assessment of PZT ceramics using the pencil lead break (PLB) method for damage detection in impedance-based SHM systems. Tests were performed on an aluminum beam with a 5H PZT patch. The results show conclusively that there is a good relationship between the power spectral density (PSD) obtained using the PLB method and the damage index computed using the electrical impedance signatures.

Therefore, the PLB method can be a useful tool for estimating the sensitivity for damage detection using the EMI technique.

REFERENCES


