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An Initial Study of Commercial Piezoelectric Diaphragms for Damage Detection Based on the Electromechanical Impedance Principle

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Abstract: Piezoelectric transducers have been extensively used in various applications in recent decades, such as in the non-destructive testing (NDT) of materials and structures. A piezoelectric transducer commonly used in NDT applications is lead zirconate titanate (PZT) ceramic, which is thin, lightweight, and minimally invasive to the structure. In this study, we analyzed the use of commercial piezoelectric diaphragms for damage detection based on the electromechanical impedance (EMI) method, which is an NDT technique used in structural health monitoring (SHM) applications. The commercial diaphragms have the advantages of being low cost and readily available. To assess their feasibility for damage detection, a low-cost diaphragm was compared with a conventional PZT ceramic with similar shape and dimensions. Tests were performed on aluminum beams, in which damage was simulated by placing a metallic bolt at different distances from the transducers. The sensitivity to damage was estimated using the correlation coefficient deviation metric (CCDM) index, which was calculated using the electrical impedance signatures obtained from each transducer. The experimental results indicate that the piezoelectric diaphragms are able to detect damage; therefore, this study provides an important contribution to the field of SHM systems based on the EMI method.

Keywords: piezoelectric transducers; diaphragm; SHM; damage detection; impedance

1. Introduction

Structural health monitoring (SHM) systems are able to monitor the health of various types of structures, detecting damage at an early stage. Damage is an adverse change that affects the present or future performance of structures. Therefore, the benefits of SHM systems are the improved safety of people who use or work with these structures, the considerable reduction in maintenance costs, and the ability to estimate the useful life of these structures [1,2].

In recent years, many techniques have been used to monitor the integrity of critical structures, such as bridges, dams, aircraft fuselages, pipelines, wind turbines, ships, oilrigs, and large machines, among others. The main objective of such techniques is to detect damage, such as cracks, corrosion, fatigue, and wear, preferably during the normal operation of the structure, thereby preventing interruption of the operation of the structure during the testing process.

The detection of the damage should be minimally invasive, using non-destructive testing (NDT) methods. One of the most promising NDT methods for damage detection in SHM systems is the electromechanical impedance (EMI) technique. The EMI technique has a simple methodology and uses small and lightweight piezoelectric transducers that do not significantly alter the mechanical properties of the monitored structure. The principle of the EMI method is based on the piezoelectric effect, which provides electromechanical coupling between the transducer and the monitored structure, thereby allowing for evaluation of the mechanical condition of the structure from the transducer electrical properties [3].

The type of piezoelectric transducer most commonly used in the EMI method is based on lead zirconate titanate (PZT) ceramics. In contrast, in this paper, we present an initial study of commercial piezoelectric diaphragms, commonly known as buzzers, for damage detection based on the EMI principle. Although previous studies [4] have reported the feasibility of these sound components to detect damage, a comparative analysis between piezoelectric diaphragms and conventional PZT ceramics with the same shape and similar dimensions is still required.

The background of the EMI method and the piezoelectric transducers used in this study are presented in the next section.

2. Electromechanical Impedance Method and Piezoelectric Transducers

2.1. Electromechanical Impedance Principle

The detection of damage based on the electromechanical impedance consists primarily of monitoring the variation of the mechanical impedance of the structure due to damage, such as cracks and corrosions, by measuring the electrical impedance of the transducer; this measurement is simple to perform.

There are various electromechanical models used to relate the electrical impedance of the piezoelectric transducer and the mechanical impedance of the monitored structure. Considering a one-dimensional model [5], which is suitable for small structures, such as aluminum beams, the electrical impedance of a PZT patch bonded to a structure is given by

$$Z_E(\omega) = \frac{1}{j\omega\tau}\left(\varepsilon_{33}^T - \frac{Z_S(\omega)}{Z_S(\omega)+Z_P(\omega)} d_{3x}^2 \hat{Y}_{xx}^E\right)^{-1} \tag{1}$$

where $Z_E(\omega)$ is the electrical impedance of the PZT patch, $Z_S(\omega)$ and $Z_P(\omega)$ are the mechanical impedance values of the host structure and the PZT patch, respectively, ε_{33}^T is the dielectric constant at a constant mechanical stress (*T*), $\hat{Y}_{xx}^E$ is the Young modulus at a constant electric field (*E*), d_{3x} is the piezoelectric constant, τ is a geometric constant, ω is the angular frequency, and *j* is the imaginary unit.

According to Equation (1), any variation in the mechanical impedance ($Z_S(\omega)$) of the structure caused by damage involves a corresponding variation in the electrical impedance ($Z_E(\omega)$) of the transducer. Therefore, structural damage can be detected by measuring and analyzing the electrical impedance of the transducer in a proper frequency range.

There are several methods for damage detection in SHM systems, such as Lamb waves [6] and acoustic emission [7]. However, the EMI method is known for its simplicity and its use of low-cost and lightweight piezoelectric transducers, allowing for multiple transducers to be installed in the structure, enabling a vast area to be monitored without significantly changing the characteristics of the host structure.

2.2. Damage Detection

As mentioned, the principle of the EMI method is to detect the variation of the mechanical impedance of the structure caused by damage by analyzing the electrical impedance of the piezoelectric transducer. This analysis is accomplished by measuring and comparing two electrical impedance signatures using damage indices, one of which is obtained for the healthy structure and used as a reference (the baseline). Therefore, the detection and quantification of structural damage can be directly performed through damage indices using the electrical impedance signatures obtained from a piezoelectric transducer installed in the host structure.

In this study, we used the correlation coefficient deviation metric (CCDM), which is an index commonly used in the literature. The CCDM index is given by

$$CCDM = 1 - \frac{\sum_{k=\omega_I}^{\omega_F}\left[\mathrm{Re}\left(Z_{E,H}(k)\right)-\overline{\mathrm{Re}}\left(Z_{E,H}\right)\right]\left[\mathrm{Re}\left(Z_{E,D}(k)\right)-\overline{\mathrm{Re}}\left(Z_{E,D}\right)\right]}{\sqrt{\sum_{k=\omega_I}^{\omega_F}\left[\mathrm{Re}\left(Z_{E,H}(k)\right)-\overline{\mathrm{Re}}\left(Z_{E,H}\right)\right]^2}\sqrt{\sum_{k=\omega_I}^{\omega_F}\left[\mathrm{Re}\left(Z_{E,D}(k)\right)-\overline{\mathrm{Re}}\left(Z_{E,D}\right)\right]^2}} \tag{2}$$

where Re designates the real part of the electrical impedance signature, $Z_{E,H}(k)$ and $Z_{E,D}(k)$ are the signatures for healthy and damaged structure, respectively, $\overline{\mathrm{Re}}\left(Z_{E,H}\right)$ and $\overline{\mathrm{Re}}\left(Z_{E,D}\right)$ are the averaged signatures under intact and damaged conditions, respectively, that are computed over a frequency range between ω_I (the initial frequency) and ω_F (the final frequency).

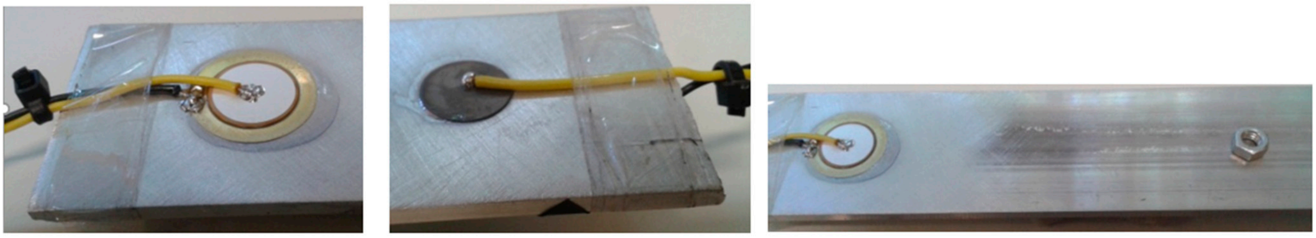
The real part of the signatures was used in this study to be more responsive to structural damage and provide higher indices [8].

2.3. Piezoelectric Transducers

The piezoelectric transducers most commonly used in SHM applications based on the EMI method are conventional PZT ceramics. These ceramics are available in thin plates with a thickness ranging from 0.1 to 2.0 mm and are coated on both sides with a nickel thin-film that constitute the electrodes. Typically, the ceramic is glued using epoxy or cyanoacrylate glue.

In this work, we performed an initial study of the applicability of piezoelectric diaphragms, commonly known as buzzers, for use in damage detection based on the EMI method. The piezoelectric diaphragm is a very simple and inexpensive sound component that has the primary function of providing sound signals in devices such as telephones, clocks and alarms. A buzzer is circular and has a brass base that protects the active element against breakage. This active element, which is a piezoelectric ceramic material, is coated by a metal film that constitutes one of its electrodes, with the base brass acting as the other electrode.

Figure 1 shows a conventional PZT patch and a piezoelectric diaphragm bonded to one of the aluminum beams used in this study.



(a) **(b)** **(c)**

Figure 1. (**a**) Piezoelectric diaphragm, "buzzer". (**b**) Conventional PZT ceramic. (**c**) Simulation of damage.

A piezoelectric diaphragm was analyzed, and the results of the analysis were compared with the results obtained using a conventional PZT ceramics. The experimental procedure is presented in the next section.

3. Experimental Setup

The tests were performed on two aluminum beams with dimensions of 500 mm × 38 mm × 3 mm. In the test setup, a conventional circular PZT ceramic, type 5A, with dimensions of 12.7 mm × 0.191 mm and a piezoelectric diaphragm with a brass plate of dimensions of 20.0 mm × 0.20 mm and an active element of dimensions of 14.0 mm × 0.22 mm are installed in each aluminum bar at a distance of 20 mm from their ends. Both transducers are fixed in the beams using cyanoacrylate glue, as shown in Figure 1.

Structural damage was simulated by adding a metal mass (nut) onto the beams at a distance ranging from 40 mm to 360 mm in steps of 80 mm from each transducer, as shown in Figure 1 (c). The nut has a mass of approximately 1 gram and dimensions of 8 mm × 4 mm. The impedance signatures were obtained using the measurement system developed in [9], which is based on LabVIEW software and a data acquisition (DAQ) device. We used a model NI-USB-6361 DAQ device, which was configured to excite the transducers with a chirp signal with amplitude of 1 V and a sampling rate of 2 MS/s. The signatures were obtained in a frequency range of 0–500 kHz with steps of 2 Hz.

4. Results and Discussion

Although the impedance signatures were obtained in a wide frequency range of 0–500 kHz, we must determine an appropriate sub-band that is sensitive to damage. Identification of this sub-band is a critical process; in this study, the proper frequency range was chosen experimentally by trial and error. Thus, the frequency range of 45–55 kHz was determined as the most sensitive to damage, providing high CCDM indices. A comparison between the real part of the impedance signatures obtained from the conventional ceramic and the piezoelectric diaphragm is shown in Figure 2 (a).

The impedance signatures obtained from the two transducers show similar trends and resonance peaks, indicating the similarity of characteristics and behavior of the two transducers. In general, the conventional ceramic provides more prominent resonance peaks with high amplitude. In addition, there are small differences in the shape of the signatures, probably due to the effect of the brass plate.

A more effective way to compare the two transducers for sensitivity to detect damage is using the damage indices. Figure 2 (b) shows the CCDM indices obtained for damage (nut) at different distances from the transducers.

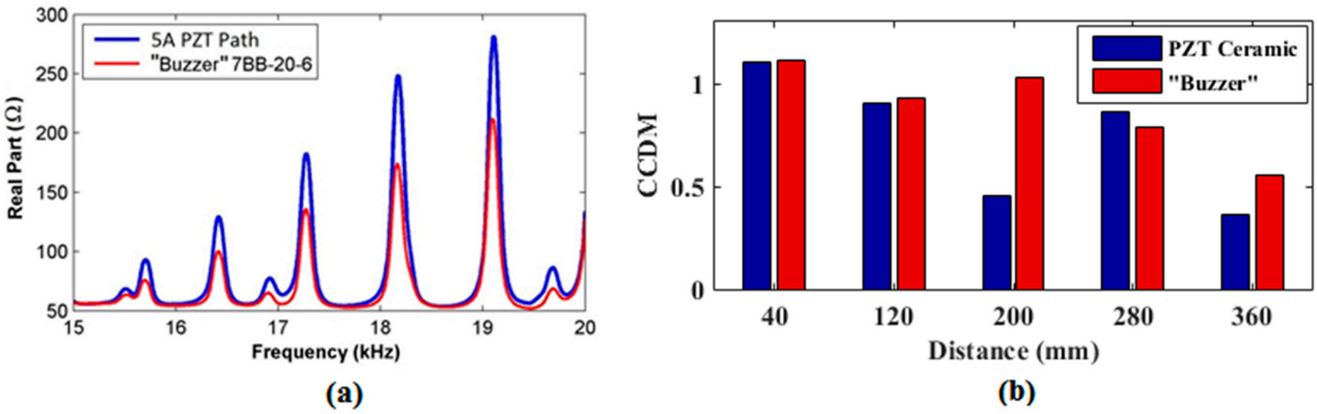


Figure 2. (**a**) Real part of the impedance signatures. (**b**) CCDM indices.

According to the results, both transducers provide similar CCDM indices. The two transducers provide indices with similar trends for different distances of damage, except for distances of 200 mm and 360 mm, where the diaphragm had provided significant higher indices. Therefore, the experimental results indicate that the piezoelectric diaphragms are feasible for use in damage detection based on the EMI method, providing similar results to those of a conventional PZT ceramic with similar dimensions.

5. Conclusions

This study analyzed the applicability of the piezoelectric diaphragms for damage detection based on the principle of electromechanical impedance. The results indicate that the diaphragm presents impedance signatures and damage indices similar to those of a conventional ceramic with similar dimensions.

Note that this work is an initial study, and only the impedance signatures over a narrow frequency range and a basic damage index were evaluated. Other important characteristics, such as temperature effects, frequency range and reproducibility of the results, require further research.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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