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Experimental Analysis of Piezoelectric Transducers for Impedance-Based Structural Health Monitoring

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Abstract: In this paper, we experimentally analyze the sensitivity of piezoelectric transducers for damage detection in structural health monitoring (SHM) systems based on the electromechanical impedance (EMI) method, which has been reported as one of the most promising methods for non-destructive detection of damage. Three types of transducers were evaluated: conventional 5H PZT (lead zirconate titanate) piezoceramics; macro fiber composite (MFC) devices; and piezoelectric diaphragms, which are commonly known as "buzzers". Tests were carried out on aluminum beams and the experimental results conclusively demonstrate that the transducers have different sensitivities for detection of structural damage and an appropriate frequency range for damage detection, which provides high sensitivity.

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

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1. Introduction

Structural health monitoring (SHM) systems have received increasing interest in recent years. These systems allow structural damage at an early stage are detected and quantified, thus increasing the safety of users and reducing maintenance costs. Among the application fields, there are the civilian infrastructure, such as bridges, and aerospace and aircraft structures.

The detection of damage must be performed by non-destructive testing (NDT) [1] using methods that are minimally invasive to the monitored structure. There are several NDT methods, such as the acoustic emission (AE), Lamb waves, comparative vacuum, eddy current, and the electromechanical impedance (EMI). The EMI method stands out from the other methods by its simplicity and by using lightweight and small size piezoelectric transducers (thickness in the order of fraction of a millimeter). These devices are like stickers on the monitored structure, allowing a large area of the structure to be monitored with the use of multiple sensors without significantly altering its mechanical properties. These characteristics make the EMI technique appropriate for monitoring aircraft structures [2, 3], in which there is greater concern about weight and aerodynamics.

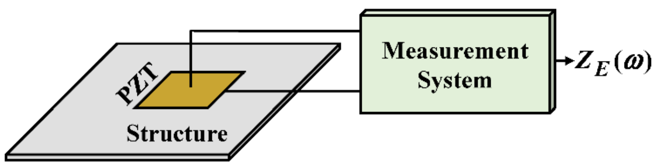
The piezoelectric transducers most commonly used in the EMI technique consist of a simple patch of PZT (lead zirconate titanate) ceramic. However, in recent years, other transducers have been used, such as the MFC (macro-fiber composite) devices and the piezoelectric diaphragms, commonly known as "buzzers". This study aims to experimentally assess these three types of piezoelectric transducers for damage detection based on the EMI method. The sensitivity of the transducers for damage detection was assessed by comparing the electrical impedance signatures in an appropriate frequency range and using damage indices.

Tests were carried out on aluminum beams and the electrical impedance signatures of the transducers were acquired in a frequency range of 0-500 kHz using a measurement systems based on a personal computer (PC) and a data acquisition (DAQ) device. The experimental results conclusively demonstrate that the transducers have different sensitivities for detection of structural damage. In addition, each transducer has an appropriate frequency range for damage detection, which provides high sensitivity. Therefore, the results presented in this paper allow selecting appropriately the piezoelectric transducer according to the application and the suitable frequency range in impedance-based SHM systems.

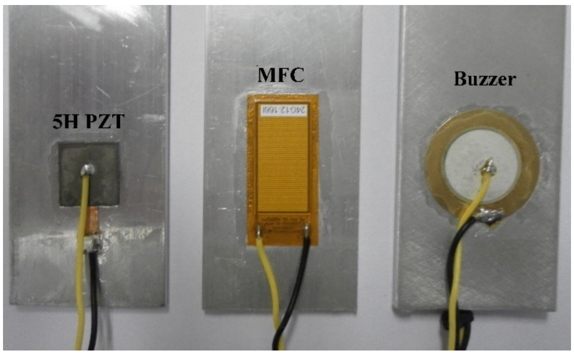
2. Damage Detection Based on the EMI Method

A basic experimental configuration of the EMI method used in this study is shown in Figure 1 (a), where a thin PZT patch is bonded to the structure to be monitored.

Figure 1. (**a**) Basic experimental configuration of the EMI method. (**b**) Aluminum beams with 5H PZT patch, MFC transducer, and piezoelectric diaphragm (buzzer).



(a)



(b)

The measurement system [4] consists essentially of a data acquisition (DAQ) device and a personal computer (PC) running the LabVIEW software. The DAQ device simultaneously excites the transducer through an excitation signal with an appropriate frequency range and acquires the corresponding response signal. The excitation and response signals are processed in the frequency domain using the fast Fourier transform (FFT) on the PC, which provides the electrical impedance signatures on the appropriate frequency range.

Therefore, in the EMI method, the transducer operates simultaneously as an actuator and a sensor, and, due to the piezoelectric effect, an interaction occurs between the electrical impedance of the transducer and the mechanical impedance of the structure. Many researchers have proposed electromechanical models to relate these two quantities. For a one-dimensional (1D) assumption, the electrical impedance of the transducer is given by [5]

$$Z_E(\omega) = \frac{1}{j\omega C_0} \left\| jZ_T \left(\frac{s_{11}}{d_{31}\ell} \right)^2 \left[\frac{1}{2}\tan\left(\frac{k\ell}{2} \right) - \frac{1}{\sin(k\ell)} + \frac{Z_S}{j2Z_T} \right] \right. \tag{1}$$

where $Z_E(\omega)$ is the electrical impedance, ω is the angular frequency, C_0 is the static capacitance for a square PZT patch of size ℓ, k is the wave-number, Z_T is the mechanical impedance of the piezoelectric patch, Z_S is the mechanical impedance of the monitored structure, d_{31} is the piezoelectric constant, s_{11} is the compliance at a constant electric field, $\|$ indicates a parallel connection, and j is the unit imaginary number.

According to Equation (1), there is a relation between the electrical impedance of the transducer and the mechanical impedance of the monitored structure. Thus, any variation in the mechanical impedance of the structure due to structural damage, such as a crack or corrosion, causes a corresponding variation in the electrical impedance of the transducer. Therefore, the structural integrity can be assessed by measuring the electrical impedance, which is easier to perform than the measurement of the mechanical impedance. The detection and quantification of structural damage is performed by comparing two electrical impedance signatures of the transducer in an appropriate frequency range, where one of the signatures is obtained when the structure is in a condition considered healthy. This comparison is performed using damage indices and the real part, imaginary part, or the magnitude of the electrical impedance signatures can be used.

The most widely used damage indices are the root mean square deviation (RMSD) and the correlation coefficient deviation metric (CCDM). The RMSD index is based on the Euclidean norm and is given by

$$RMSD = \sum_{k=\omega_I}^{\omega_F} \sqrt{\frac{\left[Z_{E,D}(k) - Z_{E,H}(k) \right]^2}{Z^2{}_{E,H}(k)}} \tag{2}$$

where $Z_{E,H}(k)$ and $Z_{E,D}(k)$ are the electrical impedance signatures (*i.e.*, the magnitude, the real part or the imaginary part) for the structure under healthy and damaged conditions, respectively, and are measured at a frequency k that ranges from ω_I (the initial frequency) to ω_F (the final frequency).

The CCDM index is based on the correlation coefficient and is simply calculated as follows:

$$CCDM = 1 - C_C \tag{3}$$

where C_C is the correlation coefficient [6].

Therefore, the EMI method allows that the health of the structure is evaluated in a simple way by comparing two electrical impedance signatures in a suitable frequency range using damage indices.

In this study, we analyzed the sensibility of different piezoelectric transducers to detect structural damage by comparing the damage indices obtained for different frequency ranges. The experimental procedure is presented in the next section.

3. Experimental Setup

Tests were performed on three aluminum beams with dimensions of 500 x 38 x 3 mm. For each beam, a type of transducer was bonded at a distance of 30 mm from its end. We used three types of transducer: a 5H PZT patch with dimensions of 15 x 15 x 0.267 mm, a MFC transducer model M2814-P2 with dimensions of 37 x 18 mm, and a piezoelectric diaphragm (buzzer) with external diameter of 27 mm. The transducers were bonded to the aluminum beams using cyanoacrylate glue. The beams were supported on a table through small rubber blocks to minimize the effects of any external vibrations. The three specimens with the piezoelectric transducers are shown in Figure 1 (b).

Structural damage was induced in the structures by placing a small steel nut with dimensions of 11 x 0.5 mm and a mass of approximately 1 g at a distance of 50 mm from the transducers. The mass loading produced variations in the mechanical impedance of the structures and could consequently be related to the structural damage.

The measurement of the electrical impedance of the transducers was performed using a system [4] based on a multifunction DAQ device, LabVIEW, and a PC. The DAQ used in the tests was a NI USB-6361 with a sampling rate of 2 MS/s (mega-samples/second), and the transducers were excited using a chirp signal with amplitude of 1 V in a frequency range of 0–500 KHz with a frequency step of 2 Hz.

4. Results and Discussion

As mentioned before, the damage detection can be performed using the magnitude, the real part or the imaginary part of the electrical impedance. In this study, we used the real part, which is known in the literature as the most sensitive to damage and less sensitive to temperature variations. The real part of the electrical impedance signatures obtained from the three transducers are shown in Figure 2. Although the signatures have been acquired in a frequency range of 0-500 kHz, a narrower band is shown to allow a reasonable analysis.

According to Figure 2, there are resonance peaks in the signatures related to the natural frequencies of the structures. Structural damage (nut) causes variations in frequency and amplitude in these peaks, which can be quantified by indices of damage. In addition, the peaks are more significant at low frequencies and tend to decrease as the frequency increases.

The PZT patch has provided impedance signatures with higher amplitude. On the other hand, impedance signatures with lower amplitude were obtained using the MFC transducer. The piezoelectric diaphragm provided impedance signatures with intermediate amplitude between the other two transducers.

Figure 2. Real part of the electrical impedance signatures.

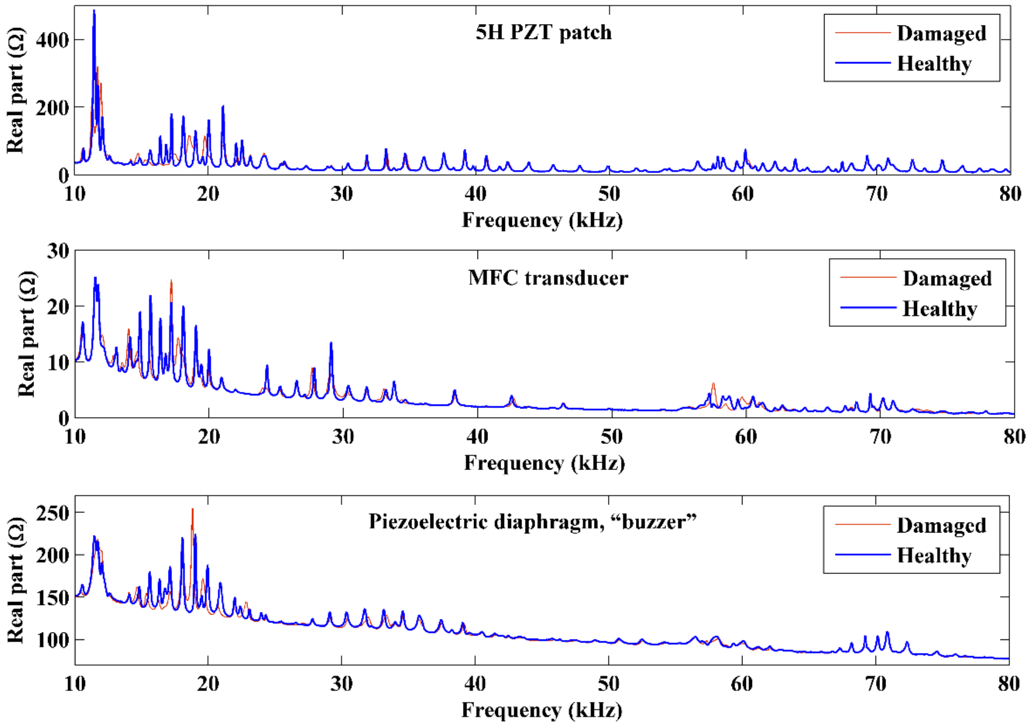
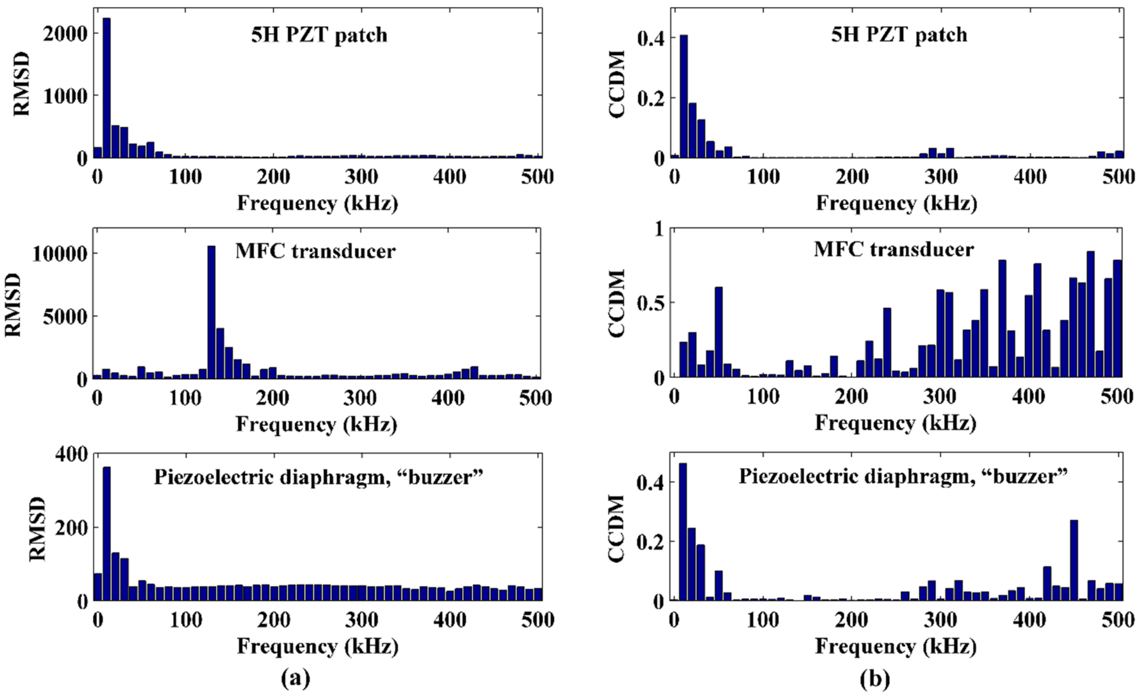


Figure 3. (**a**) RMSD indices. (**b**) CCDM indices.



The changes in the impedance signatures due to structural damage can be better compared and quantified using the RMSD and CCDM indices. The indices were calculated over the entire frequency range of 0-500 kHz using sub-bands of 10 kHz. Figure 3 shows the (a) RMSD and (b) CCDM indices obtained for the three transducers. The PZT patch and the diaphragm provided the highest indices for low frequencies around approximately 10-70 kHz. On the other hand, the MFC transducer provided higher indices at high frequencies. The piezoelectric diaphragm showed a reasonable sensitivity to detect damage, although the indices were lower compared to other transducers. However, this device has the advantage of having a very low cost.

4. Conclusions

In this paper, we experimentally analyze three types of piezoelectric transducers for damage detection based on the electromechanical impedance (EMI) method. The experimental results indicate that the transducers have different sensitivities to detect damage and the sensitivity varies significantly with the frequency range. However, it is important to note that this study does not consider an important feature of the transducers for the EMI method, which is to provide repeatable and consistent impedance signatures. The reproducibility of the results is especially important for the EMI method, since the damage detection is performed by comparing two impedance signatures.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Giurgiutiu, V. Embedded NDT with Piezoelectric Wafer Active Sensors. In *Nondestructive Testing of Materials and Structures*; Buyukozturk, O., Tasdemir, M.A., Gunes, O., Akkaya, Y., Eds.; Springer: Dordrecht, Netherlands, 2013; Volume 6, pp. 987–992.
2. Pavelko, V. Electromechanical Impedance for SHM of Aircraft Bolted Joints. In Proceedings of SPIE 8694, Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2013, San Diego, CA, USA, 10 March 2013; SPIE: USA, pp. 869410_1-14.
3. Rosiek, M.; Dragan, K.; Martowicz, A.; Uhl, T. Damage detection in riveted aircraft elements based on the electromechanical impedance measurements. *Key Engineering Materials* **2014**, 588, 54–63.
4. Baptista, F.G.; Vieira Filho, J. A new impedance measurement system for PZT based structural health monitoring. *IEEE Transactions on Instrumentation and Measur*ement **2009**, 58, 3602–3608.
5. Baptista, F.G.; Vieira Filho, J.; Inman, D.J. Sizing PZT transducers in impedance-based structural health monitoring. *IEEE Sensors Journal* **2011**, 11, 1405–1414.
6. Baptista, F.G.; Budoya, D.E.; Almeida, V.A.D.; Ulson, J.A.C. An experimental study on the effect of temperature on piezoelectric sensors for impedance-based structural health monitoring. *Sensors* **2014**, 14, 1208–1227.