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Experimental Study Employing EMI-based Piezoelectric Diaphragms to Detect Water Leakages in PVC Pipes

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Abstract. Considering the increased demand for using natural resources sustainably, water is an ultra-valuable resource to be preserved. Notwithstanding, Polyvinyl Chloride (PVC) pipes, which are mainly used in complex building water distribution systems, are still in use and present a considerable rate of water loss. Unfortunately, the recently developed Structural Health Monitoring (SHM) has not deeply covered leaks in those pipes.

To fill this gap, this approach proposes an experimental study to assess the feasibility of using Lead Zirconate Titanate (PZT) diaphragms to detect water leaks in these structures. Experimental tests were conducted by attaching one PZT diaphragm to a mini-scale water distribution system, where the leakage scenarios were simulated by opening taps. To attest to the effectiveness of the methodology, it calculated statistical metrics between the baseline (without leaks) and unknown conditions. The experimental results are promising and may be extrapolated to detect water losses in a full-scale water-distributing system.

Keywords: Monitoring Systems, PZT, Impedance Signatures, Water Distribution

Introduction

In a scenario where awareness of the need to use natural resources sustainably grows every day, water is an ultra-valuable resource to be preserved. On the other hand, Water Distribution Systems (WDSs) usually present high loss rates. Therefore, developing new systems that could detect and minimize water loss makes up a paramount strategy for a sustainable environment. To this end, some solutions simply evaluate losses in WDSs by comparing the volume of treated water injected into the system with the total water billed by the company. However, several reasons can masquerade the real loss, such as leaks in transmission and distribution piping, reservoirs, and service connections; unauthorized consumption (water theft); social water consumption (not charged by the supply company), and measurement errors caused by poor calibrations of water meters. A study presented in [1] highlights that losses are always defined from the water distribution company's

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perspective, instead of the customer's. From the user's perspective, the fundamental loss is caused by a lack of water and disruptions of service.

Structural Health Monitoring (SHM) systems have played a pivotal role in detecting water leaks, impacting positively the continuity, resilience, and economic standpoints in WDSs. Several attempts can be found in the literature to tackle this problem. A study utilizing acoustic emissions with wireless noise loggers, using Machine Learning (ML) algorithms, proposed inspection models for in-service and buried WDNs. They monitored pipes for about two years and the results demonstrated success in various scenarios [2]. ML alongside vibration analysis was also applied in [3]. In [4], the authors addressed the main challenges of non-destructive testing methods for sewer pipes. Methods such as stereo vision, Light Detection and Ranging (LiDAR), and laser 3D scanning technologies were also described. Despite the advances, the authors suggested that visual inspection techniques are the most feasible for the evaluation of underground pipes. A neural network approach was applied to SCADA data to identify leaks in WDNs. That framework used a sensor priority list based on the proximity of the pressure sensor placed in the system to localize the leaks. The authors concluded that the method could localize leaks in a search radius of 300m without recourse to a hydraulic model [5]

According to [6], Polyvinyl Chloride (PVC) has been widely used due to its high durability, corrosion resistance, low price, and easy installation. The authors also addressed an unseen review of SHM applied to PVC pipes. They discussed different methods, which include active sound waves, fibre optic sensing, hydraulic vibration, and multiple discrete sensors methods. They mentioned that the most common faults in PVC pipes are ductile and brittle. Although PZT sensors are widely used to detect faults in PVC pipes, they are used mostly as sensors and actuators separately. On the other hand, the Electromechanical Impedance (EMI) also employs PZT transducers, but a single transducer is used as both actuator and sensor at the same time. Using EMI to monitor pipes does not constitute a novelty. For example, in [7] the authors proposed modelling, simulation, and experimental study to compensate for the effects of temperature in the EMI signatures. However, they used steel pipes instead. EMI has been also applied to detect corrosion in pipes [8].

As posed above, the literature clearly shows a lack of studies to detect water losses on PVC pipes, especially if considering the EMI-based method. Accordingly, this approach proposes an experimental study to assess the feasibility of using PZT diaphragms to detect water leaks in these structures. Experimental tests were conducted by attaching one PZT to a mini-scale WDNs, where the leakage scenarios were simulated by opening taps. Results demonstrated promising to detect water losses in PVC pipes.

1. Electromechanical Impedance

PZT transducers are widely used in SHM applications, covering both low and high frequencies methods. PZT ceramics have many advantages over other materials, such as good electromechanical coupling, good stability, high rigidity, linear response to low-intensity electric fields, and low-cost [9]. According to [10], piezoelectric diaphragms consist of a metallic disk, that acts as a support and bottom electrode, on which is mounted a piezoelectric ceramic disk. The active element is covered by a thin metallic film serving as the top electrode. The main constructive difference between a piezoelectric diaphragm and a conventional ceramic is the presence of the brass disk [10]. The diaphragms are low-cost, easy to buy, light, and manufactured in different sizes.

By applying an electric field to the PZT diaphragm, a mechanical deformation is created (actuator). On the other hand, when mechanical stress is exerted on it, an electrical charge is generated on the surface of the ceramic (sensor). This electromechanical behaviour of the linear PZT piezoelectric transducer can be characterized as follows [11].

$$\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} s^E & d_t \\ d & \varepsilon^t \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \tag{1}$$

Where S, T, E, D, s, d, ε are mechanical deformation, mechanical tension, the electric field, charge density, complacency, piezoelectric deformation constant, and permittivity, respectively. The first line of the matrix (Eq. (1)) refers to the inverse effect and the second to the direct effect of the piezoelectric transducer [11].

Taking advantage of both effects, these transducers are used in SHM systems in the different phases of structural monitoring. Once a PZT is glued to the monitored structure, by using based on cyanoacrylate or an epoxy resin, it presents an electromechanical coupling, allowing the mechanical responses of the structure to be analyzed based on the electrical properties of the PZT transducer. This method is known as the Electromechanical Impedance (EMI) technique [12]. Considering that a PZT is excited by a sinusoidal voltage source V with amplitude *v* and angular frequency ω, it generates a current I with amplitude *i* and phase Φ. The electrical impedance of the transducer (Z_e) can be obtained by [12]

$$Z_e(w) = \frac{V}{I} = \frac{1}{jwa}\left(-\varepsilon_{33}^T - \frac{z(w)}{z(w)+z_a(w)}\, d_{3x}^2\, Y_{xx}^E\right)^{-1} \tag{2}$$

where j, a, ε_{33}^T, Z, Z_a, d_{3x}^2, Y_{xx}^E, Z_e are an imaginary unit, geometric constant, dielectric constant at constant mechanical stress, the mechanical impedance of the monitored structure, mechanical impedance of the transducer piezoelectric constant, Young’s modulus at a constant electric field, and electrical impedance, respectively. According to Eq. (2), changes in the structure will modify the system impedance, in turn causing a variation in the electrical impedance of the PZT transducer (Z_e)[13], [14].

From the set of impedance signatures measured, statistical metrics such as Root Mean Square Deviation (RMSD) and Correlation Coefficient Deviation Metric (CCDM) can be calculated to form indicators of structural damage. The RMSD between two impedance signatures can be calculated by the following equation.

$$RMSD = \sum_n^N \sqrt{\frac{(Z_{n,u} - Z_{n,h})^2}{(Z_{n,h})^2}} \tag{3}$$

where $Z_{n,h}$ and $Z_{n,u}$ are the electrical impedance signatures of the transducer with the undamaged structure (healthy), and in the unknown state, respectively. Both measures in the frequency n, where N is the total number of frequencies analyzed. Similarly, the CCDM metric is given by

$$CCDM = 1 - \left| \frac{\sum_n^N [Z_{n,h} - \bar{Z}_h]\,[Z_{n,u} - \bar{Z}_u]}{\sqrt{\sum_n^N [Z_{n,h} - \bar{Z}_h]^2}\,\sqrt{\sum_n^N [Z_{n,u} - \bar{Z}_u]^2}} \right| \tag{4}$$

where $Z_{n,h}$, $Z_{n,u}$, $\bar{Z}_h$, $\bar{Z}_u$ are the electrical impedance signatures of the transducer with the undamaged structure (healthy), and in the unknown condition, the average of observations for healthy conditions, and the average of the observations for the unknown state, respectively. Both measures in the frequency n, where N is the total number of frequencies analyzed. From those metrics, thresholds can be set to incur if the structure is damaged or healthy.

2. Experimental Procedure

This section describes the experimental apparatus used to investigate the feasibility of detecting water leaks in PVC pipes by employing the EMI technique. Firstly, two PZT transducers were attached to two different pipes, as shown in Figure 1. To identify the most suitable range of frequencies, two different scenarios, comprehending destructive and non-destructive, were considered (see Figure 1). A hole was made in the pipe for the first scenario, whilst a lit cap was attached to the pipe to simulate the non-destructive condition.

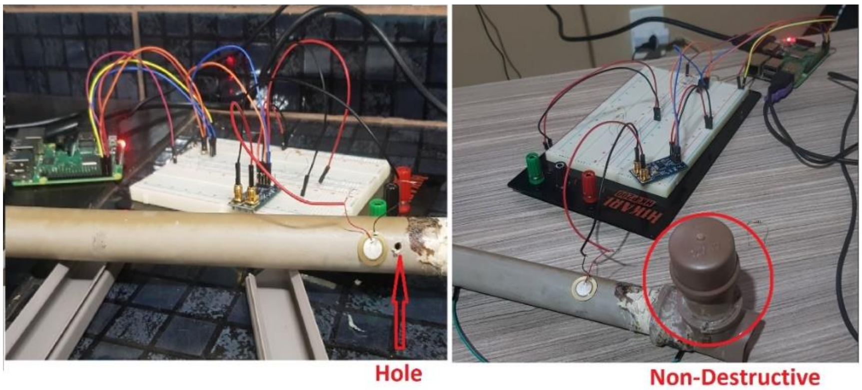

Fig. 1. Experimental setup considering two damage scenarios: destructive and non-destructive.

The impedance measurements were carried out using the system proposed by [15]. This system uses a PmodiAI device managed by a Raspberry Pi. Figure 2 shows the connection diagram for the measurement system. One calibration resistor of 1kΩ was employed. This system can measure three PZTs based on a multiplexer integrated circuit 4066 [15]. For this application, it was only used one PZT. It was considered to ranges of frequency ranging from 20kHz to 60kHz and from 20kHz to 100kHz.

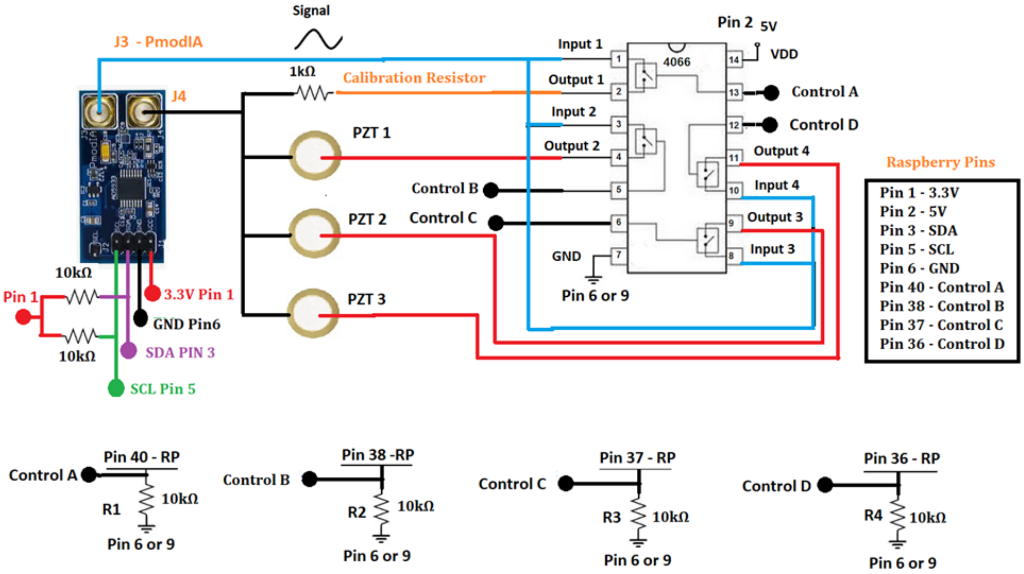

Fig. 2. Connection block for the measurement of impedance signatures.

Lastly, one PZT transducer was attached to a system of flowing water composed of PVC pipes and four taps. This setup allows us to carry out different test scenarios and simulate leaks in the network. Starting from left to right, the first tap is called the flow tap, which will always be open during monitoring to simulate the water flowing to supply the demand (distribution network), since the water in the distribution ducts will unlikely remain static. The subsequent taps, called 1, 2, and 3, are used to simulate losses in the system. There is also a pressure sensor that is connected to the system to measure the pressure in the input of the system. The idea was to keep the pressure in the pipes constant to simulate small damage (low loss of pressure). This pressure sensor is connected to a universal converter that has a display where it is possible to visualize the pressure in meters of water. Figure 3 shows the water network and the acquisition system (PmodIA and Raspberry Pi).

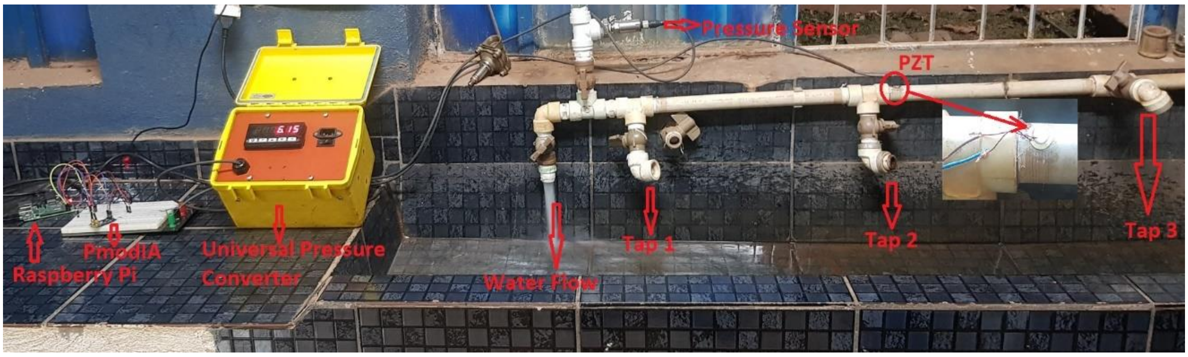

Fig. 3. Small-scale water distribution network used to assess the proposed method.

With the structure ready to be monitored, the system was first calibrated with the 1kΩ resistor [15]. Following the same procedures described in the previous experiment, tests were then carried out in different frequency ranges. However, the frequencies range from 20kHz to 60kHz was selected. It is important to mention that for all scenarios, the flow tap was used to set the desired pressure in the pipe. Eight conditions scenarios (monitoring scenarios) were considered by applying a combination of opening/closing taps, 1, 2, and 3, as summarized in Table 1. The scenario where the three taps are closed was considered healthy (no leak).

Table 1. Description of scenarios for monitoring water pipelines.

Scenarios	**Tap 1**	**Tap 2**	**Tap 3**	**Pressure**
– M1 (no leaks)	– Closed	– Closed	– Closed	– 0.61 bar
– M2	– Closed	– Open	– Closed	– 0.49 bar
– M3	– Open	– Closed	– Closed	– 0.52 bar
– M4	– Closed	– Closed	– Open	– 0.51 bar
– M5	– Open	– Open	– Closed	– 0.40 bar
– M6	– Closed	– Open	– Open	– 0.41 bar
– M7	– Open	– Closed	– Open	– 0.41 bar
– M8	– Open	– Open	– Open	– 0.30 bar

3. Results and Discussion

The impedance signatures obtained for the first test scenarios (see Figure 1) are presented in Figure 4. This figure also presents the comparisons of pipes monitoring for non-destructive and destructive damages with previously defined baseline signatures (healthy).

Figures 4(a) and 4(c) show that there is a prominent resonant peak at a frequency close to 35kHz when taking into consideration the frequency ranges in analysis. For the case of destructive damage signatures (Figures 4(b) and 4(d)), one can observe not only variations in amplitude but also a frequency shift, especially in the range of frequency from 25kHz to 35kHz (Figure 4(b)). Considering the destructive damage signatures, the amplitude peaks occur mainly in the range of frequencies from 20kHz to 60kHz.

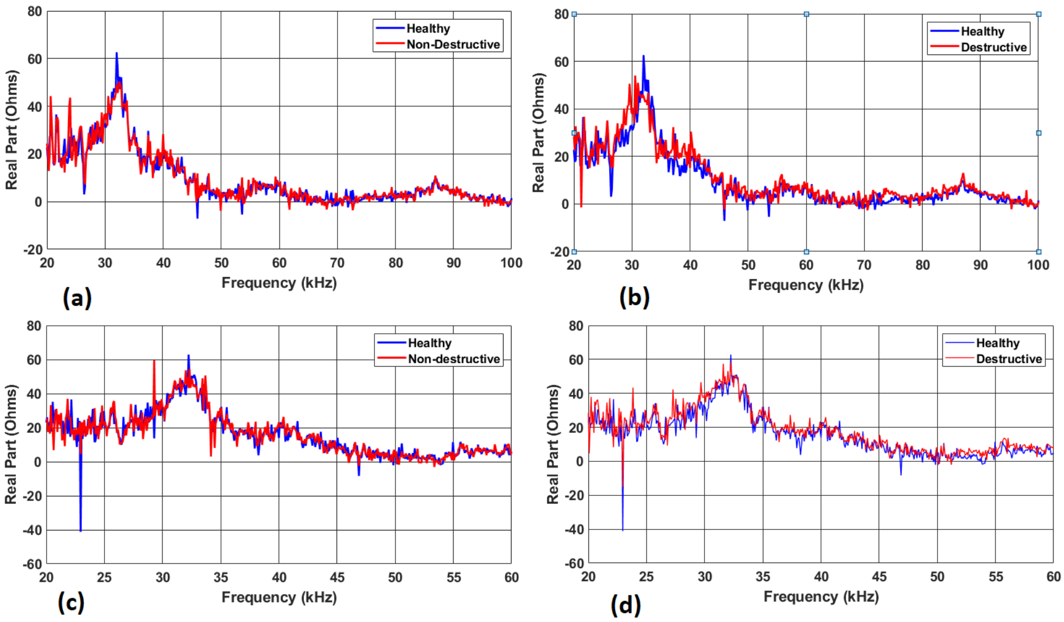

Fig. 4. Impedance signatures considering healthy scenarios versus destructive and non-destructive damages for frequency: (a)-(b) from 20-100kHz; (c)-(d) from to 60kHz.

For the impedance signatures presented in Figure 4, the RMSD and CCDM metrics were calculated by applying Eqs. 3 and 4. The healthy structural condition was used as a reference (baseline). The results are presented in Figure 5.

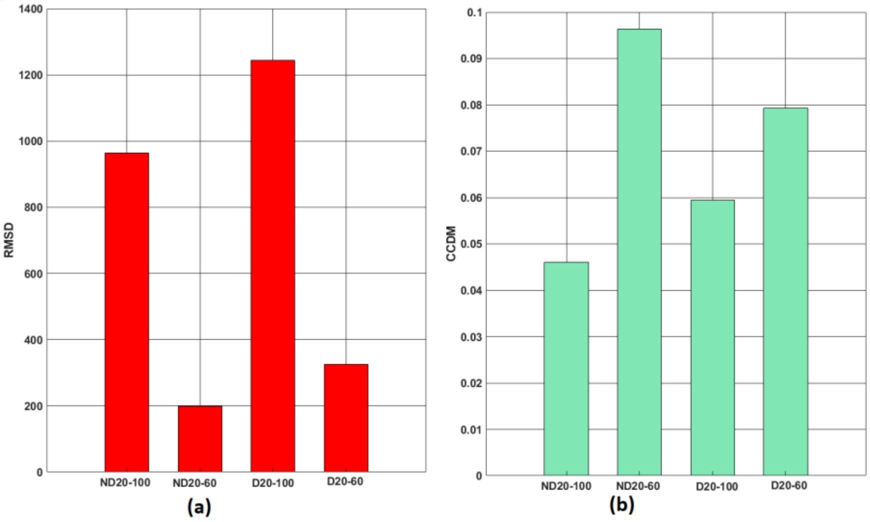

Fig. 5. Damage metrics for destructive and non-destructive conditions considering the range of frequencies of 20-60kHz and 20-100kHz: (a) RMSD; (b) CCDM.

The metrics obtained (see Figure 5) match with the results obtained in Fig. 4, where the variations occurred more to amplitudes, thus it is expected that the RMSD metrics (Figure 5(a)) are more sensitive to this type of variation. On the other hand, the CCDM (Figure 5 (b)) values are smaller, demonstrating a weak correlation between the EMI signatures (leak and non-leak). Also, the destructive damage (D) metrics were higher than the non-destructive damage (ND), except for the CCDM in the frequency range from 20kHz to 60kHz.

Lastly, the PVC network was monitored. Leaks were simulated by opening different taps (see Table 1 and Figure 3). Figure 6 shows the impedance signatures for taps 1, 2, and 3 opened (M8). Furthermore, the “healthy” state (Scenario M1) is presented. It can be seen there are subtle differences between M1 and M8 scenarios, mainly due to the reduction in the amplitude of the resonance and anti-resonance peaks.

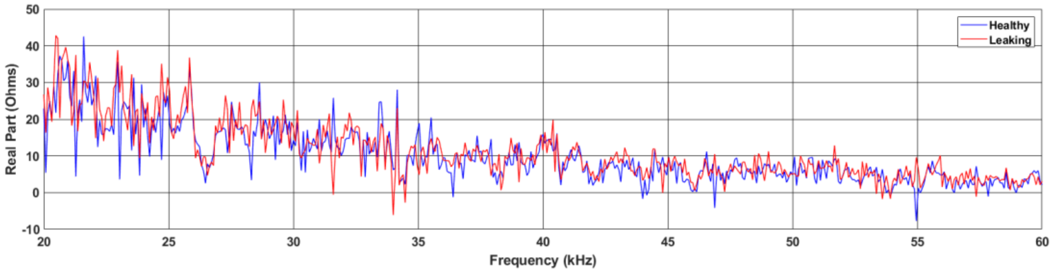

Fig. 6. Impedance signatures considering all taps closed (M1) and all taps open (M8).

To achieve the objective proposed by this work, of employing PZT diaphragms to identify leaks in PVC pipes using the EMI technique, RMSD and CCDM metrics were calculated considering all scenarios presented in Table 1. The results obtained are presented in Figure 7. It is important to mention that the metrics were determined considering the scenario named M1 (Table 1) as a reference (baseline).

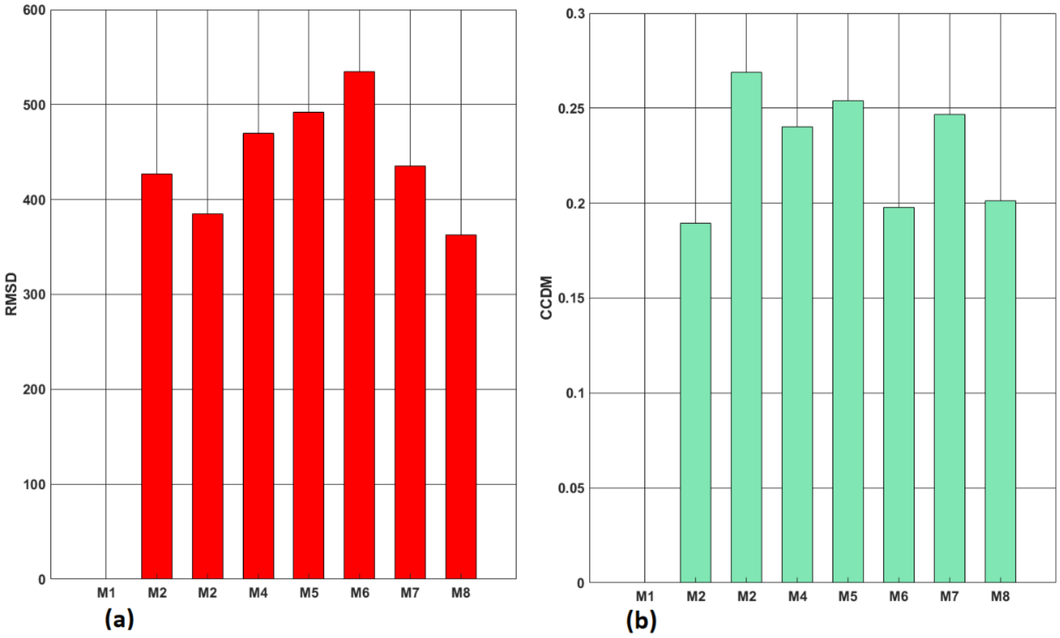

Fig. 7. Leak metrics for all scenarios: (a) RMSD; (b) CCDM.

As can be seen in Figure 7, the metrics presented subtle variations for the different scenarios. However, the damage detection could be well addressed since the differences between M1 ("no leak") and others ("leak") are clear. Again, the CCDM presented lower indices, which represent a low correlation. On the other hand, the RMSD presents higher values because impedance signatures vary more in amplitude. The location of the leak is unlikely to be addressed in this method since the metrics are very close to each other. This certainly emphasizes that the proposed method can be employed successfully in the detection of water leaks in PVC pipes.

4. Conclusion

This experimental study proposed using an EMI-based method applied to detect water leaks in PVC pipes. Based on the statistical metrics obtained, thresholds could be easily set to detect leaks in that structure. This work adds a new study perspective, as it is characterised by a low-cost method, due to the use of piezoelectric diaphragms and an acquisition system based on Raspberry Pi hardware. Unlike the commonly used methods where pressure and flow are assessed, for this approach, the monitoring is carried out through the electromechanical impedance signatures measured from the set PZT/pipe. Therefore, the behaviour of the structure, and not the water, is assessed directly. Since the method performed well with the structure built from PVC pipes, which present a low wave propagation, it could be extrapolated to assess metal pipelines that are commonly used by water companies. It could be also a relevant application in buildings, condominiums, and residences that primarily use PVC pipes.

References

[1] B. B. Azevedo and T. A. Saurin, "Losses in Water Distribution Systems: A Complexity Theory Perspective," *Water Resources Management*, vol. 32, no. 9, pp. 2919-2936, 2018/07/01 2018, doi: 10.1007/s11269-018-1976-7.

[2] A. Fares, I. A. Tijani, Z. Rui, and T. Zayed, "Leak detection in real water distribution networks based on acoustic emission and machine learning," *Environmental Technology*, vol. 44, no. 25, pp. 3850-3866, 2023/11/10 2023, doi: 10.1080/09593330.2022.2074320.

[3] T. Yu, X. Chen, W. Yan, Z. Xu, and M. Ye, "Leak detection in water distribution systems by classifying vibration signals," *Mechanical Systems and Signal Processing*, vol. 185, 2023, doi: 10.1016/j.ymssp.2022.109810.

[4] Y. Wang, P. Li, and J. Li, "The monitoring approaches and non-destructive testing technologies for sewer pipelines," *Water Sci Technol*, vol. 85, no. 10, pp. 3107-3121, May 2022, doi: 10.2166/wst.2022.120.

[5] H. M. Tornyeviadzi and R. Seidu, "Leakage detection in water distribution networks via 1D CNN deep autoencoder for multivariate SCADA data," *Engineering Applications of Artificial Intelligence*, vol. 122, 2023, doi: 10.1016/j.engappai.2023.106062.

[6] V. Q. C. Tran, D. V. Le, D. R. Yntema, and P. J. M. Havinga, "A Review of Inspection Methods for Continuously Monitoring PVC Drinking Water Mains," *IEEE Internet of Things Journal*, vol. 9, no. 16, pp. 14336-14354, 2022, doi: 10.1109/jiot.2021.3077246.

[7] R. A. Antunes, N. E. Cortez, B. M. Gianesini, and J. Vieira Filho, "Modeling, Simulation, Experimentation, and Compensation of Temperature Effect in Impedance-Based SHM Systems Applied to Steel Pipes," *Sensors*, vol. 19, no. 12, pp. 2802-2802, 2019/6// 2019, doi: 10.3390/s19122802.

[8] A. Thoriya, T. Vora, and P. Nyanzi, "Pipeline corrosion assessment using electromechanical impedance technique," *Materials Today: Proceedings*, vol. 56, pp. 2334-2341, 2022/01/01/ 2022, doi: https://doi.org/10.1016/j.matpr.2021.12.030.

[9] B. Lin and V. Giurgiutiu, "Modeling and testing of PZT and PVDF piezoelectric wafer active sensors," *Smart Materials and Structures*, vol. 15, no. 4, pp. 1085-1093, 2006.

[10] L. M. Campeiro, D. E. Budoya, and F. G. Baptista, "Lamb wave inspection using piezoelectric diaphragms: An initial feasibility study," *Sensors and Actuators A: Physical*, vol. 331, p. 112859, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.sna.2021.112859.

[11] S. O. R. Moheimani and A. J. Fleming, *Piezoelectric Transducers for Vibration Control and Damping*. London: Springer, 2006.

[12] C. Liang, F. P. Sun, and C. A. Rogers, "Coupled electro-mechanical analysis of adaptive material systems - determination of the actuator power consumption and system energy transfer," *Journal Intelligent Material Systems and Structures*, vol. 5, no. 1, pp. 12-20, 1994.

[13] M. de Oliveira, A. Monteiro, and J. Vieira Filho, "A New Structural Health Monitoring Strategy Based on PZT Sensors and Convolutional Neural Network," *Sensors*, vol. 18, no. 9, pp. 2955-2955, 2018, doi: 10.3390/s18092955.

[14] M. A. de Oliveira and D. J. Inman, "Performance analysis of simplified Fuzzy ARTMAP and Probabilistic Neural Networks for identifying structural damage growth," *Applied Soft Computing*, vol. 52, pp. 53-63, 2017/3// 2017, doi: 10.1016/j.asoc.2016.12.020.

[15] M. de Oliveira, R. Nascimento, and D. Brandao, "A New Real-Time SHM System Embedded on Raspberry Pi," in *European Workshop on Structural Health Monitoring*, Cham, P. Rizzo and A. Milazzo, Eds., 2023// 2023: Springer International Publishing, pp. 386-395.