Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25148

200 (2020) 8–13
October

Verification of pressure sensing sensitivity via EMI measurement of an external pipe for a membrane integrity test

Won-Kyu Kim[a], Junkyeong Kim[b], Yong-Soo Lee[c,*], Seunghee Park[d,*]

[a]*Department of Convergence Engineering for Future City, Sungkyunkwan University, S. Korea*
[b]*Research Strategy Team, Advanced Institute of Convergence Technology, S. Korea*
[c]*Department of Civil and Environmental Engineering, Hanyang University, S. Korea, Tel. +82-10-7491-0808; Fax: +82-2-2220-1945; email: rokmc907@gmail.com (Y.-S. Lee)*
[d]*School of Civil, Architectural Engineering & Landscape Architecture, Sungkyunkwan University, S. Korea, Tel. +82-10-3585-0825; Fax: +82-502-032-1076; email: shparkpc@gmail.com (S. Park)*

Received 1 July 2019; Accepted 18 November 2019

ABSTRACT

Membrane filtration is a technology that removes contaminants or impurities from water by passing water through membranes; it has various applications such as in water and sewage treatment. However, a disadvantage of this method is that it has difficulties responding to cases of accidental water pollution or membrane damage. Therefore, membrane damage should be monitored to prevent the contamination of drinking water. In this study, the membrane integrity test was performed by measuring the high-frequency electromechanical impedance (EMI) using a piezoelectric sensor. An attached piezoelectric sensor can detect changes in the physical properties of the membrane due to inner pressure changes. During the pressure decay test, the pressure drop due to membrane damage can be determined by measuring the EMI through an attached piezoelectric sensor. A real-scale test was performed to verify the proposed technology. During the experiment, 20 measurements were taken at each pressure step to increase reliability. According to the results, membrane damage can be monitored by detecting microscopic pressure drops using our proposed method.

Keywords: Membrane damage; Membrane integrity test; Electro-mechanical (EMI); Piezoelectric sensor; Pressure decay test

1. Introduction

Because water is the most essential element for human life, water and wastewater treatment technologies are continuously being developed for more effective and efficient water treatment. In this context, studies on membrane filtration techniques that can compensate for the shortcomings of the sand filtration technique, one of the most widely used methods for water purification, are being actively conducted. Membrane filtration is a technology that removes contaminants or impurities in water bypassing the water through a membrane and is used in various water treatment processes. Although it has the advantages of removing suspended substances and various pathogenic microorganisms to satisfy the target water quality even in a small area, it has difficulty coping with cases of accidental water pollution or membrane damage. Therefore, monitoring membrane damage to prevent the contamination of drinking water is crucial. In general, the integrity of the membrane is periodically checked to verify the reliability of the membrane module [1]. Techniques for evaluating membrane integrity are largely divided into direct and indirect methods. The direct method is applied to the membrane module, such as sound wave or acoustic detection [2] and porosity measurement [3]. Experiments conducted to prevent such situations are classified as membrane integrity tests.

---

* Corresponding authors.

The pressure decay test (PDT), which is performed by sequentially decreasing the pressure inside the membrane module, is the most commonly used direct method of detecting membrane damage [4,5]. However, the disadvantages of this method include relying on the value displayed on the pressure gauge and the long time required to detect the change in pressure. Recently, a high-frequency dynamic response measurement method using piezoelectric sensors has been proposed for structural health monitoring [6–11]. High-frequency dynamic response measurement techniques using piezoelectric sensors have attracted attention as potential tools for implementing embedded monitoring systems for the maintenance and management of infrastructure facilities. This technique uses high frequencies, usually higher than 20 kHz, from piezoelectric sensors attached to the surface to observe changes in the mechanical properties of the host structure. In this study, the PDT was performed through an electromechanical impedance (EMI) measurement using a piezoelectric sensor to overcome the method's limitations. To confirm the applicability, experiments were conducted on membrane modules in actual water sources. A piezoelectric sensor was attached to the steel pipe connected to the membrane module to measure the change in EMI during the PDT to investigate the correlation between the pressure drop and the change in impedance.

2. EMI measurement using a piezoelectric sensor

2.1. Piezoelectric sensor

In this study, a piezoelectric sensor was used for the EMI measurement during the PDT. Piezoelectric sensors have the ability to mutually convert electrical and mechanical energy, so that they can serve as both an actuator and a sensor [12,13]. Until now, piezoelectric sensors have been mainly used for structural health monitoring to detect physical changes such as structural corrosion, buckling, bolt loosening, and external cracks. For this reason, the piezoelectric sensor was adopted under the assumption that the physical characteristics of the steel pipe would be changed by the internal pressure change during the PDT. In this study, a lead zirconate titanate (PZT) patch was used as a piezoelectric sensor to generate vibrations and to measure the frequency response of the steel pipe, as shown in Fig. 1. The sensor used is Navy II type APC 850 PZT, and the size and main characteristics are shown in Table 1. The PZT patch itself has an anode and a cathode. When PZT is attached to a steel pipe, a wire connection with the cathode is impossible, so the copper paste is used to connect the cathode of the PZT as shown in Fig. 2. The input signal is a linear chirp signal, and a 10 μF ceramic capacitor is used to construct the self-sensing circuit.

Fig. 1. Navy II type APC 850 PZT.

2.2. EMI measurement of the external pipe

Currently, EMI methods are primarily used to detect structural defects such as corrosion and cracks. When the PZT patch is attached to the surface of the steel pipe (host structure) and an alternating voltage is applied to the PZT, the vibration generated by the PZT is transmitted to the steel pipe. The mechanical impedance response caused by the vibrations transmitted to the surface is shown in Fig. 2. Through the mechanical coupling between the PZT and the steel pipe and the electromechanical transformation of the PZT itself, the structural impedance reflects the electrical impedance. The EMI of the PZT, as coupled to the host structure, is given by Park et al. [14].

$$Z(\omega) = \frac{1}{i\omega C}\left(1 - \kappa_{31}^2 \frac{k_{\text{str}}(\omega)}{k_{\text{PZT}} + k_{\text{str}}(\omega)}\right)^{-1} \quad (1)$$

where $Z(\omega)$ is the EMI, C is the zero-load capacitance of the PZT, κ_{31} is the electromechanical coupling factor of the PZT, $k_{\text{str}}(\omega)$ is the dynamic stiffness of the structure, and k_{PZT} is the stiffness of the PZT. Therefore, because the pressure change in the pipe changes the dynamic stiffness of the pipe, the pressure change in the pipe can be observed by measuring the EMI of the pipe [15]. In this study, an EMI measurement system based on a self-sensing technique was used with a single PZT sensor. The EMI was measured using a self-sensing circuit board consisting of a single PZT patch and a voltage divider (capacitor) to obtain the output voltage as shown in Fig. 3 [16–19]. The self-sensing circuit

Table 1
Properties of the attached PZT material

Size (mm)			Electromechanical coupling factor		Piezoelectric charge constant (10^{-12} m/V)	
Width	Height	Thickness	κ_{31}	κ_{33}	d_{31}	d_{33}
10.00	10.00	0.508	0.36	0.72	–175	400

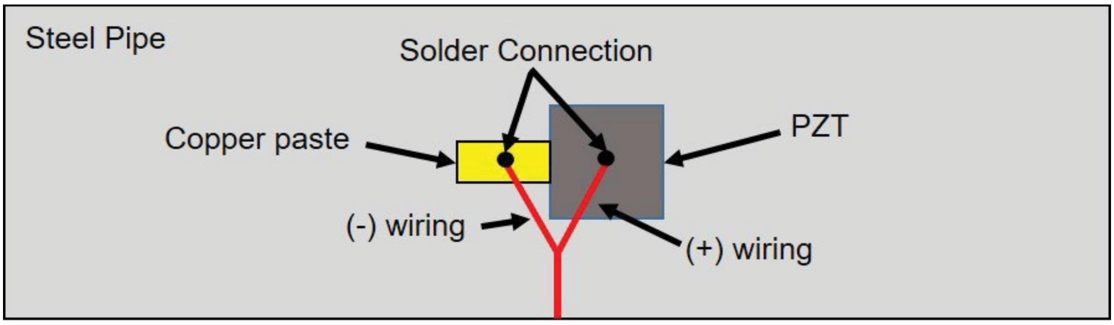

Fig. 2. Configuration of the attached PZT sensor.

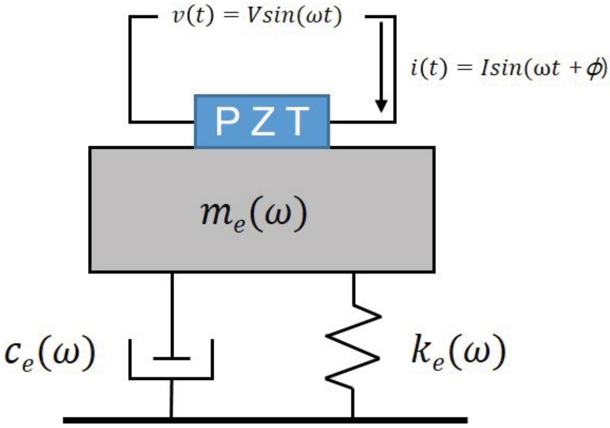

Fig. 3. Electromechanical coupling between the host structure and the PZT.

using the PZT sensor shown in Fig. 4 is suitable for use in the external pipe, because it is less expensive than other impedance measurement methods, even though the accuracy is slightly lower.

3. Experimental verification

3.1. Experimental setup and test procedure

To verify the proposed technique, field experiments were conducted on membrane modules in an actual water source. As shown in Fig. 5, one PZT patch was attached to the steel pipe connected to the membrane module for the EMI measurement. The EMI was measured using NI-DAQ equipment consisting of an arbitrary waveform generator (AWG) and a digitizer, as shown in Fig. 6. The experiment was carried out in a total of 11 steps. After setting the initial pressure inside the membrane module to 1.7 bar, the PDT was conducted by decreasing the pressure by 0.02 bar increments, and 20 EMI measurements were performed for each pressure step.

The sampling rate for digitizing the analog data (the number of data pointers measured per second) was set at 10^6. The capacity of the capacitor used was 10 nF.

3.2. Experimental results

Fig. 7 shows the results of the EMI change measurements during the PDT.

The major peak of the EMI was found between 250 and 260 kHz, and the magnified portion shows that the amplitude decreases as the pressure drops. The result of a linear regression analysis using the acquired data is shown in Fig. 8.

As shown in Fig. 8, the maximum amplitude of the EMI decreases as the pressure decreases from 1.6 bar. Through these experimental results, it was proven that a minute pressure drop in the membrane module could be confirmed by measuring the EMI using a PZT sensor.

4. Conclusions and discussions

In this study, a PZT sensor was used to verify pressure sensitivity by measuring the EMI of an external pipe in a membrane integrity test. Through the EMI measurement, the mechanical characteristics of the host structure were converted into electrical characteristics, and the change in pressure was visually confirmed; therefore, the state of the

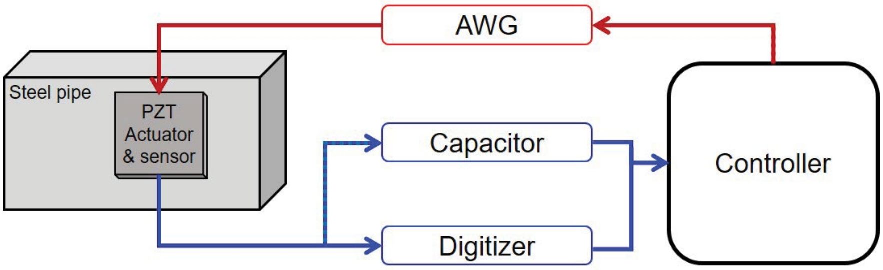

Fig. 4. Schematic diagram of the EMI measurement based on a self-sensing circuit.

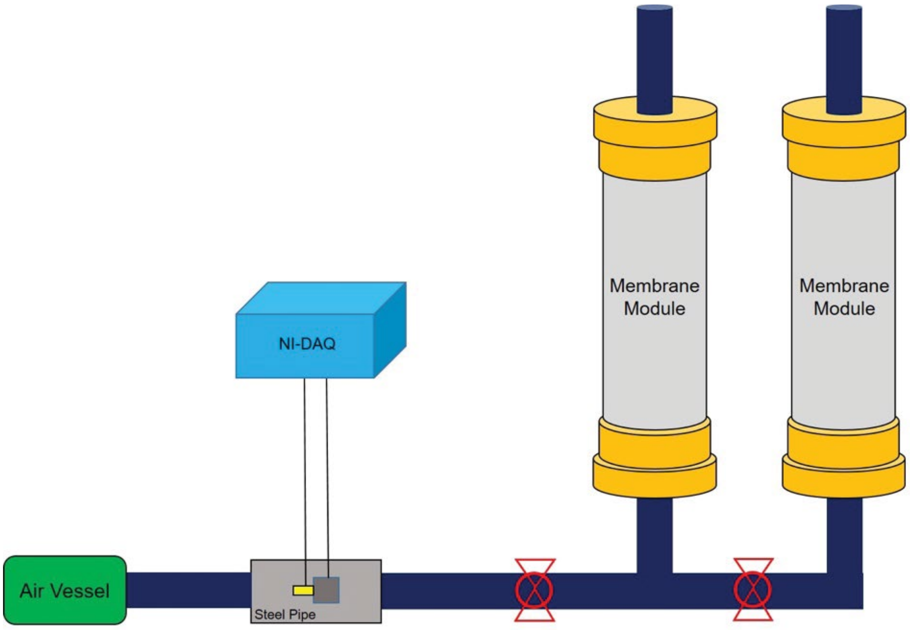

Fig. 5. Configuration of the test setup.

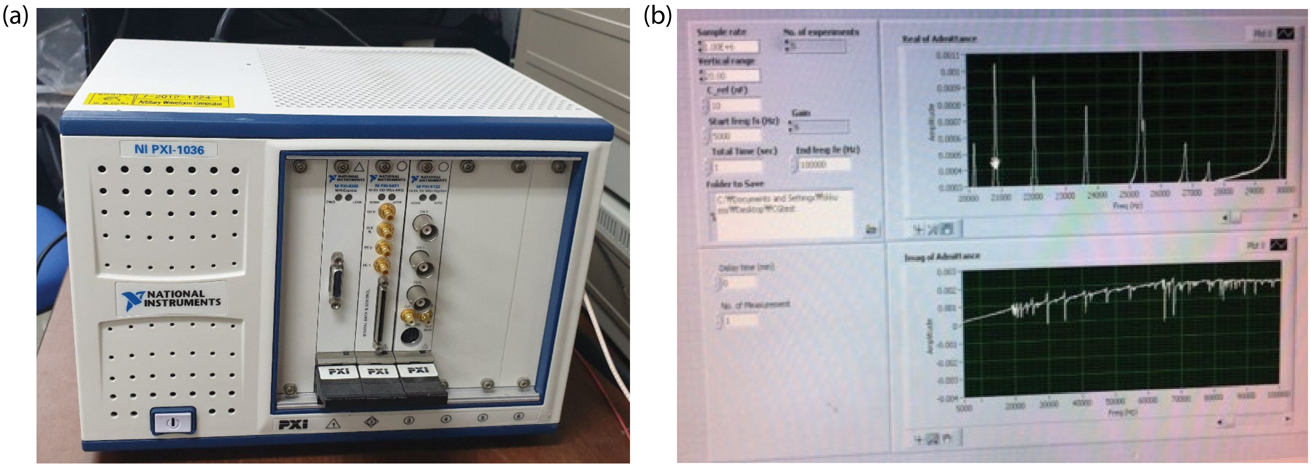

Fig. 6. Equipment setup (a) NI-DAQ equipment and (b) EMI measurement algorithm.

membrane module could be recognized using this technique. To verify the proposed technique, field experiments were conducted using membrane modules located in an actual water source. To increase reliability, 20 EMI measurements were performed at each pressure stage. During the PDT, the amplitude of the impedance also decreased as the pressure dropped from a certain range. Through a linear regression analysis of the amplitude, it is possible to observe changes in the EMI due to even a small pressure alteration. Although it was not possible to obtain visible data in all pressure sections of the experiment, it was possible to improve the pressure sensitivity because successful measurements were obtained in some sections. This result proved that microscopic damage on a membrane module can be detected by the proposed method. Most of the existing membrane damage detection experiments were applied directly to the membrane module. In this study, however, the experimental procedure could be simplified by applying it to an external pipe. In this study, the experiment was conducted on an external pipe connected only to two modules. In the future, we will be conducting experiments on pipes with more modules in other sites, which will further increase the pressure detection sensitivity. In addition, it will be able to replace the pressure gauge and could be developed for the wireless constant monitoring system. Furthermore, based on data obtained from additional experiments, it is expected that this study will be a great addition to the membrane damage diagnosis technologies.

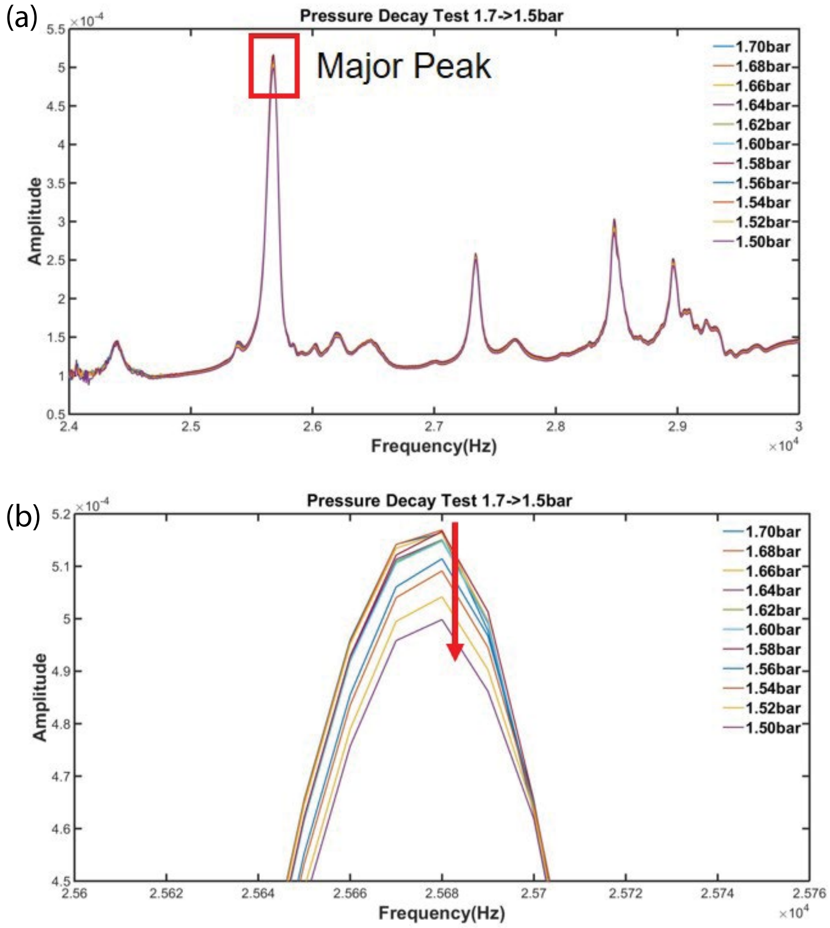

Fig. 7. EMI measurement data (a) major peak of the EMI and (b) EMI change due to pressure drop.

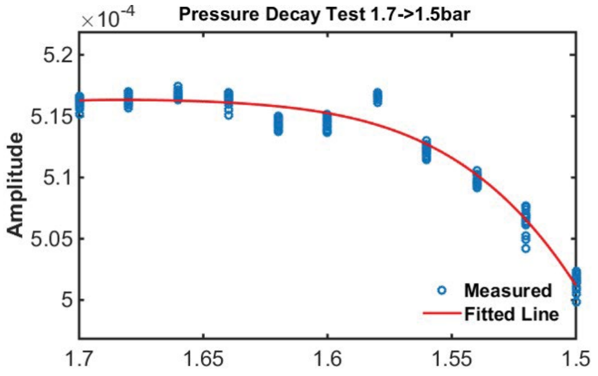

Fig. 8. Linear regression analysis of major peak changes.

Acknowledgment

This subject is supported by the Korea Ministry of Environment as “Global Top Project (2016002100004)”.

References

[1] J. Phattaranawik, A.G. Fane, F.S. Wong, Novel membrane-based sensor for online membrane integrity monitoring, J. Membr. Sci., 232 (2008) 113–124.

[2] J.M. Laîne, K. Glucina, M. Chamant, P. Simonie, Acoustic sensor: a novel technique for low pressure membrane integrity monitoring, Desalination, 119 (1998) 73–77.

[3] M.W. Phillips, A.J. Di Leo, A validatable porosimetric technique for verifying the integrity of virus-retentive membranes, Biologicals, 24 (1996) 243–253.

[4] G.F. Crozes, S. Sethi, B.X. Mi, J. Curl, B. Mariñas, Improving membrane integrity monitoring indirect methods to reduce plant downtime and increase microbial removal credit, Desalination, 149 (2002) 493–497.

[5] W.B. Krantz, C.S. Lin, P.C.Y. Sin, A. Yeo, A.G. Fane, An integrity sensor for assessing the performance of low pressure membrane modules in the water industry, Desalination, 283 (2011) 117–122.

[6] C. Liang, F.P. Sun, C.A. Rogers, Coupled electro-mechanical analysis of adaptive material systems – determination of the actuator power consumption and system energy transfer, J. Intell. Mater. Syst. Struct., 5 (1994) 12–20.

[7] V. Giurgiutiu, A. Reynolds, C.A. Rogers, Experimental investigation of E/M impedance health monitoring for spot-welded structural joints, J. Intell. Mater. Syst. Struct., 10 (1999) 802–812.

[8] G. Park, H.H. Cudney, D.J. Inman, Impedance-based health monitoring of civil structural components, J. Am. Soc. Civ. Eng., 6 (2000) 153–160.

[9] G.H. Park, H. Sohn, C.R. Farrar, D.J. Inman, Overview of piezoelectric impedance-based health monitoring and path forward, Shock Vib. Dig., 35 (2003) 451–463

[10] C.G. Lee, J.Y. Kim, S.H. Park, D.-H. Kim, Advanced fatigue crack detection using nonlinear self-sensing impedance technique

for automated NDE of metallic structures, Res. Nondestr. Eval., 26 (2015) 107–121.

[11] J.Y. Kim, C.G. Lee, S.H. Park, Artificial neural network-based early-age concrete strength monitoring using dynamic response signals, Sensors, 17 (2017), doi: 10.3390/s17061319.

[12] T.-K. Oh, J.Y. Kim, C.G. Lee, S.H. Park, Nondestructive concrete strength estimation based on electro-mechanical impedance with artificial neural network, J. Adv. Concr. Technol., 15 (2017) 94–102.

[13] C.G. Lee, S.H. Park, J.E. Bolander, S.H. Pyo, Monitoring the hardening process of ultra high performance concrete using decomposed modes of guided waves, Constr. Build. Mater., 163 (2018) 267–276.

[14] S.H. Park, D.J. Inman, J.-J. Lee, C.-B. Yun, Piezoelectric sensor-based health monitoring of railroad tracks using a two-step support vector machine classifier, J. Infrastruct. Syst., 14 (2008) 80–88.

[15] Y.-S. Lee, J.Y. Kim, C.G. Lee, S.H. Park, Applicability investigation of piezoelectric sensor-based damage detection technique for membrane, Desal. Water Treat., 143 (2019) 24–28.

[16] S.J. Lee, H. Sohn, Active self-sensing scheme development for structural health monitoring, Smart Mater. Struct., 15 (2006) 1734–1746.

[17] S.J. Lee, H. Sohn, J.-W. Hong, Time reversal based piezoelectric transducer self-diagnosis under varying temperature, J. Nondestr. Eval., 29 (2010) 75–91.

[18] J.-W. Kim, C.G. Lee, S.H. Park, K.-T. Koh, Real-time strength development monitoring for concrete structures using wired and wireless electro-mechanical impedance techniques, KSCE J. Civ. Eng., 17 (2013) 1432–1436.

[19] S.-K. Choi, N. Tareen, J.Y. Kim, S.H. Park, I. Park, Real-time strength monitoring for concrete structures using EMI technique incorporating with fuzzy logic, Appl. Sci.-Basel, 8 (2018) 1–13.