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Applicability investigation of piezoelectric sensor-based damage detection technique for membrane

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ABSTRACT

The water industry is increasingly using membrane technology for water treatment, wastewater treatment, and water reuse. However, the damage of membrane causes a drop in removal efficiency and threatens downstream use. Thus, the integrity of membrane should be monitored. To detect damage of membrane, this study used piezoelectric sensor-based high-frequency response measurement method which is used in structural health monitoring. The high-frequency responses can monitor the changes in physical properties of host structures. The pressure decay that caused by membrane damage during pressure decay test can be measured by high-frequency response signals measured using piezoelectric sensor. To verify its applicability, a lab-scale test was performed. The electromechanical impedance and guided wave were measured with different membrane conditions, and the variations in signals were quantified using root-mean-square deviation. Also, the support vector machine was used to classify the condition of membrane. According to the results, the proposed method can classify the operation condition and pressure decay of membrane.

Keywords: Membrane damage detection; Piezoelectric sensor; Electromechanical impedance; Guided wave; Pressure decay test

1. Introduction

The water industry is increasingly using membrane to treat water, waste water, and reuse water. An important factor of membrane performance is reliability, which indicates the probability that the membrane remove the desired contaminants, including pathogens. Damage of the membrane or loss of membrane integrity results in reduced removal efficiency and threatens downstream use. Therefore, it is common to periodically check membrane integrity to maintain reliability. Membrane damage may be caused by chemical attack such as oxidation, erroneous installation and maintenance, stress, and deformation of the membrane under operating conditions such as backwash or excessive motion due to coarse bubbling and by sharp objects that cannot be removed by preprocessing. [1].

Techniques for assessing membrane integrity are broadly categorized by direct or indirect methods. Direct methods apply to membrane modules and include techniques to determine whether sonic or acoustic sensing [2], porosimetry [3], and modules can maintain pressure holding or holding vacuum, such as pressure decay, bubble point, and vacuum holding methods. Indirect methods measure some properties of the permeate from the module and include microbial monitoring, turbidity monitoring, particle counting, and particle monitoring. Among these, pressure decay test (PDT) is a commonly used direct technique for evaluating membrane module integrity. [4,5].

Recently, a high-frequency dynamic response-based structural monitoring technique using a patch-type piezoelectric sensor was proposed [6–9]. The high-frequency

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dynamic response-based sensing technique that uses piezoelectric patches has emerged as a potential tool for the implementation of a built-in monitoring system for civil infrastructures. This technique utilizes high-frequency structural excitations, which are typically higher than 20 kHz from surface-bonded piezoelectric sensors, to monitor the changes in the mechanical characteristic of tested structures.

This study investigates the applicability of piezoelectric sensor-based membrane pressure decay detection method to detect damage of membrane during PDT. To this, the basic concepts for detecting membrane damage using piezoelectric sensor was proposed and verified through lab-scale test. Also, to improve performance of condition classification, the support vector machine (SVM) was applied, and the predicted conditions using SVM was compared with actual state of membrane.

2. Piezoelectric sensor-based membrane monitoring method

2.1. Piezoelectric sensor

Piezoelectric sensors can interconvert mechanical energy and electrical energy. Due to this piezoelectric effect, piezoelectric sensor can be used simultaneously as both actuator and sensor. This study employs piezoelectric sensor to generate vibration and waves to the membrane, and measure the dynamic responses of the membrane.

To obtain dynamic responses of membrane modules, the piezoelectric sensors should be attached to the surface of membrane. However, the Lead Zirconate Titanate (PZT) cannot be attached to the round surface of membrane because of its brittleness. Thus, this study used the macro-fiber composite (MFC) as a piezoelectric sensor, because the PZT cannot be attached to the circular membrane module. The MFC has flexibility, so it can be attached to round surface of membrane module.

2.2. EMI measurement for membrane monitoring

The electromechanical impedance (EMI) method has been developed for structural health monitoring, damage detection, and nondestructive testing [10,11]. If the MFC is attached to the host structure and an alternating electric voltage is applied to the MFC, the elastic waves generated by the MFC are transmitted to the host structure. The responses on the waves represent the mechanical impedance of the host structure as shown in Fig. 2. The structural impedance directly reflects the effective electrical impedance through the mechanical coupling effect between the MFC and host structure. The EMI of the MFC, as coupled to the host structure, is given by Park et al. [8].

Fig. 1. MFC.

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

where $Z(\omega)$ is the EMI, C is the zero-load capacitance of the PZT, κ_{31} is the electromechanical cross coupling coefficient of the MFC, $k_{\mathrm{str}}(\omega)$ is the dynamic stiffness of the structure, and k_{PZT} is the stiffness of the MFC.

The dynamic stiffness of membrane changes, according to the pressure decay of membrane module during PDT. Also, the EMI signals measured in the membrane surface should vary during the pressure stage. Therefore, the damage of membrane can be detected by tracking the variation of the EMI signals.

In this study, an EMI measurement system based on a self-sensing technique with a single MFC sensor was used. A voltage divider-based self-sensing circuit as described in Fig. 3 is suitable for use in membrane modules, because it is inexpensive, and has sufficient accuracy to detect the pressure decay, even though the EMI signals are less accurate than when using other impedance measurement methods [12,13].

2.3. Guided-wave measurement for membrane monitoring

The guided-wave measurement technique was applied in this study to detect pressure decay of membrane module. The guided wave was measured with self-sensing method and pitch-catch method. The self-sensing method measures the arbitrary reflected wave using single MFC sensors as similar with impedance measurement. Two sensors were used to measure pitch-catch guided wave. One was used to actuate the membrane with a high frequency, and another sensor measures the propagated wave signal. The Morlet wavelet-based tone-burst signal was generated to

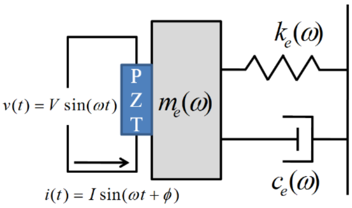

Fig. 2. Electromechanical coupling between the MFC and the host structure.

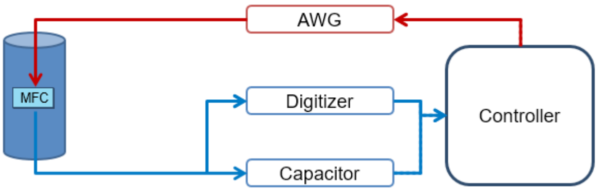

Fig. 3. Schematic diagram of self-sensing-based impedance measurement.

an analogue voltage signal through the arbitrary waveform generator. The analogue signal is changed to a guided wave by the electromechanical effect of the MFC sensor, and the guided wave propagated through surface of membrane module as shown in Fig. 4.

When the wave propagates through the surface of membrane to another MFC, the propagation characteristics vary depending on the propagation path's mechanical properties, which include the stiffness, damping, boundary conditions, etc. Thus, the changes in the mechanical properties of the structure can be estimated by capturing the changes in the propagation characteristics of the response signal [14–17], and the pressure decay of membrane modules can be measured by tracking the signal variations in guided wave.

3. Experimental verification

3.1. Experimental setup

To verify proposed method, lab-scale test was performed. The test specimen was lab-scale membrane module, and the MFC was attached to the center of module as shown in Fig. 5. The EMI and guided waves were measured using NI-DAQ (National Instruments' from U.S) system which consists of arbitrary waveform generator, digitizer, and controller as shown in Fig. 6.

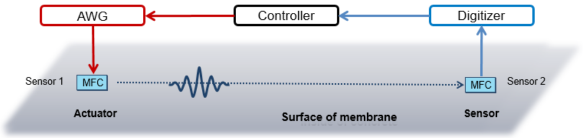

Fig. 4. Schematic diagram of pitch-catch-based guided-wave measurement.

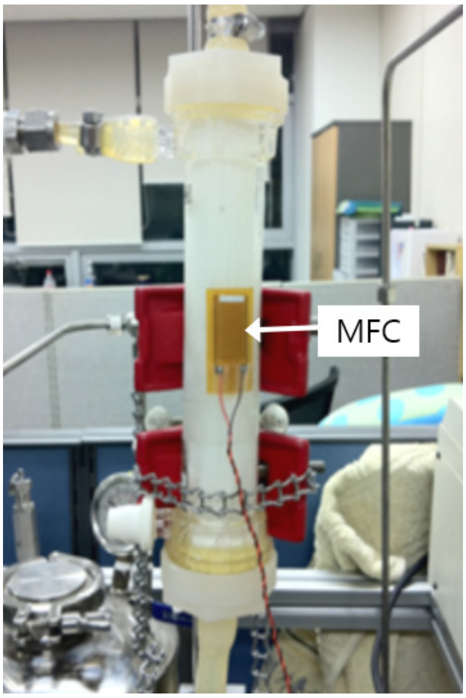

Fig. 5. Test setup.

Test was performed through two stages. In first stage, the operation conditions were changed as water flux 2.0, drain, steady, and pressured with 1 bar. And the second was pressure decay conditions with 1, 0.75, 0.5, and 0 bar. At each condition, the EMI and guided waves were measured.

3.2. Test results

Figs. 7 and 8 show the measurement result of EMI and guided wave with different operation conditions. In the impedance signal, the major peak was slightly changed with operation conditions. Especially, the major peak was greatly

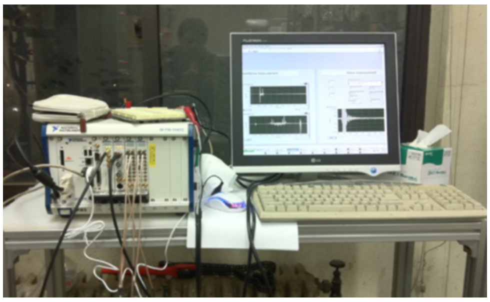

Fig. 6. Measurement equipment.

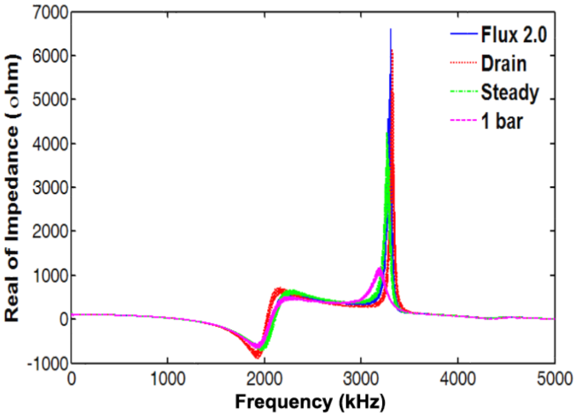

Fig. 7. Variations in EMI according to the operation condition.

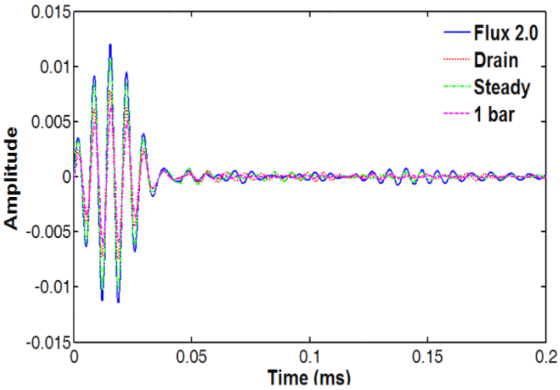

Fig. 8. Variations in guided wave according to the operation condition.

decreased at pressure with 1 bar condition. Also in guided wave, the signal was slightly changed at flux, drain, and steady conditions, but the wave signal at pressured condition was greatly changed. Thus, the EMI and guided wave can monitor the pressure change of membrane regardless the operation conditions.

Figs. 9 and 10 show the EMI and guided-wave signal variations according to the pressure changes in the membrane module. In the impedance signal, the amplitude of major peak was decreased according to the pressure decay. Also, in the guided-wave signal, the pressure decay can be detected with wave propagation velocity. The velocity of guided wave was slightly decreased according to the pressure decay, and the arrival time of first wave packet was getting higher. According to the results, the pressure decay can be measured using piezoelectric sensor-based EMI and guided-wave measurements.

3.3. Condition classification using SVM

The operation condition and pressure decay cannot directly classify with raw signals. To quantify the signal variations, the root-mean-square deviation (RMSD) was calculated as an index of signal variations. The RMSD was calculated as follows:

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}[s_{0,i} - s_{1,i}]}{s_{0,i}}} \tag{2}$$

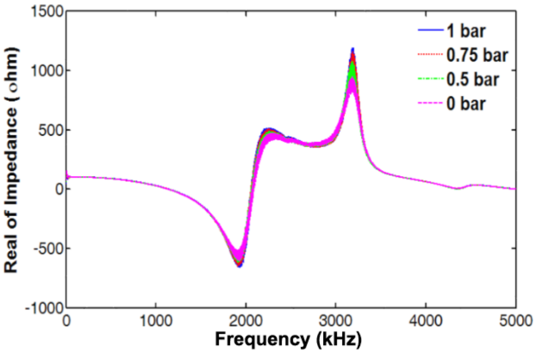

Fig. 9. Variations in EMI according to the pressure decay.

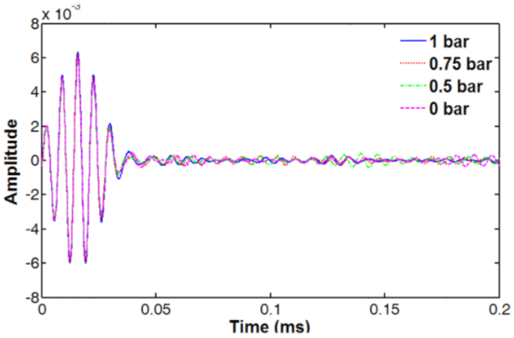

Fig. 10. Variations in guided wave according to the pressure decay.

where $s_{0,i}$ is the signal of steady state, and $s_{1,i}$ is current signals on the time or frequency domain.

Also, the SVM is used for the multi-classification problem to classify the signal variations. The RMSD of impedance and guided waves (self-sensing and pitch-catch) was calculated and inputted to the SVM. Fig. 11 shows the trained hyperplane of SVM. After training the SVM, the operation conditions and pressure decay were classified using trained SVM through inputted measured data and compared with target class as shown in Figs. 12 and 13.

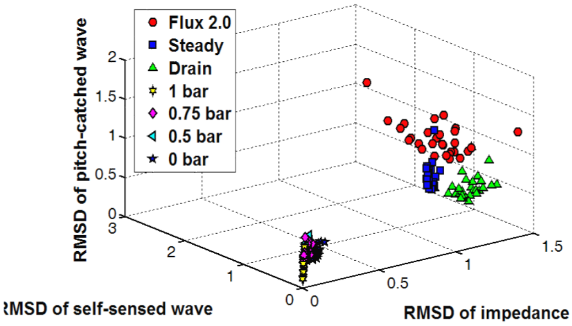

Fig. 11. Hyperplane for classify membrane condition.

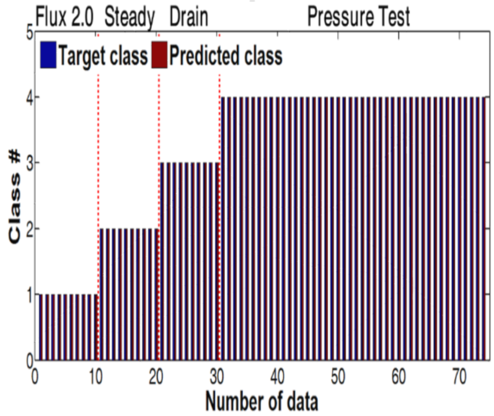

Fig. 12. Result of operation condition prediction.

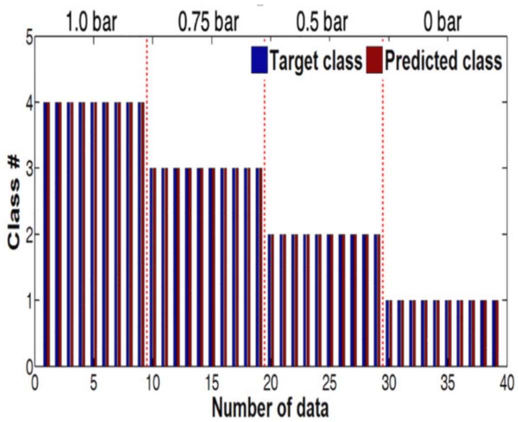

Fig. 13. Result of pressure decay prediction.

According to the results, the proposed piezoelectric sensing technique can classify the operation conditions and pressure decay with 0.25 bar. Although there are many factors that can influence to the signals, such as material/thickness of membrane casing, temperature of water, and/or other environmental factors, the applicability of proposed method was investigated through this study.

4. Conclusion

This study investigates the applicability of piezoelectric sensor-based membrane damage detection method. The EMI and guided wave can measure the mechanical properties of host structures. Thus, the condition of membrane can be detected through tracking signal variations in EMI and guided wave. The lab-scale test was performed to verify applicability of proposed method. The impedance and guided-wave signals were slightly changed according to the operation condition and greatly changed according to the pressured condition. Also the pressure decay can be detected through signal changes. The RMSD was calculated to quantify signal variations, and the SVM was trained using RMSD and target class. The operation condition and pressure decay was predicted using trained SVM and compared with target class. According to the results, the trained SVM can predict the operation conditions and pressure decay. Through this, the piezoelectric sensor-based damage detection method could be applied to the membrane structures.

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