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Experimental investigation for an isolation technique on conducting the electromechanical impedance method in high-temperature pipeline facilities

Wongi S Na [a,*], Hyeonseok Lee [b]

[a] Korea Institute of Civil Engineering & Building Technology (KICT), 283 Goyangdae-Ro, Ilsanseo-Gu, Goyang-Si, Gyeonggi-Do 10223, Republic of Korea
[b] Law School, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 500-757, Republic of Korea

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ABSTRACT

In general, the pipelines within a nuclear power plant facility may experience high temperatures up to several hundred degrees. Thus it is absolutely vital to monitor these pipes to prevent leakage of radioactive substances which may lead to a catastrophic outcome of the surrounding environment. Over the years, one of the structural health monitoring technique known as the electromechanical impedance (EMI) technique has been of great interests in various fields including civil infrastructures, mechanical and aerospace structures. Although it has one of the best advantages to be able for a single piezoelectric transducer to act as a sensor and an actuator, simultaneously, its low curie temperature makes it difficult for the EMI technique to be conducted at high temperature environment. To overcome this problem, this study shows a method to avoid attaching the piezoelectric transducer directly onto the target structure using a metal wire for damage detection at high temperature. By shifting the frequency to compensate the signature changes subjected to the variations in temperature, the experimental results indicate that damage identification is more successful above 200 °C, making the metal wire method suitable for the EMI technique at high temperature environment.

1. Introduction

Nuclear energy has drawn much attention for the last decade as one of the promising alternative energy sources to meet the fast-growing future power demands. However, it has been reported that the structural integrity of nuclear power plants (NPPs) continues to deteriorate with about 80 percent of the worldwide facilities being in operation for more than 20 years [1]. Recent nuclear disaster in Fukushima has magnified the public opposition for building new NPPs and operation of existing NPP facilities. In response to the growing concerns over NPP disasters, nuclear regulatory authorities in many countries have tightened their safety measures based on periodic nondestructive testing (NDT). Also, they have adopted and planned new safety measures based on structural health monitoring (SHM) for automated and continuous monitoring of NPP facilities as supplement of existing NDT techniques [2,3].

* Corresponding author.
E-mail address: wongi84@naver.com (W. Na).

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Among various SHM approaches, the electromechanical impedance (EMI) technique has been applied as a general method of detecting mechanical impedance changes induced by the presence of damage [4–12]. The EMI response is measured by a single piezoelectric transducer attached onto a host structure to act as both an actuator and a sensor, simultaneously. Electromechanical coupling property of piezoelectric materials allow the mechanical impedance of the host structure to be reflected into the EMI response and thereby making it possible to extract the high-frequency modal spectrum of a host structure over hundreds of kHz ranges [4,13]. In general, the piezoelectric material used for the EMI technique is a soft ceramic type, lead-zirconate-titanate (PZT) with relatively high piezoelectric constants.

However, the conventional PZT transducers have operational limitations under high-temperature environment and since the conventional technique requires the direct attachment of the PZT transducers to the surface of the target structure, it can experience a high operational temperature of over several hundred degrees. Since the conventional PZT transducers have a Curie temperature of around 200–300 °C, directly using the PZT material for health monitoring of NPP facilities maybe inadequate, as such high temperature environment leads to poor performance of the EMI technique [14]. Thus to date, several authors have investigated the performance of the EMI method at high temperatures. Kamas et al. conducted experimental and analytical studies of the EMI method up to 250 °C and investigated on the degradation of the PZT materials [15]. Yu et al. conducted experiments in high temperatures up to 600 °C with piezoelectric α-BiB_3O_6 crystals and showed acceptable results for sensing over a wide temperature range [16]. Siebel et al. discussed on the shifting of the impedance signatures subjected to variations in the temperature and used cross-correlation coefficients to compensate the temperature effects [17].

The main objective of this study is to develop a damage detection system based on the EMI technique that can be applied under high-temperature environment using a metal wire. To achieve this, one end of the metal wire (diameter of 0.5 mm and length of 200 mm made of steel) is attached to the top surface of the commercial PZT transducer fully covering it in the length direction, and the other end is attached to the surface of the target structure with a heatproof adhesive. Although the PZT transducer is not directly attached to the host structure to measure the changes in the electrical impedance of the structure, the changes in the vibration behavior (from the radial and thickness modes excitation) of the structure affects the electrical impedance of the PZT transducer attached to the metal wire. This allows the EMI technique to successfully detect damage without the direct attachment of the PZT transducer onto the structure. After EMI responses are obtained, a simple temperature compensation technique of shifting the frequency is applied to update the EMI signatures that have changed by temperature variations to identify the signature changes only induced by structural damage.

The uniqueness of the proposed system is that using a metal wire can overcome the operational limitation of a PZT transducer due to its low Curie temperature. Therefore, the proposed system can alleviate the adverse effects of high-temperature environment on EMI measurement. Also, the end of the steel wire can be applied to structures with complex geometry (e.g. elbow, T-junction and etc) since it eliminates the need for attaching the brittle PZT element onto the surface of the host structure. In this study, the EMI technique is used with a metal wire for the inspection of pipe specimen subjected to progressive wall-thinning defects under high-temperature environment. The experimental verification herein indicates the feasibility of the proposed technique on SHM of NPP facilities.

2. EMI technique & data processing

The principle of the EMI technique attributes to the electromechanical coupling effect of piezoelectric materials: piezoelectric materials generate an electric response when a mechanical stress is applied, and conversely a mechanical response is induced when an electric voltage is applied. Therefore, the EMI technique has been used for monitoring the changes in the mechanical impedance induced by the presence of structural damage in the host structure. The theoretical development of the EMI measurements to structural health monitoring was first introduced by the following one-dimensional equation which expresses the coupled relationship between electrical and mechanical impedance [4].

$$\mathrm{Y}(\omega) = Z(\omega)^{-1} = i\omega C_a\left[1-\kappa_{31}^2\left(1-\frac{Z_a}{Z_S+Z_a}\right)\right] \tag{1}$$

Here, $\mathrm{Y}(\omega)$ is the electrical admittance, which is the inverse of the electrical impedance $Z(\omega)$ of the PZT transducer. Z_S and Z_a are the mechanical impedance of the host structure and mechanical impedance of the PZT, respectively. C_a is the zero-load capacitance of the PZT and κ_{31}^2 is the electromechanical coupling coefficient of the PZT transducer. Equation 1 shows that a change in the mechanical impedance of the host structure Z_S, is reflected into the change of the measured electrical admittance $\mathrm{Y}(\omega)$, which implies the feasibility of the EMI technique for SHM applications.

After acquiring the impedance signatures, the real part of the signature is used for one of the statistical method known as root mean square deviation (RMSD) as shown in the equation below. The RMSD equation is used to calculate a single number which quantifies the damage intensity, thus larger damage will result in higher values in general. The impedance signature of an intact structure is used as the reference signature and the signature of the damaged structure is used as the corresponding signature for the RMSD calculation.

$$\mathrm{RMSD} = \left(\sum_{k=1}^{N}\left[Re(Z_k)_j - Re(Z_k)_i\right]^2 \Big/ \sum_{k=1}^{N}\left[Re(Z_k)_i\right]^2\right)^{1/2} \tag{2}$$

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