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Neural network approach for damaged area location prediction of a composite plate using electromechanical impedance technique

S. Na, H.K. Lee *

Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, South Korea

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ABSTRACT

Nowadays, breakthrough composite technologies are intensifying the complexity of structural components every day and assuring the structural integrity is becoming more essential, thus creating challenges for developing a cost effective and reliable non-destructive evaluation (NDE) technique. As conventional NDE techniques usually require expensive equipments, trained experts and out-of-service period, such techniques may be inadequate for autonomous online health monitoring of structures. In this study, a relatively new technique known as electromechanical impedance (EMI) technique is combined with a neural network technique to predict the damaged areas on a composite plate. Regardless of the advantages such as low cost, robustness, simplicity and online possibilities, this technique still has various problems to be solved. For one, locating a damaged area can be extremely difficult as this non-model based technique heavily relies on the variations in the impedance signatures. The results show that the non-homogenous property is an advantage for the study, successfully identifying the damage location for the prepared test specimen with an acceptable performance.

1. Introduction

With the advancement in composite technologies, the complexity of structural components is increasing and independently assuring the structural integrity is becoming absolutely vital. Such advancements create challenges for developing a cost effective and reliable non-destructive evaluation (NDE) technique as traditional methods such as acoustic emission, X-ray, optical, laser-optical, radiography and other various techniques require expensive equipments and experts, often making it difficult for practical applications [1–3].

On the other hand, a relatively new non-destructive evaluation technique known as the electromechanical impedance (EMI) technique is well known for its robustness and acceptable performance [4–9]. This non-model based technique uses a single piezoelectric material to act as an actuator and a sensor simultaneously, making it suitable for complex structures where damage identification is achieved by monitoring the variations in the impedance signatures. In addition, the commercialized AD5933 evaluation board from Analog Devices offers the ability to measure impedance with the current low cost of US$59, minimizing the equipment cost for conducting the EMI technique. Furthermore, the online monitoring possibility of this technique makes it a powerful tool to be used for structural health monitoring of structures, eliminating the need for the manual inspection methods as this can increase the overall maintenance cost and the down time of the structure in service. However, the EMI technique still has various unsolved problems including temperature effect, damage type identification, and damage location prediction, limiting the technique to be used for practical applications [1]. Especially, predicting the damaged area using the EMI technique is known to be extremely difficult as this technique relies on the changes in the impedance signatures which can be unpredictable at most times.

The 1-D model for the EMI technique shown in Eq. (1) was first proposed by Liang et al. [10] where it shows the coupled relationship between the electrical and mechanical impedance of the lead zirconate titanate (PZT) element and the structure, respectively.

$$Y(\omega) = i\omega a\left(\varepsilon_{33}^{T}(1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}^2 \overline{Y}_{xx}^E\right) \quad (1)$$

Here, the equation proves that the electrical admittance (inverse of impedance), $Y(\omega)$ of the PZT element is related to the mechanical impedance of the structure, Z_s and PZT element, Z_a [10]. The remaining variables ω, a, ε_{33}^T, δ, d_{3x}^2 and $\overline{Y}_{xx}^E$ represent the excitation frequency geometric constant, dielectric constant, dielectric loss tangent, coupling constant and the complex Young's modulus of the PZT element, respectively [10]. This equation proves that any changes in the structure can be identified by monitoring the changes in the impedance of the PZT element [10].

To date, damage detection of structures using Artificial Neural Networks (ANN) has been vigorously researched as they have

* Corresponding author. Tel.: +82 42 350 3623; fax: +82 42 350 3610.
E-mail address: leeh@kaist.ac.kr (H.K. Lee).

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emerged as a promising tool for identifying damages due to their pattern recognition and interpolation capabilities [11,12]. Among them, various researches have investigated using ANN in conjunction with the EMI technique in order to identify and classify damage. Min et al. [13] used ANN combined with the EMI technique to identify the damage type between a notch and loose bolt on a bolt-joined aluminum beam and a lab-scaled pipe structure. In addition, the severity of each damage type was also investigated. Lopes et al. [14] performed EMI technique on a 1/4 scale model of a steel bridge section and a space truss structure with ANN to assess the state of the structures subjected to damage by loosening bolts. Moura et al. [15] used ANN to classify the type of damage between a hole and a crack of helicopter blades with the impedance based technique resulting in a promising outcome.

In this study, an attempt to locate damaged areas is performed on a composite plate using the EMI technique. Probabilistic Neural Network (PNN) is used with the idea of the damage enhancement technique for the EMI technique in [4] to locate the damaged area on a composite plate. The damage enhancement technique was previously developed by the authors to significantly enhance the damage detection ability of the EMI technique on composite structures where the EMI technique failed to identify damage due to the absence of resonance peaks [4].

2. Impedance measuring system

The experimental setup is shown in Fig. 1. A commercialized AD5933 evaluation board manufactured from Analog Devices Co. is connected to the laptop where the evaluation software provided by the manufacturer allows one to measure the impedance signatures up to 100 kHz [16]. The evaluation board is fully powered by the data cable alone, thus resulting in a portable system for measuring the impedance of a structure. The PZT material (model PSI-5A4E) manufactured by Piezo Systems Inc. of a 0.508 mm thickness is used for this study where the positive and negative wires from the evaluation board are connected to the PZT material that is attached to the test specimen [17].

Once the impedance signature is retrieved, one of the statistical techniques known as the root mean square deviation (RMSD) is used to quantify the intensity of the damage [18]. The RMSD equation is shown below where $(Z_k)_i$ and $(Z_k)_j$ represents the reference signature of the PZT impedance and the corresponding impedance for each measurement time at the kth measurement point, respectively [18]. In general, the real part of the impedance is used here as it has been experimentally proven to perform better compared to the imaginary part for detecting structural changes [18].

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

Also shown in Fig. 1 is the repeatability performance of the AD5933 evaluation board. After 10 consecutive measurements of a test specimen, the maximum RMSD value between two signatures was 0.06%. Since the difference is very small, possible variation associated with repetitive measurements is ignored for this study.

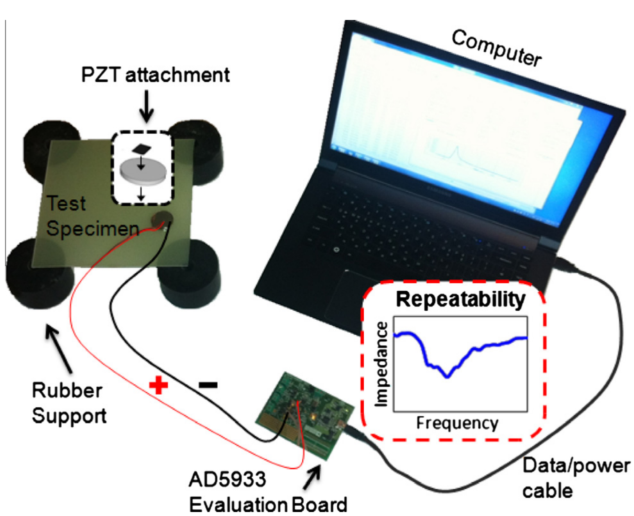

Fig. 1. General setup for measuring impedance of a test specimen.

3. Application of the damage enhancement technique

3.1. Implantation of a resonance frequency range

One of the major problems when using the EMI technique on a non-homogenous material, such as composite or concrete structures is the difficulty in damage identification due to the lack of change in the impedance signatures [4]. In the previous work [4], the authors enhanced the damage detection sensitivity by implanting a resonance frequency range for the EMI technique to successfully achieve damage identification [4]. This was achieved by attaching a 10 mm × 10 mm × 0.508 mm sized PZT material on one side of a circular metal piece having a 25 mm diameter and a 2 mm thickness. The other side of the metal piece was then partially attached onto the host structure (see Fig. 1) [4]. The damage enhancement technique proposed in [4] was tested against de-bonding and artificial cut cases to prove its ability to detect damage where the conventional method of attaching the PZT material failed to achieve [4]. In this study, this idea is used for locating damaged areas of a glass fiber–epoxy composite plate manufactured from Hankuk Carbon Co. where the properties are as follows: heat resistance temperature of 134 °C, moisture content of 0.06%, tensile strength of 454 MPa, flexural strength of 602 MPa and compressive strength of 385 MPa [19].

3.2. Impedance signature observation of a metallic structure

Since the damage enhancement technique is designed for a non-homogenous material which usually results in a peakless signature, this technique is inapplicable for homogenous materials such as a metal plate that results in multiple peaks [4]. However, the idea of finding the damaged location using the EMI technique on a metal plate can be difficult due to too many peaks. Fig. 2 shows the impedance signature changes subjected to damage on a metal plate of a size 250 mm × 70 mm × 0.3 mm. Two areas are damaged on the metal plate, one close and one far away from the PZT patch. Looking at the impedance signatures, there are a

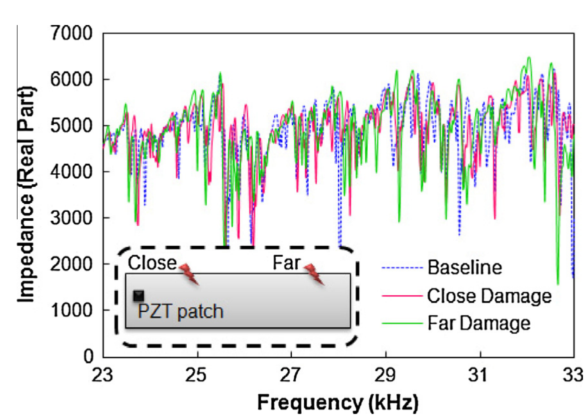

Fig. 2. Impedance signatures for intact and damaged cases for a metal plate.