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구조물 건전성 감시를 위한 스마트 PZT센서의 적용성 연구

Application of smart piezoelectric transducers to structural health monitoring

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ABSTRACT

The objective of this study is to investigate the feasibility of piezoelectric transducers as a damage detection system for civil infrastructures. There have been considerable amount of efforts by the modal analysis community to localize damage and evaluate its severity without looking at a reliable way to excite the structure. The detection of damages by modal analysis and similar vibration techniques depends upon the knowledge and estimation of various modal parameters. In addition to the associated difficulties, such low-frequency dynamic response based techniques fail to detect incipient damages. Smart piezoelectric ceramic (PZT) transducers which act as both actuators and sensors in a self-analyzing manner are emerging to be effective in non-parametric health monitoring of structural systems. In this paper, we present the results of an experimental study for the detection of damages using smart PZT transducers on the steel plate.

The method of extracting the impedance characteristics of the PZT transducer, which is electro-mechanically coupled to the host structure, is adopted for damage detection. Two damages are simulated and assessed by the bonded PZT transducers for characterization. The experimental results verified the efficacy of the proposed approach and provided a demonstration of good robustness at the realistic steel structures, emphasizing the great potential for developing an automated in situ structural health monitoring system for application to large civil infrastructures without the need to know the modal parameters.

1. Introduction

In the near future, structural health monitoring will provide compelling value for preserving and extending the lives of the civil infrastructures. Structural health monitoring technology is essentially aimed at the development of autonomous systems for continuous monitoring and integrity assessment in structures with minimum labor involvement. Low-cost smart sensors are

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key ingredient for wide adoption of structural health monitoring technique.

However, current sensing/monitoring systems suffer from various technical and economic limitations. Therefore, a smart wireless monitoring system and low-cost but high-end smart sensors such as MEMS, optical fiber and piezoelectric sensor are needed to be developed. Especially, smart piezoelectric ceramic (PZT) transducers, which act as both actuators and sensors, are emerging to be very effective sensors in structural health monitoring. This piezoelectric impedance-based structural health monitoring technique utilizes the direct and the converse electro-mechanical properties of piezoelectric materials, allowing simultaneous actuation and sensing of the structure. The basic principle is to track the high frequency (typically higher than 1MHz) electrical point impedance of a piezoelectric material bonded onto a structure. Physical changes in the structure cause changes in the structural mechanical impedance. Due to electro-mechanical coupling between the piezoelectric material and the structure, the change in structural mechanical impedance induces a change in the electrical impedance of the piezoelectric material. This effected change in the driving point impedance of the PZT transducer is used to identify incipient damage in the structure (Giurgiutiu and Rogers 1997, 1998). At such high frequencies, this technique is as sensitive as sophisticated traditional NDE techniques because the wavelength of the excitation is small enough to detect incipient and small damages. And, this technique can be applied to complex structures, as well.

In this paper, the experimental investigations on simple specimens of steel plate are presented to explore the application of PZT transducers for non-parametric damage detection. The damages are simulated by cutting cracks. These damages are simulated to study the impedance response of the PZT transducers with changes in damage location.

Conclusions on the effectiveness of the present method are derived from the experimental results, complementing the existing knowledge in structural health monitoring with PZT transducers.

2. Piezoelectric Impedance-Based Structural Health Monitoring

The impedance-based NDE technique utilizes piezoelectric materials as sensors and actuators. When a mechanical stress is applied to piezoelectric material, it generates an electric charge (the direct effect). Conversely, when an electric field is applied to it, its dimensions change (the converse effect).

For piezoelectric materials, the relation between the mechanical and electrical variables is governed by the following constitutive equations :

$$
\begin{aligned}
S_{ij} &= s^{E}_{ijkl} T_{kl} + d_{kij} E_k \\
D_i &= d_{ikl} T_{kl} + \varepsilon^{T}_{ik} E_k
\end{aligned}
\tag{1}
$$

where i, j, k, l take on values 1,2,3 (or x, y, z), S_{ij} is the strain tensor, s_{ijkl} is the compliance tensor, E_k is the electric field, ε is the permittivity, T_{kl} is the stress tensor, d_{ikl} are the piezoelectric constants, and D_i is the electric displacement. The superscripts E and T indicate that the values of constants are obtained at constant electric field and constant stress, respectively. The first equation states that the strain in the piezoelectric material is proportional to both the applied stress (equivalent to the inverse of Hook's law) and the applied electric field (the converse piezoelectric effect). The second equation states that the electric displacement in proportional to both the applied stress (direct piezoelectric effect) and the applied electric field (dielectric effect).

The basic concept of this technique is to monitor the variation in the mechanical impedance due to the presence of structural damage. If damage occurs in the structure, its mechanical impedance will change. In piezoelectric materials, the mechanical and electrical impedance are coupled, which allows us to extract structural information from electrical impedance measurements. Hence, we can detect the damage by tracking the electrical impedance of the PZT bonded on the structure and comparing it with a baseline measurement.

The interaction between a PZT and its host structure can be described by a simple 1-D model shown in Figure 1. The PZT is considered as a thin bar undergoing axial vibration in response to applied alternating voltage. One end of the bar is fixed and the other end is connected to the host structure represented by a single degree of freedom system.

Solving the equation for the PZT bar connected to the external mechanical point impedance of the structure leads to the following equation for the frequency dependant electrical admittance.

$$Y(\omega) = j\omega \frac{w_a l_a}{h_a}\left(\varepsilon_{33}^T(1 - j\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)}(d_{3x})^2 Y_{xx}^E\right) \tag{2}$$

where Y is the electrical admittance (inverse of impedance), Z_a is the mechanical impedance of the PZT, Z_s is the mechanical impedance of the structure, Y_{xx}^E is the Young's modulus of the PZT at zero electric field (inverse of compliance), d_{3x} is the piezoelectric strain constant at zero stress, ε_{33}^T is the permittivity at zero stress, δ is the dielectric loss tangent of the PZT, w_a is the width of the PZT, l_a is the length of the PZT, and h_a is the thickness if the PZT.

Then, the mechanical impedance can be obtained easily by solving Equation (2), which yields

$$Z_s(\omega) = Z_a(\omega)\left(\frac{\varepsilon_{33}^T(1 - j\delta) - \dfrac{Y(\omega)h_a}{j\omega w_a l_a}}{(d_{3x})^2 Y_{xx}^E - \varepsilon_{33}^T(1 - j\delta) + \dfrac{Y(\omega)h_a}{j\omega w_a l_a}}\right) \tag{3}$$

This equation indicates that the mechanical impedance of a structure can be determined from the electrical admittance of the PZT bonded onto the structure. In other words, structural integrity can be evaluated by measuring the electrical impedance of the PZT.

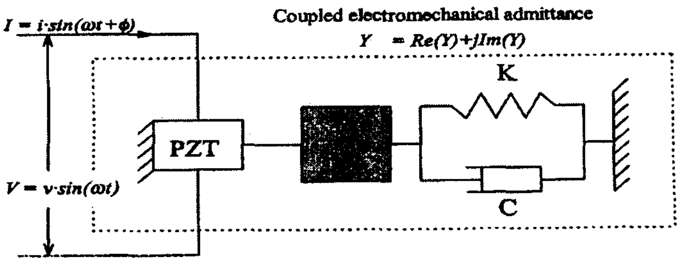

Figure 1.1-D model of a PZT with its host structure

3. Experimental setup and procedure

The experimental setup consists of specimens to be tested, PZT transducers bonded on to the specimen, an impedance analyzer, electrical wire connections, a personal computer equipped with data acquisition software and a PC-analyzer interface cable. PZT transducers of 10mm X 10mm square and 0.2mm thickness are so designed that after the bottom surface is bonded to the surface of the host structure, both electrodes of the transducer are accessible from its top surface for soldering the wires. Silver-paste adhesive consisting of hardener and electrode is used for bonding the PZT transducers on to the surface of the specimens. The electrodes of the PZT transducers are then soldered by electrical wires. The soldered wires connected to a PZT transducer are then plugged into the HP4194A impedance analyzer for the acquisition of the impedance signature (real part), extracted as a function of exciting frequency. A proper program, functional in the HP-VEE3.5 software environment, is run on a personal computer in order to control the operations of the impedance analyzer. The control and acquisition of data is achieved through the GPIB interface card and cable setup installed into the computer.

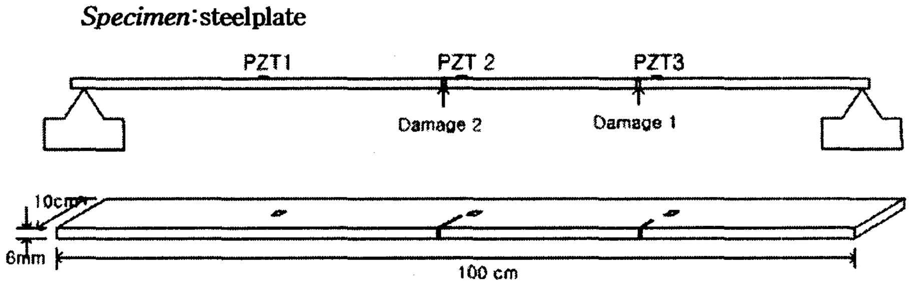

Figure2 .Experimental specimen

The thin steel plate considered measures 100cm in length, 10cm in width, and 6mm in thickness. Three PZT transducers are bonded to the upper surface of this specimen with the same distance. Then, this intact state is assessed by acquiring the impedance signatures for all of three the PZT transducers. Next, as shown in figure 2, damages are simulated on the cracks by cutting of 25mm and 30mm, respectively. The first damage is cut by the crack near to the PZT3 (2cm apart from PZT3). And, the second damage is cut by the crack near to PZT2 (2cm apart from PZT2). Each damaged state is assessed by acquiring the impedance signatures for all PZT transducers, and comparing them with the signature acquired for the undamaged or intact state.

4. Frequency range

In order to select a suitable frequency range for acquiring the impedance signatures, the PZT transducers on specimen are scanned over two frequency ranges of 2 MHz~6 MHz (at the interval 12.5 kHz) and 1 kHz~5 kHz (at the interval 1 kHz), respectively. The signature of the range of 1 kHz~5 kHz shows many sharp peaks over a wide range of frequency. This signature presents the length-directional modes. While the signature of the range of 2 MHz~6 MHz presents the thickness-directional modes. In this experiment, PZT transducers bonded on specimen are constrained strongly as the longitudinal direction by their bonding effect. Therefore, only the thickness-directional modes are available to be used, well. In other words, the only signature of the range of 2 MHz~6 MHz, which is easy to measure and sensitive to damage, is utilized herein.

5. Results and discussion

The impedance signature of the intact case and the damaged cases are shown in Figure 3 ~ 5, respectively. At the following graphs obtained from the experimental results, every signature has both valley point and peak point. Herein, the valley point presents the resonance frequency of the specimen. If the structure gets damages, its resonance frequency will shift downward. In other words, one may conclude that damage occurred based on the resonance frequency change.

Figure 3 shows signatures of the three cases (one intact case and two damaged cases) obtained from PZT 1 sensor almost coincide. In other words, the PZT 1 sensor couldn't detect any damage occurred at far location from itself. While, Figure 4 shows the red line obtained in the case of damage 2 was shifted. In other words, the PZT 2 sensor detected the damage 2 occurred at near location from itself. Thus one can conclude that the PZT 2 sensor can detect damages which occur at near location from itself, such as the damage 2. Finally, Figure 5 shows the blue line obtained in the case of damage 1 was shifted. The shift of the red line obtained in the case of damage 2 is the outcome after the damage 1. Therefore, one can judge the PZT 3 sensor detected only the damage 1 occurred at near location from itself. In other words, one can conclude that the PZT 3 sensor can detect damages which occur at near location from itself, such as the damage 1.

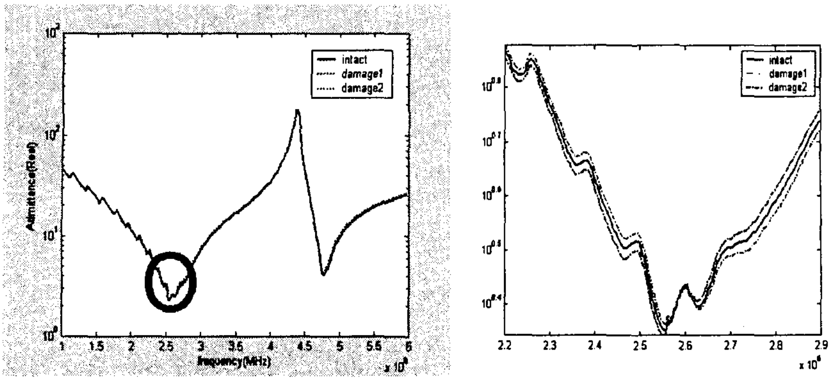

Figure. 3: PZT 1

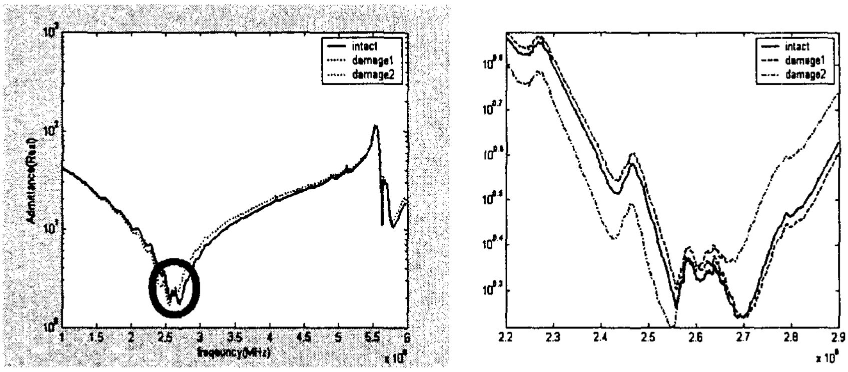

Figure. 4: PZT 2

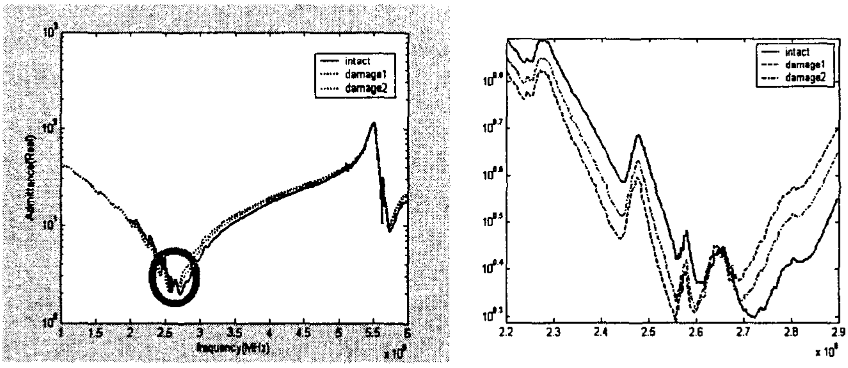

Figure. 5: PZT 3

The potential of employing smart piezoelectric (PZT) transducers for detection of damages in structures has been presented through experimental results on a laboratory sized thin steel plate. The electro-mechanical impedance technique has been adopted to assess the various states of the structure. This work is to enhance the capability of the conventional impedance-based structural health monitoring. The striking advantage of this non-parametric damage detection method over the conventional other modal analysis techniques is that of not requiring the knowledge of the modal parameters or the failure modes of the structure. And, while the global modes of structure at low frequencies are not affected by incipient-type damage, the impedance-based technique, which monitors the local modes at high frequencies, can detect incipient-type damage successfully. Therefore, the technique facilitates an avenue for minimum labor involvement without having to be highly skilled.

The PZT transducer of even a small size (1cmX1cm square) has been ascertained to be very sensitive to an incipient damage. But its sensing area was small relative to the dimension of the structure. That is, the PZT transducer detected only the damage which occurred at near location. It is expected that one can use the multiplexing method, which means the mounting of many PZT transducers on specimens to detect a local small damage exactly. And, a new impedance-based structural health monitoring technique using electrical transfer impedance can be developed to extend the sensing area. Through this technique which utilizes multiple PZT transmitter-receivers, onecan evaluate mutual information among them and estimate more specific characterizations of damage, such as, its location, extend and size.

Thus, the above result is significant as it shows that PZT transducers can be more economical for health monitoring than other smart materials in large civil-infra structures. For example, in monitoring a metallic truss bridge, the fiber optic sensors have to be laid through the entire length of the structural members, making it very expensive. But health monitoring for the same structure can be easily accomplished with a few PZT transducers spread out on the members.

Acknowledgement

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