A Preliminary Study on the Prediction of Damaged Areas on Ordinary Concrete and Lightweight Concrete Using Electromechanical Impedance Technique with Different Frequency Ranges

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ABSTRACT
The electromechanical impedance (EMI) method for NDE uses a single piezoelectric material to act as an actuator and a sensor simultaneously, and the EMI method is suitable for structures with complex surfaces. However, this technique still has wide range of problems which needs to be investigated. For one, locating damaged areas on a host structure precisely is known to be extremely difficult as this non-model based technique heavily relies on the variations in the impedance signatures. In this study, an attempt to locate the damaged areas on an ordinary concrete panel and a lightweight concrete panel using bottom ash is carried out by using different frequency ranges. Since the sensing range decreases as the excitation frequency of piezoelectric material increases, one can possibly predict the damaged areas by analyzing the impedance signatures from different frequency ranges. Statistical analysis method such as root mean square deviation (RMSD) is applied to determine the changes of the experimental structures, and the RMSD values of low frequency range and high frequency range are compared to verify the relationship between the frequency range and sensing range. Furthermore, the applicability of this method to locating the damaged areas is investigated on various materials including the lightweight concrete.

Keywords: Nondestructive evaluation, electromechanical impedance, frequency range, concrete, coal bottom ash

1. INTRODUCTION
Nondestructive health monitoring in civil engineering has become a significant issue as the increasing number of collapses and structural failures occurring in major infrastructures is reported up to date. The structure health monitoring is a technology which monitors condition of structures to prevent failures and catastrophic events due to environmental influences including earthquakes or excessive use of structures more than stipulated life span. Moreover, an effective application of nondestructive health monitoring may predict the possibility of damages on structures such as bridges or nuclear plants which need continuous maintenance. However, most of non-destructive evaluation (NDE) techniques such as acoustic emission, optical, thermography, magnetic field analysis and other various methods require expensive equipment and complicate processing, and set a limitation on practical applications.

The NDE technique known as electromechanical impedance (EMI) method with a smart material which is a piezoelectric (PZT) transducer is recently developed with the possibilities to suggest a solution for the aforementioned problems. The EMI method is developed from consideration of global static responses and the static strain measurements. The EMI technique based on the piezoelectric (PZT) material is a cost-effective method for NDE technique, and this method is suitable for most engineering materials and civil structures including reinforced concrete. The material of piezoelectric sensor is composed of lead-zirconate-titanate (PZT) which is used for EMI method as a transducer. The principle of the EMI method is to generate the mechanical vibration from the electrical signature applied on the piezoelectric sensor, and the electromechanical impedance of structure is measured via the sensor. The electrical impedance is influenced by the mechanical characteristics of the structure, and the relationship between mechanical impedance and electrical impedance was investigated from coupled electro-mechanical analysis. The frequency range of the electrical signature in the EMI method is considered between 30 kHz and 400 kHz generally. However, high frequency range above 400 kHz is considered...
as an inadequate range because the sensing area of PZT sensor becomes extremely small and the evaluated impedance signature is prone to follow the characteristic of the PZT sensor itself or the bonding area of the PZT sensor rather than the structure\textsuperscript{7}. Another obstacle of the main limitations of the EMI method is that the application on real size structure is not practicable due to difficulty in control of sensing range. In addition, the impedance signature of concrete structure changes in small amount by damage due to the non-homogeneous property of concrete rather than a metallic structure\textsuperscript{8}. Therefore, the sensing area in case of concrete structure is smaller than metallic structure generally. Among the researches on the EMI methods, the suggested hardship is investigated via the characteristic of relationship between sensing range and the excitation frequency via the PZT sensor\textsuperscript{9-11}; however, the remained limitations in application of the EMI method on the real size concrete structure need to be improved.

On the other hand, the coal bottom ash is a byproduct and a part of the non-combustible residue of coal burning industry as well as a furnace or incinerator. Up to date, most of bottom ash is disposed by burying in the ground though bottom ash contains many harmful substances such as lead and copper which can damage to the natural environment. Recycling method for bottom ash should be suggested urgently, and it was verified that coating the bottom ash with concrete reduces the leached heavy metals from the bottom ash by both physical and chemical ways\textsuperscript{17-19}. On the other hand, the density of bottom ash is smaller than the ordinary aggregates such as sand and gravel because of the porous and rough structure of bottom ash. Thus, the bottom ash could be an appropriate material for the lightweight concrete. Generally, lightweight concrete is widely used in construction areas such as a precast concrete with its benefit. Hence, it is expected to increase the utilization of bottom ash in many ways including the lightweight concrete, and the lightweight concrete panel was investigated in this research which is comprised of cement paste and bottom ash aggregates. Additionally, the suitability of electromechanical impedance method on the lightweight concrete using bottom ash was compared to the ordinary concrete.

In this study, an approach to predict damaged areas of structures is investigated via electromechanical impedance technique with different frequency ranges. The relative RMSD values of low frequency range and high frequency range are considered to verify the relationship between the sensing range and excitation frequency. Also, the applicability of the relative RMSD method is determined from the preliminary experiment with an ordinary concrete panel using normal aggregates and a lightweight concrete panel using bottom ash material.

2. EXPERIMENTAL STUDY

2.1 Specimen preparation

In the experiment, an ordinary concrete panel and a lightweight concrete panel using bottom ash were used as specimens to verify the relationship between sensing area and frequency range. The ordinary concrete panel is comprised of water, cement, fly ash, sand and gravel. The lightweight concrete panel is comprised of water, cement and bottom ash aggregates. The specific mix proportions of concrete specimens are indicated on the Table 1. The maximum size of coarse aggregate is 25 mm and a designed nominal strength of the ordinary concrete specimen is 24 MPa. The size of fine bottom ash is 0.2 mm – 5 mm, and the size of coarse bottom ash is 5 mm – 13 mm.

<table>
<thead>
<tr>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>Fly ash (kg/m³)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>174</td>
<td>280</td>
<td>858</td>
<td>916</td>
<td>53</td>
<td>2496</td>
</tr>
</tbody>
</table>

Table 1. Mix proportions of the ordinary concrete specimen and the lightweight concrete specimen by unit mass

<table>
<thead>
<tr>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Fine BA (kg/m³)</th>
<th>Coarse BA (kg/m³)</th>
<th>Fly ash (kg/m³)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>174</td>
<td>346</td>
<td>610</td>
<td>629</td>
<td>0</td>
<td>1700</td>
</tr>
</tbody>
</table>

The length and width of the ordinary concrete panel are 500 mm and 300 mm, and thickness of the ordinary concrete panel is 30 mm. The length and width of the lightweight concrete panel are 300 mm and 300 mm, and thickness of the lightweight
Concrete panel is 50 mm. The surface of the concrete specimens was ground by a hand grinder to polish for PZT sensor to be attached before the experiment. The PZT material with a thickness of 0.3 mm was used for experiment, and it was cut into length of 15 mm and width of 15 mm for experiment. The PZT material was attached on the specimens with a commercialized epoxy adhesive which consists of hardener and resin to be mixed each other. The attached PZT sensor was left to be cured for one day at room temperature to achieve perfect adhesion between the PZT sensor and the specimens. Then, copper tape and electrical wires are attached on the both sides of the PZT sensor to apply electrical signatures directly. The attached location of the PZT sensor at the case of the ordinary concrete panel is the center. The attached location of the PZT sensor of the lightweight concrete panel is 70 mm from the center.

2.2 Electromechanical impedance method and data processing

The principle of the EMI method is measuring the changes in mechanical properties of the specimen by impedance value via the PZT sensor which transforms the electrical signature into mechanical strain, and vice versa. The applied electrical signature is generated by Agilent 33250A which is a function generator, and the response signature from the specimen is measured by Agilent MSO6034A which is an oscilloscope. The automated impedance measuring method is based on the low cost system which has great accessibility. Also, the measurement of electrical impedance is conducted with a good reliability due to electrical signature being measured in a steady state function. The measured voltage data is converted to the impedance value via the equation which introduces relationship between the approximated impedance of the PZT sensor and the voltages.

\[
Z_p = \frac{R_z(V_o - V_i)}{V_o}
\]

In the equation, \(Z_p\) is the impedance value of the PZT material and \(R_z\) is the resistance in the measurement system. The value of resistance was 200 \(\Omega\) in the experiment. The value \(V_i\) is an input voltage generated by the function generator and \(V_o\) is an output voltage measured by the oscilloscope respectively. The measured voltage value from the oscilloscope was processed by MATLAB software. The setup of the system including the equipment and specimens is shown in Figure 1. The function generator and the oscilloscope are connected to each side of the PZT sensor. Since the electrical signature is very sensitive to external factors, the experimental specimens were detached from the floor by a rubber mass. Hence, the external noise by mechanical vibration was controlled in the experiment.

Figure 1. The experimental setup including function generator, oscilloscope and a concrete specimen.
2.3 Results

The experiment was conducted with two different specimens that are an ordinary concrete panel and a lightweight concrete panel. In the case of the concrete panels, the damage was created by a hand grinder with concrete cutting wheel. The length of cutting section was 70 mm, and the depth was 10 mm. The locations of damages were 50 mm, 100 mm and 150 mm from the PZT sensor. Also, the damages were created in consecutive order from the farthest one. The farthest damage was created first, and other damages were created in consecutive order. The reference impedance signatures were measured before each damage scenario, and the corresponding impedance signatures were measured after each damage scenario.

The frequency range covered wide range between 100 kHz and 500 kHz in the experiment, and the sub-RMSD values were obtained from the low frequency range and the high frequency range, respectively. The ratios of sub-RMSD values of each frequency range to the total RMSD value were determined to verify the relationship between the sensing area and the frequency range. Since the propagation range of mechanical wave is affected by its frequency, the sensing area in the case of the low frequency range is larger than the high frequency range. Hence, the proportion of sub-RMSD in the low frequency range decreases when the distance between damage and PZT sensor decreases. On the other hand, the proportion of sub-RMSD in the high frequency range increases when the distance between damage and PZT sensor decreases. The experimental results from the cases of the ordinary concrete panel and the lightweight concrete panel indicates same tendency in the relationship between the sensing area and the frequency range as shown in Table 2. In addition, the impedance graph of raw specimens is shown on the Figure 2.

<table>
<thead>
<tr>
<th></th>
<th>ORDINARY CONCRETE PANEL</th>
<th>LIGHTWEIGHT CONCRETE PANEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage location</td>
<td>RMSD ratio (100 kHz – 300 kHz)</td>
<td>RMSD ratio (400 kHz – 500 kHz)</td>
</tr>
<tr>
<td>150 mm</td>
<td>50.36 %</td>
<td>30.50 %</td>
</tr>
<tr>
<td>100 mm</td>
<td>43.89 %</td>
<td>33.96 %</td>
</tr>
<tr>
<td>50 mm</td>
<td>39.54 %</td>
<td>41.92 %</td>
</tr>
<tr>
<td>150 mm</td>
<td>45.44 %</td>
<td>27.98 %</td>
</tr>
<tr>
<td>100 mm</td>
<td>41.05 %</td>
<td>32.50 %</td>
</tr>
<tr>
<td>50 mm</td>
<td>40.25 %</td>
<td>48.05 %</td>
</tr>
</tbody>
</table>

Table 2. Sub-RMSD ratio values to total RMSD values of each frequency range of the specimens.

Figure 2. Impedance graph of raw specimens (solid line: ordinary concrete, dotted line: lightweight concrete)
3. SUMMARY

The electromechanical impedance method using PZT material for nondestructive health monitoring is a very promising technique with its effectiveness and applicability. The condition of structure is analyzed by its own impedance signature measured by PZT sensor which acts as an actuator and a sensor simultaneously. Nevertheless, the damage locating is very difficult in real size structure due to the influences by environmental factors such as temperature and vibration noise. In this paper, the improved method in the damage locating was investigated by using different frequency ranges. The partial frequency ranges in the EMI method was selected respectively to verify the relationship between the sensing area and the frequency range, and the experimental results indicated the steady tendencies via the sub-RMSD ratio values to the total RMSD values. The sub-RMSD ratio values in the low frequency range and the high frequency range indicated different tendencies to the distance between the created damages and the location of PZT sensor. In addition, the experiments were conducted with two different kinds of materials including the ordinary concrete panel and the lightweight concrete panel. The possibility of investigating the damage locating method using the different frequency ranges was studied from this paper, and the applicability of this EMI method to the various concrete materials was considered. The consistency and sensitivity need to be investigated in the EMI method using different frequency range in the future.

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