Post-earthquake Damage Detection Using Embedded Electro-mechanical Impedance Sensors for Concrete Dams

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SUMMARY:
In present paper, a novel methodology is proposed to detect the post-earthquake damage in concrete dams by using of embedded electro-mechanical impedance (EMI) sensors. Firstly, PZT was embedded in the concrete to form a small cylinder, which is the earthquake damage sensor and then is placed inside the concrete dam during the construction. The variations in the impedance spectral of the sensors before and after earthquake were extracted as the damage-sensitive features and utilized to detect the damage quantitatively. To verify the proposed method, a scale model of a high concrete dam was fabricated and shaking table tests were carried out. The experimental results demonstrate that the embedded EMI sensors are sensitive enough to detect the incipient damages, which provides a promising tool to detect the structural damages after the earthquake for the concrete dams.

Keywords: Post-earthquake damage detection, Concrete dam, Impedance sensor

1. INTRODUCTION

Several large-scale hydro projects are under construction in the southwest of China. Most of them adopt the high concrete dams with over 200-m high. However, earthquakes are frequent and have high intensities in the area. Once the strong earthquake occurs, the structural damage is inevitably happened. Thus it is urgently motivated to develop the damage detection techniques for civil structures after the earthquake. However, it is difficult for the currently-used non-destructive test techniques to detect the earthquake damages in the bulky structures such as concrete dams.

Due to the smart materials possessing self-sensing as well as self-actuating properties, they can serve as built-in sensors for damage detection and health diagnostics. Piezoelectric-based approaches have provided an innovative approach for the structural health monitoring and damage detection of civil structures with the advantages of structural simplicity, low cost, quick response and high reliability. The impedance-based approach is based on the electromechanical coupling property of piezoelectric materials. The electrical impedance is measured at high frequencies, typically higher than 30 kHz. At such high frequencies, the wavelength of the excitation is small and is sensitive enough to detect minor changes in the structural integrity. Moreover, the impedance-based approach integrates sensing as well as actuating functions into one element, which avoids the limitation that the traditional methods need both sensors and actuators.

The objective of this paper is to propose a novel method for detecting the post-earthquake damage by using of embedded electro-mechanical impedance (EMI) sensors. Firstly, the measuring principle of EMI approach was briefly reviewed. Secondly, the embedded EMI sensor was presented. Finally, the effectiveness of the proposed method was verified by the scale modeling test of concrete dam.

2. MEASURING PRINCIPLE OF EMI SENSORS

Based on the principle of electro-mechanical coupling effect between the host structure and the bonded PZT sensor, the electro-mechanical impedance-based (EMI-based) damage detection method is getting many interests in the recent years (Park et al, 2003). The mechanical aspect of the PZT is described by its short-circuited mechanical impedance. The PZT is powered by voltage or current.. The integrated electro-mechanical system may be electrically represented by the electrical impedance which is affected by the dynamics of the PZT and the host structure (Giurgiutiu and Rogers, 1997; Park et al., 2006). The principle of EMI-based damage detection is schematically shown in Fig. 2.1.

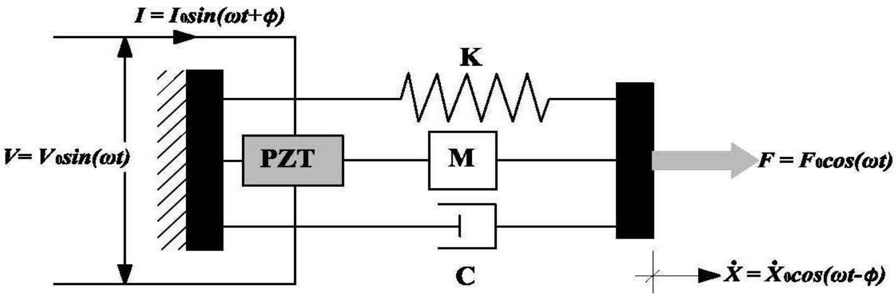


Figure 2.1. A SDOF system under dynamic excitation

The mechanical impedance, Z_s of the host structure idealized as a SDOF system (in Fig. 2.1), is defined as the ratio of a harmonic excitation force *F(ω)* at an angular frequency ω to the velocity response $\dot{x}(\omega)$ in the frequency domain. Similarly, the electrical impedance, Z_a of the PZT patch is defined as the ratio of a harmonic input voltage *V(ω)* at an angular frequency *ω* to the current response *I(ω)* in the frequency domain. The apparent electro-mechanical impedance, *Z*, of the PZT as coupled to the host structure is given by

$$Z(\omega) = \left[i\omega C \left(1 - k_{31}^{\ 2} \times \frac{Z_s(\omega)}{Z_a(\omega) + Z_s(\omega)} \right) \right]^{-1} \tag{2.1}$$

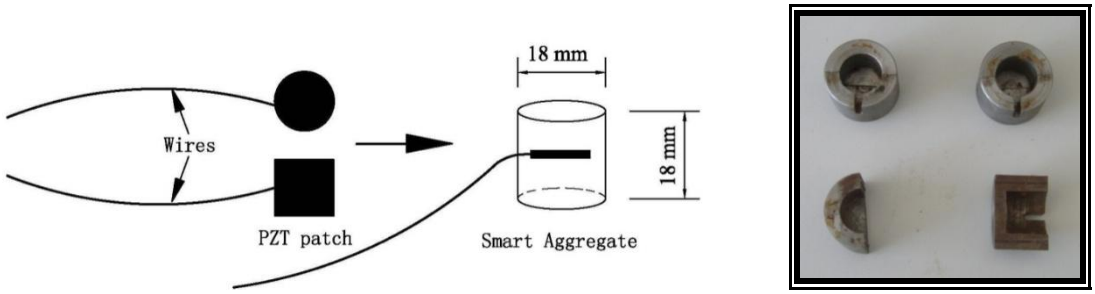
where *C* is the zero-load capacitance of the PZT, and κ31 is the electromechanical coupling coefficient of the PZT. It is obviously that the variations in Z_s induced by the structural damage will results in the changes in the measured *Z*. The electro-mechanical impedance technique permits damage detection and health monitoring because it can directly measure the high frequency local impedance which is very sensitive to local damage. Hence, changes of the mechanical properties of the host structure may be detected by monitoring the variations of the electro-mechanical impedance functions shown in Eqn. 2.1.

In another way, as the admittance is the inverse of the impedance, the EM admittance is directly related to the mechanical impedance of the host structure. The variation in the PZT EM admittance over a range of frequencies is analogous to that of the frequency response functions of a structure, which contains vital information regarding the health state of the structure. Since all other PZT properties remain constant, it is the structural mechanical impedance *Z* that uniquely determines the overall admittance signature. Thus, any change in the EM admittance signature is an indication of a change in the structural integrity which may be caused by the presence of structural damage.

3. EMI SENSORS AND DAMAGE INDEX

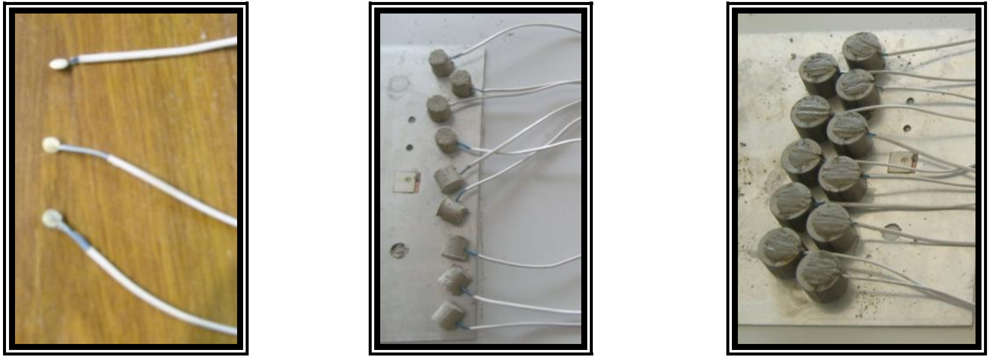
3.1 Embedded EMI Sensors

Recently, an embedded PZT approach, which is named as smart aggregate, was proposed to detect the damages in concrete structures (Song et al., 2008). The smart aggregates are formed by embedding a waterproof piezoelectric patch with lead wires into a small concrete block before casting them into a larger concrete structure. In this way, the smart aggregates will have almost no effect in changing the material properties and the structural properties of the host concrete structures. Nevertheless, the smart aggregates are only applied to the elastic wave-based approach for structural health monitoring. In this study, we propose the embedded PZT for EMI-based damage detection for concrete dam. The fabrication process of the embedded impedance sensors is demonstrated in Fig. 3.1.



a) Schematic process of the fabrication of the smart aggregate

b) Steel Mould



c) Wires + PZT patch

d) Fabrication of the smart aggregate

e) Smart aggregates

Figure 3.1. Fabrication process of the smart aggregates

3.2 EMI-based Damage Index

To quantify the damage, several pattern recognition techniques have been reported in the literature for EMI-based approach (Park *et al.*, 2003). Root mean square deviation (RMSD) was firstly proposed as damage index by Giurgiutiu and Rogers (1997) to quantitatively evaluate the changes that occurred in the signatures due to the damage. The effectiveness of RMSD as damage index has been investigated by numerical simulations as well as experimental study (Park *et al.*, 2006; Yang *et al.*, 2008).

The root mean square deviation (RMSD) of the impedance and admittance signatures is used as damage metric for damage quantification of the impedance-based approach and is given by:

$$RMSD(\%) = \sqrt{\frac{\sum_{i=1}^{n}(R_i^1 - R_i^0)^2}{\sum_{i=1}^{n}(R_i^0)^2}} \times 100 \qquad (3.1)$$

where the resistance of the PZT, R_i^0, is measured at the healthy condition of the structure; R_i^1 is the corresponding post-damage value at the *i*-th measurement point, and *n* is the number of sampling points.

In the charts of damage index, the larger the difference between the baseline reading and the subsequent reading, the greater the value of calculated RMSD is. The values of damage indices intrinsically denote the changes of structural dynamic properties. These changes may be caused by the variations in the geometrical conditions, the environmental temperature and the presence of structural damages. For a damage detection technique, larger RMSD values detected by a sensor indicate the higher sensitivity to structural damage of this sensor (Yang et al., 2008). The calculated values are able to reveal the health state of the structure after each damage phase.

4. EXPERIMENTAL VERIFICATIONS

4.1 Experimental Setup and Test Programs

The experimental study was performed in order to investigate the aseismic performance of Huangdeng Concrete Gravity Dam with 203-m high, which is located in Yunnan province, China. A scale model of a dam monolith was designed by scaling down the geometric and material properties from Huangdeng Concrete Gravity Dam. The damage detection has been performed during the shaking test on the dam model by using the shaking table facility at the Earthquake Engineering Institute, Dalian University of Technology, Dalian, China.

The experimental set-up was illustrated in Fig. 4.1 for seismic damage detection of model dam. The embedded EMI sensors were connected with Agilent 4294A Impedance Analyzer. The Impedance Analyzer was controlled by a PC via a programmable USB-GPIB interface card. The Impedance Analyzer excited the embedded EMI sensors and simultaneously recorded the impedance/admittance signatures received by the EMI sensors. The sinusoidal sweep signals, with amplitude of 0.5 volt, were input to the EMI sensors over the predetermined frequency ranges. The measured impedance/admittance signals of the EMI sensors were stored on the hard disk of the PC. According to Park et al. (2003), the frequency ranges higher than 500 kHz and less than 70 kHz may not be suitable for monitoring applications. After trial-error tests, 140 kHz-220 kHz was selected to detect the seismic damages for model dam in this study.

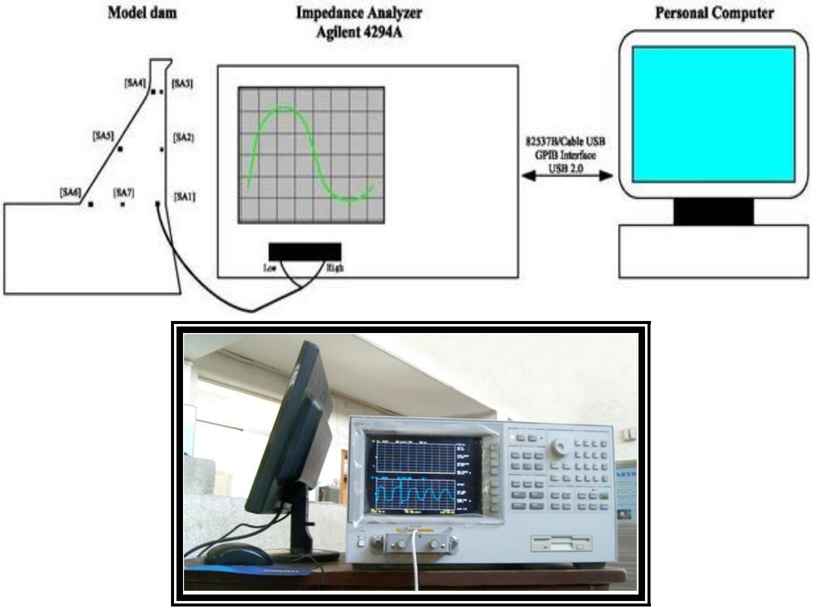


Figure 4.1. Experimental set-up for EMI method for damage detection

The excitations generated by shaking table were artificially seismic waves with Peak Ground Acceleration (PGA) 0.2g, 0.5g, and 0.7g, respectively. The load cases of model test are listed in Table 4.1. For different load cases, the embedded EMI sensors were employed to detect the seismic damages in model dam. In total, seven EMI sensors have been placed in the model dam, whose locations were shown in Fig. 4.2. Before and after each load case, the damage detection was performed by using of the EMI sensors in the model dam.

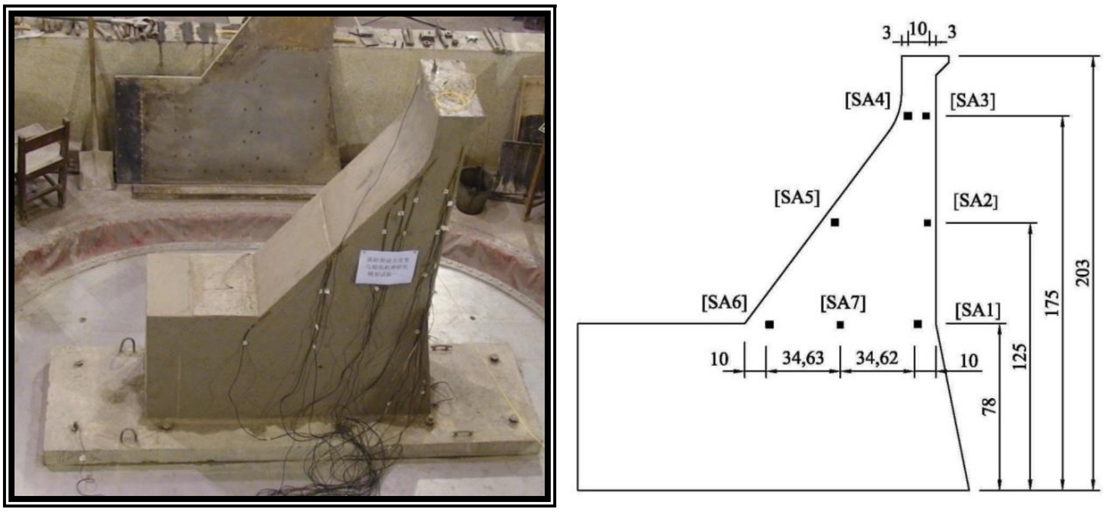


Figure 4. Locations of the embedded EMI sensors in the model dam (SA: EMI sensor)

Table 4.1. Test program and corresponding damage phase

Test No.	Load case	Damage phase
1	No shaking	Healthy status
2	[a]PGA=0.2g (i.e. load case 1)	No visible crack (i.e. damage phase 1)
3	[a]PGA=0.5g (i.e. load case 2)	Incipient crack (i.e. damage phase 2)
4	[a]PGA=0.7g (i.e. load case 3)	Major crack (i.e. damage phase 3)

[a]PGA= Peak Ground Acceleration

4.2 Experimental Results

By using of the measured data of impedance and admittance, the RMSDs of each EMI sensor were calculated for each damage phases, with respect to the healthy status of model dam (i.e. before load case 1). The computed values of RMSDs were listed in Table 4.2. In the table, R X, G and B represent resistance, reactance, conductance and susceptance of the EMI sensors, respectively. It can be seen that almost all RMSD values present an increasing trend when the seismic excitations of model dam become more and more intensive. But for damage phase 1 (i.e. after load case 1), the RMSD values of reactance for sensor 1 and sensor 5 are less than 1%, while the RMSD value of susceptance for sensor 1 is less than 1%. In the case of damage phase 2 (i.e. after load case 2), the RMSD value of reactance for sensor 1, as well as the RMSD values of susceptance for sensor 1 and sensor 6, are all less than 1%. According to Yang *et al.* (2008), the RMSD value less than 1% cannot reliably reveal the damage information due to the sensing limit of the sensor. Actually, after damage phase 2, the damages have been appeared close to sensor 1, sensor 5 and sensor 6. Another observation can be found that most of RMSD-G values are greater than RMSD-R values. For damage phase 2 and 3, the maximum values of RMSD-Gs are about 1.7 times as those of RMSD-Rs. Even in damage phase 1, the maximum value of RMSD-G is about 1.4 times as that of RMSD-R. Based on the above results, we can find that the damage index based on the real part of admittance is more sensitive than other damage indices to detect the seismic damage for model dam. The experimental results clearly demonstrate that the variations in the damage indices based on measured impedance/admittance signatures can be used to detect the structural damage after the earthquake.

Table 4.2. The calculated values of damage indices RMSD (%)

Damage phase	Sensor No.	RMSD-R	RMSD-X	RMSD-G	RMSD-B
1	1	2.2031	0.4602	5.1351	0.7170
	2	4.0974	8.1096	8.1714	4.8457
	3	2.2165	5.4134	5.9382	1.3382
	4	1.8660	5.9678	6.0584	5.0910
	5	4.0122	0.8306	3.1168	1.1024
	6	5.8714	3.1329	5.8687	2.5127
	7	1.1350	1.2921	5.3110	2.1643
2	1	2.1429	0.9676	2.5037	0.9799
	2	9.8696	12.6460	15.3820	17.7700
	3	12.1425	26.3677	20.4071	6.8721
	4	10.2222	15.1110	20.8200	26.1440
	5	9.1100	3.9679	11.1010	3.9848
	6	5.1657	2.9838	5.2911	0.9115
	7	3.6815	2.6932	3.8174	3.8729
3	1	18.2190	5.8975	16.7890	6.5505
	2	10.2730	14.5900	18.7790	20.5380
	3	28.7800	51.0970	49.0780	13.8970
	4	14.0755	29.2830	50.0710	52.8690
	5	19.1160	7.4537	21.5820	7.3219
	6	18.6280	13.8520	18.5050	13.0304
	7	9.9649	8.8467	13.0200	11.2976

Note: The underlines in the table denote the RMSD values less than 1%.

5. CONCLUSIONS

A novel method to detect the post-earthquake damage for high concrete dam was presented in this paper. The embedded EMI sensors have been fabricated by embedding the waterproof PZT patches with lead wires into the small concrete blocks, which provide the protections for the PZT sensors. And the embedded EMI sensors were embedded inside the dam at the predetermined positions. The impedances and admittances of the embedded EMI sensors were measured before and after earthquake. The scale model tests of a high concrete dam were performed to verify the effectiveness of the proposed method. The damage indices based on the RMSDs of measured data were studied to quantitatively evaluate the damage in the model dam. From the results, the RMSD-G was found to be more sensitive than other damage indices. It is concluded that the proposed method of the embedded EMI sensors can effectively detect the seismic damage for a scale model of high concrete dam, which provides a potential means to monitor the damage in real dam.

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