

Development of Dual PZT Based Impedance Measurement Techniques for Large-Scale Structures

H. J. LIM¹, H. M. SONG and H. SOHN

ABSTRACT

In this study, new impedance measurement techniques are developed specially for structural health monitoring of large-scale structures. Electromechanical (EM) impedance based damage detection techniques, which utilize the electromechanical coupling effect between a piezoelectric transducer such as lead zirconate titanate (PZT) and a host structure, have been shown to be very sensitive to local damage near the PZT. However, when the impedance of the host structure becomes excessively large compared to that of the PZT, the impedance measurement becomes difficult. This impedance mismatch has been hampering the application of the impedance based damage detection techniques to large-scale structures. In this study, new impedance measurement techniques are developed for impedance measurement of large-scale structures using a dual PZT transducer, which is composed of two separate but concentric PZT segments. Impedance signals obtained by the proposed techniques are compared to those measured by conventional self-sensing circuit and commercial impedance analyzer. It is demonstrated that the proposed techniques can successfully measure the EM impedance of areal-scale bridge structure even then the conventional techniques fail to do so.

INTRODUCTION

Electromechanical (EM) impedance-based damage detection techniques have been shown to be very sensitive to local damage [1-2]. Since nonintrusive surface-mounted PZTs are used for EM impedance measurement, a variety of EM impedance techniques have been explored for structural health monitoring (SHM) applications [1-3, 6]. Conventionally, EM impedance signatures are measured using commercial impedance analyzers or self-sensing circuits [2, 6]. The impedance analyzers, which are originally designed for high precision impedance measurement of electronic components, are expensive and bulky, making them less attractive for field applications [3]. The self-sensing circuits are low costs and light weight, but the impedance is indirectly

¹Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea

measured by adding a reference capacitor or resistor in series with the PZT [6]. Here, both techniques share difficulties in measuring EM impedance signals when the mechanical impedance of a host structure becomes excessively large. To overcome the limitation, new impedance measurement techniques are developed in this study so that EM impedance signals can be measured even from large-scale structures.

This paper is organized as follows. First, the design of a dual PZT is described. Then, two new impedance measurement techniques using either a single dual PZT or a pair of dual PZTs are developed. Then, the experimental results from laboratory and actual field testing are shown to verify the superior performance of the proposed EM impedance measurement techniques over conventional ones.

DUAL PZT BASED IMPEDANCE MEASUREMENT TECHNIQUES

Description of a dual PZT transducer

A dual PZT consists of concentric ring and circular PZT segments as shown in Figure 1 [4-5]. These two PZT components can be activated independently or simultaneously for ultrasonic wave excitation and sensing. This unique design of the dual PZT makes it possible to improve the impedance measurement as described below.

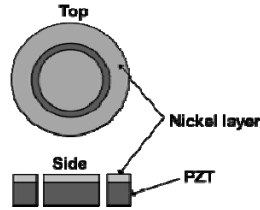


Figure 1. A schematic representation of a dual PZT transducer.

Dual PZT impedance measurement

Using the dual PZT, EM impedance is measured by exciting the ring segment of the dual PZT and measuring the response using the inner circular segment in a pulse-echo mode as shown in Figure 2 (a). This impedance measurement technique allows the direct measurement of the pulse-echo response without any reference capacitor or resistor, providing much larger response than the conventional impedance measurement techniques. Also it is acceptable since a same strain field is subjected to both ring and circular PZTs [5]. Using the dual PZT, the EM impedance is calculated dividing the input voltage applied to the ring segment (V_{in}) by the output current measured from the inner circular PZT (I_{out}):

$$Z(\omega) = \frac{V_{in}(\omega)}{I_{out}(\omega)} = \frac{V_{in}(\omega)}{i\omega C_{PZT} V_{out}(\omega)} \quad (1)$$

where V_{out} and C_{PZT} represent the output voltage and electric capacitance of the inner circular PZT, respectively. Note that similar EM impedance can also be measured by exciting the inner circular PZT and measuring the output current from the outer ring

PZT, instead. In this study, the outer ring and inner circular segments are used for excitation and sensing, respectively, because a larger PZT is preferred for excitation and a smaller PZT for sensing [5].

Double dual PZT impedance measurement

The peaks in the EM impedance signal in Eq. (1) can be seen as the resonant peaks of the host structure's steady-state vibrations. Here, the standing waves at the resonance peaks are produced by constructive superimposition of the incident waves generated by the PZT and the reflected waves from the structural boundaries [7]. However, as the size of a host structure and its impedance increases, the reflective waves become weak resulting in the decrease of the resonance peaks in the EM impedance signal. To overcome this limitation, a second dual PZT is placed near the existing dual PZT to force the generation of standing waves by creating additional incident waves propagating the opposite direction (Figure 2 (b)). This impedance measurement with the excitation of the second dual PZT is named as double dual PZT based impedance measurement in this study.

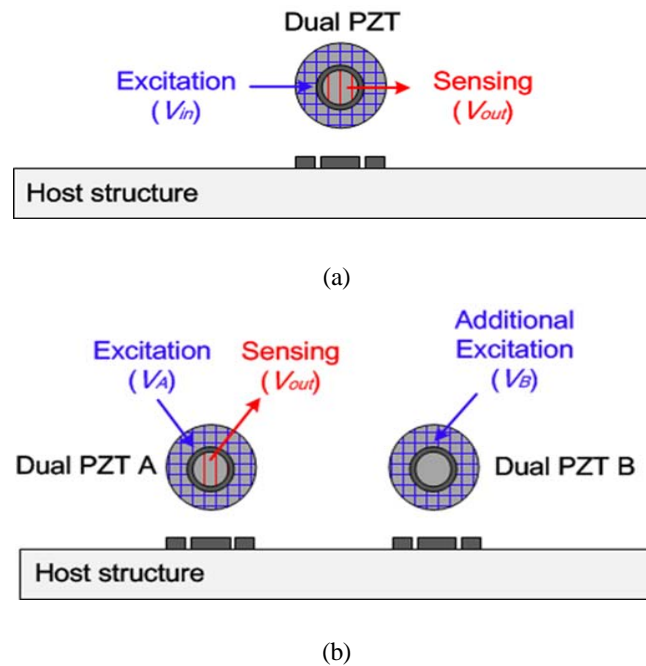


Figure 2. A schematic representation of dual PZT based impedance measurement techniques for large-scale structures: (a) Dual PZT impedance measurement and (b) double dual PZT impedance measurement.

EXPERIMENTAL VERIFICATION

Experiment overview

Here, the impedance signals measured by the proposed dual PZT and double dual PZT based impedance techniques are compared with those obtained by a conventional

impedance analyzer and a self-sensing technique using a laboratory specimen and from a real field test of a bridge structure.

Laboratory experiment

Experimental setup

Figure 3 (a) shows the experimental setup for measuring impedance signals from a steel I-beam specimen. The dimensions of the top and bottom flanges are 530 mm x 300 mm x 15 mm, and 530 mm x 300 mm x 10 mm for the web. Two identical dual PZTs (APC 852 type), PZTs A and B in Figure 3 (a), are placed 40 mm apart each other on the top flange. The outer and inner diameters of the ring PZT, the diameter of the inner circular PZT disk, and the thickness are 10 mm, 6 mm, 4 mm and 0.508 mm, respectively. The excitation was provided by the outer rings of PZTs A and B, and the corresponding response was measured by the inner circular disk of PZT A. The data acquisition system composed of a controller (NI-PXI 8105), an arbitrary waveform generator (AWG, NI-PXI 5421), a digitizer (DIG, NI-PXI 5122) and multiplexers (MUX, NI-PXI 2593) was used for EM impedance measurement using the proposed techniques and the self-sensing circuit based technique. A conventional impedance analyzer, Agilent 4294A, shown in Figure 3 (b) was also used. All EM impedance signals were measured in the frequency range of 10-100 kHz with 10 Hz resolution. Also, ten impedance signals obtained from each technique were averaged in the time domain to improve the signal to noise ratio.

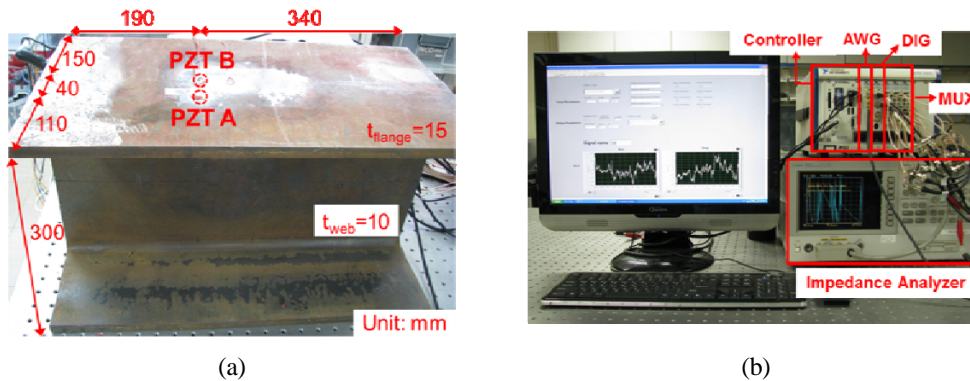


Figure 3. Experimental setup for the EM impedance measurement: (a) A steel I-beam and (b) data acquisition system.

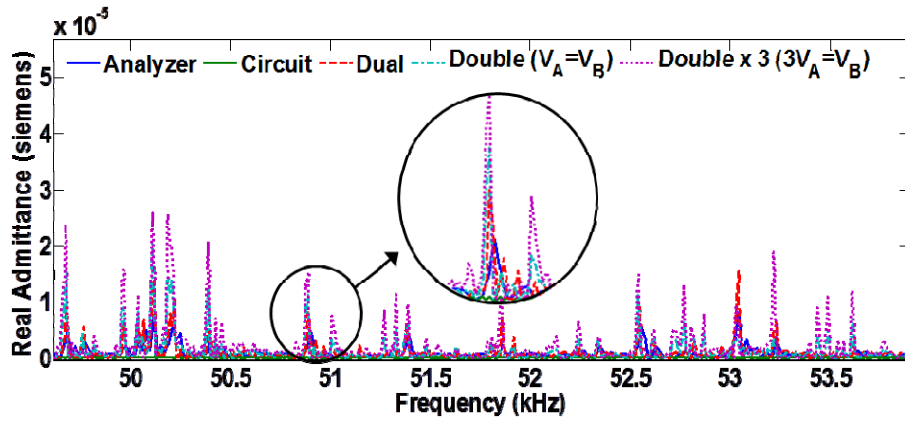
Experimental results

Figure 4 (a) shows the real part of EM admittance (inverse of impedance) signals obtained from the I-beam specimen using five different techniques: (1) impedance analyzer, (2) self-sensing circuit with $V_{in}=1$ Volt, (3) dual PZT with $V_{in}=1$ Volt, (4) double dual PZTs with $V_A=V_B=1$ Volt and (5) double dual PZTs with $V_A=1$ Volt and $V_B=3$ Volts. All EM admittance signals were obtained from the inner circle segment of PZT A. Similar resonance peaks were obtained from all measurement techniques except the self-sensing circuit. No distinctive resonance peaks were obtained using the self-sensing technique.

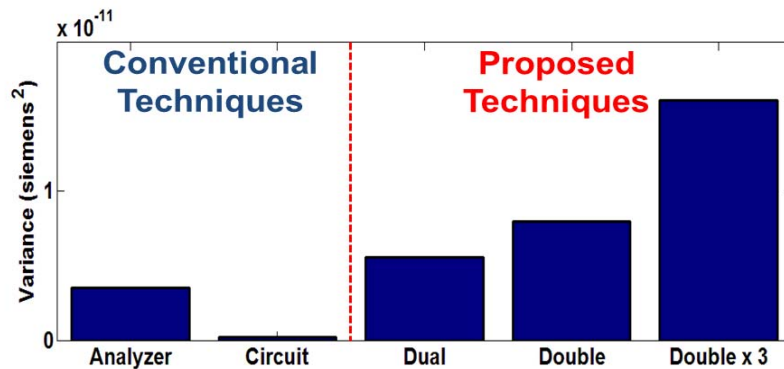
To quantitatively compare the presented measurement techniques, the variance of the EM admittance signal obtained from each technique is computed and compared as shown in Figure 4 (b). Here, the variance is used as an indicator of the resonance peak level, showing how far a set of EM admittance values are spread out from the mean admittance value:

$$Var = \frac{1}{n-1} \sum_{i=1}^n (Y_i - \bar{Y})^2 \quad (2)$$

where, n , Y_i and \bar{Y} represent the data length of the EM admittance signal, i^{th} value and mean value of the EM admittance, respectively. As shown in Figure 4 (a), the proposed dual PZT based measurement techniques show much larger variance than the conventional measurement techniques. Note that in the case of the double dual PZT impedance, the resonance peak level increases as the additional excitation increases. It can be answered by the fact that amplifying the additional excitation voltage is equivalent to amplifying the amplitude of reflected waves.



(a)



(b)

Figure 4. EM admittance signals obtained from the proposed and conventional measurement techniques. (a) EM admittance signals and (b) the variance of EM admittance signals from each measurement technique.

Real scale experiment

Target bridge description

The feasibility of the proposed techniques was tested at Ramp-G Bridge in Goyang, Kyunggi, South Korea. This 90 m-long curved double-span ramp is composed of a concrete deck and two steel box girders as shown in Figure 5.



Figure 5. Ramp-G bridge in South Korea and the inspected spot. (a) Overview of the bridge and (b) bottom view of the bridge.

Experimental setup

Figure 6 (a) shows the inspected spot inside the box girder. Two identical dual PZTs (APC 852 type), PZTs A and B, are installed 500 mm apart each other on the inspected spot (Figure 6 (b)). The outer and inner diameters of the ring PZT, the diameter of the inner circular PZT segment and the thickness are 20mm, 12 mm, 10 mm and 0.508 mm, respectively. The excitation was given by the outer rings of PZT A and B, and the corresponding response was obtained by the inner circle segment of PZT A. The configuration of the data acquisition system was identical to the one as previously shown in Figure 3 (b). At the same manner with the laboratory test, all EM impedance signals were obtained in the frequency range of 10-100 kHz with 10Hz resolution. Also, twenty impedance signals obtained from each technique were averaged in the time domain to improve the signal to noise ratio.

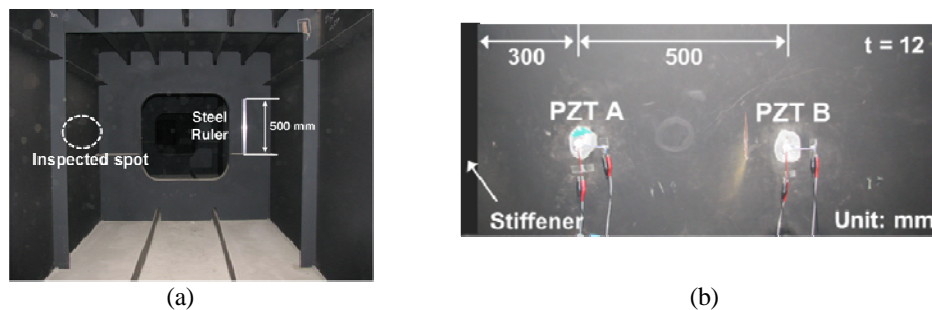
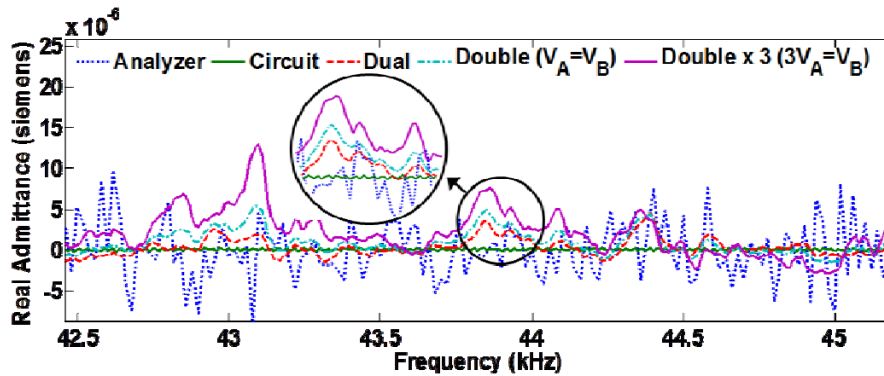


Figure 6. An inspected spot inside the target bridge: (a) Interior of the box girder and (b) inspected spot where two dual PZTs are attached.

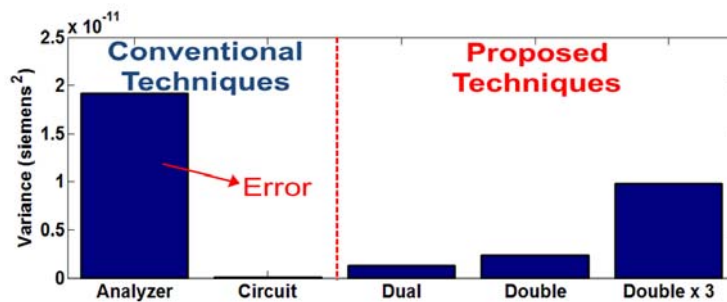
Experimental results

At the similar manner with the previous laboratory test, five different techniques are considered to compare the performance: (1) impedance analyzer, (2) self-sensing circuit with $V_{in}=5$ Volts, (3) dual PZT with $V_{in}=5$ Volts, (4) double dual PZTs with $V_A=V_B=5$ Volts and (5) double dual PZTs with $V_A=5$ Volts and $V_B=15$ Volts. All EM admittance signals were obtained from the inner circular PZT A. It is noticeable that only the proposed techniques succeeded to obtain EM admittance signals as shown in Figure 7 (a). The self-sensing technique did not show any distinctive resonance peaks and the impedance analyzer obtained a very noisy signal hard to be used for SHM application.

To quantitatively evaluate the resonance peak level, the variance of the EM admittance signal obtained from each technique is calculated and compared as shown in Figure 7 (b). The proposed techniques show much larger variance than the conventional techniques, except the case of the impedance analyzer. However, the large variance from the impedance analyzer can be ignored by its high noise level shown in Figure 7 (a). A possible reason of the noisy signal from the impedance analyzer may be on the weak excitation voltage capacity of the impedance analyzer (0.5 Volts), while the proposed system can magnify the excitation voltage up to 6 Volts. It is also noticeable that in the case of double dual PZT impedance, the sharper and magnified resonance peaks are obtained as the additional excitation voltage is amplified. The experimental results demonstrate superior performance of the proposed EM impedance measurement techniques.



(a)



(b)

Figure 7. EM admittance signals obtained from the proposed and conventional measurement techniques. (a) EM admittance signals and (b) the variance of EM admittance signals from each measurement technique.

CONCLUSION

This study proposed new dual PZT based EM impedance measurement techniques for large-scale structure applications. First, the configuration of a dual PZT is introduced and two EM impedance measurement techniques, (1) dual PZT impedance measurement and (2) double dual PZT impedance measurement, are described. Then the feasibility of the proposed techniques is validated by the laboratory and actual field testing. The experimental results demonstrated that the proposed techniques successfully obtain EM impedance signatures from large-scale structures showing much larger responses compared to conventional techniques. Additional research for theoretical formulation and numerical verification of the proposed techniques will be followed. Also, application of the proposed techniques to damage detection in large-scale structure has to be considered.

ACKNOWLEDGEMENTS

This work is supported by U-City Master and Doctor Course Grant Program of Korea Ministry of Land, Transport and Maritime Affairs. Also, the authors would like to express thanks to Dr. Chang Guen Lee at Korea Expressway Corporation for making the bridge available for testing.

REFERENCES

1. G. Park, H. Sohn, C.R. Farrar and D.J. Inman. 2003. "Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward," *The Shock and Vibration Digest*, 35(6), pp. 451-463
2. A. N. Zagari and V. Giurgiutiu. 2001. "Electro-Mechanical Impedance Method for Crack Detection in Thin Plates," *Journal of Intelligent Material Systems and Structures*, 12, pp. 709-718
3. F. B. Baptista, J. Z. Filho and D. J. Inman. 2012. "Real-time multi-sensors measurement system with temperature effects compensation for impedance-based structural health monitoring", *Smart Materials and Structures*, 11(2), pp. 173-186
4. H. Sohn and S. B. Kim 2010. "Development of dual PZT transducers for reference-free crack detection in thin plate structures", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 57 (1), pp. 229-240
5. C. M. Yeum, H. Sohn and J. B. Ihn. 2011. "Lamb wave mode decomposition using concentric ring and circular PZT Transducers", *Wave Motions*, 48, pp. 358-370
6. M. K. Kim, E. J. Kim, Y. K. An, H. W. Park and H. Sohn. 2011. "Reference-free impedance based crack detection in plates", *Journal of Sound and Vibration*, Journal of Sound and Vibration, 330, pp. 5949-5962
7. E. J. Kim, M. K. Kim, H. Sohn and H. W. Park. 2011. "Investigating electro-mechanical signals from collocated piezoelectric wafers for the reference-free damage diagnosis of a plate", *Smart Materials and Structures*, 20, 065001 (12pp)