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Development of a wireless-based multi-channel impedance sensing system for structure local damage detection

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ABSTRACT

This work presents development of a wireless-based multi-channel impedance sensing system for detecting location of structure local damage. The system is composed of a wireless impedance sensor, application software, and local damage detection schemes. The wireless impedance sensor is consists of a microprocessor, wireless communication module, and an AD5933 impedance chip as well as two multiplexers. The sensor not only has the properties of cost-efficient, low power requirements, small size, and simple deployment, but also has the multi-channel function that allows the user to monitor seven-channel PZT patch from a single device. Users can communicate with these sensors through the dongle with computer wirelessly. Through the application software we developed, the measurement parameters and sampling period can be set and record the measured impedance data on the computer. When the sensor is in idle state, it can be switched into sleep mode to reduce power consumption. Herein, local damage detection schemes include root-mean-square deviation (RMSD) index to locate the local damages of the structure. The feasibility of the proposed wireless impedance-based sensing system was assessed using a 1/8-scale three-storey steel-frame model with various damage scenarios. It was confirmed experimentally that good sensing quality can be achieved via proposed system and locations of structure local damages can be identified effectively.

1. INTRODUCTION

The approaches of structural health monitoring (SHM) can be classified as global and local monitoring. The global structural monitoring methods are conventionally adopted vibration-based (acceleration-based) schemes. These methods identify damage by detecting modal property change, such as natural frequencies, modal damping, or mode shape. However, vibration-based methods are not very effective in detecting tiny or incipient damage locality. Therefore, the electro-mechanical-impedance

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(EMI)-based damage detection method has been studied extensively as a powerful technique at localizing damage (Liang et al.1994; Sun et al. 1995; Park et al. 2000; Bhalla et al, 2004).

When many sensors and diagnostic methods are implemented, wireless communication appears to be an attractive approach as conventional wired sensor systems can only deploy limited numbers of sensors because of cost constraints or excessive complexity. Wireless sensors are expected to diminish these problems by simplifying the installation of wired sensors. Smart wireless sensor networks (WSNs) are an attractive sensing technology for SHM applications because of their low manufacture costs, low power requirements, small size, and simple deployment (i.e., lack of cables) (Lin et al. 2012).

The development of wireless impedance sensor node has been investigated by several studies in literature. Mascarenas et al.(2009) and Park et al. (2010) designed the sensing node based on an Atmega128 microcontroller. Nguyen et al. (2011) proposed wireless impedance sensor node based on an Imote2 platform. The aforementioned sensors all contained an AD5933 impedance measurement chip individually. They also provided wireless telemetry and multiplexers. The Atmega128 MCU based nodes had limited storage memory and low clock speed. That has constraints in collection of the response signal in multiple PZT and processing data in sensor node. In addition, the Imote2 may be a powerful and promising smart wireless sensor platform for SHM. It consists of a 32 bit XScale processor with 32 MB RAM and a flash memory of 32 MB. However, the Imote2-based sensor node is more expensive relatively compared to the other platforms. For these key points, a low cost and large enough storage memory platform for impedance-based SHM is presented in this work.

This study presented a novel impedance-based wireless sensor SHM system for detecting structural local damage. A low cost wireless impedance sensor node based on Jennic platform, called JN-IMP, was developed. The Jennic microprocessor offers an enhanced 32-bit RISC processor and a fully compliant 2.4GHz IEEE802.15.4 transceiver (SoC) with a RAM of 128 KB and a flash memory of 512 KB. JN-IMP also integrated an AD5933 impedance chip as well as two multiplexers. It is designed with the properties of cost-efficient, low power requirements, small size, and simple deployment. The feasibility of the proposed wireless impedance-based sensing system was assessed using a 1/8-scale three-storey steel-frame model with various damage scenarios. It was confirmed experimentally that good sensing quality can be achieved via proposed system and locations of structure local damages can be identified effectively.

2. ELECTROMECHANICAL IMPEDANCE-BASED METHOD

The Impedance-based damage detection approach utilizes the electromechanical coupling effect between active surface-bonded piezoelectric patches and host structural. Liang et al. (1994) first proposed an analytical model of this method. The electromechanical is related to the mechanical impedance of a host structure, thus allowing monitoring the properties of the host structure using the measured electrical impedance. When damage occurred to structure, the mechanical impedance of structure will be changed. Therefore, if the mechanical impedances of the piezoelectric patch remain undamaged, any changes in the EMI signal correlates with the damage in structure. A piezoelectric patch-structure bonded system can be modeled as a circuit system (Park et al. 2007), shown in Fig.1.

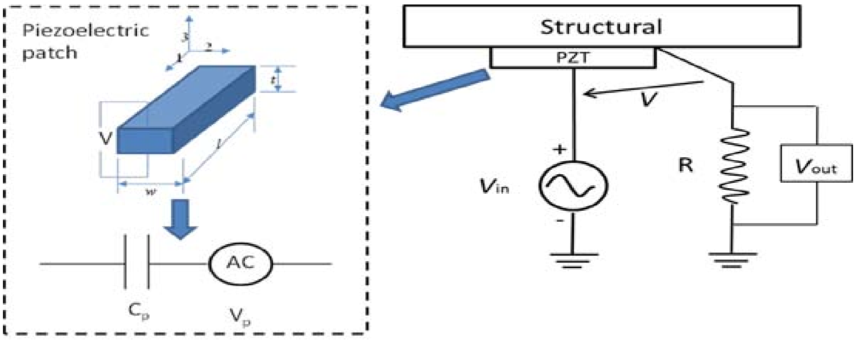


Fig. 1 Diagram of PZT-structure bonded system

Herein, piezoelectric patch is modeled as a capacitor (C_p) and a self sensing-actuation voltage source (V_p) caused by input voltage (V_{in}). The output voltage, couple with V_p and V_{in}, can be expressed as

$$V_{out}(\omega) = \frac{Z_R(\omega)}{Z_R(\omega) + Z_P(\omega)}\left(V_{in}(\omega) + V_p(\omega)\right) \tag{1}$$

Where Z_R is the electrical impedance of the resister and Z_P is electrical impedance of piezoelectric patch. Subsequently, the electrical impedance of piezoelectric patch can be written as

$$Z_P(\omega) = Z_R(\omega)\left\{\frac{V_{in}(\omega) + V_p(\omega)}{V_{out}(\omega)} - 1\right\} \tag{2}$$

Since the self sensing-actuation voltage source (V_p) is related to structural mass, as confirmed by numerous researchers(Liang et al. 1994). Equation(2) indicates that theZ_P has significant response to structural damage. A piezoelectric patch-structure bonded system can be further modeled as an electro mechanical admittance (EMA) model (Inverse of EMI). The electro mechanical admittance model can be expressed as

$$Y(\omega) = \mathrm{j}\omega\frac{wl}{t}\left\{\left(\bar{\varepsilon}_{33}^{T} - d_{31}^{2}\hat{Y}^{E}\right) + \frac{Z_p(\omega)}{Z_p(\omega) + Z_s(\omega)} d_{31}^{2}\hat{Y}^{E}\left(\frac{\tan(kl)}{kl}\right)\right\} \tag{3}$$

where w, l, and $t$are the width, length, and thickness of the piezoelectric patch;$\hat{Y}^E$is the complex Young's modulus of the piezoelectric patch at zero electric field;$\bar{\varepsilon}_{33}^{T}$is the complex dielectric constant of piezoelectric patch; $d_{31}^{2}$is the coupling piezoelectric constant in the x direction at zero stress; $k = \omega\sqrt{\rho/\hat{Y}^{E}}$ is the wave number that is related to mass density ρ,$\hat{Y}^{E}$; and excitation frequency ω, respectively; Z_p and Z_s are the mechanical impedances of the piezoelectric patch and the host structure, respectively.

Although the EMI provides a qualitative method for detecting structural damage, the quantification approach need be established. A simple statistical algorithm, which is based on frequency-by-frequency comparisons, referred to Root Mean Square Deviation (RMSD), was used to develop the quantitative assessment of damage in previous research(Yang et. al. 2008). The RMSD is defined as

$$RMSD = \sqrt{\frac{\sum_{i=a}^{b}(I_i^D - I_i^U)^2}{\sum_{i=a}^{b}(I_i^U)^2}} \quad 100 \tag{4}$$

Where $I_i^U$and $I_i^D$are the real part of impedance of piezoelectric patch at the I^{th}frequency point in undamaged and damaged structures, respectively. In a RMSD damage metric chart, the greater numerical value of the metric, the larger the difference between the baseline reading and the subsequent reading indicates the presence of damage in a structure.

This section expressions all hardware and software design of proposed novel wireless sensor system. The wireless impedance sensor is consists of a Jennic microprocessor, a SHT21 temperature/humidity integrated chip, and an AD5933 impedance chip as well as two multiplexers (ADG708). Jennic offers an enhanced 32-bit RISC processor and a fully compliant 2.4GHz IEEE802.15.4 transceiver (SoC) with a RAM of 128 KB and a flash memory of 512 KB. The Photo and block diagram of sensing node is illustrated in Fig. 2

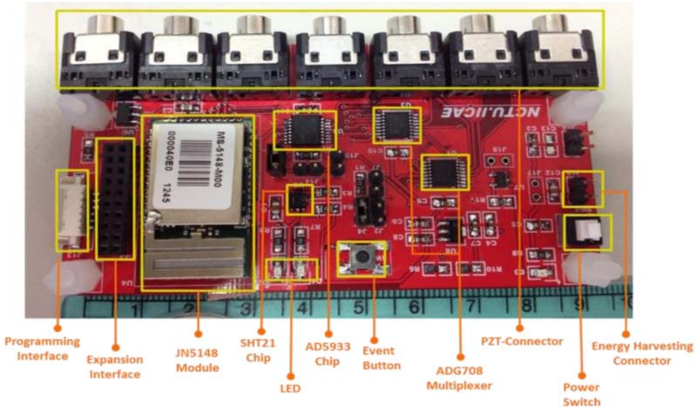


Photo of wireless impedance sensor(JN-IMP).

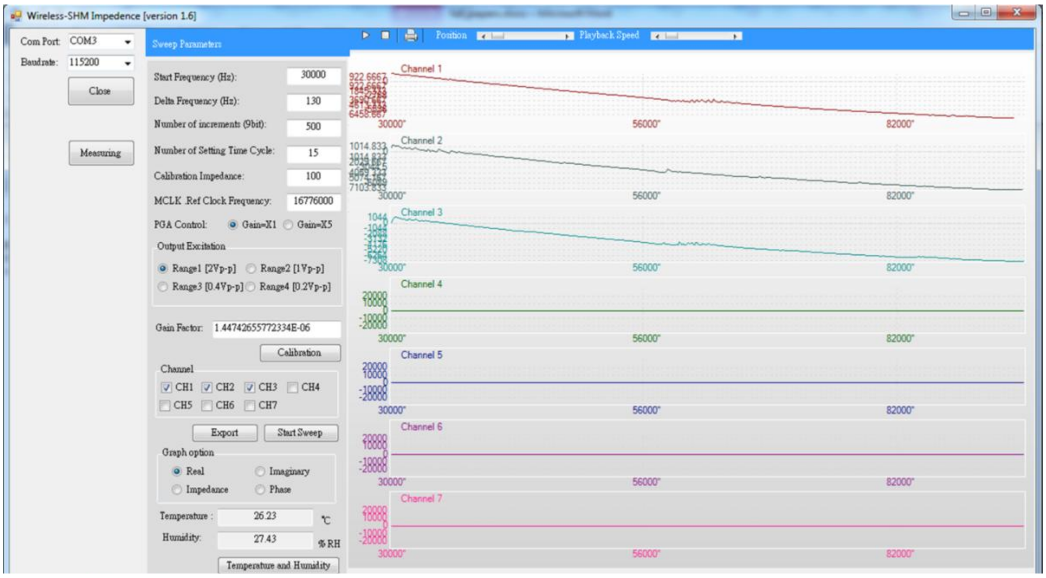
The AD5933 was first proposed for measuring EMI impedance signatures by Mascarenas et al. (2007). The impedance chip can be programmed to take a measurement from 1-100 kHz. The AD5933 consists of an on-board frequency generator, a Digital-to-Analog (D/A) converter, A/D converter. Furthermore, a discrete Fourier transform (DFT) is processed by an on-board DSP engine. The AD5933 is the most important component to interact with the piezoelectric material.

There are several important points to contribute to the flexibility of the JN-AD5933. First, the ability to wirelessly transfer allows the sensor node to be placed in non-reachable locations, without the constraints of a cable-based DAQ system. Second, the ability to quickly change the system setting of sweep parameters, through the self-made wireless transfer instructions. Finally, the ability to efficiently change the firmware on the microcontroller, through the on-board FTDI chip, allows the sensing node to further extend. The features are described in Table 1.

Table.1 Features of the proposed JN-IMP

Model	AD5933
Impedance Range	1 kΩ–10 kΩ
Frequency Range	1 kHz–100 kHz
Excitation Voltage	1.98 V_{p-p}
Temperature Resolution	> 0.03 ºC
Temperature Range	-40 ~ +125°C (-40 ~ +257°F)
Wireless function	2.4 GHz IEEE 802.15.4 / Zigbee
Transmission Range	Standard Power (20 m) / High power (up to 1km)
Power Supply Options	Commercial batteries (3.6-7.2V) 2AA Ni-MH rechargeable battery withSolar Panels (3V)
Dimensions	91.6 x 48 x 7 (mm)
Weight	45(g)
Cost	$US 50

A host computer is employed to transmit command parameters and receives the data from JN-IMPwirelessly. A .NET C#based user interface was designed to convenience handling the raw and processed data as shown in Fig. 3. The sweep parameters panel let the user define the system setting with the required frequency ranges, number of frequency points and increased of delta frequency. The user interface combines the ability to measure data and analyse the data for damage indicators and display the results.



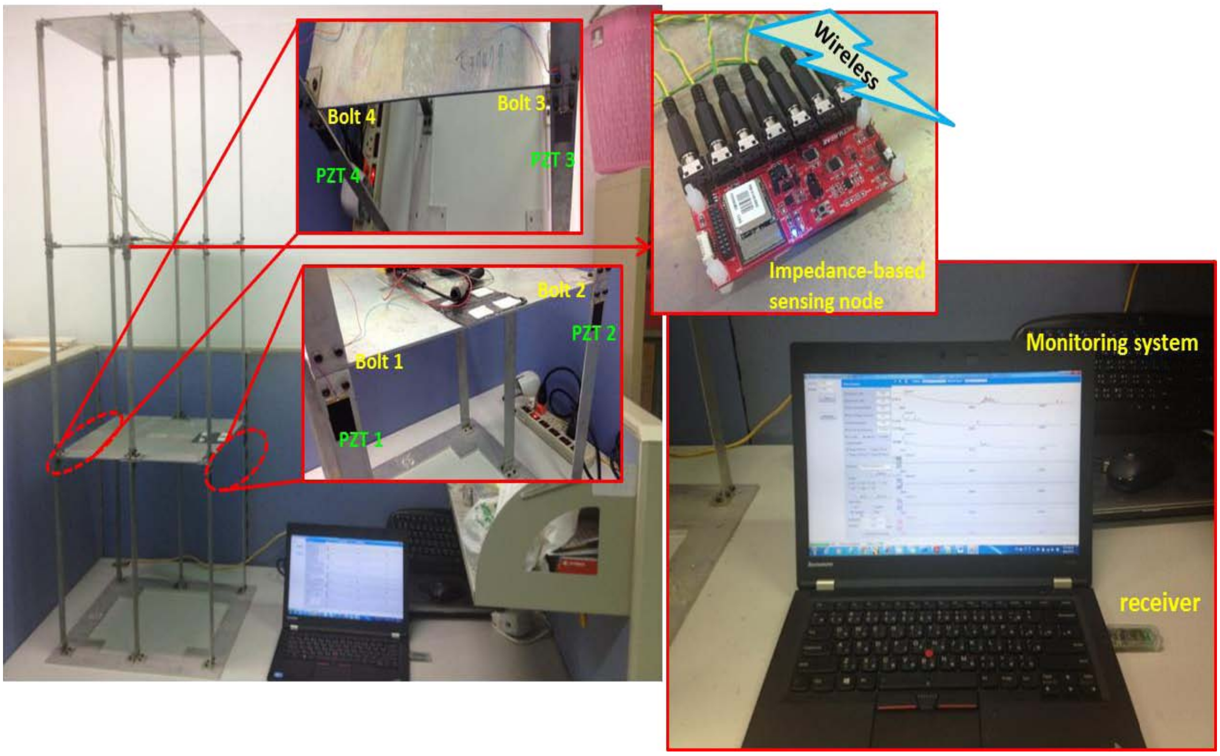
Com Port: COM3
Baudrate: 115200
Start Frequency (Hz): 30000
Delta Frequency (Hz): 130
Number of increments (9bit): 500
Number of Setting Time Cycle: 15
Calibration Impedance: 100
MCLK Ref Clock Frequency: 16776000
PGA Control: ● Gain=X1 ○ Gain=X5
Output Excitation: ● Range1 [2Vp-p] ○ Range2 [1Vp-p] ○ Range3 [0.4Vp-p] ○ Range4 [0.2Vp-p]
Gain Factor: 1.44742655772334E-06
Channel: ☑ CH1 ☑ CH2 ☑ CH3 ☐ CH4 ☐ CH5 ☐ CH6 ☐ CH7
Graph option: ● Real ○ Imaginary ○ Impedance ○ Phase
Temperature: 26.23 ℃
Humidity: 27.43 %RH

Fig.3 The user interface of Wireless-SHM Impedance system

4. EXPERIMENTAL VERIFICATION

4.1. Experimental Study in bolted loosen

A 1/8-scale three-storey steel frame model, shown in Fig. 4, was utilized to evaluate the performance of the JN-AD5933 and local damage detection schemes. Each floor weighed about 3.8 kg and each column had a cross-sectional area of 80 mm and was 440 mm in height. Four PZT patches are respectively close bonded to the joint of the columns in 1st floor. A series of damage scenarios were listed in Table 2. First, all bolts were fastened in C1. Then, the bolt 1 was loosened in C2. Subsequently, bolt 2 and bolt 3 were loosened in the next scenarios in C3 and C4, respectively. Finally, the bolt1 were refastened in C5.

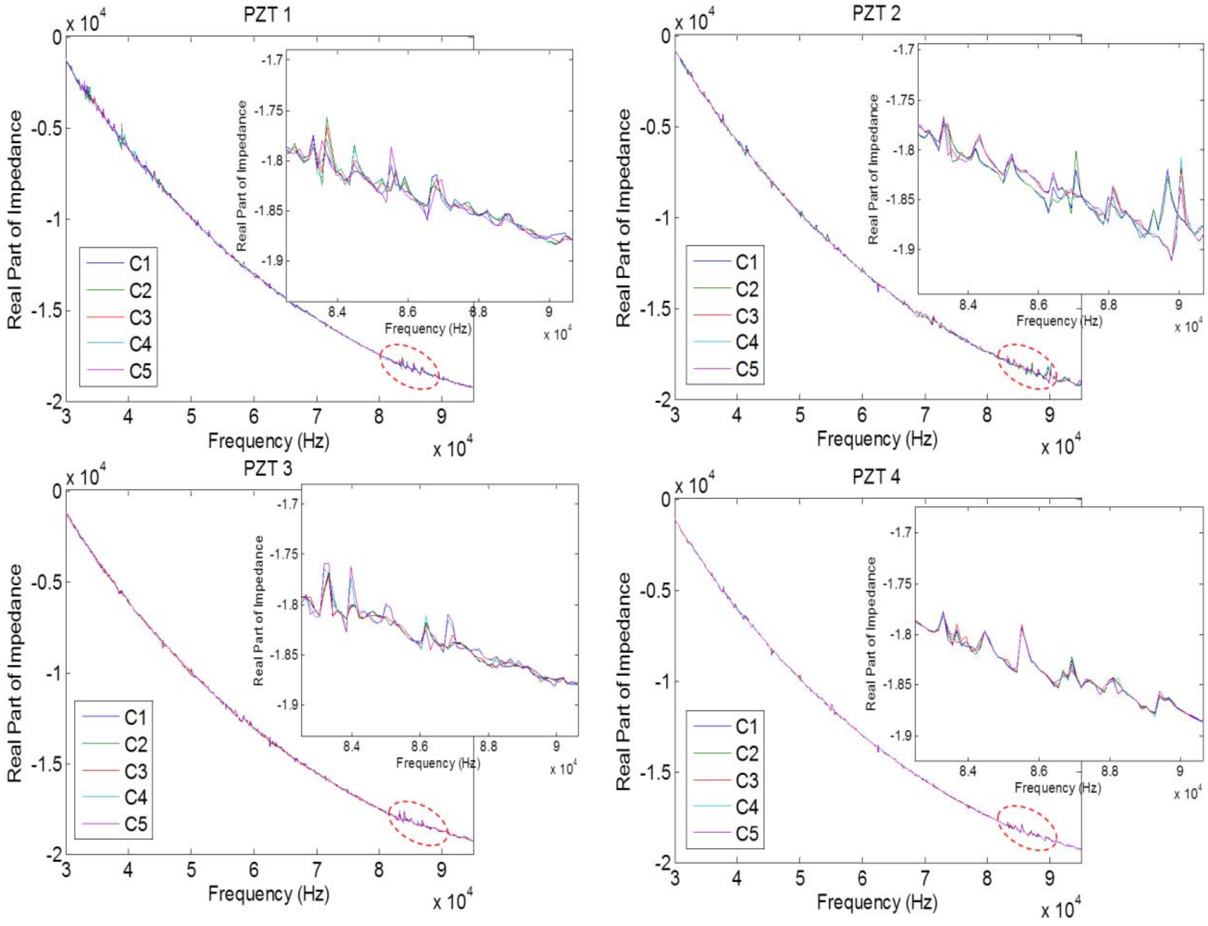


F Experimental setup for wireless impedance measurement device in a 1/8-scaled three-storey steel frame model.

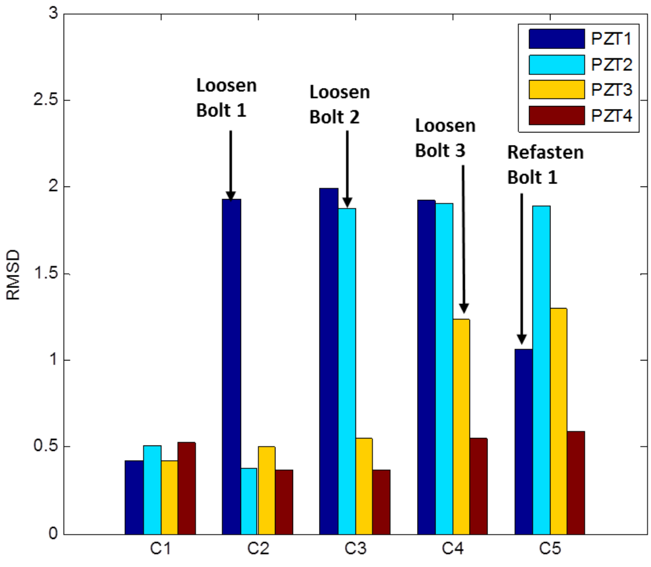
Damage scenarios for detecting bolt loosen on a 1st floor.

Case	Damage Description	Loosened Bolts
1	No damages	None
2	Loosen bolt 1	1
3	Loosen bolt 2 (Bolt 1 & 2 are loosened)	1,2
4	Loosen bolt 3 (Bolt 1 ,2 & 3 are loosened)	1,2,3
5	Bolt1 refastened	2,3

The system was programmed to monitor the impedance of the PZT in the frequency range of 30-95 kHz. Figure 5 illustrations a impedance signatures at various damage cases from four PZT. A very distinct bandwidth was measured in the frequency range of 83-89 kHz, so special attention was heeded to this area so as to monitoring this feature would change for bolted joints loosen (in this case). The damage metric chart based on RMSD is constructed to identify the local damage. As shown in Fig. 6, the highest value identifies the damage of loosen bolt significantly.

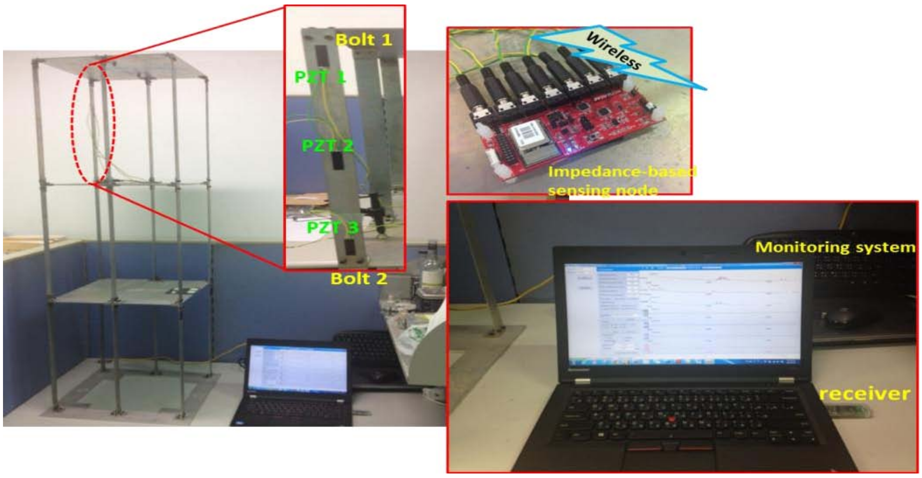


Measured impedance signatures at various damage cases from four PZT patches.



RMSDindex for damage cases.

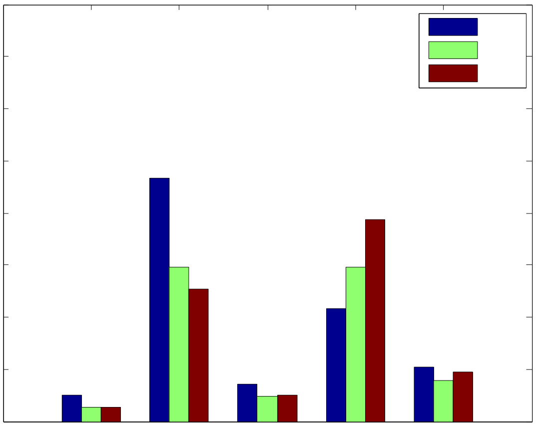
Three PZT patches are respectively bonded to columns at upper, middle and lower point in 3st floor as shown in Fig. 7. A series of damage scenarios were listed in Table 3. First, all bolts were fastened in Case 1. Then, the bolt 1 was loosened in Case 2. Next the bolt 1 were refastened in Case 3. Subsequently, bolt 2 were loosened in the next scenarios in Case 4 and refastened in Case 5 once again.



F Experimental setup for local damage detection in a 1/8-scaled three-storey steel frame model.

Damage scenarios for detecting damage location on a3st floor.

Case	Damage Description	Loosened Bolts
1	All fastened	None
2	Loosen bolt 1	1
3	Bolt1 refastened	None
4	Loosen bolt 2	2
5	Bolt2 refastened	None



RMSDindex for damage cases.

Figure 8 expressions a impedance signatures at various damage cases from three PZT. The highest RMSD value identifies the damage of joint by nearest PZT. Otherwise, from the furthest PZT get the lowest RMSD value. This characteristic can be used to detect the location of the damage.

5. CONCLUSIONS

In this study, a local structural damage is detected using an EMI-based method by low-cost wireless impedance sensor was presented. Firstly, the low-cost wireless impedance sensor based on Jennic platform, with the properties of cost-efficient, low power requirements, small size, and simple deployment. Secondly, this system combines the ability to measure data and analyze the data for damage indicators and display the results through the user interface created by .NET C#. Finally, performance of all system was verified experimentally using a 1/8-scale three-storey steel-frame model. It was confirmed experimentally that good sensing quality can be achieved via proposed system and locations of structure local damages can be identified effectively. The next generation of JN-IMP is planned for the future. Firstly, the ability of wireless trigger for the device is planned. Secondly, temperature compensation model will be considered. Finally, an automatically spectrum scanning mechanism will be designed.

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