Smart Structures and Systems, *Vol. 25, No. 4 (2020) 423-432*
DOI: https://doi.org/10.12989/sss.2020.25.4.423

EMI based multi-bolt looseness detection using series/parallel multi-sensing technique

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(*Received April 29, 2019, Revised October 21, 2019, Accepted November 8, 2019*)

Abstract. In this paper, a novel but practical approach named series/parallel multi-sensing technique was proposed to evaluate the bolt looseness in a bolt group. The smart washers (SWs), which were fabricated by embedding a Lead Zirconate Titanate (PZT) transducer into two flat metal rings, were installed to the bolts group. By series connection of SWs, the impedance signals of different bolts can be obtained through only one sweep. Therefore, once the loosening occurred, the shift of different peak frequencies can be used to locate which bolt has loosened. The proposed multi input single output (MISO) damage detection scheme is very suitable for the structural health monitoring (SHM) of joint with a large number of bolts connection. Another notable contribution of this paper is the proposal of 3-dB bandwidth root mean square deviation (3 dB-RMSD) which can quantitatively evaluate the severity of bolt looseness. Compared with the traditional naked-eye observation method, the equivalent circuit based 3-dB bandwidth can accurately define the calculation range of RMSD. An experiment with three bolted connection specimens that installed the SWs was carried out to validate our proposed approach. Experimental result shows that the proposed 3 dB-RMSD based multi-sensing technique can not only identify the loosened bolt but also monitor the severity of bolt looseness.

Keywords: bolt looseness detection; PZT; impedance; series/parallel multi-sensing technique; equivalent circuit; 3 dB-RMSD

1. Introduction

Bolts are widely used in the joint connections (Wang *et al*. 2013a). For example, as shown in Fig. 1, many bolts are used in a steel bridge joint. Due a variety of factors, such as dynamic loads, corrosion (Huo *et al*. 2018, Peng *et al*. 2019), and improper installation, a bolt may experience loosening (Kong *et al*. 2018, Yuan *et al*. 2019). The integrity and reliability of bolted joints have a direct impact on the safety of the entire structure, and, it is of great significance to develop an effective method to detect the locations and the degree of loosening bolts in multi-bolt joints.

For the past few years, the monitoring of bolt looseness has already attracted much attention (Ruan *et al*. 2015, Wang *et al*. 2013b). Various techniques (Caccese *et al*. 2004, Razi *et al*. 2013, Suda *et al*. 2008, Yasui and Kawashima 2000, Zadoks and Yu 1997) and smart materials (Chen *et al*. 2018b, Khomenko *et al*. 2015, Ren *et al*. 2018) have been applied to bolt pre-load monitoring. Due to their wide bandwidth and dual actuating and sensing ability (Song *et al*. 2007, 2013, Xu *et al*. 2018, Zheng *et al*. 2018), piezoceramic materials, for example, Lead Zirconate Titanate (PZT) (Park *et al*. 2005, Tawie *et al*. 2010, Liu *et al*. 2013), have been widely used in the fields of SHM (Giurgiutiu and Zagrai 2000, Ihn and Chang 2008, Park *et al*. 2007, Sohn *et al*. 2003, Li *et al*. 2019), such as stress wave based communication (Ji *et al*. 2015, Siu *et al*. 2014a, b, Wu *et al*. 2019), concrete hydration monitoring (Negi *et al*. 2018, Priya *et al*. 2018, Wang and Zhu 2011), bond-slip detection (Jiang *et al*. 2017, Li *et al*. 2018, Di *et al*. 2019), energy harvesting (Ewere and Wang 2014, Ewere *et al*. 2014, Sodano *et al*. 2005, Wang *et al*. 2015) and damage detection (Chen *et al*. 2018a, Jiang *et al*. 2018, Karayannis *et al*. 2015, Lu *et al*. 2018). Using PZT transducers, scholars also proposed various advanced bolt looseness detection algorithms. Huo *et al*. (2017a, c) employed the time reversal approach to detect the pre-load looseness. In his papers, the experimental results show that, compared with the traditional active sensing method, the received signal has a high signal to noise ratio (SNR). An attenuation-based diagnostic method was proposed by Yang and Chang (2006a) to assess the fastener integrity by observing the attenuation patterns of the resultant sensor signal, experimental tests demonstrated that the proposed approach is sufficiently reliable and durable (Yang and Chang 2006b). Structural health monitoring of signal bolted joint and multi-bolted joint were investigated by using PZT enabled linear and nonlinear acoustic/ultrasound methods (Amerini and Meo 2011, Fierro and Meo 2018). However, for all afore-mentioned approaches, two or more

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http://www.techno-press.org/?journal=sss&subpage=7
ISSN: 1738-1584 (Print), 1738-1991 (Online)

transducers were required to emit and sense the acoustic/ultrasound waves. This requirement limits its application in many in-situ cases.

Electro-mechanical impedance (EMI) is another technique to monitor the working condition of structures (Ayres *et al*. 1998, Giurgiutiu and Zagrai 2002, Park *et al*. 2001, Soh *et al*. 2000). In this manner, a piezoceramic patch that is attached to the host structure acts as both an actuator and a sensor (Bhalla and Soh 2004a, b), taking the advantage of the piezoelectric effect (Jaffe el al. 2012, Liu *et al*. 2017). By monitoring the impedance signature, the intact and damage state can be determined (Fan *et al*. 2018a, b, Huynh and Kim 2017). For bolt looseness monitoring, a piezoceramic transducer can be bonded onto or embedded into the structures (Huo *et al*. 2017a, Wang *et al*. 2019). Using the spectral element method (SEM) based EMI approach, Ritdumrongkul *et al*. (2003) quantitatively identified the looseness of bolts through a bonded PZT patch. The equivalent structural parameters were employed by Lim *et al*. (2006) to process the measured admittance signatures. In addition, PZT based smart washers that were made by integrating PZT transducers into different types of washers were developed to monitoring the bolt looseness (Huo *et al*. 2017a, Mascarenas *et al*. 2005, Yang and Chang 2006b, Yin *et al*. 2016). Huo *et al*. (2017b) proposed an EMI enabled method to monitor the bolt looseness using PZT embedded washer. The experimental results demonstrate the feasibility of this approach. With the development of wireless technique, researches have been done by coupling wireless monitoring with EMI technique (Annamdas and Radhika 2013, Yang *et al*. 2009, Zhou *et al*. 2010). Mascarenas *et al*. (2007) presented a wireless impedance sensor node equipped with PZT-enhanced washers to measure and record the electrical impedance signals. However, due to the large number of bolts at the joint of components, it is necessary to develop a simple but practical approach to detect the location and degree of bolt looseness.

The idea of parallel interrogation was first proposed by Park *et al*. (2001). Hey *et al*. (2006) presented an optimized parallel interrogation algorithm for localizing damage in an aluminum plate. The experimental results show that the parallel interrogation approach can effectively shorten the required time and keep high test accuracy simultaneously. Yang *et al*. (2010) used four different methods to interrogate nine PZT patches to estimate the location of damage. A multi-sensing electromechanical impedance method was presented by Na and Lee (2013) to monitor the damage development in multiple aluminum plates. The same methodology was applied by Na (2017) to detect the wall thickness loss of pipeline facilities. Priya *et al*. (2018) used the series/parallel connected smart sensing PZT units (SSU) to monitor the early-age characteristics of concrete and a methodology of extracting the electrical admittance from overall admittance signature was proposed.

In this paper, we proposed a multi-sensing SHM approach using the EMI technique to monitor bolted connections. Two issues, (1) the characteristics of impedance and admittance signals of PZTs in a series/ parallel circuit and (2) how to select appropriate calculation bandwidth in a series/parallel connection circuit for admittance and impedance signals, were addressed. Three steel bolted connection specimens were used to validate the proposed idea. PZT enabled smart washers (SWs) (Huo *et al*. 2017a) were employed to form a multi input and single output (MISO) SHM system. The SWs were series/parallel connected so that one impedance/ admittance signal contains multi-spot structural information. Therefore, the proposed approach can save time and manpower cost effectively. To fully understand the characteristics of series/parallel connected PZT based sensors, equivalent circuit analysis was employed and the series connected SWs were adopted in our research. The equivalent circuit analysis was also carried out to accurately define the calculation bandwidth of each peak frequency. A damage index named 3-dB bandwidth root mean square deviation (3dB-RMSD) was proposed to quantitatively evaluate the degree of damage development. Experimental results validated that the proposed EMI SHM approach can detect multi-bolt looseness effectively.

Fig. 1 A bolt connected joint of steel bridge

2. Methodology

2.1 Equivalent circuit analysis of PZT transducer

After Liang *et al*. (1997) first proposed the single-degree-of-freedom (DOF) mass-stiffness-damping system of EMI model of a piezoceramic transducer, such technology has been widely used in the sensory of mechanical characteristics of structures. In addition to the dynamic analysis, circuit analysis is also valuable for understanding the electrical behavior of the multi-sensing technique of PZT. There are four different equivalent circuit models, including (1) Van Dyke model (Standards Committee of the IEEE Ultrasonics and Society 1987); (2) Sherrit model (Sherrit *et al*. 1997); (3) Guan model (Guan and Liao 2004) and (4) Easy model (Kim *et al*. 2008), which were widely employed for analyzing the EMI characteristics of PZT. Considering the high accuracy and quick performance estimation of the equivalent circuit, the Easy model was adopted in this paper to define the 3-dB bandwidth range of multi-sensing technique.

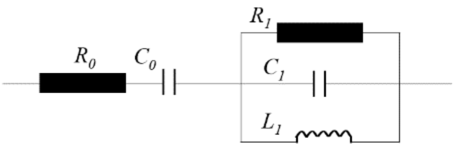


Fig. 2 The Easy model of free PZT

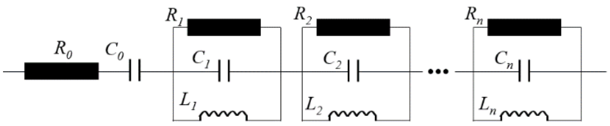


Fig. 3 The Easy model of coupled PZTs

The Easy model, as shown in Fig. 2, is a series connection of an RLC circuit with a resistor and a capacitor. The impedance of a free PZT can be expressed as (Kim *et al*. 2008)

$$Z_{free}(\omega) = R_0 + \frac{1}{j\omega C_0} + \frac{1}{\frac{1}{R_1} + \frac{1}{j\omega L_1} + j\omega C_1} \tag{1}$$

where the R_1, L_1, and C_1 represent mechanical damping, mass, and elastic compliance, respectively. R_0 is electrostatic resistance and C_0 is electrostatic capacitance. It should be noted that a free PZT means that the PZT was not coupled with a structure.

When a PZT is coupled to a structure, the resonances of the structure can be presented as the series connection of multi-paralleled RCL circuits, as shown in Fig. 3.

The impedance of coupled PZT can be estimated as follows

$$Z_{coupled}(\omega) = R_0 + \frac{1}{j\omega C_0} + \sum_{i=1}^{n} \frac{1}{\frac{1}{R_i} + \frac{1}{j\omega L_i} + j\omega C_i} \tag{2}$$

It should be noted that the values of R_0 and C_0 should be determined according to the measured impedance of coupled PZT, rather than duplicating the values determined for an uncoupled PZT model (Kim *et al*. 2008).

2.2 3-dB bandwidth-based damage index

The damage severity can be quantified by comparing the intact signals and damaged signals in the EMI method. Quantitative evaluation approaches, such as root mean square deviation (RMSD), mean absolute percentage deviation (MAPD), and correlation coefficient (CC), have already been reported (Park and Inman 2006, Park *et al.* 1999, Sun *et al.* 1995, Zagrai and Giurgiutiu 2001). However, all these mentioned above methods are calculated in the whole range of sweep frequency. The individual peaks of impedance cannot be used to locate the damage position and evaluate the state of damage. Therefore, they are inapplicable to the multi-sensing technique. To overcome all this problem, based on the equivalent circuit analysis of the PZT transducer, the 3-dB RMSD based damage index was proposed.

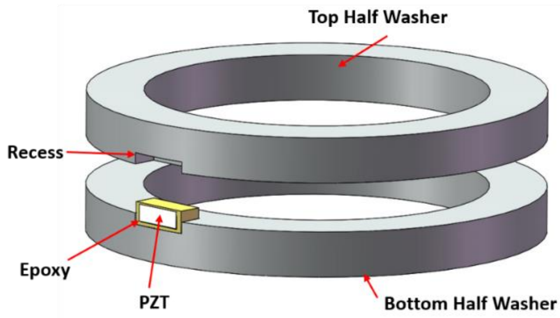


Fig. 4 The design diagram of smart washer

The 3-dB RMSD is an RMSD value calculated in the 3-dB bandwidth of peak frequency. Thus, only a portion of the data points are considered and the 3-dB RMSD is calculated as

$$RMSD_{3dB} = \sqrt{\frac{\sum_{i=m}^{n}\{Re(Z_0(\omega_i) - \bar{Z}_0) - Re(Z_1(\omega_i) - \bar{Z}_1)\}^2}{\sum_{i=m}^{n} Re(Z_0(\omega_i) - \bar{Z}_0)^2}} \tag{3}$$

where the $Z_0(\omega)$ is the impedance signal in the range of 3-dB bandwidth under healthy condition (baseline); $Z_1(\omega)$ is the impedance signal under damaged condition. $\bar{Z}_0$ and $\bar{Z}_1$ are the mean values of the $Z_0(\omega)$ and $Z_1(\omega)$; m and n are the first and last point of 3-dB bandwidth of intact condition, respectively.

3. Experimental setup for multi-sensing bolt looseness monitoring

3.1 PZT based smart washer

A smart washer (SW) is fabricated by embedding a piezoceramic patch into two pre-machined metal rings (Huo *et al*. 2017b). An SW can function as both an actuator and a sensor. The design diagram is shown in Fig. 4. In this paper, three PZT based smart washers were fabricated for the monitoring of bolts looseness using the multi-sensing technique.

For the proposed multi-sensing technique, it is very important to fabricate each SW has a unique peak frequency that can be used to locate the particular SW. For simplicity, three different sizes of PZTs were used for the fabrication of the three SWs so that they have different impedance characteristics. The dimension and material properties of PZT patches are shown in Tables 1 and 2, respectively. The photographs of PZTs and the fabricated smart washers were shown in Figs. 5 and 6.

Table 1 Size of PZTs

No.	Width (mm)	Length (mm)	Thickness (mm)
1	4	4.8	1
2	4	5.8	1
3	4	8.0	1

Table 2 Properties of piezoelectric sensors

	Properties							
	Density ($kg\ m^{-3}$)	Poisson ratio	Young modulus (GPa)	Piezoelectric coefficients			Dielectric coefficients	
				d_{31}, d_{32} ($nC\ N^{-1}$)	d_{33} ($nC\ N^{-1}$)	d_{15} ($nC\ N^{-1}$)	$\varepsilon_{11}, \varepsilon_{22}$ ($nF\ m^{-1}$)	ε_{33} ($nF\ m^{-1}$)
Values	7450	0.3	46	0.186	0.42	0.66	0.1504	0.1301

Fig. 5 The picture of embedded PZTs

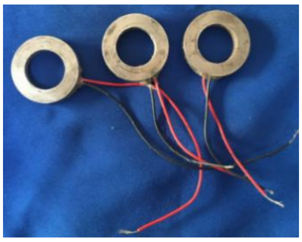


Fig. 6 Three fabricated smart washers

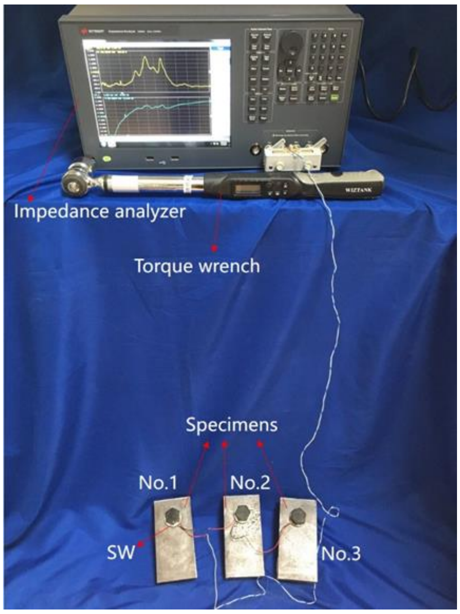


Fig. 7 Experimental setup of multi-sensing monitoring system

3.2 Bolted connection steel plate specimens and instrumentation setup

To verify the proposed multi-sensing approach for pre-load monitoring, three pairs of rectangular steel plate specimens (size: 100 mm × 80 mm × 20 mm) that can be connected by bolts are used in this research. The nominal diameter of three bolts is 20 mm. A torque wrench was used to apply the pre-load. The impedance signals were obtained by an impedance analyzer (Keysight E4990A). The experimental setup of the smart washer based multi-sensing monitoring system is shown in Fig. 7.

Table 3 Test scenarios

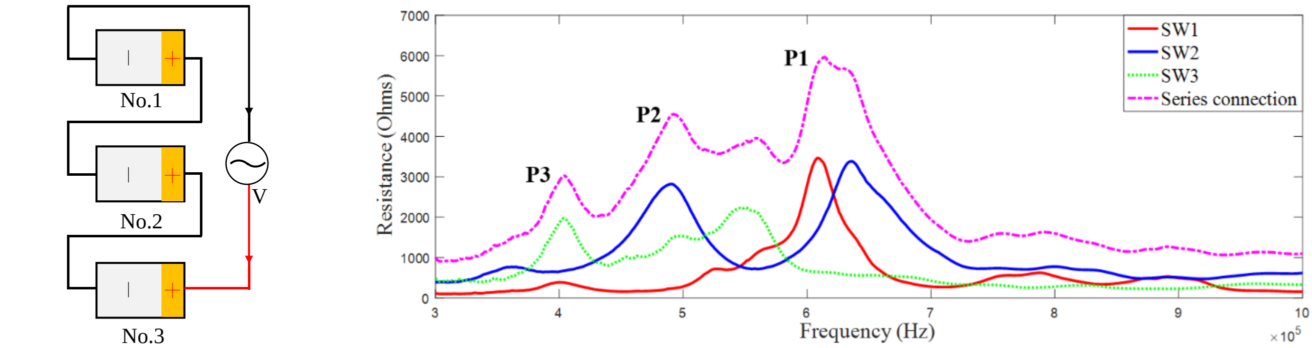
Loading cases	Bolt No. 1	Bolt No. 2	Bolt No. 3
L1	200	200	200
L2	150	200	200
L3	100	200	200
L4	50	200	200
L5	0	200	200
L6	0	150	200
L7	0	100	200
L8	0	50	200
L9	0	0	200

3.3 Test procedure

In this study, three PZT based smart washers were mounted on three bolt specimens. The location and the degree of bolts looseness were investigated by loosening No. 1 and No. 2 bolts successively. Since the range of torque wrench is 0-200 N·m, the torque was applied from 0 N·m to 200 N·m with an interval of 50 N·m. The test scenarios are listed in Table 3.

In Table 3, Li (i = 1, 2, 3..., 9) represents the ith loading, and the unit is N·m. Each test scenario was repeated for 10 times. It should be noted that the 200 N·m is assumed as the initial state, which means that L1 is the baseline. In the experiments, No. 3 bolt was kept tight and No. 1 and No. 2 bolts are the testing bolts.

A sweep frequency signal was generated from 300 kHz to 1 MHz to locate the peak frequencies of three series/ parallel connected smart washers. The resistance signal which is the real part of impedance with series/parallel connection was obtained. Based on the equivalent circuit that is described in *Section 2.1*, the performance of resistance value and peak frequencies were analyzed. The characteristics of series and parallel of smart washers were discussed in *Section 4*. Furthermore, according to the performance analysis of series and parallel connection of SWs, a pre-load monitoring test of three bolted connection steel plate specimens were implemented to validate the correctness of the proposed approach.



(a) The series connection of PZTs

(b) The individual and series-connected resistance signals of three SWs

Fig. 8 The diagram and the resistance signals of series connection of three embedded PZTs

4. Multi-sensing analysis of PZT bases smart washer

There are two ways to carry out the multi-sensing technique to detect the looseness of multi-bolts, that is, parallel and series connection. In this paper, the resistance which is the real part of the impedance signal is used. From Eq. (1), the resistance $R(\omega)$ can be written as

$$R(\omega) = R_0 + \frac{R_1\omega^2 L_1^2}{\omega^2 L_1^2 - R_1^2\left(\omega^2 C_1 L_1 - 1\right)^2} \tag{4}$$

For the multi-sensing technique in series connection, the $R_s(\omega)$ is

$$R_s(\omega) = R_1(\omega) + R_2(\omega) + \cdots + R_n(\omega) = \sum_{i=1}^{n} R_i(\omega) \tag{5}$$

where i is the number of parallel/series connected sensors.

Substituting Eq. (4) into Eq. (5) gives the expression of $R_s(\omega)$ as

$$R_s(\omega) = \sum_{i=1}^{n} R_0^i + \sum_{i=1}^{n} \frac{R_1^i(\omega L_1^i)^2}{(\omega L_1^i)^2 - \left\{R_1^i(\omega^2 C_1^i L_1^i - 1)\right\}^2} \tag{6}$$

The parallel connection of PZTs can also be obtained as Eq. (7)

$$\frac{1}{R_p(\omega)} = \frac{1}{R_1(\omega)} + \frac{1}{R_2(\omega)} + \cdots + \frac{1}{R_n(\omega)} = \sum_{i=1}^{n} \frac{1}{R_i(\omega)} \tag{7}$$

Substituting Eq. (4) into Eq. (7) results in

$$R_p(\omega) = \frac{1}{\sum_{i=1}^{n} \frac{1}{R_0^i + \frac{R_1^i(\omega L_1^i)^2}{(\omega L_1^i)^2 - \left\{R_1^i(\omega^2 C_1^i L_1^i - 1)\right\}^2}}} \tag{8}$$

Eqs. (6) and (8) clearly show the difference of resistance value between series and parallel connection, that is, a series connection cumulates the resistance amplitude while a parallel connection suppresses the amplitude. Due to the high sensitivity and accuracy of the series connection, it is used in the pre-load detection of multi-bolt experiment. Fig. 8(b) presents the individual and series resistance signals of three SWs before they are mounted the specimens.

In Fig. 8(b), three peak frequencies that are marked as P1, P2 and P3 can be obtained with series connection (purple dashed line). P1, P2 and P3 corresponding to the peak frequencies of SW1, SW2, and SW3, respectively. Therefore, the location and degree of bolt looseness can be evaluated by analyzing the shift of P1, P2, and P3.

5. Multi-sensing analysis of PZT bases smart washer

5.1 Location detection of loosening bolt

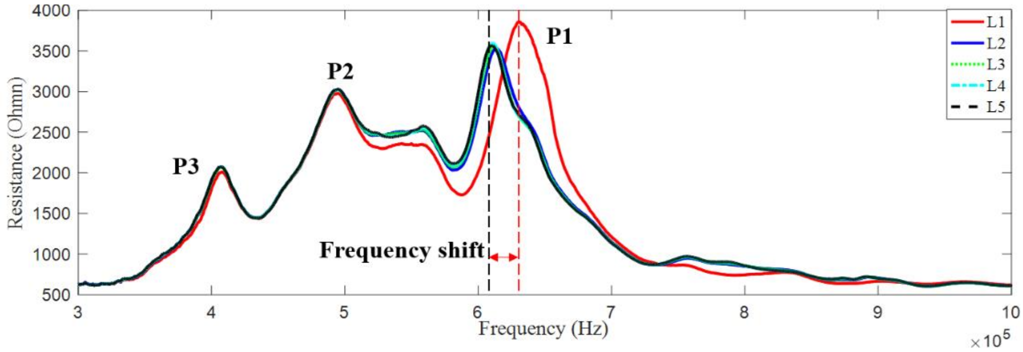
With the decrease of pre-load, the peak frequency of the resistance curve will shift (Shao *et al.* 2016). Fig. 9(a) and Fig. 9(b) corresponding to the average value of 10 times repeated experiments.

In Fig. 9(a), the frequency shift of P1 means that the torque of bolt No.1 is loose. Similarly, for Fig. 9(b), the frequency shift only occurs in P2 which reveals that bolt No. 2 is loose. The frequency of resistance signal shifts to the left with the decreases of torque, which means the decrease of resonating frequency. It should be noted that the shifted frequency in Fig. 9(a) is larger than that in Fig. 9(b). The reason is that the sensitivities of the three SWs are different. The SW bonded onto bolt No. 1 has a higher sensitivity than that of bolt No. 2. Therefore, the shifted frequency of P1 is much larger than that of P2.

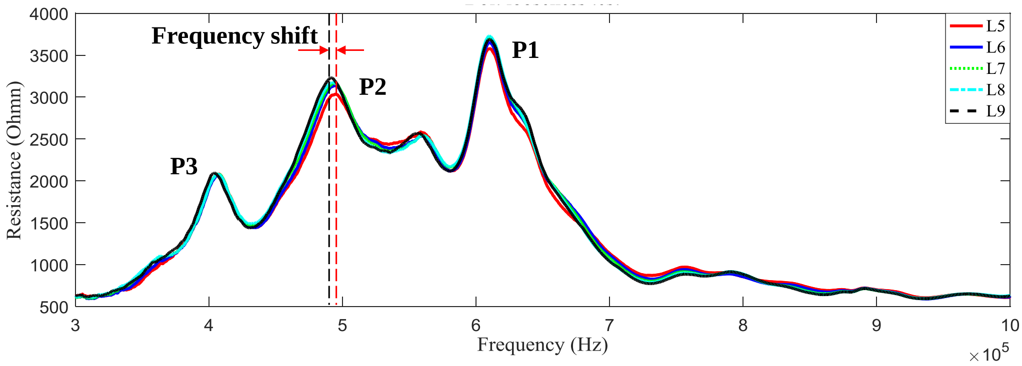
5.2 Location detection of loosening bolt

In this paper, the real part impedance signal of L1 in Fig. 9(a) is considered as an intact state. Based on the 3-dB RMSD index, the looseness degree of three bolts can be quantitatively evaluated by comparing the resistance signals under different looseness scenarios with L1. However, it is difficult to define the 3-dB frequency ranges of P1, P2, and P3 in Fig. 9 directly. Therefore, the equivalent circuit was applied to find the 3-dB frequency ranges of P1, P2, and P3.

According to *Section 2.1*, the R_0 and C_0 are approximately 630 Ω and 200 nF, which can be obtained from curve L1 in Fig. 9(a) (Kim *et al.* 2008). The resonating



(a) Bolt looseness of No. 1



(b) Bolt looseness of No. 2

Fig. 9 Bolt looseness tests for bolt No.1 and bolt No.2

Table 4 Equivalent circuit components of P1, P2 and P3

Peak frequency	ω (Hz)	Q	$L_1(\omega)$ (μH)	$C_1(\omega)$ (nF)
P1	633375	10	80.465	0.785
P2	494250	7	107.51	0.964
P3	408062.5	10	53.48	2.844

frequencies P1, P2, and P3 are 633375 Hz, 494250 Hz, and 408062.5 Hz, respectively. The $R_1(\omega)$ is calculated as following equations

$$R_1(\omega) = R_s(\omega) - R_0 \tag{9}$$

$$L_1(\omega) = \frac{R_1(\omega)}{\omega \cdot Q} \tag{10}$$

$$C_1(\omega) = \frac{1}{L_1(\omega) \cdot \omega^2} \tag{11}$$

$L_1(\omega)$ and $C_1(\omega)$ can be obtained by Eqs. (10)-(11). Q is the quality factor, and, in this experiment, it can be measured by the impedance analyzer. The calculated equivalent circuit components of P1, P2, and P3 are listed in Table 4.

Substituting the component values into Eq. (6), the real part of equivalent circuit curves of P1, P2, and P3 can be obtained and shown in Fig. 10. Fig. 10 also clearly shows the 3-dB ranges of peaks P1, P2, and P3.

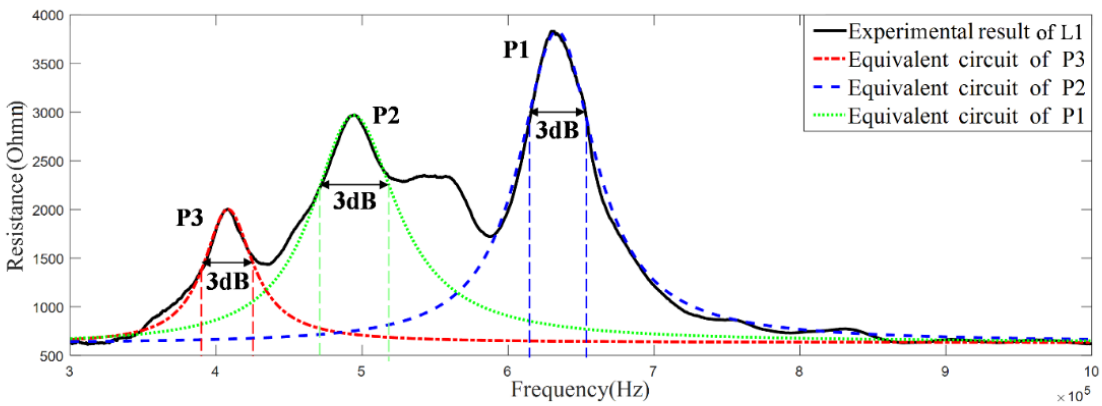


Fig. 10 Equivalent circuit analysis of the 3-dB frequency band for three peak frequencies

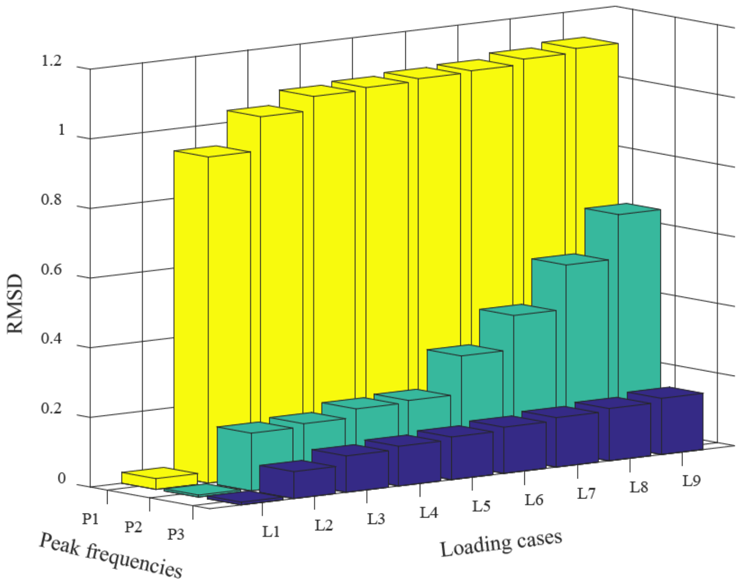


Fig. 11 3-dB RMSD values under different loading scenarios

Table 5 The 3-dB frequency ranges of P1, P2, and P3

Peak frequency	Range (Hz)	Correlation coefficient
P1	610625 - 657437.5	0.993
P2	467562.5 - 522687.5	0.991
P3	391000 - 426000	0.994

The correlation coefficient (CC) values in the 3-dB frequency band between equivalent circuits and experimental results were also calculated. The 3-dB frequency ranges and the CC values of the equivalent circuit of P1, P2, and P3 are listed in Table 5. All CC values are up to 0.99, which means that, for the three peak frequencies, the equivalent circuits agree well with the baseline L1 in the range of 3-dB frequency band.

In order to test the robustness of the proposed approach, each loading case was repeated ten times. Based on Eq. (3), 3-dB RMSD values under different loading scenarios can be obtained. The averaged 3-dB RMSD values in each loading case are shown in Fig. 11. In Fig. 11, the 3-dB RMSD values clearly show the location and severity of bolt looseness. Specifically, the 3-dB RMSD of P1 increases gradually from L1 to L5, which reveals that the torque of bolt No. 1 decreases, whereas bolt No. 2 and No. 3 keep tight. From L5 to L9, the 3-dB RMSD values of P2 increases as the torque decreases, indicating that bolt No.2 is loosening its torque. The 3-dB RMSD values almost have no change from L1 to L9, which means that there is no looseness occurs to bolt No. 3.

6. Conclusions

This paper presents a multi-sensing technique to monitor bolt looseness. Three smart washers (SWs), which were fabricated by embedding Lead Zirconate Titanate (PZT) transducer into two flat metal rings, were series/parallel connected in three specimens. The findings of this research can be summarized as:

(1) The impedance/admittance signals of multi-bolts can be obtained through only one sweep by using the proposed multi-sensing technique.
(2) The proposed multi-sensing technique holds great potential for large scale structure monitoring by reducing the number of required channels for the data acquisition system and by reducing the wiring cost.
(3) Different peak frequencies in the impedance/admittance curve corresponding to different locations of bolts. Once looseness occurred, the shift of resonating frequency can indicate the location of the loosening bolt.
(4) Based on the 3-dB bandwidth which defined by the equivalent circuit, the proposed 3-dB RMSD can quantitatively evaluate the degree of bolt looseness.
(5) Experimental results validate that the proposed multi-sensing technique not only locates the position but also reveals the severity of loosening bolts.

Acknowledgments

This work was supported by the Major State Basic Research Development Program of China (973 Program, grant number 2015CB057704). The authors would like to thank for the financial supports.

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