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Pre-load monitoring of bolted connection using PZT interface-based impedance measurement

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ABSTRACT

Bolt connections have been widely used to join segmental members in civil and mechanical structures owing to their advantages of convenience, time efficiency and high strength. However, after a long-term service life under severe environmental conditions or significant loads, bolt connections may experience decreases in their pre-load that could threaten the functionality and safety of a whole structure. In this study, we propose a PZT interface-based impedance measurement method to monitor the pre-load change in bolted girder connections. The proposed method is experimentally verified on the bolted joint of a steel girder structure. A PZT interface prototype is designed and attached to the girder connection to acquire the sensitive impedance data under different bolt pre-loads. Then, the damage-sensitive features are extracted from the measured impedance data and used to detect the pre-load changes in the test connection. The experimental results reveals that the bolt looseness-induced pre-load changes can be monitored by using the PZT interface-based impedance measurement.

1. INTRODUCTION

Bolted connections have been widely used in steel structures such as bridges, pipelines, and buildings. The strength of the bolt connection is guaranteed by axial forces of bolts. However, as discontinuous parts of structures, bolted connections are often influenced by severe repeated loading and various environmental conditions. As the result, a decrement of bolt preload could be occurred, carrying potentials that could threaten the stability of whole structures. Among recent methods to assess the structural condition of bolted joints (Wang *et al.* 2013, Park *et al.* 2015, Nguyen *et al.* 2016), the acoustic-based, the piezoelectric active sensing, and the electromechanical impedance methods are commonly used. The acoustic-based method utilizes the

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acoustoelastic effect to estimate the bolt preload via measuring ultrasonic time of flight, velocity ratio, or mechanical resonant frequency shift. The piezoelectric active sensing method detects the bolt torque-loss via measuring ultrasonic attenuation, ultrasonic energy, or delay time of waves.

Also enabled by the piezoelectric effect, the electromechanical impedance-based damage detection technique has been studied intensively by many researchers (Liang *et al.* 1994, Park *et al.* 2003, Nguyen and Kim 2012, Huynh *et al.* 2015, Park *et al.* 2015, Huynh and Kim 2017, 2018). The method utilizes high-frequency electromechanical impedance responses measured by a piezoelectric sensor to assess the integrity of a structure. The utilization of high frequencies allows the technique to detect minor changes in the structure induced by damage events. Importantly, the technique can be integrated with low-cost wireless impedance sensors to efficiently monitor *in-situ* structures (Huynh *et al.* 2017). Several research attempts have been made on implementing the impedance-based technique to damage detection in bolted structures (Ritdumrongkul *et al.* 2004, Mascarenas *et al.* 2007, Kim *et al.* 2011, Nguyen *et al.* 2017, Ryu *et al.* 2017). Their experimental and numerical studies have demonstrated the effectiveness of the impedance-based method.

One of the important issues for the impedance monitoring of bolted joints is on identifying sensitive frequency bands of impedance signatures. In practices, the sensitive impedance signatures are often determined by trial-and-errors. Based on the previous works (Nguyen *et al.* 2011, Huynh and Kim 2014), this study presents a PZT interface-based impedance measurement method to monitor the pre-load change in bolted girder connections with pre-determined sensitive frequency bands. The proposed method is experimentally verified on the bolted joint of a steel girder structure. A PZT interface prototype is designed and attached to the girder connection to acquire the sensitive impedance data under different bolt pre-loads. Then, the damage-sensitive features are extracted from the measured impedance data and used to detect the pre-load changes in the test connection.

2. BOLT PRE-LOAD MONITORING METHOD

2.1 PZT Interface-based Impedance Monitoring in Bolted Connection

As schematized in Fig. 1, the PZT interface-based impedance measurement method is proposed to monitor the pre-load change in bolted girder connections (Huynh and Kim 2014, 2016). The interface device is an aluminum beam which has a flexible section in the middle and two bonded sections. The flexible section, where the PZT sensor is installed, is intentionally designed to make the PZT patch freely vibrate when being mounted on the host structure. To obtain the EMI signatures, an impedance analyzer is used to simultaneously excite the PZT sensor on the interface by a harmonic voltage $V(\omega)$, see Fig. 1. The output harmonic current $I(\omega)$ is then measured and the ratio between $V(\omega)$ and $I(\omega)$ is defined as the EMI $Z(\omega)$, in which the structural mechanical impedance (SMI) of the PZT sensor $Z_a(\omega)$ and the host structure $Z_s(\omega)$ (i.e., interface-anchorage system) are coupled together (Liang *et al.* 1994), as follows:

$$Z(\omega)=\frac{V}{I}=\left\{i\omega\frac{w_a l_a}{t_a}\left[\hat{\varepsilon}_{33}^{T}-\frac{1}{Z_a(\omega)/Z_s(\omega)+1}d_{3x}^{2}\hat{Y}_{xx}^{E}\right]\right\}^{-1} \quad (1)$$

where $\hat{Y}_{xx}^{E}=(1+i\eta)Y_{xx}^{E}$ is the complex Young's modulus of the PZT patch at zero electric field; $\hat{\varepsilon}_{xx}^{T}=(1-i\delta)\varepsilon_{xx}^{T}$ is the complex dielectric constant at zero stress; d_{3x} is the piezoelectric coupling constant in the *x*-direction at zero stress; and w_a, l_a, and t_a are the width, length, and thickness of the PZT patch, respectively. The parameters η and δ are structural damping loss factor and dielectric loss factor of piezoelectric material, respectively.

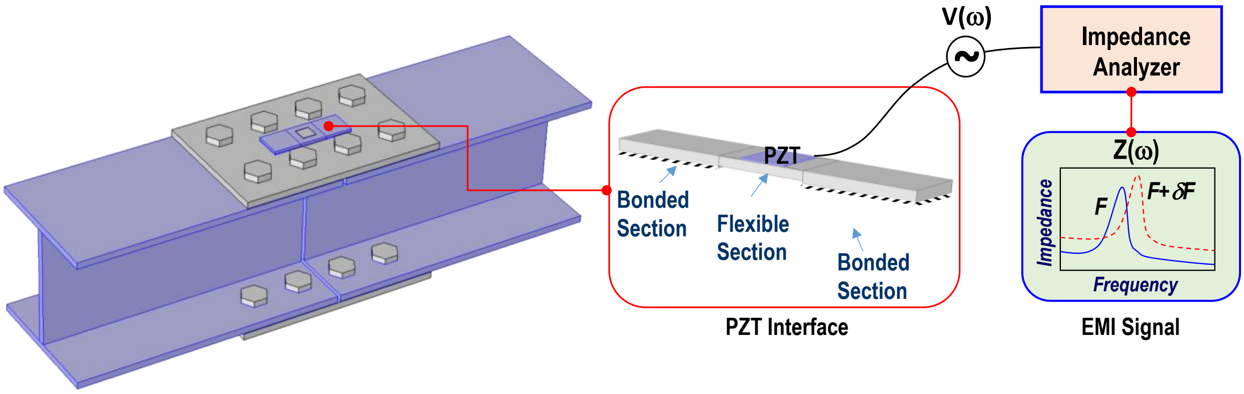

Fig. 1 PZT interface-based impedance monitoring for bolted connection

As shown in Fig. 1, the PZT interface is surface-attached to a bolted connection to sense the impedance responses which represents the coupling between the interface structure and the connection. When the structural parameters of the bolt connection are altered by damages (e.g., bolt looseness or pre-load change), the coupling responses will be changed. Consequently, the impedance signatures of the connection can be shifted. Thus, the structural integrity of the bolting structure can be estimated by monitoring the impedance changes obtained from the PZT interface. It is known that the resonant responses of a structure are closely associated with its sensitive impedance signatures. Therefore, the sensitive frequency bands of the PZT interface can be easily pre-determined by analyzing its local dynamic characteristics (Huynh *et al.* 2015).

2.2 Quantification of Pre-load Change

To detect a pre-load change event, damage-sensitive features are commonly extracted from the measured impedance data. In this study, we employed the RMSD (i.e., root-mean-square deviation) impedance index, as follows (Giurgiutiu *et al.* 1999)

$$RMSD=\sqrt{\sum_{i=1}^{N}\left[Z^{*}(\omega_i)-Z(\omega_i)\right]^2\Big/\sum_{i=1}^{N}\left[Z(\omega_i)\right]^2} \quad (2)$$

where $Z(\omega_i)$ and $Z^*(\omega_i)$ signify the impedance responses at the i^{th} frequency before and after a damage event, respectively; *N* denotes the number of swept frequencies. If the RMSD index is close to zero, there is no pre-load change in the monitored bolted connection; otherwise, there is bolt-looseness or pre-load change.

3. EXPERIMENTAL EVALUATION ON BOLTED GIRDER CONNECTION

3.1 Experimental Setup

The test-setup of a lab-scaled steel girder is shown in Fig. 2. The girder was assembled from two single H-shaped beams (H – 200x180x8x100 mm) by splice plates (200x310x10 mm) and 8 bolts at two flanges (d – 20 mm). A PZT interface having a flexible section (33x30x4 mm) and two outside bonded sections (33x35x5 mm) was designed and surface-mounted at the middle of the splice plate. The interface was equipped with a PZT-5A (15x15x0.51 mm) at the flexible section. By analyzing the local dynamic responses of the PZT interface, it is expected that the sensitive impedance signatures will be occurred in the frequency band of 10-35 kHz.

The wireless SSeL-I impedance measurement system developed by Pukyong National University was adopted (Nguyen *et al.* 2011). The system consists of a laptop connected to a wireless captain node and a remote SSeL-I node connected to the PZT interface, see Fig. 2. To acquire the EM impedance from the bolted connection, the PZT sensor was excited by a harmonic voltage of 1 V in the frequency band of 10-55 kHz by using the remote node. The acquired impedance signal was then wirelessly sent back to the laptop via the captain node.

The pre-load change in the bolted connection was introduced by reducing the torque of bolts. As the healthy state, all bolts were fastened by the torque of 160 Nm. Four of eight bolts (i.e., Bolts 1-4) on the splice plate were selected to introduce four bolt-loosening events, see Fig. 2. For each of Bolts 1-4, the torque was loosened to to the torque of 110 Nm (31% torque-loss), 60 Nm (62% torque-loss), and 0 Nm (100% torque-loss). The girder was placed in the basement laboratory where temperature was controlled near 22 ^oC by air-conditioners to avoid temperature effects. The impedance signals were measured before and after each level of the bolt pre-load.

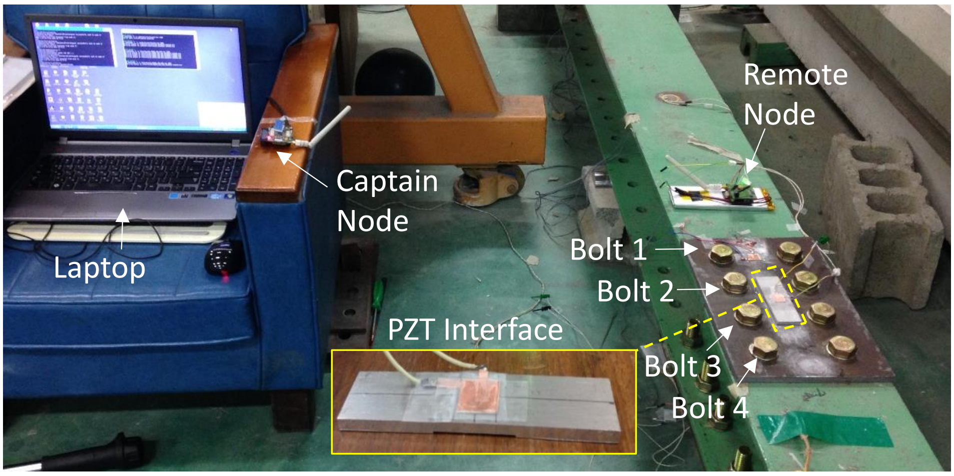

Fig. 2 Test-setup of a steel girder connection

3.2 Bolt Pre-load Monitoring Result

The impedance responses of the bolt connection in 10-35 kHz under the Bolt 1-loosening cases are shown in Fig. 3. Two sensitive frequency bands (i.e., 12-20 kHz and 28-33 kHz) were observed in the figure. It is shown that the impedance signature was sensitively varied according to the loss of bolt torque. The first sensitive frequency band in 12-20 kHz experienced both the frequency and magnitudes shifts while the second one in 28-33 kHz showed only slight changes in the peak frequency and almost no noticeable changes in the magnitudes.

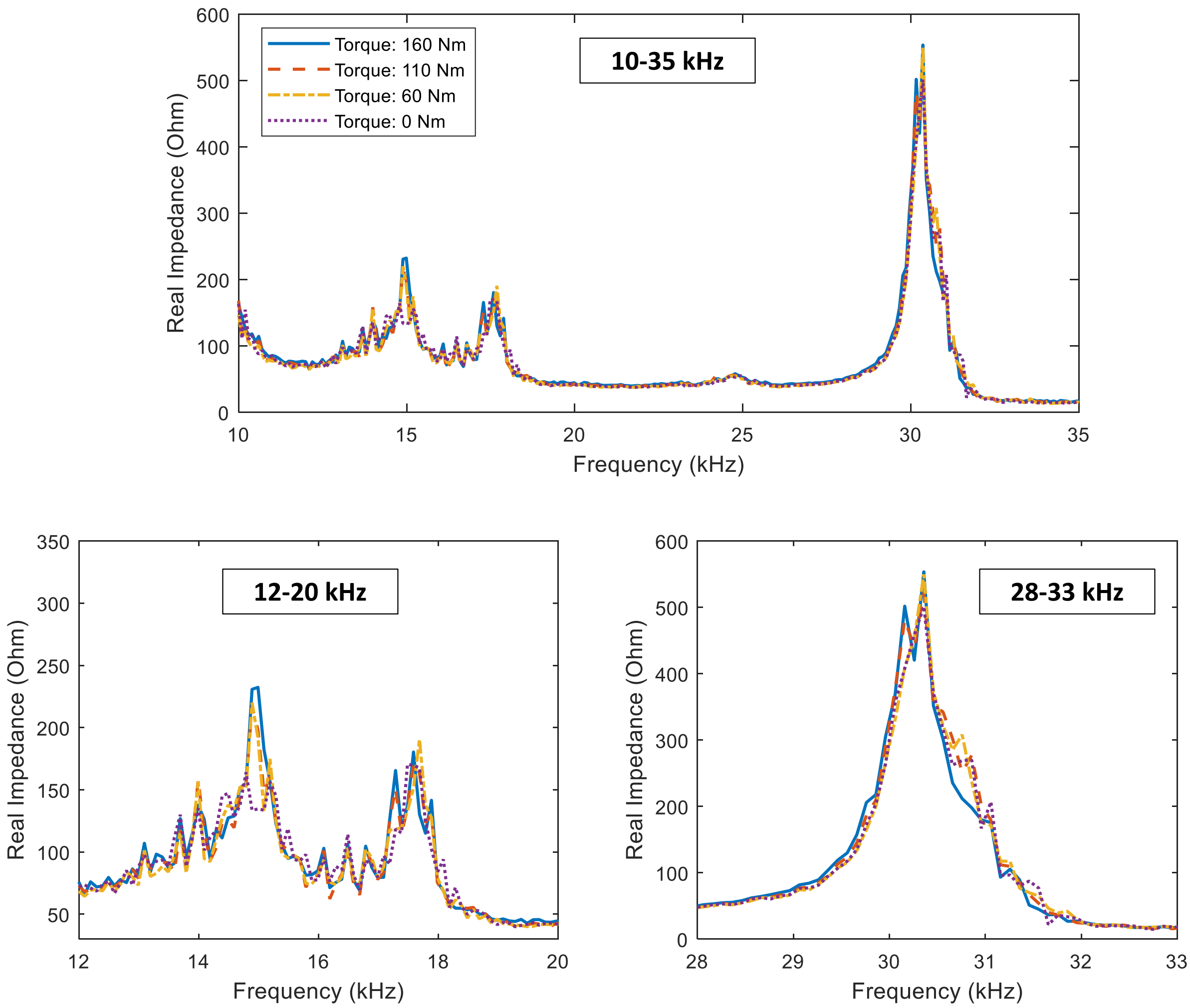

Fig. 3 Impedance responses of bolted connection under Bolt 1 Looseness

Fig. 4 shows the pre-load change monitoring results using the RMSD index. The whole frequency range 10-35 kHz was used for the calculation. For Bolts 1-4, when the torque was reduced gradually from 160 Nm to 0 Nm, the corresponding RMSD index was considerably changed from unnoticeable values to significant values. Interestingly, when Bolt 3 was loosened completely, the RMSD index indicated the highest value among four bolts (Bolts 1-4). This may be due to the bolted connection tested in this study was not completely symmetric. Despite that, the results demonstrated the feasibility of the PZT interface-based pre-load monitoring method. For the tested connection, the torque reduction of 50 Nm (31% torque-loss) in a single bolt can be distinguished clearly from the RMSD chart, see Fig. 4.

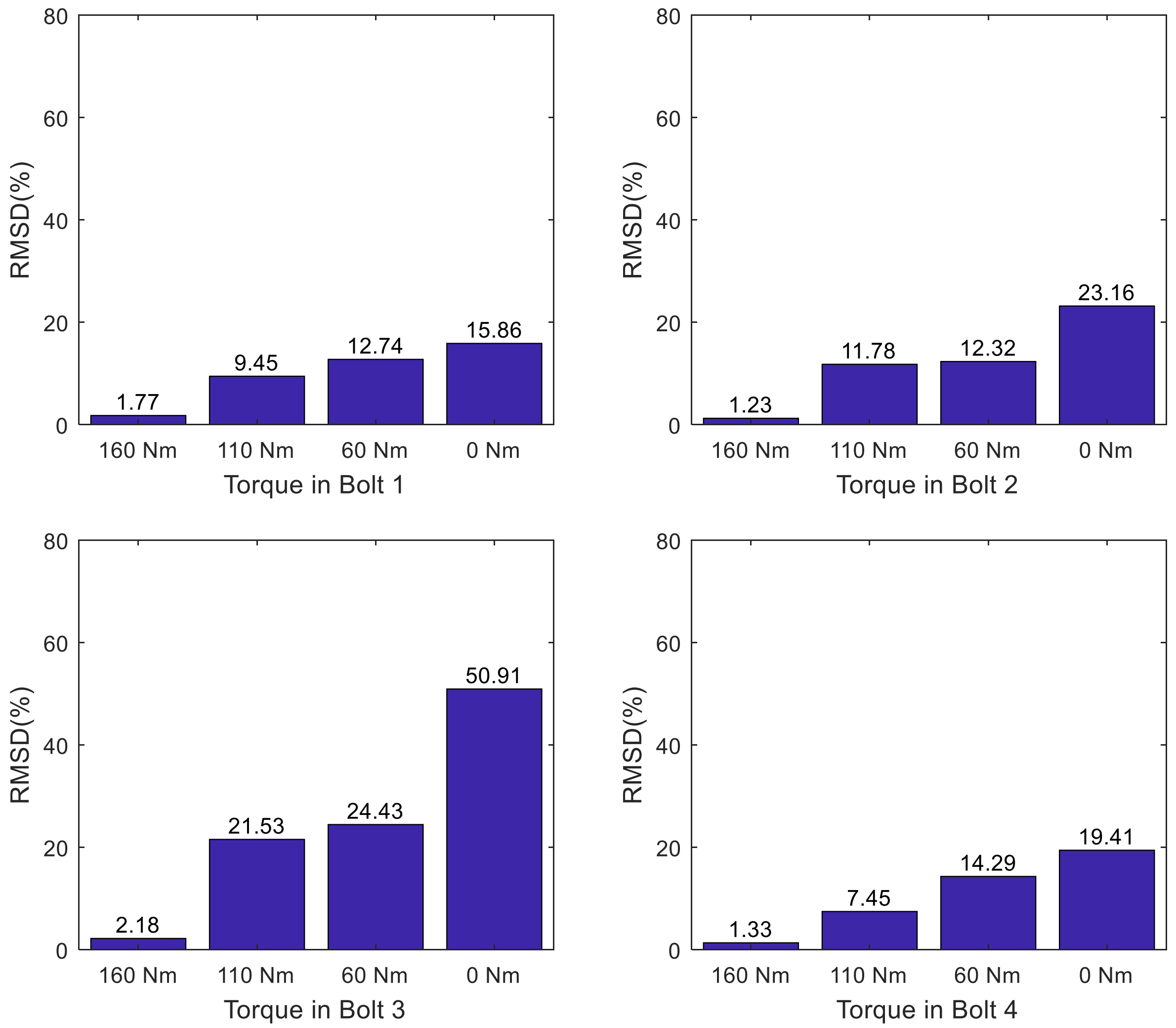

Fig. 4 Pre-load change detection results

4. CONCLUSION

In this study, we proposed a PZT interface-based impedance measurement method to monitor the pre-load change in bolted girder connections. The proposed method was experimentally verified on the bolted joint of a steel girder structure. A PZT interface prototype was designed and attached to the girder connection to acquire the sensitive impedance data under different bolt pre-loads. Then, the damage-sensitive features were extracted from the measured impedance data and used to detect the pre-load changes in the test connection. The experimental results revealed that the bolt looseness-induced pre-load changes can be monitored by using the PZT interface-based impedance measurement.

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