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Bolt looseness diagnosis for steel beam connection using wireless impedance-based method

Chẩn đoán tình trạng lỏng bu-lông cho liên kết dầm thép bằng phương pháp đo trở kháng không dây

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Abstract

Bolted connections are widely used to link load-carrying members in steel structures. The bolt fastening force is critically important to guarantee the strength of a bolted joint. Bolt looseness could carry potentials that may result in the failure of the bolted joint, threatening the stability of a whole structural system. This study has been motivated to monitor the bolt looseness in a steel beam connection by using a wireless impedance-based method. The main idea of the method is to monitor bolt looseness-induced changes in electromechanical impedance responses of the joint. Wireless impedance sensing technology was applied to perform automated impedance measurements with minimal costs. Also, the piezoelectric interface technique was implemented to predetermine sensitive frequency ranges in the impedance measurements. The feasibility of the method was evaluated for impedance monitoring of a realistic steel beam joint with multiple bolts. The obtained results showed that loosened bolts in the tested joint were successfully detected, thus demonstrating the feasibility of the method and showing its promising future applications to steel structures in the field.

Keywords: Bolt looseness detection; bolted connection; steel structures; wireless impedance sensor; impedance response; *PZT interface.*

Tóm tắt

Mối nối bu-lông được sử dụng rộng rãi để liên kết các thành phần chịu lực trong kết cấu thép. Trong đó, lực siết của bu-lông đóng vai trò rất quan trọng trong việc đảm bảo độ cứng của liên kết. Việc mất mát lực siết mang những nguy cơ dẫn đến sự phá hoại liên kết, sau đó là đe dọa đến sự ổn định của toàn bộ hệ thống kết cấu. Bài báo này giới thiệu một phương pháp giám sát việc lỏng bu-lông cho liên kết dầm thép bằng kĩ thuật đo trở kháng không dây. Ý tưởng chính của phương pháp này là giám sát sự biến đổi của tín hiệu trở kháng của liên kết trước và sau khi bu-lông bị lỏng.

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Công nghệ cảm biến không dây được áp dụng để thực hiện các phép đo trở kháng một cách tự động từ xa với chi phí thấp. Ngoài ra, để xác định trước các dải tần số nhạy trong các phép đo trở kháng, kỹ thuật giao diện áp điện (PZT interface technique) được ứng dụng. Tính khả thi của phương pháp trên được đánh giá thông qua các đo đạc trở kháng trên một liên kết dầm thép thực với nhiều bu-lông. Kết quả thu được cho thấy các bu-lông bị nới lỏng trong liên kết dầm thép được chẩn đoán một cách chính xác, qua đó cho thấy tính khả thi và triển vọng ứng dụng của phương pháp đo trở kháng không dây vào các công trình thực tế.

Từ khóa: Cảm biến không dây; điện-cơ; giao diện áp điện; cảm biến áp điện; ứng xử trở kháng; theo dõi sức khỏe công trình.

1. Introduction

Bolted connections have been widely used in steel structures such as bridges, pipelines, and buildings. The strength of a bolt connection is guaranteed by the preload of bolts. However, as discontinuous parts of structures, bolted connections are often influenced by severe repeated loading and various environmental conditions. As the result, bolt looseness can be occurred in the connection, carrying potentials that could threaten the stability of a whole structure.

Recently, the impedance-based technique has been studied by many researchers and emerged as an innovative damage detection tool [1-5]. Several research attempts have been made on employing the impedance-based technique to damage detection in bolted structures [3,6,7]. Basically, the impedance-based method utilizes high-frequency electromechanical (EM) impedance responses measured by a piezoelectric (e.g., PZT) 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.

To efficiently monitor *in-situ* structures, the impedance-based technique has been integrated with low-cost wireless impedance sensors [8]. The wireless impedance sensing technology would allow to perform automated impedance measurements with minimal costs. However, the application of the wireless impedance-based technique has been limited by the narrow frequency range of the low-cost wireless impedance sensor, currently less than 100 kHz [8]. To obtain accurate results, therefore, it is important to predetermine the sensitive frequency bands below 100 kHz for wireless impedance measurements in practices.

The piezoelectric interface technique (i.e., PZT interface) has been recently developed and can be a promising solution to deal with the above issue [3-5]. The technique is basically an alternative attachment method for the PZT sensor. The PZT is indirectly attached to the host structure via a substrate structure called ‘interface’. The structural and geometrical properties of the PZT interface can be adjusted to create strong resonances (i.e., sensitive frequencies) in a desired frequency band, typically below 100 kHz to enable wireless impedance measurements.

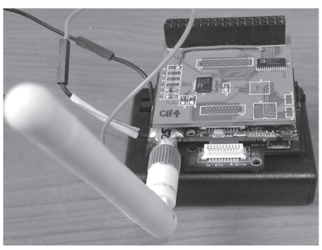
This study introduces a wireless impedance-based method, that combines the wireless impedance sensing technology with the piezoelectric interface technique, for monitoring the bolt-loosening occurrence in a steel beam connection. The main idea of the method is to monitor bolt looseness-induced changes in EM impedance responses of the joint. The feasibility of the method was evaluated for bolt-loosening monitoring of a realistic steel beam joint. The obtained results showed that loosened bolts in the test structure were successfully detected, thus demonstrating the feasibility of the method and showing its promising future applications to steel structures in the field.

2. Wireless impedance-based method

2.1. Wireless impedance sensor node

The research group at Pukyong National University has developed smart wireless impedance sensor nodes [3,9]. In this paper, a low-cost wireless impedance sensor, SSeL-I, developed by Nguyen *et al.* [9] was adopted to acquire the impedance responses from bolted connections. Figure 1 shows a prototype and schematic design of the wireless impedance sensor SSeL-I. The wireless sensor node has three layers: a battery board, the Imote2 sensor platform, and the SSeL-I impedance sensor board. The Imote2 platform is used to control the impedance board and the battery board is used to power the sensor node.

The key component of the impedance board is a low-cost impedance chip, AD5933 that enables the high-frequency impedance measurement. The AD5933 chip has the following embedded multi-functional circuits: function generator, digital-to-analog converter, current-to-voltage amplifier, anti-aliasing filter, ADC, and discrete Fourier transform (DFT) analyzer. The AD5933 interacts with an ADG706 multiplexer to allow sixteen sensing channels on a single sensor node. An SHT11 sensor is also integrated into SSeL-I board to monitor the temperature and humidity of the environment. The Imote2 platform is designed with a PXA27x processor which has a clock speed of 13-416 MHz, SRAM of 256 kB, flash memory of 32 MB and SDRAM of 32 MB. This platform also integrates with many I/O options and a wireless radio CC2420 (2.4 GHz Zigbee RF) for data transmission. The large memory and high operating speed of Imote2 allow it to enable advanced and complicated SHM techniques. Although the AD5933 chip allows the scanning frequency below 100 kHz, a SSeL-I unit costs only 300 USD, which is much lower than the prices of commercial impedance analysers.



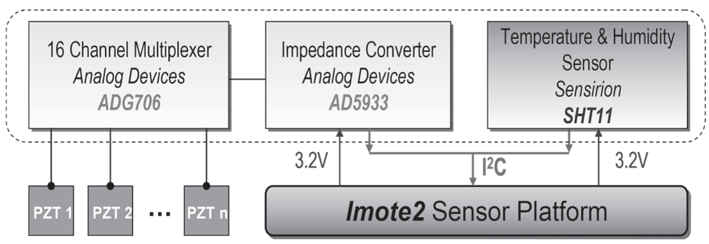


Figure 1. A prototype and schematic design of SSeL-I impedance sensor

An operating software, the so-called 'SSeL SHM Tools', was developed for the SSeL-I sensor node. The tool is programmed on TinyOS platform which is a free and open source with a huge library for designing wireless sensor networks. The 'SSeL SHM Tool' embedded software was described in details in Nguyen *et al.* [9]. At the base station, the user makes a sensing request to the remote node from the captain node by using the 'RemoteControl' component of the tool. The request should contain the measuring frequency range and the number of channels defined for the remote node. When the request is received, the remote node starts to measure the impedance responses in the defined frequency range via the defined channels. When the measurement is completed, data is wirelessly transmitted to the captain node. At the base station, the measured impedance signals are calibrated. Then, the impedance features are extracted by using the 'ImpedanceComponent' of the tool for the condition assessment of the monitored structure.

2.2. Piezoelectric interface technique

The piezoelectric interface technique is a solution to predetermine effective frequency bands of impedance responses and to reduce them to below 100 kHz for the wireless impedance sensing. Huynh *et al.* [4] developed a PZT interface which is a portable device for wireless impedance monitoring of prestressed systems. In this study, the PZT interface was employed to monitor the structural condition of bolted structures. 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), 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.

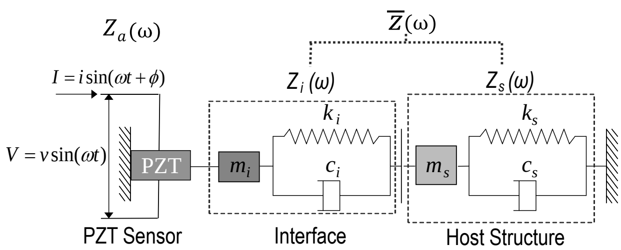


Figure 2. PZT interface -host structure system

Figure 2 shows a simplified impedance model that theoretically describes coupled dynamic responses of a PZT interface-host structure system [5]. The PZT interface-host structure is modeled as a 2-degree of freedom (dof) spring-mass-damper system, in which m_i, c_i, k_i and m_s, c_s, k_s are the masses, damping coefficients, and spring stiffness of the interface and the host structure generated at the PZT driving point. In the model, one dof refers to the host structure (i.e., a bolted joint) represented by the impedance Z_s and the other refers to the interface represented by its impedance Z_i.

The resultant impedance $\bar{Z}$ of the interface-bolted joint system at the PZT driving point is defined as the ratio between the excitation force F_i and the velocity x_i, as follows:

$$\bar{Z}(\omega) = \frac{F_i}{\dot{x}_i} = \frac{K_{11}K_{22} - (K_{12})^2}{i\omega K_{22}} \qquad (1)$$

in which, the terms $[K_{ij}]$, $i,j = 1, 2$ are the dynamic stiffness of the 2-dof system, as follows:

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{12} & K_{22} \end{bmatrix} = \begin{bmatrix} -\omega^2 m_i + i\omega c_i + k_i & -i\omega c_i - k_i \\ -i\omega c_i - k_i & -\omega^2 m_s + i\omega(c_i + c_s) + (k_i + k_s) \end{bmatrix} \qquad (2)$$

The overall impedance of the PZT interface-bolted joint system can be obtained [1,5], as follows:

$$Z(\omega) = \left\{ i\omega \frac{w_a l_a}{t_a} \left[\hat{\varepsilon}_{33}^T - \frac{1}{Z_a(\omega)/\bar{Z}(\omega) + 1} d_{31}^2 \hat{Y}_{11}^E \right] \right\}^{-1} \qquad (3)$$

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; $\hat{\varepsilon}_{33}^T = (1 - i\delta)\varepsilon_{33}^T$ is the complex dielectric constant at zero stress; d_{31} is the piezoelectric coupling constant in 1-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.

The 2-dof impedance model should contain two resonant peaks in its impedance signatures that represent the two coupled vibration modes of the PZT interface-host structure system. When the bolted joint is damaged (e.g., bolt looseness), its structural parameters (m_s, c_s, k_s) are altered, resulting in the variation in the overall impedance according to Eq. (2) and Eq. (3). For damage detection, the *RMSD* (i.e., root-mean-square deviation) index was extracted from the measured impedance signals. The *RMSD* index can be computed, as follows [10]:

$$RMSD = \sqrt{\sum_{i=1}^{N}\left[Z^*(\omega_i) - Z(\omega_i)\right]^2 \Big/ \sum_{i=1}^{N}\left[Z(\omega_i)\right]^2} \tag{4}$$

where $Z\left(\omega_i\right)$ and $Z^*\left(\omega_i\right)$ signify the impedance responses at the i^{th} frequency before and after a damage event, respectively; N denotes the number of swept frequencies. Ideally, $RMSD \approx 0$ indicates that the bolted joint is healthy (i.e., no bolt-loosening) and $RMSD > 0$ reveals that the joint is loosened (i.e., bolt-loosening).

3. Experimental evaluation

3.1. Test-setup of steel beam

Figure 3 shows the test-setup of a lab-scaled steel beam. The beam 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. The PZT interface was designed with sensitive frequency bands below 100 kHz.

The SSeL-I impedance measurement system consists of a laptop connected to a wireless captain node and a remote SSeL-I node connected to the PZT interface, see Fig. 3. 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.

As the healthy state, all bolted 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. For each bolt-loosening event, the torque was loosened to 0 Nm (completely loosened). The impedance signals were measured before and after each bolt looseness event.

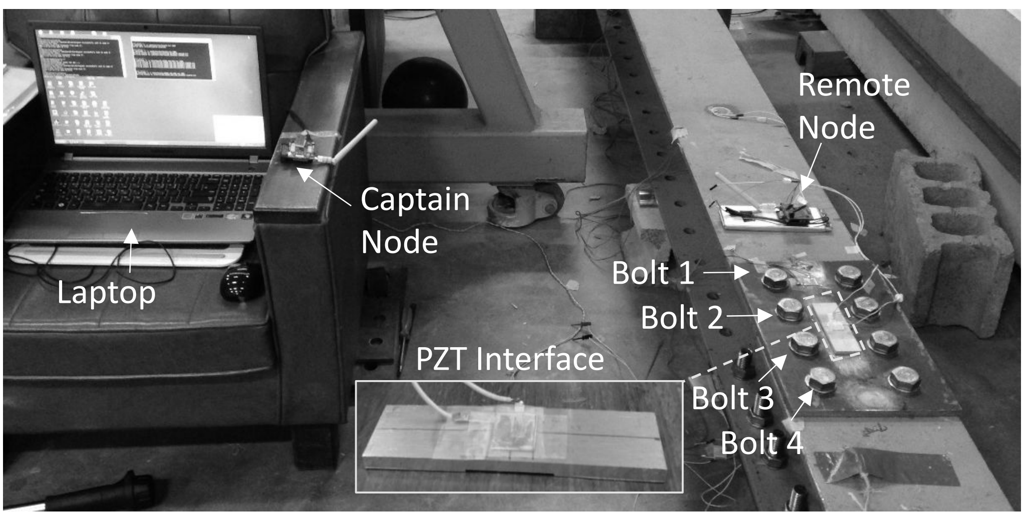


Figure 3. Test-setup of a steel beam connection

3.2. Wireless bolt looseness detection results

Figure 4 shows the impedance responses of the bolt connection in the frequency band 10-55 kHz under the loosened case of Bolt 1. Two resonant bands (i.e., 10-20 kHz and 24-34 kHz) which are below 100 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 resonant band in 10-20 kHz experienced both the frequency and magnitudes shifts while the second one in 24-34 kHz showed only slight changes in the peak frequency and almost no noticeable changes in the magnitudes.

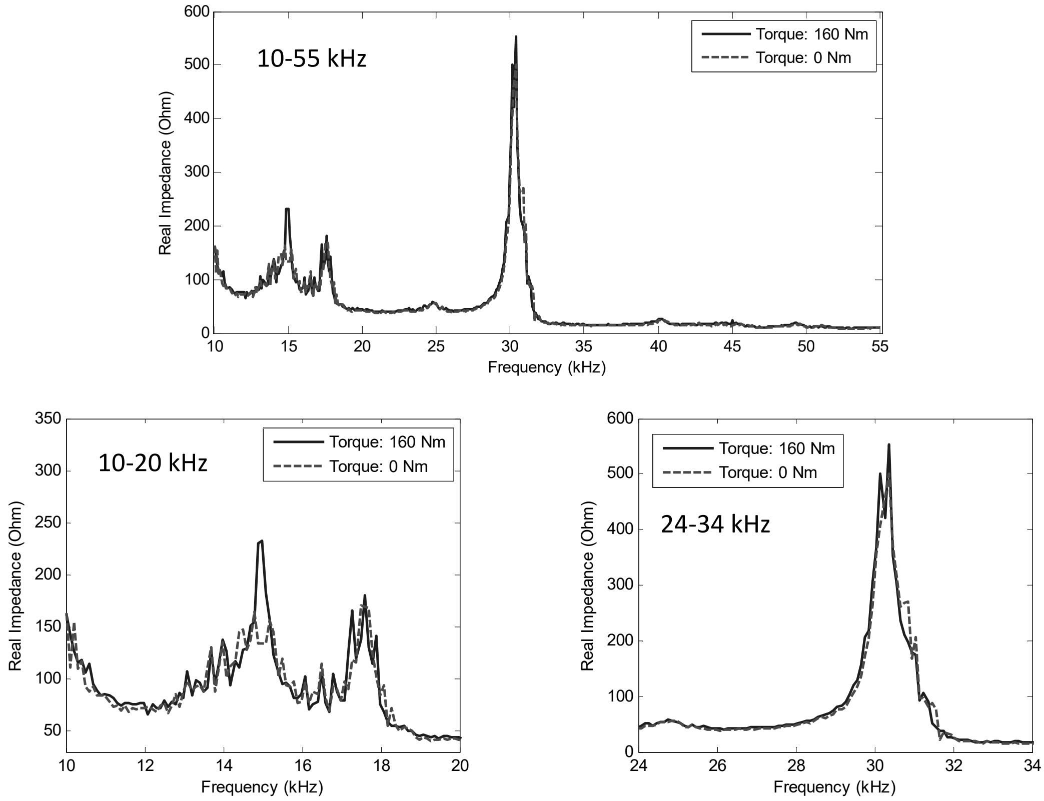


Figure 4. Impedance responses of bolted connection under Bolt 1 Looseness

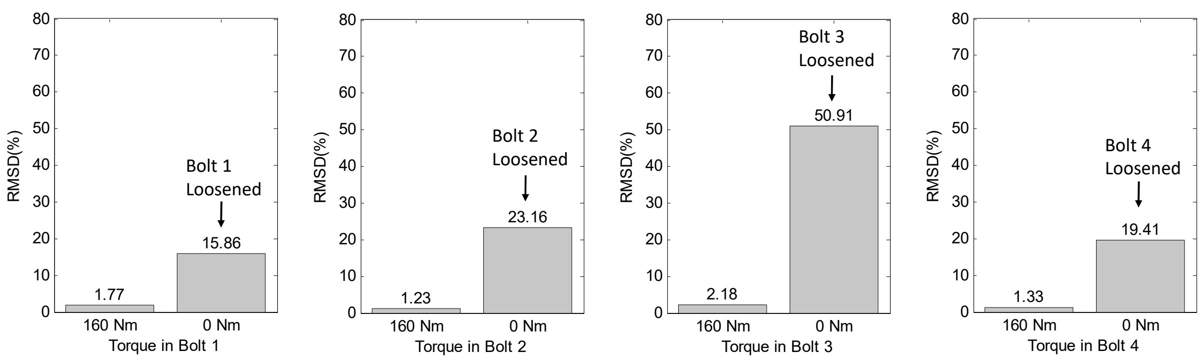


Figure 5. Wireless bolt-loosening detection results

Figure 5 shows the wireless bolt-loosening monitoring results using the *RMSD* index. The whole frequency range 10-55 kHz was used for the calculation. It is observed that when the bolt torque was reduced from 160 Nm to 0 Nm (completely loosened), the *RMSD* index was considerably increased 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, these results demonstrated the feasibility of the wireless impedance-based method for bolt-loosening detection in bolted joints.

4. Conclusion

In this study, bolt looseness in a steel beam connection was detected using a wireless impedance monitoring method via the PZT interface. Firstly, the wireless impedance sensing system was adopted for automated and cost-effective monitoring of impedance responses from structural connections. Secondly, the PZT interface technique was employed to deal with the narrow measurable frequency range of wireless impedance sensor node and to predetermine sensitive frequency ranges in the impedance measurement. Finally, the wireless impedance sensor was integrated with the PZT interface technique for damage detection in a lab-scaled bolted beam connection. Impedance responses of the test structure were wirelessly measured under a set of bolt-loosening events. The change in impedance responses was quantified using the *RMSD* index for distinguishing the bolt-loosening events in the connection. The results showed successful bolt-loosening detection and thus demonstrated the feasibility of the wireless impedance-based bolt-loosening detection method. Despite the promising results, the future study remains to test the practicality of the method on large-scale steel structures in the field.

Acknowledgement

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