Mechanical Systems and Signal Processing 174 (2022) 109068

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Synchronous detection of bolts looseness position and degree based on fusing electro-mechanical impedance

Lintao Wang [a,b], Bo Yuan [b], Zhenbang Xu [a], Qingchao Sun [b,*]

[a] CAS Key Laboratory of On-orbit Manufacturing and Integration for Space Optics System, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Jilin, Changchun 130033, China

[b] School of Mechanical Engineering, Dalian University of Technology, Liaoning, Dalian 116024, China

ARTICLE INFO

Communicated by Kihong Shin

Keywords:
Bolt looseness detection
Electro-mechanical impedance
Frequency shift
Multi-frequency ranges

ABSTRACT

Looseness is the most common form of failure in bolt connections, which can cause safety accidents by reducing the rigidity of the structural connection, and the detection of bolt looseness is vital to maintain the health of the structure. However, due to the limitations of existing methods, it is difficult to detect the position of loose bolt and degree of looseness synchronously. In this study, an Electro-mechanical impedance (EMI) detection method based on fusing multi-frequency ranges was proposed. Firstly, the feasibility of bolt looseness detection based on EMI technology was analyzed through theoretical deduction; secondly, the qualitative relationship between excitation frequency and detection range was explored through finite element simulation, which provides a basis for the proposed fusing multi-frequency ranges method, and the conclusion was verified in four-bolted flange structure; finally, a detection method for bolt looseness was proposed, which uses the impedance shift as the damage index, and detect the position of loose bolt and degree of looseness synchronously by fusing EMI in multiple frequency ranges. The verification results show that the proposed method can identify the loosening status of bolts in the flange structure with high accuracy.

1. Introduction

The mechanical system is assembled by various parts, and the assembly forms include bolted connection, glued connection, and welding. The Bolted connection has been widely used due to its advantages of easy disassembly and reliable connection. However, bolted connections are prone to looseness under the excitation of vibration loads [1,2], and it may cause serious safety accidents if the bolt looseness cannot be detected early. Therefore, it is of great significance to develop the detection method of bolt looseness.

There have been many different methods used to detect the loosening of bolts, such as based on the vibration response [3-5]. Acoustoelastic [6] and Electro-mechanical impedance (EMI). The method based on EMI is currently a hotspot for many researchers because of its light weight, small size and high accuracy. Firstly, the PZT is glued to the structure by epoxy resin, then the EMI spectrum of the PZT is collected to analyze the damage of the structure, and when the bolt loosens, the EMI spectrum will change according to the electro-mechanical coupling effect. In addition, the detection frequency of EMI method is really high, and the frequency is inversely proportional to the wavelength, resulting in this method is very sensitive to small structural damage.

The basic conception of EMI was proposed by Liang [7], in this paper, one-dimensional EMI coupling model was established and the

* Corresponding author.
E-mail address: qingchao@dlut.edu.cn (Q. Sun).

https://doi.org/10.1016/j.ymssp.2022.109068
Received 24 October 2021; Received in revised form 14 February 2022; Accepted 19 March 2022
Available online 6 April 2022
0888-3270/

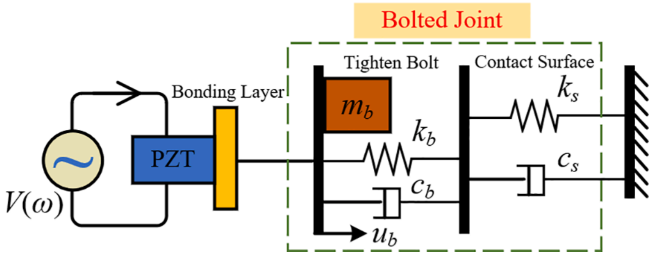


Fig. 1. Impedance model of the bolted joint system.

relationship between electrical impedance and structure mechanical impedance was deduced, which laid the foundation for subsequent research. After that, EMI-based damage detection methods have been widely developed in many fields, Mateusz et al. applied EMI-based method to detect the damage of riveted wing panels, and use Root Mean Square Deviation (RMSD) as an index to evaluate the degree of damage [8]. Peairs D. M. used it to detect damage of gas pipelines and achieved good results [9], others like truss structures [10], pin connections [11] are also verified. As for the detection of bolt looseness, Ritdumrongkul established the numerical model to recognize the degree of bolt looseness on a simple beam [12], Park G used damage index to detect the looseness of the pipes connection bolts [13]. In Wang's paper [14], by proposing a new evaluation index, only two PZTs were used to detect the looseness of the four-bolted plate structure, but the degree of bolt looseness was ignored. Since the EMI signatures are affected by both the degree of bolt looseness and the distance between the bolt and PZT, a minor looseness that is closer to the PZT and a severe looseness that is far from the PZT may have the same damage index [15]. Therefore, in order to locate the loose bolts and identify the degree of looseness, multiple PZTs are required. Pavelko identified the looseness of the 3-bolted Mi-8 helicopter tail beam and three PZTs were used [16], Martowicz use 12 evenly distributed PZTs to locate the loose bolts of a four-bolted flange [17], excellent results were obtained, but the installation process of 12 PZTs is expensive and complicated.

In recent studies, it was found that the EMI signatures obtained under the specific excitation frequency have specific sensing region [18,19], and with the increase of the excitation frequency, the effective sensing region of the PZT transducers is gradually becoming smaller [20]. This means that the impedance signatures under different excitation frequency ranges correspond to different sensing regions, and when multiple frequency ranges are used for damage detection, the location information of damage can be included, which improves the accuracy of damage location. Min et al. divided the impedance of the structure at a wide frequency range into multiple sub-ranges of frequency, and input the damage index of each sub-ranges into the neural network (NN), which can identify the type and severity of damage [21]. Kuang et al. used two frequency ranges 20–140 kHz and 5 MHz-10 MHz to detect damage at steel rebar and found that compared with the impedance obtained under low-frequency excitation [12], the impedance obtained under high-frequency excitation has a smaller detection range and is more sensitive to damage.

Most of the above studies use damage index (i.e. RMSD) to detect the damage of structure, but in Khayatazad's research [22], RMSD can significantly distinguish whether the structure is damaged, but it is not sensitive to the degree of damage. Some scholars proposed to use impedance frequency shift as a damage feature. It's based on the structural damage will change the resonance frequency of the structure, and the existing research has proved that the impedance peak is consistent with the resonance frequency of the structure [23], thus the impedance frequency shift can characterize the degree of damage. Fan et al. use impedance frequency shift as the damage feature to identify the damage of aluminum plate [15]. Cherrier et al. combined the damage index and impedance frequency shift as features to draw the damage localization map of composite structure [24]. Shao et al. Established the relationship between impedance frequency shift and bolt preload [25], The experimental results show that the impedance frequency shift has a linear relationship with the preload of the bolt.

By summarizing the above research, it could be found that to detect the position of loose bolt and degree of looseness synchronously, multiple PZTs usually need to be arranged on the structure, which brings complexity to the installation. Therefore, based on the relationship between excitation frequency and detection range, a practical detection method was proposed in this work, which fusing the EMI of structure measured under multiple frequency ranges. In chapter 2, the feasibility of bolt looseness detection based on EMI was analyzed through theoretical deduction. In chapter 3 and chapter 4, finite element model that couples the electrostatic field and the mechanical field was established, and the relationship between excitation frequency and detection range was explored, which was also verified in experiments; in addition, the feasibility of using impedance shift as damage index was explored. In chapter 5, a loose bolt detection method that fusing multi-frequency ranges EMI was proposed, which could detect the position of loose bolt and degree of looseness synchronously. The verification results show that the proposed method improves the accuracy and practicability of detection.

2. Theoretical background

Fig. 1 shows a simplified one-dimensional impedance model including bolted joint (m_b, k_b, c_b) and contact surface (k_s, c_s). And when a harmonic voltage excitation V is applied to the PZT, a harmonic force f_b is introduced into the impedance model at the PZT driving point. The equation of motion of the system under the external force f_b can be obtained as:

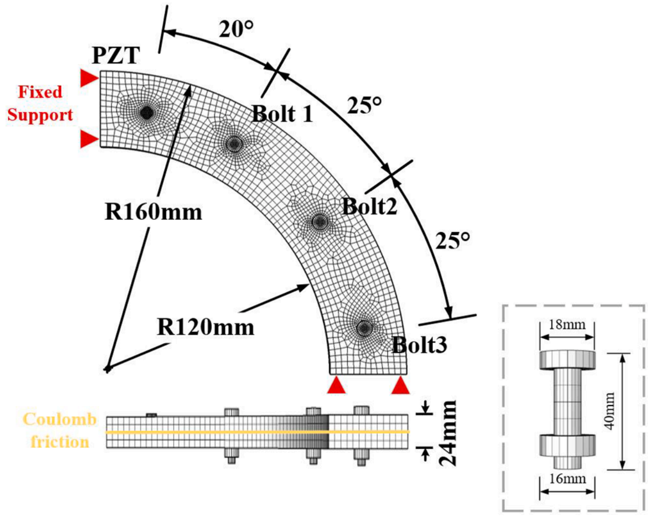


Fig. 2. Model diagram for simulation.

$$m_b\ddot{u}_b + \frac{c_b c_s}{c_b + c_s}\dot{u}_b + \frac{k_b k_s}{k_b + k_s}u_b = f_b \tag{1}$$

where $\ddot{u}_b$, $\dot{u}_b$, u_b represent the acceleration, velocity and displacement of the mass m_b respectively. Under the harmonic force $f_b = F_b e^{j\omega t}$, the displacement of the system can be expressed as $u_b = U_b e^{j\omega t}$, where U_b and F_b represent the amplitude of displacement and external force respectively, ω is the angular frequency. Combined with the definition of impedance, the mechanical impedance of this model can be obtained, as follows:

$$Z_0(\omega) = \frac{f_b}{u_b} = -\omega^2 m_b + j\omega\frac{c_b c_s}{c_b + c_s} + \frac{k_b k_s}{k_b + k_s} \tag{2}$$

Subsequently, using the one-dimensional electro-mechanical analytical model proposed by Liang et al. [1], the relationship between the electrical impedance $Z(\omega)$ of the PZT patch and the mechanical impedance of the host structure $Z_0(\omega)$ was established:

$$Z(\omega) = Y(\omega)^{-1} = [i\omega\frac{w_A l_A}{h_A}(\overline{\varepsilon}_{33}^T - \frac{Z_0(\omega)}{Z_0(\omega) + Z_S}d_{32}^2\overline{Y}_{22}^E]^{-1} \tag{3}$$

where w_A, l_A and h_A are the width, length and height of the PZT, respectively; ω is the excited frequency of PZT; $\overline{\varepsilon}_{33}^T$ represents the complex dielectric constant at zero stress; $\overline{Y}_{22}^E$ represents complex modulus of PZT at zero electric field; d_{32} represents piezoelectric constant. It can be clearly seen that the mechanical impedance of the host structure is closely related to the EMI of PZT patch, and according to Eq. (2), the loosening of bolts will cause changes in damping and stiffness, and it will shift the peak frequency of the host structure impedance, which naturally causes the EMI of the PZT patch to change. Therefore, it provides a theoretical basis for use the EMI peak frequency shift to detect the loose state of bolts in the structure.

3. Simulation

In order to explore the influence of bolt loosening on the peak frequency of the EMI, the electro-mechanical coupling simulation was carried out by the COMSOL Multiphysics Finite element analysis software. For the purpose of improving the calculation efficiency, the host structure adopts a quarter of the flange model, and a PZT with a size of Φ6 × 1 mm is bonded on the flange, the specific size and location are shown in Fig. 2. The materials of PZT plate and host structures are PZT-5H and structural steel respectively. The size of each bolt is M6. The system damping ratio is set to 0.005. The largest size of the meshed finite elements is 0.9 mm, and meet the requirement that each half wavelength should consist of three to five nodal points. An excitation voltage of 1 V is applied to the PZT transducer.

In the simulation, modal analysis was performed to obtain the resonance frequency of the structure, and then piezoelectric harmonic analysis was performed near the resonance frequency. It could be found that the resonance frequency of the structure roughly corresponds to the peak frequency of the EMI, which means that the peak frequency of impedance can reflect the dynamic characteristics of the structure. After analysis of multiple frequency ranges, the frequency range around 56 kHz was selected as scanning frequency range for the piezoelectric harmonic analysis.

Table 1
Simulation settings.

Damage state	Description
Tight	All bolts are tightened to 35kN
1-32kN	Bolt 1 loose to 32kN
1-29kN	Bolt 1 loose to29kN
1-26kN	Bolt 1 loose to 26kN
1-23kN	Bolt 1 loose to 23kN
3-32kN	Bolt 3 loose to 32kN
3-29kN	Bolt 3 loose to 29kN
3-26kN	Bolt 3 loose to 26kN
3-23kN	Bolt 3 loose to 23kN

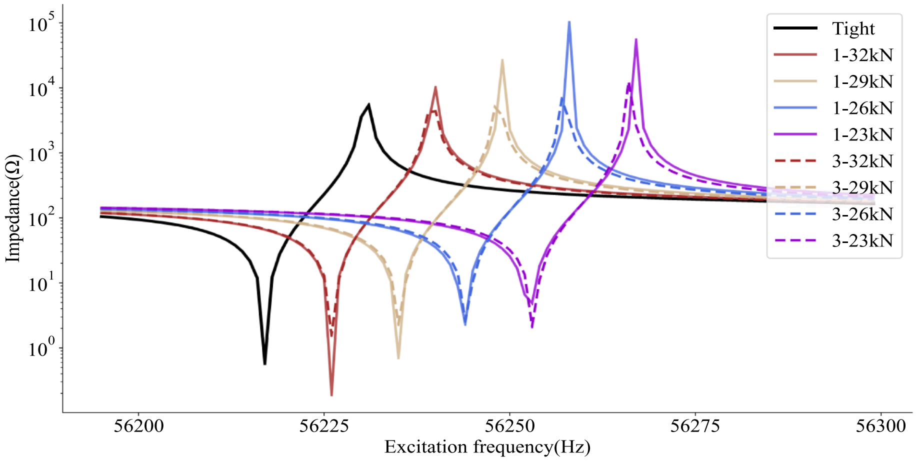


Fig. 3. Numerical simulation results of bolt loosening to varying degrees.

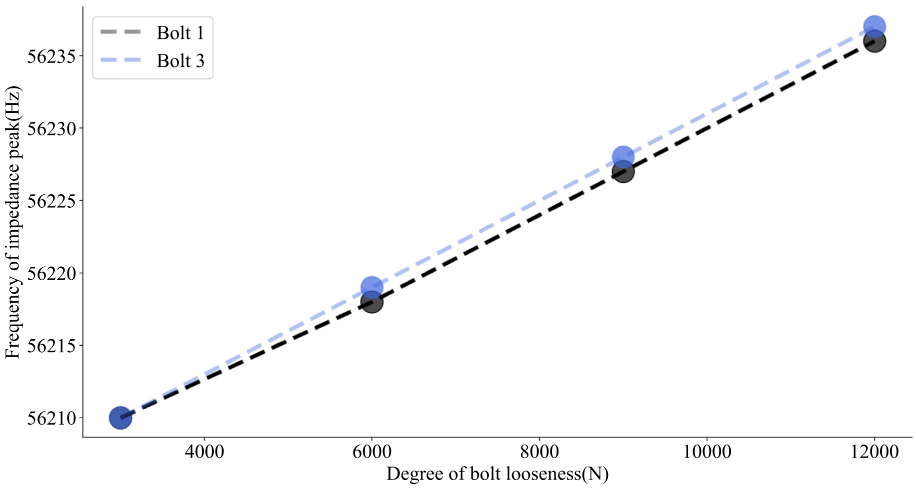


Fig. 4. Correspondence between bolt looseness and impedance peak frequency.

3.1. *Degree of bolt looseness*

To verify the feasibility of using shift of impedance peak as damage index, the influence of bolt looseness on the impedance shift was explored. The simulation of bolt loosening to varying degrees was carried out, and the specific damage conditions are shown in Table 1. The EMI spectra obtained under various damage conditions are shown in Fig. 3.

As can be seen from Fig. 3, bolt looseness will cause the peak frequency of impedance to shift, and the more severe the bolt looseness, the greater the shift, and the degree of bolt looseness has almost a linear relationship with the frequency shift, As shown in

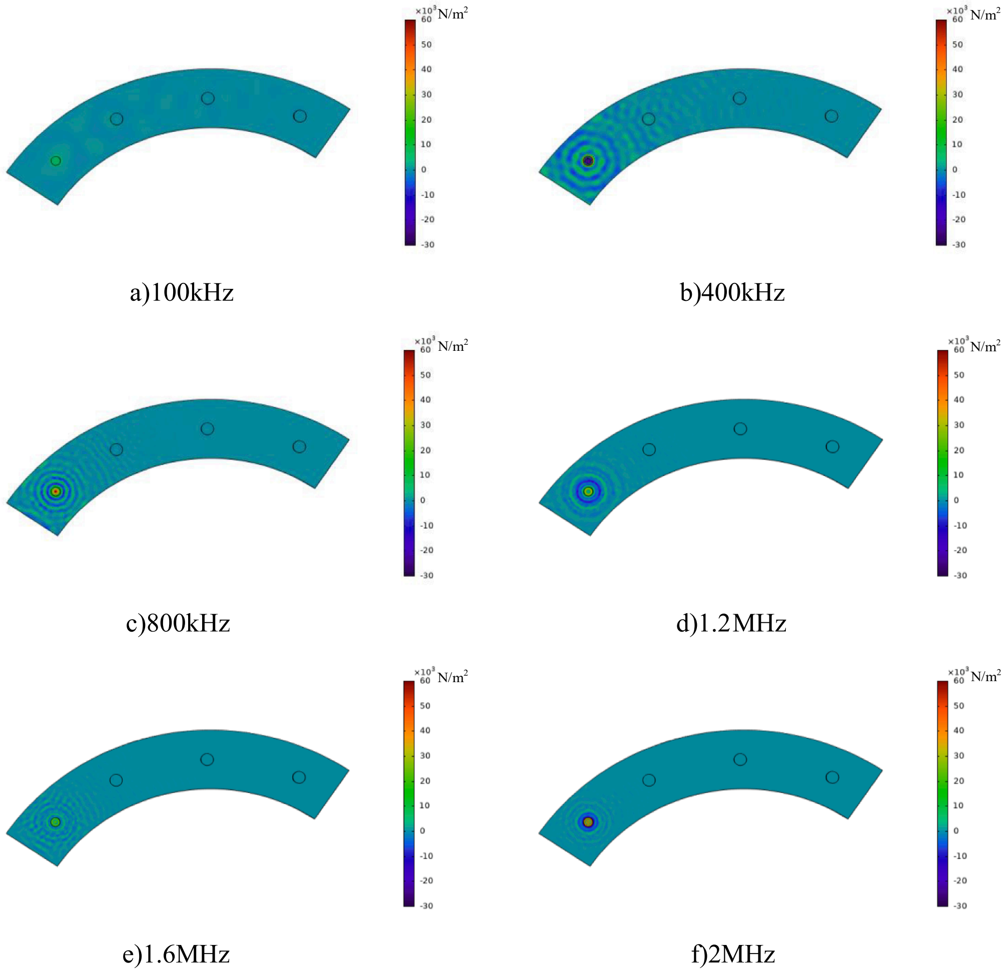


Fig. 5. Stress cloud diagram under different excitation frequencies.

Fig. 4. Therefore, the impedance shift is an effective damage feature for detecting bolt looseness.

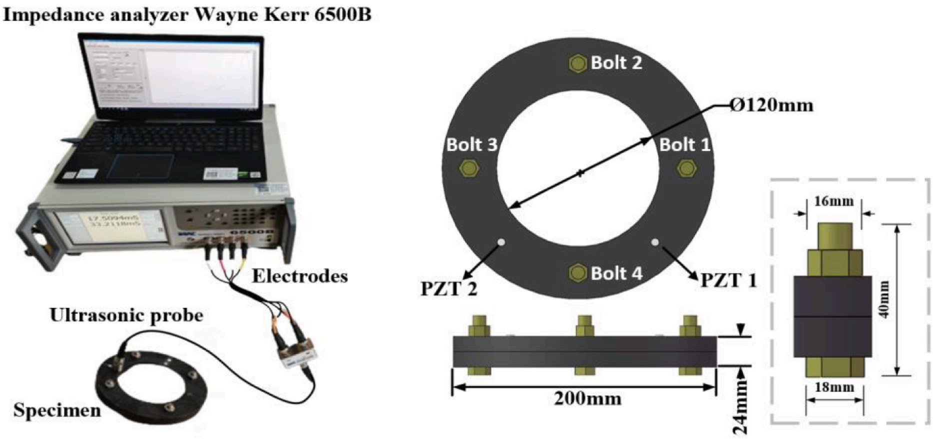
In addition, some other conclusions can be drawn: when the excitation frequency is about 56 kHz, the loosening of bolt 1 and bolt 3 will cause a similar degree of shift, which means that at this excitation frequency, the PZT is not sensitive to the position of the loose bolt.

3.2. Excitation frequency

It can be seen from the above conclusions that when using the impedance signal obtained under a single frequency range excitation, the degree of bolt looseness can be detected, but the loose bolt cannot be located. Therefore, in order to locate the loose bolts, it is necessary to integrate the information of multiple frequency ranges. In this section, the influence of excitation frequency on the effective detection range of PZT was explored.

When the PZT is excited, the piezoelectric material converts an electrical signal of a certain frequency into a vibration signal of a corresponding frequency, thereby exciting the host structure. Therefore, the relationship between the excitation frequency and the effective detection range can be explored by calculating the stress cloud diagram generated by the structure at different excitation frequencies. Fig. 5 shows the stress cloud graphs at 100 kHz, 400 kHz, 800 kHz, 1.2 MHz, 1.6 MHz, and 2 MHz excitation frequencies. In order to improve the credibility of the comparison, the legend scales in all figures remain the same.

It can be seen from Fig. 5 that when the excitation frequency is 100 kHz, the vibration signal transmitted by the PZT can almost cover the entire model, which means that the PZT should be able to detect damage at any position; as the excitation frequency increases, The stress distribution on the host structure gradually surrounds the PZT plate and presents an obvious ring shape, which means that the range that the excitation signal can be transmitted to is gradually reduced; when the excitation frequency is increased to 2 MHz, the excitation signal can be transmitted to a small area concentrated in the vicinity of the PZT plate. Therefore, it can be concluded that as the excitation frequency becomes higher, the energy decays faster and the effective detection range becomes smaller,



Schematic diagram of experimental system (b) Specimen size

Fig. 6. Experimental setup.

Table 2
Material properties.

Material property	PZT	Flange (40Cr)	Unit
Mass density	7500	7850	kg/m^3
Young's modulus	56	211	Gpa
Poisson's ratio	0.36	0.3	–
Piezoelectric constants	275	–	10^{-13}C/N
Relative permittivity	3200	–	–
Dielectric loss factor	0.02	–	–

Table 3
Experimental setup.

Damage state	Description
Tight	All bolts are tightened
1-initial	Bolt 1 occurred initial looseness, All other bolts are tightened
1-severe	Bolt 1 occurred severe looseness, All other bolts are tightened
2-initial	Bolt 2 occurred initial looseness, All other bolts are tightened
2-severe	Bolt 2 occurred severe looseness, All other bolts are tightened
3-initial	Bolt 3 occurred initial looseness, All other bolts are tightened
3-severe	Bolt 3 occurred severe looseness, All other bolts are tightened
4-initial	Bolt 4 occurred initial looseness, All other bolts are tightened
4-severe	Bolt 4 occurred severe looseness, All other bolts are tightened

which means that when the EMI obtained in multiple frequency ranges is used, certain position information can be extracted from it, and then it is possible to locate the loose bolt.

4. Experimental investigations

4.1. Experimental setup

To demonstrate the feasibility of the proposed method, the experimental system shown in Fig. 6 was established. A four bolted flange was used as the specimen, and two PZT plates (Φ6 × 1 mm) were pasted to the surface of the flange by epoxy resin. The specific positions and dimensions are shown in Fig. 6(b). The size of each bolt is M10 × 1 × 40 mm, and the strength class of the bolts is 12.9 with the material is alloy steel. The material properties of the PZT plate and flange are shown in Table 2.

According to the piezoelectric effect, when the PZT is driven in the AC electric field, it will produce deformation and drive the structure to vibrate, and the vibration of the structure will also cause the coupled PZT to deform and make the PZT generate current, and the EMI was obtained by calculating the ratio of the input voltage and the measured current.

During the measurement, the EMI of the PZT was measured by ultrasonic probe and transmitted to the WK6500B impedance analyzer, the excitation voltage was selected as 1 V. In addition, since the impedance peak frequency is more sensitive to the change of

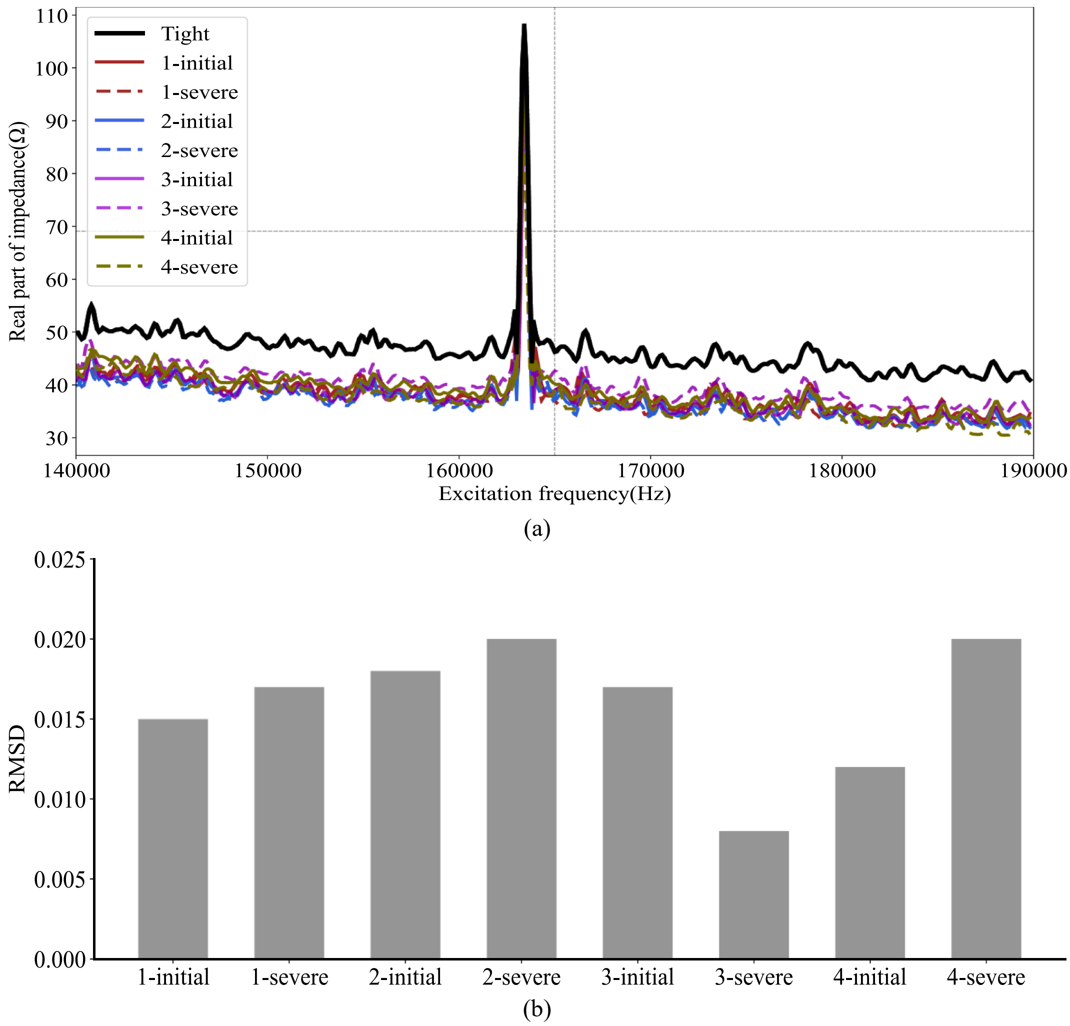


Fig. 7. (a) The EMI spectrum (140 kHz–190 kHz) of PZT 1. (b) RMSD under various damage states.

temperature, the room temperature was controlled to maintain 20℃ during the experiment.

4.2. Results and discussion

In the experiment, when the pre-tightening force of the bolt reaches 35000 N, it was considered to be in a healthy state; at the same time, each bolt has two damage states: initial looseness (25000 N) and severe looseness (15000 N), the pre-tightening force was measured by the ultrasonic measurement technology proposed in Ref. [26], and before the test, PZT should be pasted on the head of the bolt by epoxy resin. 9 types of damage states were measured, as shown in Table 3, and in each condition, the EMI of the 2 PZT plates under excitation of three frequency ranges are obtained, namely 140–190 kHz, 510–520 kHz, and 3.47–3.48 MHz. In the next section, the measurement results of PZT 1 were analyzed.

4.2.1. Impedance spectrum in 140–190 kHz frequency range

Fig. 7(a) shows the measured EMI of PZT 1 at 140–190 kHz under various damage states. It can be found that the ordinate of impedance is more sensitive to structural damage. When the bolt is loosened, the ordinate of impedance drops significantly. Because the signal under low-frequency excitation is greatly affected by the boundary conditions, the collected impedance is more complicated, and there are many impedance peaks interfering with each other. Therefore, in this frequency range, the Root Mean Square Deviation (RMSD) was selected as the damage index, and the calculation formula was shown in Eq. (4). In the formula, N represents the number of points in the frequency sweep interval; h_i represents the value of the *i-th* point in a healthy state, in this paper, it represents the impedance value when the bolt is fully tightened; and d_i represents the value of the *i-th* point in the damaged state, in this paper represents the impedance value when the bolt is loose.

Fig. 7(b) shows the RMSD between the impedance in various damaged states and the impedance in healthy states. It can be seen

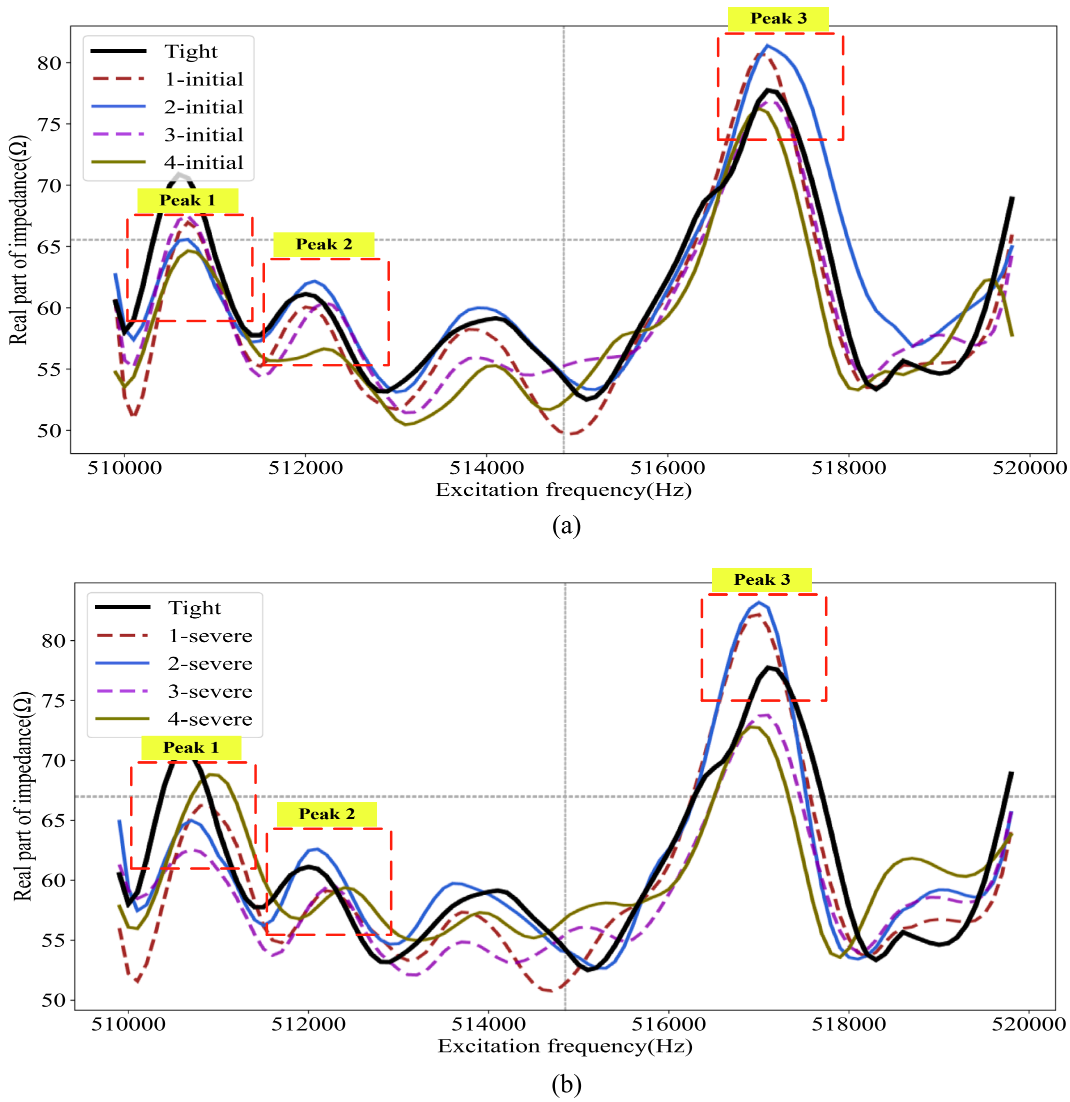


Fig. 8. The EMI spectrum (510 kHz–520 kHz) of PZT 1 when the bolt in (a) initial looseness, (b) severe looseness.

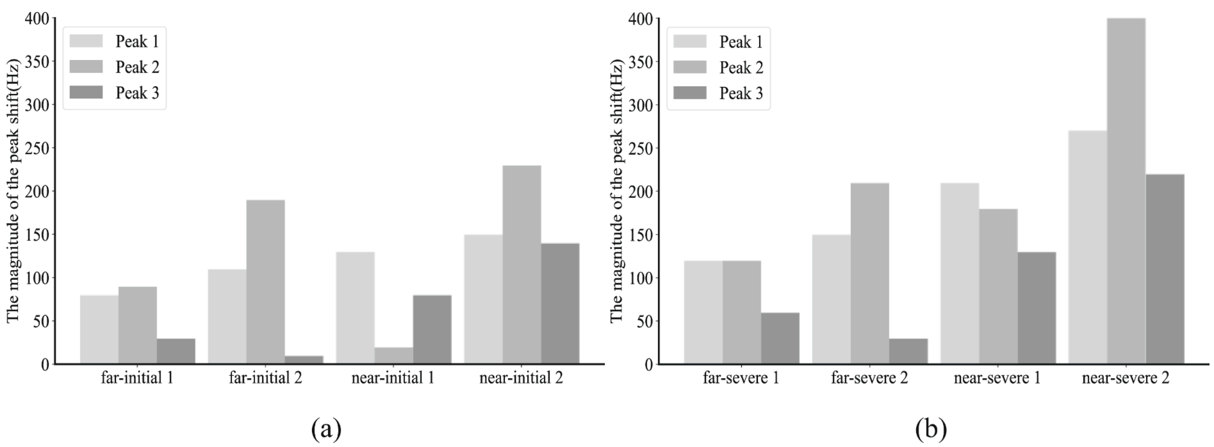


Fig. 9. Comparison of impedance shift of PZT 1 in the 510–520 kHz frequency range when the bolt in (a) initial looseness, (b) severe looseness.

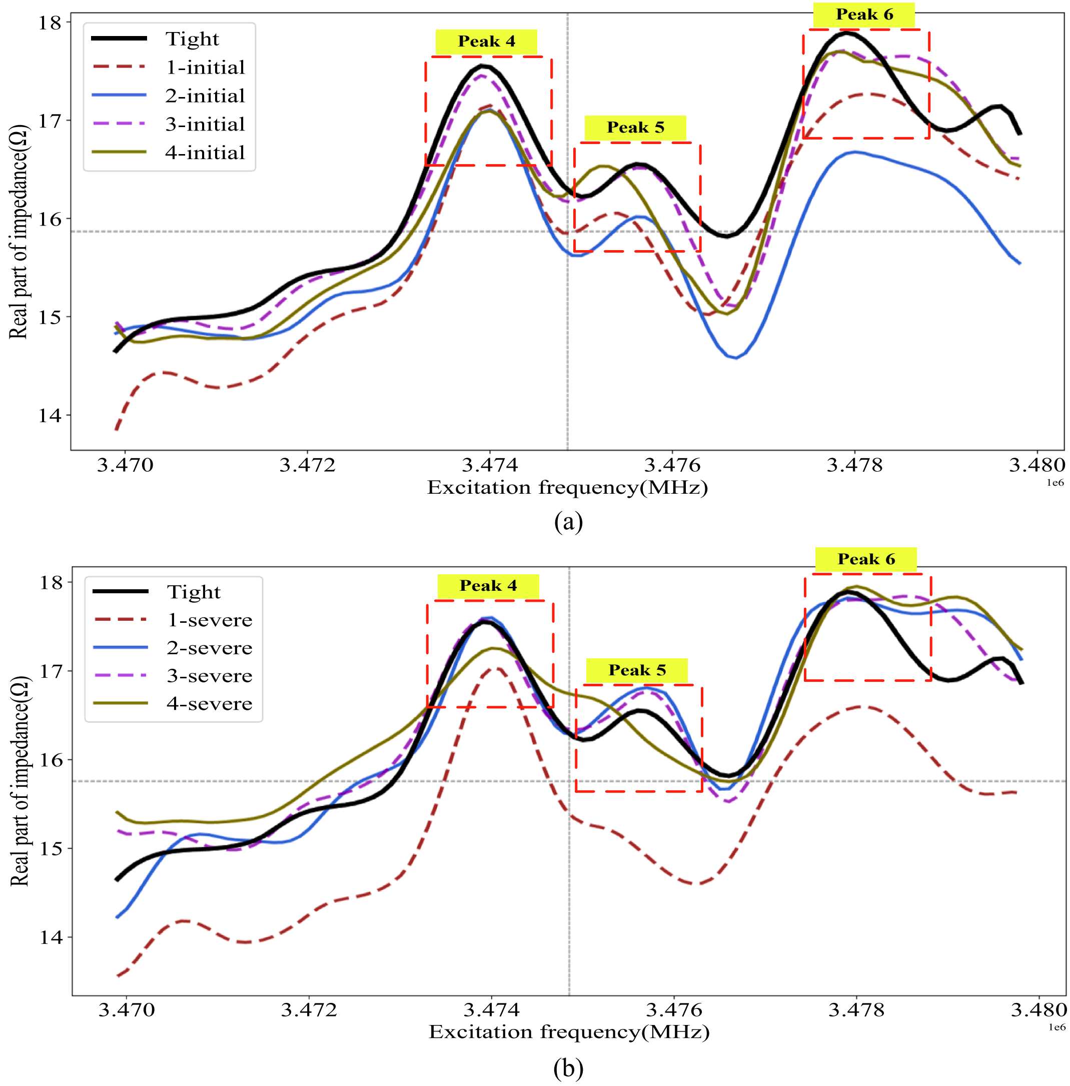


Fig. 10. The EMI spectrum (3.47 MHz–3.48 MHz) of PZT 1 when the bolt in (a) initial looseness, (b) severe looseness.

that RMSD is more sensitive to whether these bolts are loose, but it cannot distinguish the degree of bolt looseness, nor the position of loose bolt, so it can be used to qualitatively judge whether looseness occurs.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(d_i - h_i)^2}{\sum_{i=1}^{N}h_i^2}} \tag{4}$$

4.2.2. Impedance spectrum in 510–520 kHz frequency range

Fig. 8 shows the impedance experiment results of PZT 1 in the 510–520 kHz frequency range. Fig. 8(a) represents the experimental results when the bolts are initially loosened, and Fig. 8(b) represents the experimental results when the bolts are severely loosened. It can be seen from Fig. 8 that when the bolt is loosened, the impedance peak frequency has shifted significantly.

In order to further explore the law of impedance peak shift caused by bolt loosening, three peaks in this frequency range were extracted, namely peak 1, peak 2, and peak 3 in Fig. 8. The comparison of the impedance peak shift in each loose state is plotted in Fig. 9. In order to more intuitively express the influence of the distance between the loose bolt and the PZT on the impedance peak shift, Fig. 9 divides the four bolts into near-field bolts and far-field bolts according to the distance to the PZT. Since bolt 1 and bolt 4 are located near PZT 1, bolt 2 and bolt 3 are located far away from PZT 1. Therefore, in Fig. 9, near 1 represents bolt 1, near 2 represents bolt 4, far 1 represents bolt 2, and far 2 represents bolt 3.

It can be seen from Fig. 9(a) that when the bolts are initially loosened, the impedance peak shift of the bolts in the near field of PZT

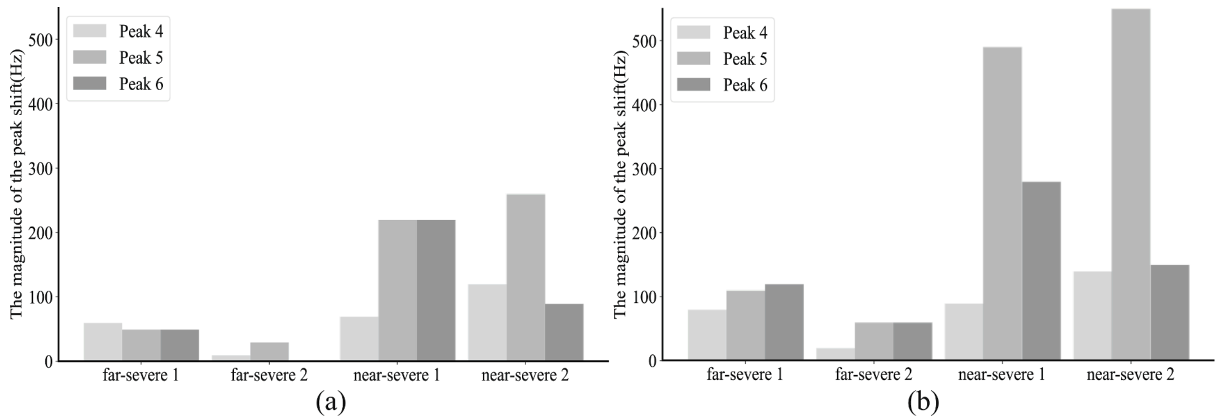


Fig. 11. Comparison of impedance shift of PZT 1 in the 3.47–3.48 MHz frequency range when the bolt in (a) initial looseness, (b) severe looseness.

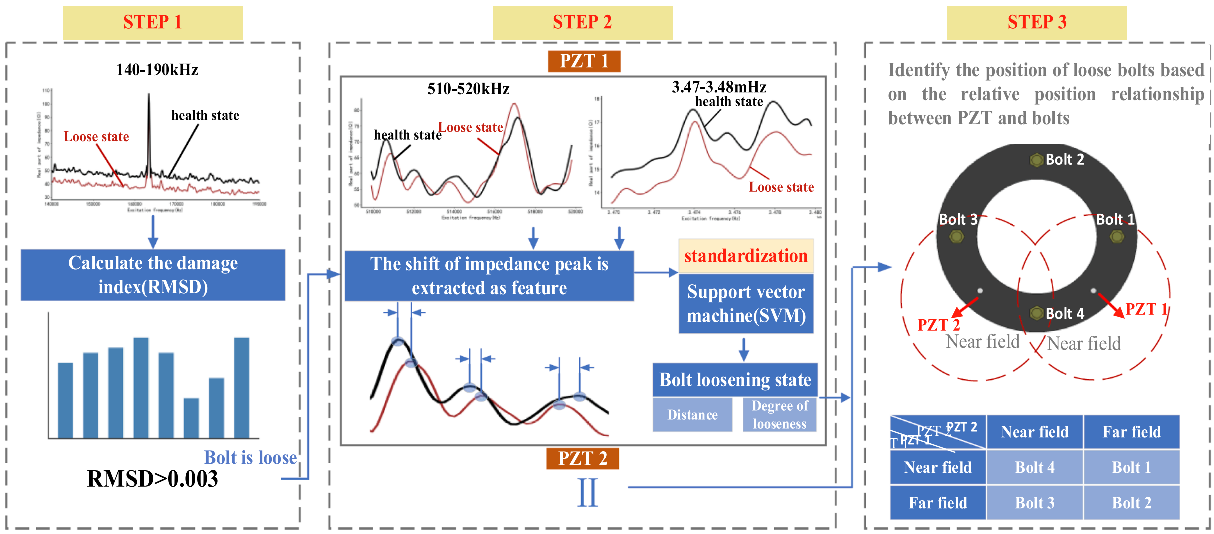


Fig. 12. Flow chart of detection strategy.

and the bolts in the far field of PZT is almost the same, which means that when the bolts are initially loosened, the location of the loose bolt cannot be identified; It can be seen from Fig. 9(b) that when the bolt is severely loosened, the impedance peak shift caused by the loosening of the bolts in the near field of PZT is significantly greater than that of the far field. From the above analysis, it can be seen that only using the impedance in the 510–520 kHz frequency range cannot accurately identify the state of bolt looseness, because it is difficult to distinguish between the loose bolts located near the PZT and the loose bolts located far away from the PZT.

In addition, by comparing Fig. 9(a) and Fig. 9(b), it can be found that the peak shift caused by severe bolt loosening is greater than initial bolt loosening. This means that the greater the degree of bolt looseness, the more obvious the impedance peak shift, which is consistent with the law obtained by the simulation.

4.2.3. Impedance spectrum in 3.47–3.48 MHz frequency range

Fig. 10 shows the impedance experiment results of PZT 1 in the 3.47–3.48 MHz frequency range. Fig. 10(a) represents the experimental results when the bolts are initially loosened, and Fig. 10(b) represents the experimental results when the bolts are severely loosened. Similarly, three peaks in this frequency range were extracted, namely peak 4, peak 5, and peak 6 in Fig. 10. The comparison of the impedance peak shift in each loose state is plotted in Fig. 11.

It can be seen from Fig. 11 that the loosening of the bolts in the far field of PZT merely cause a slight shift of the impedance peak, while the loosening of the bolts in the near field of PZT will cause obvious shift, which means that under the excitation of this frequency, the impedance of PZT is not sensitive to the loosening of the far field bolts, and is mainly affected by the loosening of the near field bolts. Therefore, by comparing Fig. 9 and Fig. 11, it can be concluded that with the increase of the excitation frequency, the effective detection range of the PZT is also reduced, under the excitation of the 3.47–3.48 MHz frequency range, only the loosening of the bolts located in the near field of PZT can be detected.

Table 4
The fusion of the identification results of each PZT.

PZT 1	PZT 2			
	Near-initial	Near-severe	far-initial	far-severe
Near-initial	4-initial	*4-loose	1-initial	*1-loose
Near-severe	*4-loose	4-severe	*1-loose	1-severe
far-initial	3-initial	*3-loose	2-initial	*2-loose
far-severe	*3-loose	3-severe	*2-loose	2-severe

Summarizing the above analysis of the experimental results, the following conclusions can be drawn: (1) The shift of the impedance peak is an effective damage feature. When a bolt is loosened in the structure, it will significantly cause the impedance peak to shift. Therefore, by analyzing the shift of the impedance peak, the loosening state of the bolt can be identified. (2) Using the EMI of a single frequency range for detection has limitations that it is difficult to identify the location and degree of bolt looseness synchronously. The response of the excitation in the 140–190 kHz frequency range can qualitatively reflect whether the bolt is loose, but it cannot be located and quantified; the response of the excitation in the 510–520 kHz frequency range cannot distinguish between loose bolts located in the near field or far field of the PZT; when excitation is performed in the 3.47–3.48 MHz frequency range, only the loosening of the bolts located in the near field of PZT will affect the impedance peak, which means that only the loosening of the bolts near PZT can be identified in this frequency range. (3) With the increase of the excitation frequency, the effective detection range of PZT is obviously reduced, which is also consistent with the law obtained in the simulation.

According to the above conclusions, using a single frequency range for detection has limitations, and it is found that the impedance obtained under different excitation frequencies reflects the structural damage in different ranges. Therefore, when the impedance information of the same PZT obtained at different frequency ranges was integrated, the distance between the loose bolt and the PZT and the degree of bolt looseness can be identified synchronously.

5. Detection method

5.1. Method

Based on the previous research, this section proposes a bolt looseness detection method based on fusing impedance of multi-frequency ranges. The detection process is divided into three steps, as shown in Fig. 12.

Step 1: RMSD of each PZT in the frequency range of 140–190 kHz was calculated to preliminarily judge whether bolts loosened in the structure, when it is judged that the bolts are loose in the current state, and then go to step 2.
Step 2: Obtain the impedance of each PZT under multi-frequency ranges, the impedance peak shift is extracted as the damage feature, and input it into the Support Vector Machine (SVM) to identify the loosening state (The distance between the PZT and loose bolt, and degree of bolt looseness).
Step 3: Based on the results of each PZT obtained by step 2 and combining the relative position relationship between the PZT and the bolt to determine the position of loose bolt and degree of looseness.

5.2. Example

To verify the feasibility of the method proposed above, this section takes the data obtained in the experiment as example to establish the detection model, and the detection accuracy of the model is explored.

Before the detection starts, the model needs to be deployed using experimental data. Firstly, the threshold value in Step 1 should be determined. RMSD in the 140–190 kHz frequency range under various damage states was calculated, as can be seen from Fig. 7(b), RMSD after bolts loosened was usually greater than 0.005, and RMSD between repeated measurement results was less than 0.002 in a healthy state. Therefore, 0.003 was selected as the threshold value to judge the bolt loosening of the structure, if the RMSD between the current state and the calibrated health state is greater than 0.003, it is considered that the bolt has been loosened.

Then, the SVM models need to be trained with experimental data. The impedance spectra of each PZT in two frequency ranges: 510–520 kHz and 3.47–3.48 MHz, under various loosening states were measured by experiments. The shift of the impedance peak between the damaged state and the healthy state was extracted as the damage features. Then, the SVM model was established for each PZT separately, and the damage features were input into the model for training, the training goal of the model were set as the loosening degree of the bolt and the distance between the loose bolt and the PZT, specifically, there are 4 kinds of situations, namely severe loosening of near-field bolt, initial loosening of near-field bolt, severe loosening of far-field bolt, and initial loosening of far-field bolt. In the experiment, the measurement of impedance is repeated five times under each damage state, three sets of data are taken for training, and the other set is used for testing.

Finally, the SVM identification results of each PZT should be integrated to determine the specific location of the loose bolt. The corresponding relationship between identification results and the number of loose bolts is shown in the Table 4, which is derived from the relative position relationship between the PZT and bolt. It is worth noting that when the bolt loosening degree identified by two PZTs is inconsistent (as marked by * in the table), the model is considered to have failed to identify the bolt loosening degree, and half

Table 5
Model comparison.

Model	Accuracy on the training set	Accuracy on the test set
Model shown in Fig. 12	87.5%	81.25%
Single low-frequency range model	58%	56%
Single high-frequency range model	68.75%	65.6%

of the target is considered to have been achieved when calculating the accuracy of the model.

After the deployment of the model, the above methods were used to calculate the accuracy of detection on the training set and the test set respectively. It was found that the model proposed in this paper correctly identified 21 of 24 samples in the training set and 13 of 16 samples in the test set, and the recognition accuracy was 81.25%. By analyzing the samples with errors detected in the test set, it was found that most of them are wrong in identifying the looseness degree, and only one of them is wrong in identifying the position of the loose bolt. Therefore, the detection model proposed in this paper can effectively identify the position of the loose bolt and estimate the degree of the looseness in most cases, and realize the synchronous detection of the position of loose bolt and degree of looseness.

5.3. Discussion

In order to verify the effectiveness of the proposed model, the effectiveness of using multiple frequency ranges was discussed in this section.

First of all, the model in Fig. 12 that only uses the impedance in the 510–520 kHz frequency range and the impedance in the 3.47–3.48 MHz frequency range was established, which are respectively recorded as a single low-frequency range model and a single high-frequency range model. Table 5 shows the accuracy of the three models in the training set and test set.

It can be seen that when only the impedance under single frequency range was used for damage detection, the accuracy is only about 60%, which is slightly higher than guessed, but the detection accuracy of the proposed mode is as high as 81.25%, which means that the fusion of impedances in multiple frequency ranges will greatly improve the accuracy of damage detection.

6. Conclusion

In order to detect the position of loose bolt and degree of looseness synchronously, a detection method that fusing multi-frequency ranges EMI was proposed, the main conclusions are as follows:

A one-dimensional EMI model that couples the piezoelectric material and the host structure was established, and the electrical impedance equation for the coupling system is derived, which clarifies the damage detection mechanism of the EMI technology.

The finite element simulation model was developed to explore: (1) the influence of bolt looseness on impedance frequency peak; (2) the relationship between excitation frequency and effective detection range. The results show that the bolt looseness will cause the shift of impedance frequency peak, and the more serious the degree of bolt looseness, the greater the impedance peak shift; in addition, with the increase of the excitation frequency, the effective detection range of the PZT becomes smaller.

An EMI-based detection experiment platform was established, and the conclusion obtained in the simulation was further verified. Based on the relationship between the excitation frequency and detection range that obtained in simulation and experiment, a loose bolt detection method that fusing multi-frequency ranges EMI was proposed, which can not only detect the position of the loose bolt, but also the approximate degree of looseness of the loose bolt. The accuracy of the detection model was evaluated, and the results show that the detection accuracy of the proposed model on the test set reached 81.25%, which indicates that the proposed method has certain accuracy and feasibility.

Funding

This work was supported by the National Natural Science Foundation of China (No. 51935003) and National Defense Basic Scientific Research Program of China (JCKY2019203B031).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H. Gong, J. Liu, X. Ding, Study on the Mechanism and Influencing Factors of Preload Decline for Bolted Joints under Vibration, J. Mech. Eng. 55 (11) (2019) 138–148.
[2] Q. Lin, Y. Zhao, Q. Sun, K. Chen, Reliability evaluation method of anti-loosening performance of bolted joints, Mech. Syst. Sig. Process. 162 (2022), 108067.
[3] F. Wang, G. Song, A novel percussion-based method for multi-bolt looseness detection using one-dimensional memory augmented convolutional long short-term memory networks, Mech. Syst. Sig. Process. 161 (2021), 107955.
[4] S. Cao, N. Guo, C. Xu, Robust damage localization in plate-type structures by using an enhanced robust principal component analysis and data fusion technique, Mech. Syst. Sig. Process. 162 (2022), 108091.

[5] Q. Li, X. Jing, A novel second-order output spectrum based local tuning method for locating bolt-loosening faults, Mech. Syst. Sig. Process. 147 (2021), 107104.
[6] X. Qin, C. Peng, G. Zhao, Z. Ju, S. Lv, M. Jiang, Q. Sui, L. Jia, Full life-cycle monitoring and earlier warning for bolt joint loosening using modified vibro-acoustic modulation, Mech. Syst. Sig. Process. 162 (2022), 108054.
[7] C. Liang, F. Sun, C.A. Rogers, Electro-mechanical impedance modeling of active material systems, Smart Mater. Struct. 5 (2) (1996) 171–186.
[8] M. Rosiek, K. Dragan, A. Martowicz, T. Uhl, Damage Detection in Riveted Aircraft Elements Based on the Electromechanical Impedance Measurements, Key Eng. Mater. 588 (2014) 54–63.
[9] D.M. Peairs, G. Park, D.J. Inman, Improving Accessibility of the Impedance-Based Structural Health Monitoring Method, J. Intel. Mat Syst. St.r 15 (2) (2004) 129–139.
[10] X. Liu, Z. Jiang, Design of a PZT patch for measuring longitudinal mode impedance in the assessment of truss structure damage, Smart Mater. Struct. 18 (12) (2009) 125017.
[11] Y. Liang, D. Li, S.M. Parvasi, G. Song, Load monitoring of pin-connected structures using piezoelectric impedance measurement, Smart Mater. Struct. 25 (10) (2016) 105011.
[12] S. Ritdumrongkul, Y. Fujino, Identification of the Location and Level of Damage in Multiple-Bolted-Joint Structures by PZT Actuator-Sensors, J. Struct. Eng. 132 (2) (2006) 304–311.
[13] G. Park, H.H. Cudney, D.J. Inman, Feasibility of using impedance-based damage assessment for pipeline structures, Earthq. Eng. Struct. D 30 (10) (2001) 1463–1474.
[14] F. Wang, Z. Chen, G. Song, Monitoring of multi-bolt connection looseness using entropy-based active sensing and genetic algorithm-based least square support vector machine, Mech. Syst. Sig. Process. 136 (2020), 106507.
[15] X. Fan, J. Li, H. Hao, S. Ma, Identification of Minor Structural Damage Based on Electromechanical Impedance Sensitivity and Sparse Regularization, J. Aerospace Eng. 31 (5) (2018) 4018061.
[16] V. Pavelko, Electromechanical impedance for SHM of aircraft bolted joints, in: T.Y. Yu, A.L. Gyekenyesi, P.J. Shull, A.A. Diaz, H.F. Wu (Eds.) Proceedings of SPIE, SPIE-INT SOC Optical Engineering, Bellingham, 2013.
[17] A. Martowicz, A. Sendecki, M. Salamon, M. Rosiek, T. Uhl, Application of electromechanical impedance-based SHM for damage detection in bolted pipeline connection, Nondestruct Test Eva 31 (1) (2016) 17–44.
[18] Y. Hu, Y. Yang, Wave propagation modeling of the PZT sensing region for structural health monitoring, Smart Mater. Struct. 16 (3) (2007) 706–716.
[19] K. Juan, X. Bin, Local damage detection for steel rebar by impedance measurements of PZT sensors, Proc. SPIE (2012).
[20] B.S. Divsholi, Y. Yang, Health Monitoring of Steel Structures Using Sub-frequency Electromechanical Impedance Technique, J. Nondestruct. Eval. 31 (3) (2012) 197–207.
[21] J. Min, S. Park, C. Yun, C. Lee, C. Lee, Impedance-based structural health monitoring incorporating neural network technique for identification of damage type and severity, Eng. Struct. 39 (2012) 210–220.
[22] M. Khayatazad, J. Deschodt, M. Loccufier, H. De Backer, W. De Waele, Experimental And Numerical Study Of RMSD -A Damage Index Of Electro-Mechanical Impedance-Based Structural Health Monitoring Project,2020.
[23] T. Wang, B. Tan, M. Lu, Z. Zhang, G. Lu, Piezoelectric Electro-Mechanical Impedance (EMI) Based Structural Crack Monitoring, Appl. Sci. 10 (13) (2020) 4648.
[24] O. Cherrier, P. Selva, V. Pommier-Budinger, F. Lachaud, J. Morlier, Damage localization map using electromechanical impedance spectrums and inverse distance weighting interpolation: Experimental validation on thin composite structures, Struct. Health Monit. 12 (4) (2013) 311–324.
[25] J. Shao, T. Wang, H. Yin, D. Yang, Y. Li, Bolt Looseness Detection Based on Piezoelectric Impedance Frequency Shift, Appl. Sci. 6 (10) (2016) 298.
[26] Q. Sun, B. Yuan, X. Mu, W. Sun, Bolt preload measurement based on the acoustoelastic effect using smart piezoelectric bolt, Smart Mater. Struct. 28 (5) (2019) 55005.