A nonlinear Lamb wave-based tight contact stage identification and pretightening state quantitative monitoring method for bolts

Longzhen Tian (✉ tianlongzhen@csu.edu.cn)
Central South University https://orcid.org/0000-0002-6951-1496

Tiantian Wang
Central South University

Jinsong Yang
Central South University

Jingsong Xie
Central South University

Zhikang Zhang
Hunan University

Research Article

Keywords: Bolt loosening, Tight contact stage, Nonlinear Lamb waves, Phase reversal, Degradation process, Quantitative monitoring

Posted Date: May 5th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2830404/v1

License: ☑️ This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
A nonlinear Lamb wave-based tight contact stage identification and pretightening state quantitative monitoring method for bolts

Longzhen Tian¹, Tiantian Wang¹,²*, Jinsong Yang¹, Jingsong Xie¹, Zhikang Zhang²

(1. School of Traffic & Transportation Engineering, Central South University, Changsha 410075, China; 2. College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China)

Abstract: Bolt connections are subjected to severe service conditions, such as cyclic loading and mechanical shock, leading to loosening failure. Commonly, the degradation of the bolt pretightening state is a multistage process, consisting of the tight contact stage (TCS) and significant loosening stage. Therefore, utilizing a single model to monitor the pretightening state in the full degradation stage is difficult. Here, a method based on nonlinear Lamb waves to identify the TCS of bolts and quantitatively monitor the pretightening state to bolt loosening is proposed. In the proposed method, phase reversal technology is first adopted to enhance the sensitivity and reduce the calculation errors of nonlinear damage indexes for bolt loosening in the TCS, and then the phase reversal relative nonlinear coefficient (PRC) is constructed. This indicator overcomes the disadvantage that linear indicators are insensitive to early loosening and realizes the identification of critical points between the TCS and the significant loosening stage, which provides a prerequisite for constructing a staged loosening monitoring model. After the TCS is determined, a quantitative monitoring model for loosening, which fuses seven nonlinear damage indexes, is established based on canonical correlation forests to evaluate the pretightening state. To verify the effectiveness of the method, an experimental study of bolts is carried out, the lamb signals under different loosening states are measured, and the monitoring effects of different indicators are compared and analyzed. The comparison results show that the proposed method has higher accuracy than conventional approaches.

Keywords: Bolt loosening; Tight contact stage; Nonlinear Lamb waves; Phase reversal; Degradation process; Quantitative monitoring

1. Introduction

As a basic connection method, bolted joints have the advantages of easy repeated disassembly, reusability, and low cost. This method is widely used in demountable structures in machinery, aerospace, and civil engineering applications [1]. Bolt connections are subjected to cyclic loading, mechanical shock, and other harsh operating conditions that can cause loosening failure during service. In bolt loosening,
the contact part changes resulting in some nonlinear effects leading to nonlinearities and a multistage (tight contact stage and significant loosening stage) bolt degradation process; this makes it difficult to use a single model for quantitative monitoring the pretightening state of early bolt loosening [2][3]. Therefore, it is important to identify the tight contact stage (TCS) and the significant loosening stage and to carry out quantitative monitoring of the early loosening pretightening state in TCS for maintaining equipment and reducing safety accidents.

In recent years, with the development of artificial intelligence and machine learning, several researchers have identified the nut rotation angle or screw length to judge bolt loosening based on machine vision [4][5][6]. Information on the bolt rotation angle or the length of the bolt rod can be extracted. Either way, visible bolt loosening indicates that the bolt has lost some of its preload. This detection method is meaningless. Na et al. and Zhou et al. achieved bolt loosening identification by establishing the relationship between the electrical impedance and mechanical impedance of the piezoelectric ceramic piece [7][8]. While electromagnetic interference (EMI) technology is more influenced by the environment, ultrasonic-based monitoring has been more widely adapted to different engineering applications. In particular, bolt loosening monitoring technology based on linear Lamb waves has been extensively developed. Wang et al. analyzed the bolt connection contact surface’s true contact area from a microscopic perspective and constructed energy indicators to characterize bolt loosening [9]. Hei et al. and Li et al. established the relationship between the preload force of the bolt connection and the Lamb wave energy to detect bolt loosening [10][11]. Xu et al. and Jiang et al. collected ultrasonic signals based on the time-reversal method. Bolt loosening was detected using the relationship between the maximum amplitude of the signal and the bolt preload force [12][13]. A virtual time reversal method for damage localization was proposed by Kannusamy et al. [14]. Many scholars have found that the observation of small changes in the preload force through ultrasonic energy dissipation indicators is challenging when the bolt preload force is large. This is because the real contact area changes little when the bolt preload is large, resulting in saturation of the energy dissipation index. It is difficult to detect early loosening in TCS.

The nonlinear Lamb wave technique, which is more sensitive to early minor damage, has attracted the attention of researchers. In previous studies, the contact acoustic nonlinearity of bolted connections was analyzed theoretically, and different damage indexes were extracted using a vibroacoustic modulation method to monitor bolt loosening and solve the saturation effect of energy dissipation [15][16][17]. However, the nonlinear Lamb wave showed a nonmonotonic correlation with the degree of damage and lost its effectiveness for monitoring late-stage damage. Chen et al. investigated the effect of cracks on the ultrasonic nonlinear effect. When the damage developed into macroscopic cracks, its influence on the nonlinear effect was smaller [18]. Zhu et al. showed that the relationship between nonlinear ultrasound indicators and sample fatigue life was nonmonotonically correlated, with a peak at the late stage of fatigue damage [19]. The nonlinear damage indexes proposed by Qin et al. based on the vibroacoustic modulation method showed a nonlinear relationship with the degree of bolt loosening. Since the bolt loosening degradation process is nonlinear and nonmonotonic, it was difficult to use a single monitoring model for both the tight contact stage and the significant loosening stage [20]. Notably, most of the abovementioned studies of bolt loosening are qualitative. Quantitative monitoring of bolt loosening first requires the identification of critical points between the tight contact stage and the significant loosening stage.
For quantitative monitoring, the traditional linear Lamb wave technique has a saturation effect that is insensitive to microdamage during early bolt loosening. The nonlinear Lamb wave technique shows a non-monotonic relationship, which is multistage, as the bolt degradation process progresses, which peaks at near complete bolt loosening [2][3]. As mentioned above, it is difficult to apply a single monitoring model for the full degradation process. Therefore, there is an urgent need to develop a nonlinear Lamb wave data-driven method to solve the nonlinear, multistage problem in the bolt degradation process. This method can be used to accurately determine the critical point between the tight contact stage and the significant loosening stage and then monitor the pretightening state of bolt loosening in TCS.

In this paper, a phase reversal-based method for tight contact stage identification and pretightening state quantitative monitoring of early bolt loosening is proposed. The method first constructs the phase reversal relative nonlinear coefficient (PRC) using the phase reversal technique. This indicator realizes the identification of critical points between the tight contact stage and the significant loosening stage. Then, a quantitative monitoring model incorporating seven nonlinear damage indicators is developed based on the canonical correlation forest (CCF) to quantitatively evaluate the pretightening state of early loosening in the tight contact stage. The remainder of this paper is structured as follows: Section 2 introduces the phase reversal-based method for tight contact stage identification and pretightening state quantitative monitoring of early bolt loosening. Section 3 describes the experimental setup and excitation signals in detail. The nonlinear relationship of bolted connections from tightened to fully loosened states is analyzed. The effectiveness of linear and nonlinear indicators for monitoring the early loosening of bolts is compared and analyzed to verify the accuracy of the monitoring model. Section 4 gives the conclusions of this paper.

2. Methodology

2.1. Quantitative monitoring method

The degradation process of the bolt pretightening state is divided into the tight contact stage and the significant loosening stage, which makes it difficult to apply a single monitoring model to the full degradation stage [2][3][20]. Therefore, a method for identifying the critical point of the TCS and quantitatively monitoring the pretightening state of bolt loosening based on nonlinear Lamb waves is proposed.

The framework of the proposed quantitative monitoring method is shown in Fig. 1, which is divided into four parts: data acquisition, critical point identification of the TCS, nonlinear damage index extraction, and quantitative monitoring model. The Lamb wave signals are first collected for normalization. The phase reversal technique is used to construct PRC indicators on the normalized signals. The critical point between the tight contact stage and the significant loosening stage is identified by PRC, and a suitable monitoring torque is selected for monitoring the pretightening state of bolt loosening in TCS. The seven nonlinear damage indexes (PRC, \(PB_{\text{max}}\), \(PB_{\text{sum}}\), \(PB_{\text{mse}}\), \(PE_{\text{svd}}\), \(PE_{\text{psd}}\), \(PE_{\text{e}}\)) are then extracted based on the phase reversal technique, and the CCF model is established by fusing the seven damage indexes. The accuracy of quantitative monitoring for early bolt loosening is improved by quantifying the bolt pretightening state with multidimensional nonlinear feature information, and experiments are designed to verify the accuracy of the quantitative monitoring model.
2.2. Nonlinear damage index extraction

2.2.1. Phase reversal

The bolt head and the surface of the connection structure are microscopically rough, and the preload force for early bolt loosening is always high. The contact area of the bolt connection does not change significantly, resulting in linear energy indicators that are insensitive to early bolt loosening. Changes in the contact part of the bolt in TCS cause several mechanical phenomena that lead to nonlinear effects, so the nonlinear Lamb wave, which is sensitive to minor damage, is used to monitor the pretightening state of the bolt for early loosening. A schematic diagram of bolt loosening monitoring based on phase reversal is shown in Fig. 2. Lamb waves interact with nonlinear effects to produce higher harmonics as they propagate through the bolted structure [21]. The frequency domain of the fundamental signals collected by the active sensing method has a second harmonic amplitude that is too small, and the errors in the extraction of the damage indexes are too large. Phase reversal technology increases the nonlinear effects when passing through the bolted nonlinear and uncertainty region, which can significantly reduce the calculation errors of nonlinear damage indexes.

The theoretical derivation of the second harmonic generated by the nonlinear effect is shown in Eq. 1.
\[ u(x,t) = A_1 \sin(kx - \omega t) - \frac{\beta k^2 x A_1^2}{8} \cos[2(kx - \omega t)] + \cdots \]
\[ = A_1 \sin(kx - \omega t) + A_2 \cos[2(kx - \omega t)] + \cdots \] \hspace{1cm} (1)

The expression for the relative nonlinear coefficient \( \beta' \) is given in Eq. 2 [22].

\[ \beta' = \frac{8A_2}{A_1^2} \] \hspace{1cm} (2)

Compared to the fundamental wave, the amplitude of the second harmonic is extremely low and difficult to measure. The calculation is minor. It is difficult to accurately characterize the nonlinearity of the bolted structure with large errors. Therefore, in this paper, a Lamb wave phase reversal method for exciting the inverted Lamb wave signals is proposed to enhance the amplitude of the second harmonic and reduce the calculation errors of \( \beta' \).

When a sine Lamb wave signal with phase \( \theta \) and another signal with phase \( (\theta + \pi) \) are excited, the following is obtained according to Eq. 1.

\[ u_1(x,t) = A_1 \sin(kx - \omega t + \theta) + A_2 \cos[2(kx - \omega t) + \theta] + \cdots \] \hspace{1cm} (3)
\[ u_2(x,t) = A_1 \sin(kx - \omega t + \pi) + A_2 \cos[2(kx - \omega t) + \theta + \pi] + \cdots \] \hspace{1cm} (4)

When two sine Lamb wave signals with the same amplitude of frequency and phase difference of \( \pi \) are excited synchronously, the following is obtained from Eq. 3 and Eq. 4.

\[ u(x,t) = u_1(x,t) + u_2(x,t) = 2A_2 \cos[2(kx - \omega t) + \theta] + \cdots \] \hspace{1cm} (5)

As seen from Eq. 5, the fundamental and odd harmonics cancel each other, and the even harmonics superimpose on each other to increase twice.

The phase reversal relative nonlinear coefficient (PRC) is recreated from \( \beta' \), as shown in Eq. 6.

\[ PRC = \frac{8A_p}{A_{ave}^2} \] \hspace{1cm} (6)

where \( A_p \) is the second harmonic amplitude of the phase reversal superposed signal and \( A_{ave} \) is the average amplitude of the two fundamental signals in Eq. 2.

In this paper, the Lamb wave signal with phase difference \( \pi \) cannot be excited simultaneously due to the limitation of the test conditions. The two signals are acquired separately and superposed using MATLAB.

2.2.2. Bispectral analysis

Bispectral analysis is a cutting-edge research direction in frequency-domain signal processing that can effectively analyze the nonlinear system information of non-Gaussian signals. The phase information is retained while reflecting the signal energy. It can be used to measure the nonlinear characteristics of Lamb wave signals [23]. The bispectrum of a deterministic signal \( x(t) \) is defined in Eq. 7 [24].

\[ B(\omega_m, \omega_n) = X(\omega_m)X(\omega_n)X^*(\omega_m + \omega_n) \] \hspace{1cm} (7)

where \( X(\omega_m) \) is the Fourier transform of the signal \( x(t) \) and \( X^*(\omega_m + \omega_n) \).
Here, * represents the complex conjugate operation.

Bispectral analysis of phase reversal signals is performed in this paper. Since the bispectral analysis of phase reversal signals is complex-valued, the nonlinear characteristics of phase reversal signals cannot be quantified directly. Therefore, the bispectrum of phase reversal signals is projected onto a one-dimensional frequency space by taking diagonal slices to remove the redundant information. The computational effort of bispectral diagonal slicing is still large. Therefore, secondary feature extraction is carried out to obtain the maximum value of bispectral slices \(PB_{\text{max}}\), the summation value of bispectral slices \(PB_{\text{sum}}\) and the mean squared error of bispectral slices \(PB_{\text{mse}}\).

2.2.3 Information entropy

The information entropy approach is very sensitive to nonlinear dynamical features. In the field of SHM, the complexity of nonlinear systems is quantified by extracting the entropy value of Lamb wave signals [25][26]. The phase reversal singular spectral entropy \(PE_{\text{svd}}\), phase reversal power spectral entropy \(PE_{\text{psd}}\) and phase reversal energy entropy \(PE_e\) are proposed to quantify the nonlinear characteristics of the bolted structure.

\(PE_{\text{svd}}\) is the singular spectrum analysis of the phase reversal signal and calculates the information entropy of the singular value spectrum, thereby quantitatively describing the complex state characteristics of the time series [26].

\(PE_{\text{psd}}\) is used to quantitatively describe the energy distribution of the phase reversal signal in the frequency domain space [27].

\(PE_e\) is the EMD decomposition of the phase reversal signal to obtain n IMFs, and the corresponding energies \(E_1, E_2, E_3, \cdots, E_n\) are calculated [28]. \(PE_e\) is calculated according to Eqs. 8 and 9.

\[
P_j = E_j / \sum_{j=1}^{n} E_j
\]

\[
PH_e = -\sum_{j=1}^{n} p_j \log p_j
\]

2.3. Canonical correlation forests

To solve the problem of nonlinearity in the quantitative monitoring of the pretightening state of bolts for early loosening, multidimensional time-frequency domain damage indexes are fused by canonical correlation forests (CCFs) to build a quantitative monitoring model. The structure diagram of CCF is shown in Fig. 3. CCF is a new decision tree integration method for predictive classification. The CCF algorithm establishes the projection mapping space where the output information is maximally correlated with the input features based on canonical correlation analysis (CCA) and bagging during the training process. Its maximum gain segmentation is calculated, which makes CCF more rounded and accurate when performing hyperplane segmentation. CCF does not require parameter selection for engineering applications.
3. Experimental validation

3.1. Experimental setup

5083Al is widely used in ships, aircraft and high-speed trains because of its excellent corrosion resistance and cold workability. Two pieces of 5083 aluminum plates are selected as bolted connectors. The mechanical properties are shown in Table 1. Six groups of identical M16 bolts and nuts are prepared to collect the Lamb signal with a tightening torque of 100 N·m. PZT is attached to the surface of the aluminum plate to excite and sense Lamb wave signals. Its parameters are shown in Table 2. Most of the current research divides the joint into upper and lower plates, and the ultrasonic signal is excited from the upper plate PZT through the bolts sensed by the lower plate PZT[16][17]. Bolted connections in engineering applications are almost always directly superimposed on the upper and lower plates, so this paper designs the specimens according to the actual application. The specimen model is shown in Fig. 4. Two sets of PZT sensors are arranged on both sides of the upper plate bolts. These sensors are called PZT1, PZT2, PZT3 and PZT4 for convenience, where PZT1 excites the PZT2 sensing signal for the experimental group and PZT3 excites the PZT4 sensing signal for the control group. The SHM system (Nanjing Smart Monitoring Technology Co., Ltd.) is used to connect the PZT and excite the signal with a maximum sampling frequency of 60 MHz and a resolution of 12 bits. The experimental setup is shown in Fig. 5.

Table 1: Mechanical properties of the aluminum plates

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL5083</td>
<td>2800</td>
<td>70.3</td>
<td>0.33</td>
<td>500×500×2</td>
</tr>
</tbody>
</table>

Table 2: Parameters of PZT

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
</table>
Due to the dispersion and multimodal characteristics of Lamb waves, the higher the frequency is, the more complex the modes are. The nonlinear features are difficult to extract [30]. To avoid modal mixing, the plate is limited to a lower frequency thick product, and the dispersion curve of the Lamb wave in the plate is shown in Fig. 6. The $S_0$ mode Lamb wave is excited at a low frequency, and the nonlinear higher harmonics caused by minor damage remain in the $S_0$ mode. The $S_0$-$S_0$ modal pair can be a good solution to the above problem [31]. The Lamb wave is excited at the $S_0$ mode of low frequency in the experiment, and the sweep range is 50 kHz - 250 kHz. Two sine signals with a center frequency of 190 kHz, 5 periods, an amplitude of 7 V, an added Hanning window, and a phase difference of $\pi$ are finally selected to excite the specimen.
wave packet and the mode are more distinct. The excitation signal is shown in Fig. 7.

![Fig. 6. Dispersion curve: (a) group velocity dispersion and (b) phase velocity dispersion curves.](image)

3.2 Results and discussion

3.2.1 Critical point identification of TCS

Nonlinear Lamb waves are more sensitive to the initial stage of damage. When the later stages of damage are monitored, there is no monotonically increasing or decreasing linear relationship [19][20] and there is no engineering application. The bolt connection condition is examined in the torque range of the full degradation stage from 10 N·m to 100 N·m by characterizing bolt loosening with the $PRC$. A torque gradient of 10 N·m is set, and the bolt connections are loaded using a constant torque wrench. The test is repeated three times, and the test results are shown in Fig. 8. In the same set of tests, as the bolt connection torque decreases and the bolt loosening increases, $PRC$ gradually increases and peaks at 30 N·m. The $PRC$ decreases at 20 N·m and 10 N·m, which are close to the fully loosened state. The nonlinear Lamb wave fails to monitor the bolt as it approaches complete loosening. The $PRC$ is not linearly correlated with the bolt pretightening state over the full degradation stage. Therefore, it is difficult to monitor both the tight contact stage and the significant loosening stage of the bolt using a single monitoring model, which is needed to determine the critical point between the tight contact stage and the significant loosening stage.
This method mainly applies the nonlinear Lamb wave to identify the critical point of the TCS and quantitatively monitor the pretightening state of bolt loosening. Determining the critical point of the TCS according to the PRC is required in the full degradation stage to reasonably select the bolt early loosening monitoring torque. The torque range of the TCS judged by the PRC ranges from 30 N·m to 100 N·m. To set a certain threshold, the bolt torque range for monitoring early loosening is set from 50 N·m to 100 N·m. The torque gradient is 5N·m with 11 bolt connection states since 5N·m is a relatively small torque gradient for M16 bolts. The same six sets of bolted connections are loaded 10 times using a constant torque wrench. PZT 1 and 2 are used to sense 660 (6×10×11) sets of Lamb wave signals and extract their damage indexes to establish the dataset, as shown in Table 3. Here, 495 sets of data are used to establish the quantitative bolt loosening monitoring model and 165 sets of data are used for testing. PZT 3 and 4 sense 165 sets of signals that are used to verify the accuracy of the developed model.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Number of cases</th>
<th>Total of training data</th>
<th>Total of testing data</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT 1-2</td>
<td>11</td>
<td>495</td>
<td>165</td>
</tr>
<tr>
<td>PZT 3-4</td>
<td>11</td>
<td>0</td>
<td>165</td>
</tr>
</tbody>
</table>

3.2.2 Comparison of linear and nonlinear damage indexes

Following the test procedure in section 3.2.1, two types of time domain signals can be obtained for the eleven torque states. The time-domain diagram of the signal in the partial torque state is shown in Fig. 9. The phase reversal signals are obtained by superimposing the two signals after normalizing the time domain signal. It can be seen from the enlarged view of the time-domain diagram that the fundamental amplitude is mostly canceled after the superposition of the two fundamental signals. The superimposed phase reversal signal resembles a sine waveform, and the period is roughly one-half of the fundamental signals.
Fig. 9. Time domain signals under different torque gradients: (a) 50 N·m condition; (b) 50 N·m S0 wave packet enlarged view; (c) 75 N·m condition; and (d) 100 N·m condition.

The S0 wave packets of fundamental signals and the phase reversal signal are truncated. The FFT is performed, and the corresponding spectra are plotted in Fig. 10 and Fig. 11. In the frequency-domain diagram, the fundamental frequency is approximately 190 kHz. Because the fundamental amplitude is too large, the second harmonic amplitude is masked, making it difficult to extract the second harmonic for characterizing bolt loosening. The frequency-domain characteristics of the fundamental amplitude and second harmonic amplitude are not linearly related to the magnitude of the bolt torque. After the signal processing of phase reversal, the amplitude is mostly canceled at approximately 190 kHz. The amplitude of the second harmonic is significantly higher, and its frequency is twice as high as the frequency of fundamental signals. Through the time-frequency domain analysis of the fundamental signals and the phase reversal signals, the phase reversal technology increases nonlinear effects when passing through the bolted nonlinear and uncertainty region and has a significant effect on extracting the nonlinear Lamb wave damage indexes.
The time-domain plots of the signals at different torque states do not show significant differences. Three linear characteristic values, namely, the normalized amplitude, correlation coefficient and phase displacement, are extracted to reflect the change in the signal waveform. The trends of the three randomly selected datasets with torque are shown in Fig. 12. The three linear characteristic values do not show any significant trend with bolt loosening in TCS. The large variation between different sets of data is caused by the nonlinearity of bolt degradation, which makes quantitative monitoring of bolt loosening difficult in TCS.

The acquired fundamental signals are processed by phase reversal. The $S_0$ wave packet of the fundamental signals and the phase reversal signals are intercepted. The average value of the two fundamental wave amplitudes and the second harmonic amplitude of the phase reversal signals are taken to calculate the $PRC$. The $S_0$ wave packet of phase reversal signals is intercepted to calculate $PB_{max}$, $PB_{sum}$, $PB_{mse}$, $PE_{svd}$, $PE_{psd}$ and $PE_c$. The damage indexes in the TCS obtained by three sets of tests were randomly selected, and the trends are shown in Fig. 13. The nonlinear damage indexes exhibit a good linear trend with decreasing bolt torque.
Fig. 12. Linear damage index trend diagram in TCS: (a) normalized amplitude; (b) correlation coefficient; and (c) phase displacement.

Fig. 13. Nonlinear damage index trend diagram in the TCS: (a) PRC; (b) $PB_{\text{max}}$; (C) $PB_{\text{sum}}$; (d) $PB_{\text{mse}}$; (e) $PE_{\text{psd}}$; (f) $PE_e$; and (g) $PE_{\text{svd}}$.

PRC represents the degree of nonlinearity of the signal in the first-order frequency domain space. $PB_{\text{max}}$, $PB_{\text{sum}}$ and $PB_{\text{mse}}$ represent the degree of nonlinearity in the second-order frequency domain space. Their trends should be consistent. With the
loosening of the bolt, the nonlinearity increases gradually, and the damage indexes increase gradually. $PE_{psd}$ represents the uncertainty of the signal in the frequency domain space. When the power spectrum is concentrated in part of the frequency components, the corresponding frequency spectrum lines is less, and $PE_{psd}$ becomes smaller. $PE_e$ is the sum of the energies of each IMF component. With the bolt loosening gradually, the amplitude of the second harmonic becomes larger. The frequency components of the power spectrum become more concentrated, and $PE_{psd}$ decreases. The energy of the signal passing through the bolted connection is smaller, and $PE_e$ decreases. However, $PE_{svd}$ has no specific physical meaning because of its weak interpretability. Compared with the linear damage indexes, the nonlinear indexes constructed in this paper possess good results in characterizing the pretightening state of bolt loosening in the TCS.

3.3.3 Monitoring model validation

The dataset is fed into the CCF model for training and testing. To facilitate engineering applications, the parameters of CCF are taken as default values in this paper. One hundred CCTs are set to train the model, and the final classification is determined by the voting results of the CCTs. Fig. 14 shows the confusion matrix for the classification results of the PZT1 and 2 test data and the validation results of the PZT3 and 4 test data. The classification results of the quantitative monitoring model possessed an accuracy of 95.15%, and the validation results of the test sets established by PZT3 and PZT4 possessed an accuracy of 94.54%. The quantitative monitoring model of the pretightening state for bolt loosening in TCS has an excellent monitoring effect.

To verify the effectiveness of the quantitative bolt loosening monitoring model, three nonlinear damage indexes proposed in this paper are selected: $PRC$, $PB_{max}$ and $PB_{sum}$. A dataset is create from the signals sensed by PZT1 and 2 and input it to a CCF model for validation. Three of the above traditional linear damage indexes are selected, and the dataset is built in the same way as above to validate the model developed in this paper. The results are shown in Table 4. The accuracy of the quantitative bolt loosening monitoring model in the TCS established with multidimensional nonlinear damage indexes is 95.15%, the accuracy of the model established with three-dimensional nonlinear damage indexes is 89.09%, and the accuracy of the model established with conventional three-dimensional linear damage indexes is 78.18%.

During the loosening monitoring of bolts, nonlinear damage indexes have a better quantitative monitoring effect than linear damage indexes. The proposed model of TCS identification and quantitative monitoring of the pretightening state for bolt loosening overcomes the disadvantage that linear indicators are insensitive to early loosening with the phase reversal technique, identifies the critical point of TCS with $PRC$, and achieves quantitative monitoring of bolt loosening with fused multidimensional nonlinear damage indexes, which has a good monitoring effect and high accuracy rate.

<table>
<thead>
<tr>
<th>Table 4: Classification accuracy among three methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Multidimensional nonlinear damage indexes</td>
</tr>
<tr>
<td>Three-dimensional nonlinear damage indexes</td>
</tr>
<tr>
<td>Three-dimensional linear damage indexes</td>
</tr>
</tbody>
</table>
Fig. 14. Classification results (confusion matrix) of eleven conditions: (a) classification results of PZT1 and 2 test data and (b) validation results of PZT3 and 4 test data.

4. Conclusions

In this paper, a method based on nonlinear Lamb waves to identify the TCS of bolts and quantitatively monitor the pretightening state for bolt loosening in the TCS is proposed. The main conclusions of this paper are described as follows.

a. The phase reversal technique is used to construct the PRC, which overcomes the disadvantage that linear indicators are insensitive to early loosening and reduce computational errors. The identification of the critical point of bolts between the tight contact stage and the significant loosening stage is realized by using PRC, and the monitoring torque of bolt loosening is reasonably selected, which provides the prerequisite for constructing the monitoring model of bolt loosening.

b. Seven nonlinear damage indexes are extracted based on phase reversal technology. A quantitative monitoring model based on CCF fused nonlinear damage indexes is established to monitor the pretightening state of bolt loosening in TCS. Experiments are designed to verify the effectiveness of the proposed method in this paper. The results show that nonlinear damage indexes have a better monitoring effect.
than linear damage indexes in the TCS, and the model has a higher accuracy rate. Quantitative monitoring is achieved only for a single bolt in this study. In the future, the proposed method should be improved to achieve quantitative monitoring of complex multibolt loosening.

References


[27] Z. Hong, Y. Xu, A Novel Weak Signal Detector Based on Power Spectrum Entropy Under Low SNR, 2021 28th International Conference on Telecommunications
(ICT), 2021, pp. 1-6.


**Statements and Declarations**

**Acknowledgements:** This work was supported by the China National Railway Group Limited (Grant number P2021J036), the Natural Science Foundation of Hunan Province China (Grant No. 2021JJ40765), the Young Elite Scientists Sponsorship Program by CAST(Grant number 2020QNRC001).

**Financial interests:** The authors have no relevant financial or non-financial interests to disclose.

**Data availability:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.