Smart Structures and Systems, *Vol. 24, No. 3 (2019) 293-301*
DOI: https://doi.org/10.12989/sss.2019.24.3.293

Detection and location of bolt group looseness using ultrasonic guided wave

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(Received December 21, 2018, Revised May 16, 2019, Accepted June 17, 2019)

Abstract. Bolted joints are commonly used in civil infrastructure and mechanical assembly structures. Monitoring and identifying the connection status of bolts is the frontier problem of structural research. The existing research is mainly on the looseness of a single bolt. This article presents a study of assessing the loosening/tightening health state and identifying the loose bolt by using ultrasonic guided wave in a bolt group joint. A bolt-tightening index was proposed for evaluating the looseness of a bolt connection based on correlation coefficient. The tightening/loosening state of the bolt was simulated by changing the bolt torque. More than 180 different measurement tests for total of six bolts were conducted. The results showed that with the bolt torque increases, value of the proposed bolt-tightening index increases. The proposed bolt-tightening index trend was very well reproduced by an analytical expression using a function of the torque applied with an overall percentage error lower than 5%. The developed damage index based on the proposed bolt-tightening index can also be applied to locate the loosest bolt in a bolt group joint. To verify the effectiveness of the proposed method, a bolt group joint experiment with different positions of bolt looseness was performed. Experimental results show that the proposed approach is effective to detect and locate bolt looseness and has a good prospect of finding applications in real-time structural monitoring.

Keywords: bolt looseness; ultrasonic guided wave; correlation coefficients; structural health monitoring

1. Introduction

Due to the advantages of simple construction, fatigue resistance, detachable connection, high reliability and good integrity, bolt joints are widely used in the structure and equipment of various industries such as civil engineering, mechanical, aviation and etc (Chen and Xu 2012, Kedra and Rucka 2015, Ruan *et al.* 2015). The operation of the entire structure and equipment may be affected by the looseness of the bolt and preload deterioration. Detection and timely maintenance of bolted joints can prevent catastrophic events and to reduce costs. The methods of detecting the health state of bolt used are the torque wrench method, resistance strain gauge measurement method (Ritdumrongkul *et al*. 2003, Gyuhae *et al.* 2003), detection method based on structural modal information (Todd *et al*. 2004) and ultrasonic guided wave method. Detection of torque wrench requires considerable manpower and time. Due to the friction of the bolted connection, it is difficult for the torque wrench to accurately control the pre-tightening force. For resistance strain gauge method, integration of the strain gauge often requires significant hardware modification. Excitation structure by using PZTs can sense impedance information. This method cannot monitor and identify the multi-scale connection state changes of the structure, and requires large-scale signal acquisition and array when applied to complex structures. The vibration characteristics such as frequency and mode are the overall characteristics of the structure, and the looseness of the bolt is a local phenomenon, so the detection method based on such characteristics is not sensitive. Therefore, many studies in this field have attempted to identify the looseness of the bolt from the change in the wave characteristics of the elastic wave through the bolt.

Ultrasonic guided wave is a kind of stress wave, which can interact with different damages in structures by advantages of their high sensitivity to micro-damage and low energy attenuation through long distance, so it has tremendous potential in structural non-destructive evaluation (NDE) (Rose 1999, Lu *et al.* 2010, Wang *et al.* 2018). There are nonlinear factors such as contact, friction and preload in the bolt connection, which complicates the theoretical analysis. Researchers use simple theoretical models and work with experimental data to study this problem. Light *et al*. (1993) applied the cylindrically guided wave technique to detect corrosion wastages and cracks in cylindrical objects. Yang and Chang (2006) compared monitored signals to baselines recorded from the structure prior to initiation of damage, and generated damage image for aluminium plate. The single bolt loosening index and torque proposed by Aymerich and Meili (2000) approximately satisfies the tangent relationship. An and Sohn (2012) combined impedance and elastic wave techniques and analyzed the sensitivity of the single bolt loosening when the temperature changes.

Piezoceramics (PZT), with attractive features such as active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation, have been widely researched in real-time structural monitoring

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

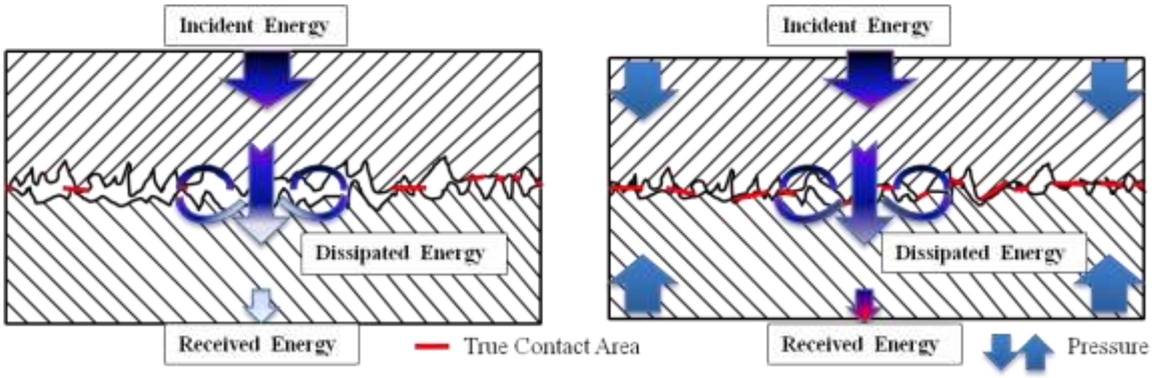


Fig. 1 Energy transmission at the microcontact interface

(Cuc *et al*. 2012). There are studies about structure-embedded sensors (Zumpano and Meo 2006, Zhao *et al*. 2007), whereas other authors preferred to use patches bonded to the surfaces (Wang *et al*. 2007, Quaegebeur *et al*. 2012, Enrique *et al.* 2016). PZT transducers were used for both excitation and registration of ultrasonic waves. With the continuous application of guided waves, scholars have made in-depth research on damage identification from metal plates, cylindrical objects to single bolts and the bolt group joint. At present, there are many studies on the identification of single bolt loosening. Due to complication of the receiving signal of guided wave in the propagation process of the bolt group joint and the difficulties in engineering application, there are a few studies on assessing the loosening/tightening health state of the bolt group nodes.

Scholars have proposed a number of indicators to deal with the bolt signals obtained from the experiments. Comparing the differences between damage signal and the baseline signal is one of the most direct and effective methods, which can estimate the degree of structural damage according to the difference between them. Michaels (2008) studied the difference between the pre-flaw baseline waveforms and post-flaw waveforms by the means of subtracting the damage signal from the baseline signal. A series of characteristics of time domain and frequency domain were analyzed to estimate the structure damage. This method ordinarily doesn't need to establish complex mathematical models. It can be flexibly operated according to different structural types and is suitable for practical engineering.

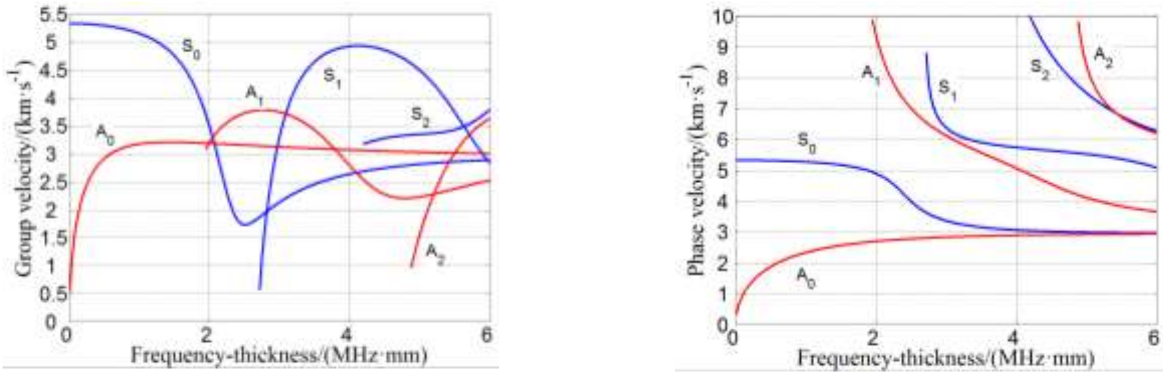
In this study, piezoelectric patches were utilized as transducers to assess the health state of a bolted joint. Various tests were performed by increasing the applied bolt torque to simulate various configurations, i.e., from a full loosened state to a tight configuration. For the ultrasonic method, a tightening/loosening state index based on the correlation coefficient of mathematical statistics was developed. In contrast with the previous studies which used a damage index to estimate bolted status, in this approach the relationship between correlation damage index and the bolt torque is established. The experimental results show that the proposed tightening/loosening state index exponentially increases with the applied bolt torque. The proposed method not only characterizes the degree of bolt looseness, but also the location of the single loose bolt can be determined successfully by applying appropriate sensor array.

2.The proposed method and principle

Differences between wave propagation signals were caused mainly by the changes of the contact area between the plates in the micro and macro scale. On macro level, this effect is caused by the variations of the radius of area around the bolt where two plates interact with each other (Huda *et al.* 2013). In the micro-scale, the surface of any machined object is rough. As a result, when ultrasonic waves propagate across the contact surface at the bolted joints, only part of the ultrasonic wave energy passes through it. The actual contact area is less than the overlapping area on the contact surface and the actual contact area is the protruding part of the two steel plates in this paper. The actual contact area of two plates is related to the applied pressure to them in a certain pressure range according to the Hertzian contact theory (Yang and Chang 2006). The action of fastening a bolted joint can be regarded as imposing higher contact pressure at the imperfect contacts. Therefore, by increasing the fastening torque, the true contact area will increase and the wave will propagate across the interface with less energy loss (Esteban and Rogers 2000). The greater the actual contact area is, the more effective of the signal from one piece of steel to another spread, as illustrated in figure 1.

It has been found through experiments that the magnitude of the transmitted wave energy is reflected in the amplitude of the response signal (Liu *et al*. 2014), and the magnitude of the response signal can be used to determine the corresponding bolt preload. In this paper, the relationship between the looseness index and the bolt torque is found by comparing the difference of the amplitude of the signal under different torques with the baseline signal.

In the field of non-destructive testing, wave propagation phenomena can be used to perform non-destructive evaluation of material properties and to monitor and locate



(a) Group velocity dispersion curves

(b) Phase velocity dispersion curves

Fig. 2 Dispersion curves for Lamb waves in a steel plate

defects in critical structures. The selection of the excitation signal is particularly important for the data analysis of the received signal. The Rayleigh wave is a free wave on a semi-infinite solid surface. The stress on the boundary is zero and decays with the depth of the wave. The Lamb wave is a plane strain wave generated in the free plate, and the stress on the upper and lower surfaces of the plate is zero. Lamb waves are faster and more efficient than longitudinal and transverse waves, which are suitable for non-destructive testing of the thin plates. According to the wave mechanics, the wave equation of the guided wave in the free slab can be expressed as the tensor expression (Lamb 1917)

$$\mu \cdot u_{i,jj} + (\lambda + \mu) \cdot u_{j,ji} + \rho \cdot f_i = \rho \cdot \ddot{u}_i \qquad (i, j = 1, 2, 3) \tag{1}$$

Where u_i is the displacement along the x-axis, f_i is the body force along the x-axis, ρ is the material density, and λ and μ are the Lame constants. The expressions for the Lame constants are as follows (Lamb 1917)

$$\lambda = \frac{2\mu\upsilon}{1-2\upsilon} \qquad \mu = \frac{E}{2(1+\upsilon)} \tag{2}$$

Where E is the Young's modulus and υ is the Poisson's ratio.

Lamb waves are complex in terms of excitation, propagation, reception, and signal processing, all of which are determined by the multimode and dispersion characteristics of the Lamb wave. Lamb wave is divided into symmetric modes (S0, S1, ...) and anti-symmetric modes (A0, A1, ...) according to the distribution of vibration displacement in the plate (Wang and Yuan 2007). Because of the multi-modal phenomenon, even a single Lamb wave mode can generate other modes by interacting with either boundary or crack. Another characteristic of Lamb wave is dispersion, which means the wave velocity will change with the frequency and the propagation distance. Mode transitions can occur when a defect or end face is encountered. These all make Lamb wave signal analysis complicated. In order to effectively apply Lamb waves in non-destructive testing, the detection scheme is usually determined based on the dispersion characteristics of Lamb waves (expressions below) (Rose 1999).

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{\left(q^2-k^2\right)^2} \quad \text{(Symmetric mode)} \tag{3}$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{\left(q^2-k^2\right)^2}{4k^2pq} \quad \text{(Antisymmetric mode)} \tag{4}$$

where $p^2 = \frac{\omega^2}{c_L{}^2} - k^2$, $q^2 = \frac{\omega^2}{c_T{}^2} - k^2$, $k = f/c$ is the wave number, f is the frequency, c is the wave velocity.

The above Rayleigh-Lamb equation is numerically solved by programming in MATLAB. The velocity of Lamb waves is dependent not only on the material but also on the product of plate thickness and the excitation frequency. The dispersion characteristics of the Lamb wave are reflected by a series of curves, as shown in Figs. 2(a) and 2(b). The diagram shows that many wave components with different group velocities exist at the high frequency range. Because the wave velocities are different in different frequency-thickness products, After a period of wave propagation, the phenomenon of wave packet diffusion will occur, which will lead to the superposition of wave packets, reflected waves and direct waves. If a structure is excited by a broadband pulse, many wave components with different frequencies will travel at different speeds and the pulse shape will change as it propagates along the plate. This brings difficulties to feature extraction of guided waves. So, attempts have been made to limit the bandwidth of the excitation to a low frequency range over which there exist only two fundamental modes (A0 or S0). The excitation signal selected according to the dispersion curve is shown in Fig. 5. A propagating wave is reflected and/or partially transmitted, when it encounters a defect or boundary. Then the measured loose signal may be compared with the non-damage signal, and damage detection can be carried out based on based on comparison of the resulting signals transmitted by the wave on the rough surface.

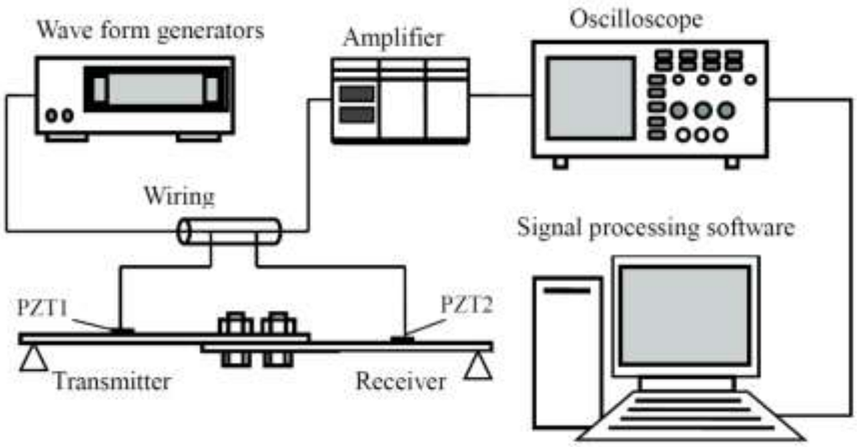
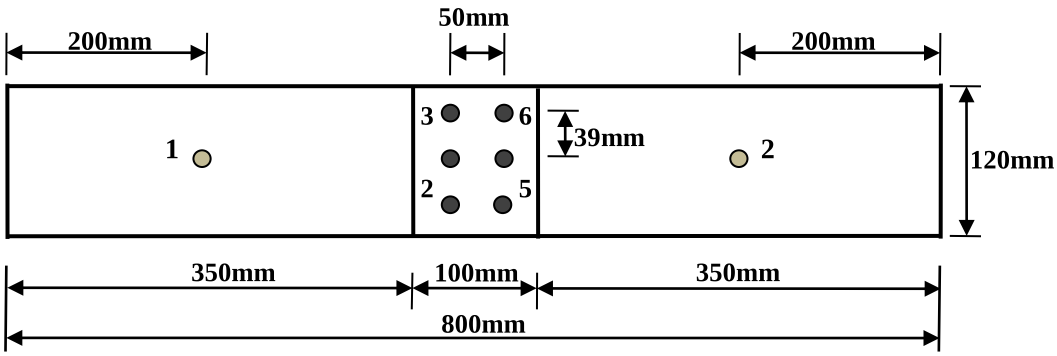
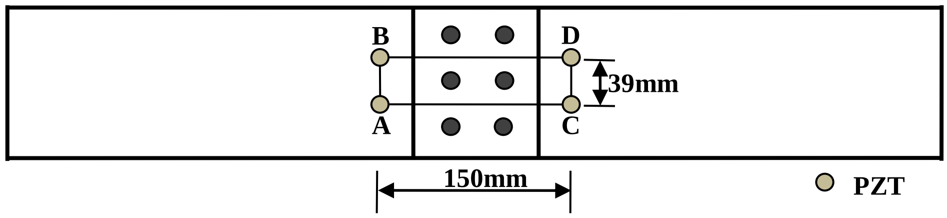


Fig. 3 Scheme of the experimental system used for the experiments



(a) Bolt looseness detection



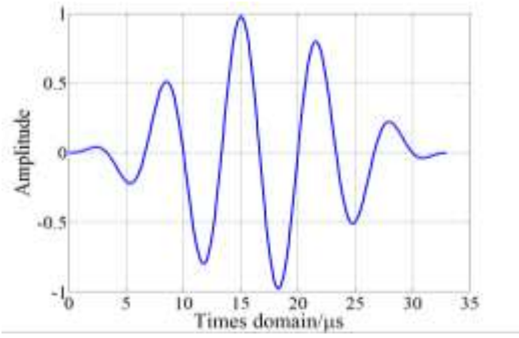
(b) Bolt looseness location

Fig. 4 Experimental Configuration

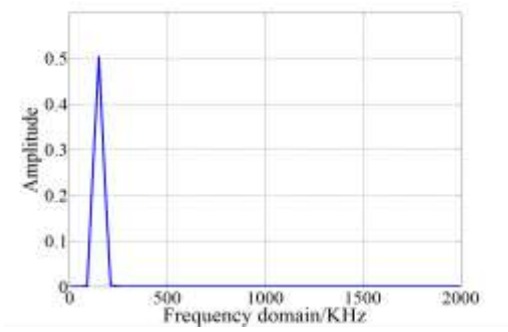
3. The experimental setup and process

In experiment, actuators were placed on one side of the joint and the sensors on the other side. The power amplifier can strengthen the signal-to-noise ratio. The modulation signal was transmitted from the function generator, which can give a certain voltage value to the signal. The electrical signal was transformed into mechanical vibration signal by the positive piezoelectric effect of PZT. This layout allows the wave to propagate through the bolt group joint, carrying information to the sensor about the health state of the connection itself. Finally, the signal was sampled by the oscilloscope after translated into electrical signals by the inverse piezoelectric effect of the sensing PZT. Waveforms were digitized with a sampling rate of 5 MHz and averaged over 25 waveforms to minimize the impact of noise. The experimental arrangement is shown schematically in Fig. 3.

Two rectangle steel plates with the size of 450 mm×120 mm×4.5 mm were connected together bysix M8.8 bolts with diameter of 14mm with washers and nuts and the size of connection area is 100 mm×120 mm×9 mm. The piezoelectric ceramic chip with the thickness of 2mm and diameter of 16 mm was selected as the sensor. The experiments in this study have 2 objectives: (1) to assess the loosening/tightening health state of a bolted structure, and (2) to locate the position of the loose bolt using four PZTs.

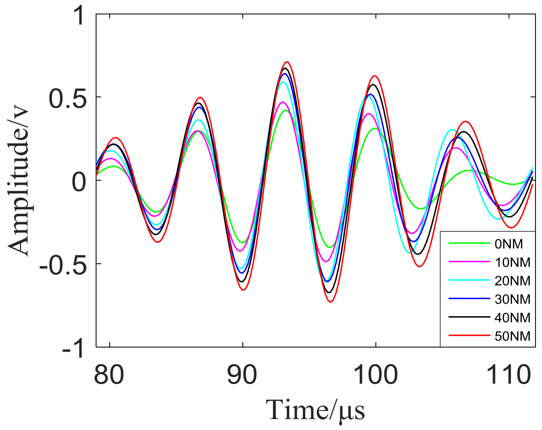


(a) Time domain

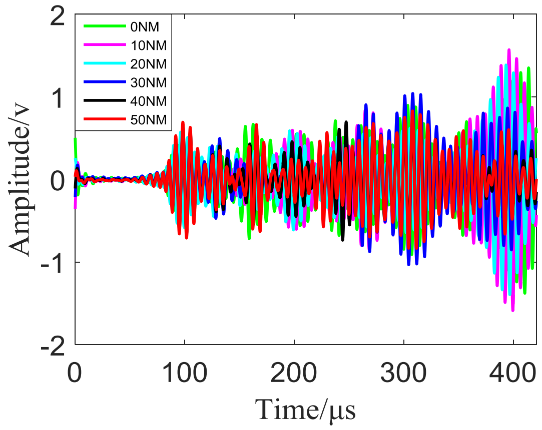


(b) Frequency domain

Fig. 5 Time and frequency domain of the excitation signal



(a) The enlarge diagram of head wave



(b) Sampled signal of different conditions

Fig. 6 The sampled signal and the detail diagram of head wave

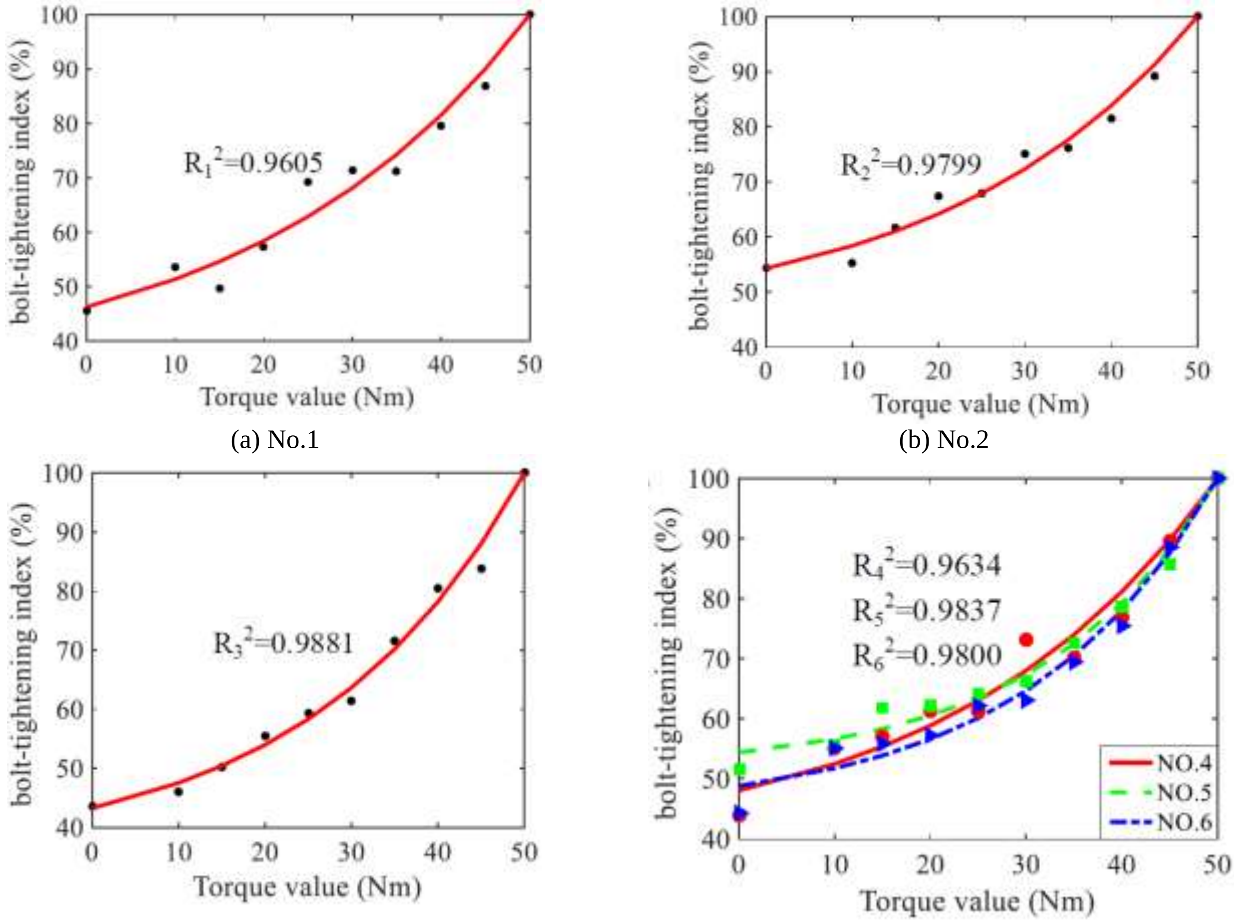
The layout of the sensors for detection and location experiments is shown in Fig. 4. Specific experimental details will be described in the corresponding analysis.

For bolt looseness detection in the bolt joints with Lamb wave, the result obtained is very sensitive to the excitation frequency and the cycle of the incident signal. The parameters of the excitation signal need to be tested to select the optimal excitation frequency and period. Considering the thickness of the steel plate is 4.5 mm, so the middle connecting part's thickness is 9 mm in present study, 150 KHz was selected as excitation frequency. An appropriate window function can minimize the effect of the dispersion and facilitate the collection of signals. A Hanning-windowed sinusoidal tone-burst with 5 cycles at center frequency of 150 KHz was used as excitation signal as shown in Figs. 5(a) and 5(b).

4. The experimental results and analysis

4.1 Bolt looseness detection

The change of applied torque to the bolts was chosen as the key variable to evaluate the influence of the damage degree to the signal. The torque of No.1 bolt changes from 0 Nm to 50 Nm with the interval torque 5 Nm. During experiment, a digital torque wrench was used to set the other bolts to a fixed torque of 50 Nm. The waveforms are compared in Figs. 6(a) and 6(b). The influence of different torque on bolts is shown from the enlarged diagram of head wave (S0 mode). The increase of the true contact surface reduces the dissipation of energy at the interface between the connected plates. With the increase the fastening torque, the energy of the head wave will increases. The transmitted wave energy is reflected in the amplitude of the response signal, so the peak of the head wave also increases. Less influence on variability of registered waveforms has the stress and tension state due to bolt tightening process. The rise of amplitude and energy values is due to the decreased attenuation as the bolt load is increased. Fig. 6(b) is a comparison of time domain signals for the entire signal collected. Compared to fully fastened bolt, the superposition and dispersion phenomenon of the loosened configuration is more serious. This regularly changing wave packet appears not only in the head wave but also in each of the opposing wave packets. After the head wave, the wave of A0 mode arrives, the dispersion and superposition of the waves occur. Therefore, the higher degree of loosening , the more severe superposition of the received signal, and the larger envelope of the obtained amplitude curve. The small difference in the head wave is not conducive to analysis for bolt-tightening index. However, the received signals of the



(a) No.1 (b) No.2

(c) No.3 (d) No.4, No.5 and No.6

Fig. 7 *DIcc* results vs torque, for the six kinds of loosened configurations

whole band obtained under different torques have great differences. Therefore, the correlation of the damage signals can be used to achieve the detection of loose bolts.

The correlation coefficient between the baseline signal and the damage signal is an effective bolt-tightening index, which does not depend on the transformation of the local signal amplitude and only depend on the waveform of the whole signal. Due to the complexity of joint damage of the bolts, the general bolt-tightening index is often difficult to apply. The correlation coefficient was developed as the bolt-tightening index. The correlation coefficient of the baseline condition and signals get from the bolts at different torques can be used to describe the difference of the signals. The DI_{CC} between the damage and the baseline signal reflect the damage degree of the structure. The DI_{CC} of two waveforms can be expressed as follow

$$DI_{CC} = \frac{C_{BD}}{\sigma_B \sigma_D} \times 100\% \tag{5}$$

where C_{BD} is the covariance of two waveforms

$$C_{BD} = \sum_{k=1}^{N} \left(B_k - \mu_B\right)\left(D_k - \mu_D\right) \tag{6}$$

Where μ is the mean of the sampled signal and N is the length of the date. For the above formula, B denotes the baseline signal and D denotes the different conditions of the damage signal; σ_B and σ_D denote the standard deviations of the two signals respectively, as shown by Eq. (7) below

$$\sigma_B \sigma_D = \sqrt{\sum_{k=1}^{N} \left(B_k - \mu_B\right)^2} \sqrt{\sum_{k=1}^{N} \left(D_k - \mu_D\right)^2} \tag{7}$$

In order to understand the overall tendency of the DI_{CC} at different health states, 10 different torque configurations of six bolts were tested. Torque changes in one of the 6 bolts, while the other bolts remain tight. This procedure was repeated for several different torque values. For each torque value, three measurements were made, and the mean value was used for the calculation of DI_{CC}. More than 180 different measurement tests for total of six bolts were conducted. Figs. 7(a)-7(d) shows the bolt-tightening index DI_{CC} under different bolt torque value from 0 to 50 Nm in six kinds of loosened configurations experiments. It is evident that the bolt-tightening index DI_{CC}, which can be considered that 100% indicates that the bolt is in a state of no damage, increases as the bolt torque increases. By comparison, when the bolt changes from tight to loose, the DI_{CC} value of the No. 2 loosened configuration is slower

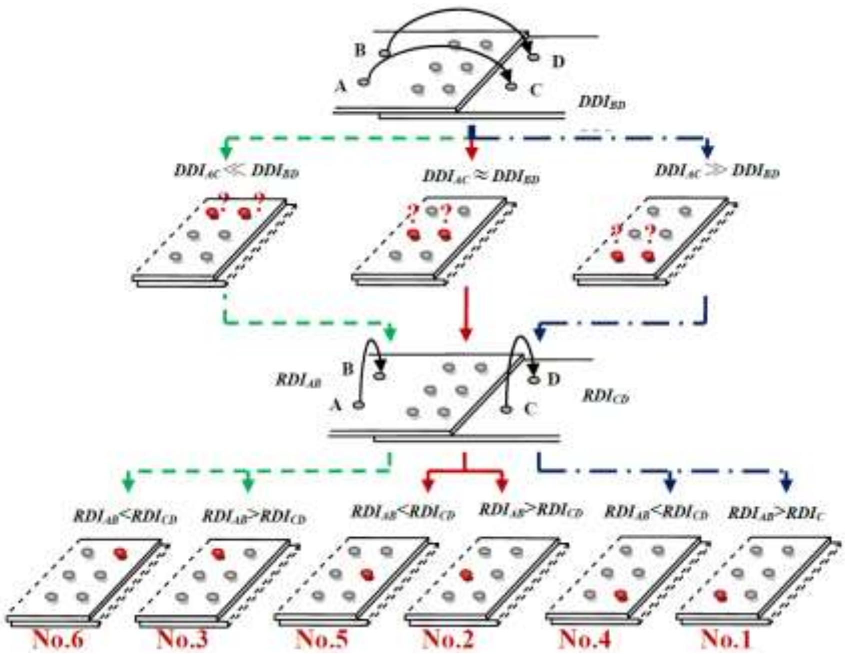


Fig. 8 Flow diagram of the bolt looseness location

Table 1 Result of bolt-locating index

Sensing path	No.1	No.5
A--B	0.0632	0.0109
C--D	0.0305	0.0355
A--C	0.5870	0.3211
B--D	0.2141	0.3025

than that of No. 1 and No. 3, and No.5 is slower than No.4 and No.6. The analysis shows that the sensitivity of the DI_{CC} value is related to the angle between the two piezoelectric ceramics and the loosened bolt. The increase of the angle will make the superposition and dispersion phenomenon of waves more serious, and also make the difference between the detection signal and the baseline signal more obvious. The results highlighted that the DI_{CC} index is highly sensitive to the bolt-tightening state, providing a reliable and promising index able to assess the health state of bolted joints.

Fig. 7 shows how the DI_{CC} Trend value changes, by increasing the torque applied at the joint. The graphs highlight, in all cases, that the trend is well approximated by an exponential function

$$DI_{CC} = (1-\xi)e^{a(T-T_{\max})} + \xi \tag{8}$$

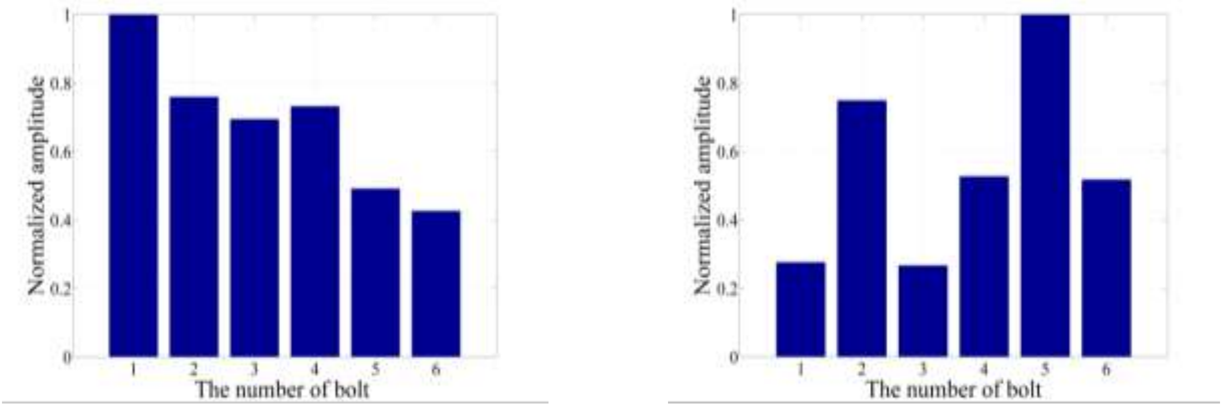
This equation is a fitting curve where the parameters in the equation have been extrapolated by a careful study of the experimental results. Where T is the bolt torque, T_{max} the maximum torque bolt , ξ the index value which related to the angle between the loose bolt and the Piezoceramics , and α is a factor proportional to the slope of the curve. As shown in Fig. 7, the accuracy of the exponential function, with respect to the experimental results, is higher than 95%. This means that the correlation coefficient method, based on the calculation of the DI_{CC}, provides a reliable and thoroughly sensitive index in detecting the health state of bolted structures.

4.2 Bolt looseness location

The developed bolt-tightening index is highly sensitive to the looseness of a single bolt through the above analysis. The bolt-tightening index can be used as the bolt-locating index. The bolt-locating index can be expressed as

$$DI = 1 - DI_{CC} \tag{9}$$

DI represents the degree of damage reflected on the corresponding path. Four paths in this experiment are used to locate the loose bolt. For single loose bolt analysis, the loose bolt torque is set to 0NM and the other bolts torque are set to 50NM. The sensor array is arranged as shown in Fig. 4. The bolt-locating factor calculated by the A--B path mainly reflects the looseness information of the bolts No.1, 2 and 3, and C--D path reflects the bolts No.4, 5 and 6; the bolt-locating factor calculated by the A--C path reflects the looseness information of the bolts No.1,2,4,5, and B--D path reflects the bolts No.2,3,5,6. It can be seen from the



(a) No.1 (b) No.5

Fig. 9 The result of localization based on bolt-locating index

sensor array that signal obtained from the A--B path and C--D path does not pass through the bolt joints. The looseness information is mainly provided by the reflected wave received by the sensor, and this bolt-locating factor is defined as the reflection bolt-locating factor *RDI*. The signal obtained from A--C path passes through the bolt joints, and the damage information acts directly on the bolt-locating factor, so defining such damage as a direct bolt-locating factor *DDI*. The high sensitivity of the developed bolt-tightening index allows the bolt positioning to be achieved by the above four paths. Position the row and column where the damage bolt is located by comparing the value of *DDI* and *RDI*. The positioning process of the bolt is shown in Fig. 8.

Through the process described above, the bolt group joint was subjected to a positioning experiment of the loose bolt. The results obtained prove that the proposed positioning method can well locate the single looseness bolt. The results from bolt-locating index of No.1 and No.5 are shown in Table 1.

Mathematical methods are used to more intuitively locate loose bolts. The value of the reflection damage index is much smaller than the value of the direct damage index we can see directly from Table 1. In order to facilitate the damage location processing, we amplify the *RDI* to the same order of magnitude as the *DDI* firstly.

$$DDI_l \le nRDI_l \le DDI_l + RDI_l \tag{10}$$

where DDI_l and RDI_l are the larger of the *DDI* and *RDI*, and n is the integer which can determine by the calculation. Then the smaller RDI was amplified by the calculated integer *n*. According to the size of two *DDI* to decide how to carry out the allocation of the damage index to the different bolt, and finally determine the position of damage bolt. Each bolt damage index is superimposed by the following equation

$$DI = RDI + \alpha DDI_b + \beta DDI_s \tag{11}$$

where *RDI* is the reflection bolt-locating factor close to the sensing path，DDI_b and DDI_s are the larger and smaller values of the direct bolt-locating factor. α, β are weight coefficients can determine by follow

$$\frac{DDI_b}{DDI_s} = \eta \tag{12}$$

η as a threshold value, the corresponding empirical value is obtained from many experiments. According to this experiment, 2 is used as a threshold for bolt positioning. If the $\eta < 2$, the value of α, β are 0.5 for the middle bolts and for the edge bolts are taken separately 0.5 and 0 based on the influence of the sensing path. If the $\eta > 2$, the value of α, β are 0.5 for the middle bolts and for the edge bolts are taken separately and 1and 0 are based on the influence of the sensing path.

For the loosening of bolts No1 and No.5, the result of localization based on bolt-locating index are shown in Figs. 9(a) and 9(b). It can be seen from the positioning results that the proposed algorithm can be highlight for the single bolt loosening. The damage position can be directly determined by setting the threshold，and more experiments need to be done in order to increase the accuracy of the threshold. The positioning effect of the middle bolt is better than that of the edge bolt. The experimental results validate the reliability and practicality of the proposed looseness index. It is clear that the developed correlation coefficient index can effectively reflect the bolt looseness and locate the single loose bolt.

5. Conclusions

In this study, new indices were developed to assess and locate the loosening/tightening health state of a bolted structure by using the ultrasonic method. The correlation coefficient index provided results to be able to assess the health state of a bolted joint with an overall percentage error lower than 5%. It was observed that the index trend as a function of the applied torque was well approximated by a exponential function. This means that the calculation of the bolt-tightening index, provides a reliable and thoroughly sensitive index in detecting the health state of bolted structures. The single damage bolt was located paths through a further developed bolt-locating index by using four PZTs. The proposed method of using a small number of active piezoelectric actuator/sensors to quickly and conveniently obtain the health state of the bolt group joint by calculating the correlation index has potential applications for non-destructive structural monitoring. Detection of multiple bolt damages is another issue worthy of investigation. The use of Lamb waves seems more viable than other tools for its exclusive responses to different damage status, so intensive investigation and improvement are also matters for further research.

Acknowledgments

The authors are grateful for the financial support from the National Key Research and Development Program of China (Project No. 2017YFC0703410), and National Natural Science Foundation of China (NSFC) under Grant Nos. 51478079, 51778104.

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