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Technical Note

Quantitative evaluation of bolt connection using a single piezoceramic transducer and ultrasonic coda wave energy with the consideration of the piezoceramic aging effect

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Abstract

In this paper, a method to quantitatively evaluate the status of bolted connection by using a single piezoceramic transducer and coda wave is proposed. The so-called coda wave was inherited from the seismological community to name the late part of a seismogram. Coda wave is a slowly decaying wave after being scattered multiple times due to medium heterogeneities or boundaries, and it is extremely sensitivity to small changes and highly repeatable. The bolt connection is good application of coda wave since the presence of the microscopically rough surfaces and the boundary along the bolt interface generate scattering events. Stress wave generated by a Lead Zirconate Titanate (PZT) transducer is often used to evaluate the status of bolted connection. However, with the aging of a PZT transducer, the amplitude of the excitation signal decreases, and the signal energy does not correctly reflect the real status of the bolt connection. In this paper, a single PZT transducer, acting as both an actuator and a sensor, is used to transmit and receive stress wave signal. The stress wave signal received by PZT sensor consists of two parts, one is the direct wave whose amplitude is related to the excitation signal, and the other part is the backscatter wave (coda wave) produced by microscopically rough surfaces and the boundary along the interface of a bolt connection. Coda wave amplitude is affected by both heterogeneity of microscopically rough surfaces and PZT performance. To eliminate the effects of PZT aging, coda wave is normalized through the amplitude of the direct wave, and the magnitude of coda wave energy (CWE) only reflects the change of connection states. The main innovation of this paper is to establish the quantitative relationship between the bolt connection status and the CWE with a single PZT transducer. An experiment on the

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evaluation of the bolt connection status was carried out in this research. The results indicate that quantitative evaluation on the bolt-connected structure can be achieved through CWE, thus verifying the proposed method.

Keywords: coda wave, coda wave energy (CWE), bolted connection, piezoceramic transducer, lead zirconate titanate (PZT)

(Some figures may appear in colour only in the online journal)

1. Introduction

Bolt connection is a typical mechanical coupling method [1], and it is widely applied in many industrial fields such as mechanical engineering, aerospace engineering and civil engineering [2]. The bolt connection state (i.e. tightness degree), as indicated by the fastening force/axial pre-tightening force, is directly related to the reliability and safety of the entire structure or system [3, 4]. Structures are often subjected to environmental factors and dynamic loadings [5–7], and these loadings are often transferred to the bolts and may gradually lose the bolted connections [8]. Therefore, to carry out the health monitoring of bolted connection it is vital to ensure structure safety. Direct measurement of axial pre-stress of every single bolt is almost impossible due to the high cost of a load cell [3, 5]. In practical application, the connection status of bolt is obtained mostly by methods of indirect measurement or monitoring, such as the acoustoelastic effect based method, the piezoelectric active sensing method, and the piezoelectric impedance method [6].

直接放抗压元件太贵

The detection principle of the method based on acoustoelastic effect is that the velocity of the ultrasonic wave propagated along the bolt changes with its axial stress. This method is to estimate the bolt axial pre-stress by measuring the time-of-flight (TOF), the velocity ratio, and the mechanical resonant frequency shift. Jhang *et al* [6] adopt a method to improve the accuracy of the TOF measurement by using the phase detection technique. Johnson *et al* [8] proposed an ultrasonic velocity ratio method for measuring bolt axial stress. Based on the pseudo-continuous wave technology, Joshi and Pathare [9] use carrier phase detection to track the frequency of mechanical resonance of bolts. Although the acoustoelastic effect based method can be used for estimating the bolt axial pre-stress [10, 11], it is difficult for a large scale implementation for real-time monitoring of a large number of bolts due to the high cost of the sensors/probes [12, 13].

声弹效应方法测TOF，但是探头太贵了

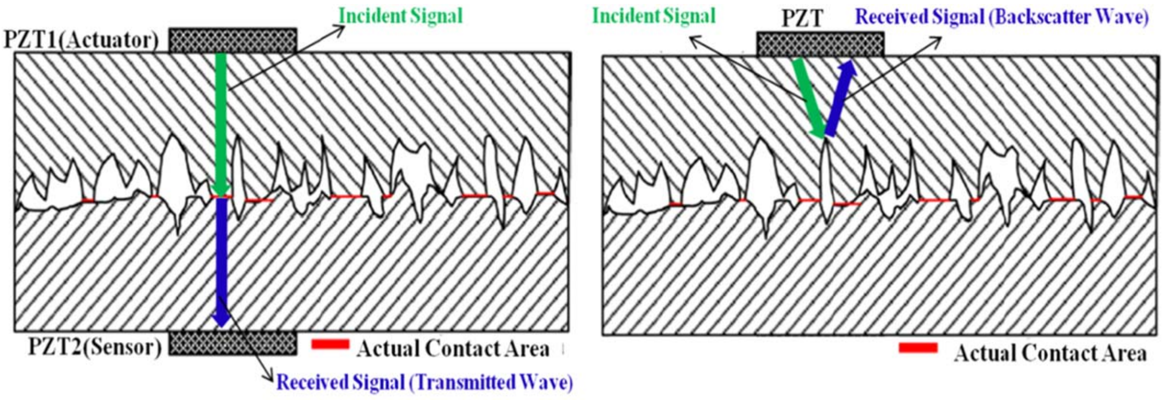
Piezoceramic is a kind of particular dielectric substance with a direct piezoelectric effect and inverse piezoelectric effect [14–18]. As a type of piezoceramic material with strong piezoelectric effect, PZT (Lead Zirconate Titanate) has been widely applied in various fields [19–23] because of its advantages of dual sensing and actuation [24], energy harvesting [25], high bandwidth [26, 27], and low cost. Due to its good coupling ability, PZT can also be embedded in other materials to form a composite structure [15, 18, 28]. Huo *et al* [29, 30] proposed a piezoceramic-based transducer, called smart washer (SW), that was fabricated by embedding a piezoceramic patch into two pre-machined flat metal rings. Experimental results show that the piezoelectric impedance and piezoelectric active sensing technology are effective methods to evaluate the status of bolted connection [3, 6, 13, 31–33]. The piezoelectric impedance technology is a non-parametric structural health monitoring technology [34–39], which can be used to carry out real-time monitoring on the bolt connection status. The impedance method requires the measuring equipment to have a broadband swept-frequency signal output and high-precision signal sampling capability [35, 40]. The active sensing technology usually requires two PZTs [3, 4, 41–43]. One PZT transducer bonded to the side of the bolt-connected structure is utilized as an actuator to generate stress waves, and simultaneously, the other PZT transducer installed on the other side acts as a sensor to detect the response signal. Depending on the pre-stress on the bolt connection, the effective contact area of a bolted joint interface is different, thus the stress wave generated by PZT propagating across the interface has a different amplitude, and the wave energy is used to evaluate the status of bolted connection [3, 4, 6].

PZT的优势

压电阻抗，压电主动传感技术

A problem associated with PZT transducers is the deterioration in the dielectric constant and piezoelectric response with time, often being referred to as aging [44]. With the aging of PZT, the amplitude of the excitation signal decreases [45], and the signal energy does not correctly reflect the real status of the bolt connection. Due to this problem, PZT systems require frequent maintenance and replacement to keep the working performance. The key to solve this problem is to record the stress wave signal propagating across bolt-connected structure and excitation signal at the same time, and the signal energy can be corrected using the amplitude of the excitation signal. The common monitoring method of installing PZT at both ends of the bolt joint device cannot realize the energy correction. When the stress wave propagates across the rough surface [46, 47], the non-contact surface produces a backscatter wave, which carries the information of the bolt joint state. One possible solution is that a single PZT transducer, acting as both an actuator and a sensor, is used to transmit and receive stress wave signal. This monitoring method obtains not only the amplitude information of the excitation signal, but also the scattering wave produced by microscopically rough surfaces of bolt-connected structure. Recently, taking advantage of the fact that the scattering waves [48–50] provide rich information, the application on the basis of coda wave interferometry (CWI), where the term ‘coda’ is originally used in the geophysics context [51–55], has been used in the nondestructive testing (NDT) community [56–58]. The method focuses on monitoring time-lapse

PZT会老化，信号需要根据激励信号来矫正，两个PZT就不行



(a) Signal transmission (b) Signal backscatter

Figure 1. Diagram of the principle of the bolted connection state monitoring.

velocity changes with high relative resolution by comparing coda signals measured at different times. Therefore, the diffuse ultrasound based on CWI analysis makes it possible to study stress-induced changes within small perturbations. At present, coda wave is mostly used to evaluate non-uniformity of rock in the geophysics context [59–64] and NDT of concrete structures [58], and no related paper has been reported in bolt tightening monitoring. Due to the high sensitivity to the detection of heterogeneity, coda wave can be used to evaluate the heterogeneity of the rough surface which reflects the magnitude of the pre-tightening force of the bolt. Therefore, bolted connection can be characterized by the coda wave.

introduce cuda wave

This study proposes a method for the quantitative evaluation of the state of bolted connections based on ultrasonic coda wave energy (CWE) method. Compared with the existing ultrasonic energy method, the proposed method only requires a single piezoceramic transducer to realize the monitoring bolt tightness. The energy of a coda wave is normalized through the amplitude of a direct wave, and the CWE only reflects the bolted connection state, achieving the quantitative evaluation on the bolted connection state. The rest of the paper is organized as follows. First, the principle of detecting bolt joint state based on CWE is introduced. Then, the platform for testing bolt connections is fabricated, and the relationship between the CWE and bolted connection state was established. Through experimental results, the effectiveness of quantitative evaluation of the state of bolted connections through CWE is verified.

2. Detection principle

The two surfaces joined by a bolt are rough microscopically [46, 47]. With the increase of the loading, the real contact area increases correspondingly. The real contact area in the bolted connection structure reflects the magnitude of the pre-tightening force of the bolt. Therefore, different bolted connection states can be characterized by the contact area [5, 6, 46, 47].

螺栓松紧度转化为接触面积

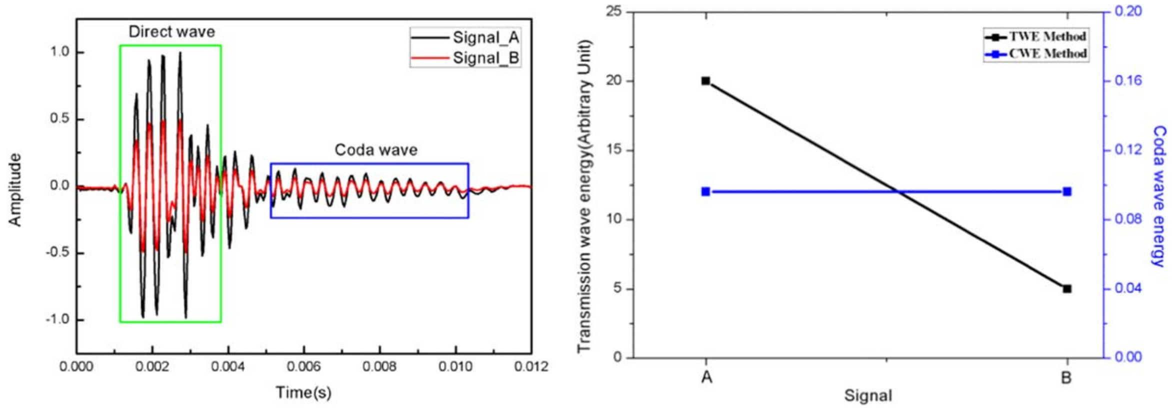
A common monitoring method is the active sensing method that installs PZT transducers on both ends of the bolt joint and monitors the bolt joint state by using the change of TWE [3, 6]. The principle of the TWE approach is illustrated in figure 1(a). One PZT transducer bonded on one side is utilized as an actuator to generate a bulk wave. Simultaneously, the other PZT transducer installed on the other side acts as a sensor to detect the wave response. With increase of the bolt looseness, the contact force decreases, resulting in less true contact area. As a result, less energy can be propagated to the sensor. The sensor signal can be decomposed by an n-level wavelet packet decomposition into 2^n frequency bands. The signal energy E_T can be calculated by the wavelet packet-based analysis [5] as

TWE 波能传播理论

$$E_T = \int_0^T (\|X_1\|^2 + \|X_2\|^2 + \ldots + \|X_{2^n}\|^2)dt, \quad (1)$$

where X_m is the waveform of the frequency band m, $m = 1, \ldots, 2^n$; and T is the length of waveform. This monitoring method is greatly affected by transmission wave energy (TWE). However, the TWE is related to not only the connection state, but also the status of the PZT. With two transducers, in addition to the transmitted wave signal, the coda wave (forward scattering wave) signal is also recorded. The coda wave is affected by both the heterogeneity of microscopically rough surfaces and the PZT performance, therefore it is difficult to eliminate the effect of PZT performance when PZT transducers are on both sides of a bolt joint. In such a case, the coda wave (forward scattering wave) cannot be used to evaluate the bolt connection status with the consideration of the PZT aging. The key to eliminate the effect of PZT aging is to record the signal that propagates across bolt-connected structure and the excitation signal at the same time, and the signal energy can be corrected using the amplitude of the excitation signal.

In fact, after the stress wave propagates across the contact surface, the non-contact surface produces a backscatter wave, which carries the information of the bolt joint state. The monitoring method based on backscatter wave enables the signal excitation and reception by installing only a single PZT at one side of the bolt joint structure, as is illustrated in



(a) Different amplitude waveforms (b) Energy calculated by TWE and CWE

Figure 2. Waveforms and energy calculated by TWE and CWE.

Coda wave energy 单侧PZT接收微尾波信号

figure 1(b). An obvious feature of the backscatter wave is that there is a strong coda wave after the direct wave. When two surfaces, which are rough microscopically, the actual contact area increases as the load increases, and the degree of heterogeneity of the contact surface decreases. The CWE is related to the degree of heterogeneity, therefore the pre-load on the bolt connection can be evaluated based on to the CWE. To further analyze the relationship between the CWE and the bolted connection state, the coda wave energies at different connection states are calculated by

$$E = \int_{t_1}^{t_2} (w(t)/w_0)^2 dt, \tag{2}$$

where $w(t)$ is signal of filtered waveforms; w_0 is the maximum amplitude of $w(t)$; and $[t_1, t_2]$ is the interval of coda wave. Since only one PZT transducer is used, the effect of the inconsistency among PZT transducers and the aging effect can also be eliminated. In this paper, the CWE is normalized by the amplitude of the direct wave signal. In equation (1), even if X_m is normalized by the maximum value, PZT aging cannot be eliminated. This is due to the fact that the signal is divided into direct and tail waves during naturalization, while X_m does not separate the coda wave from the signal.

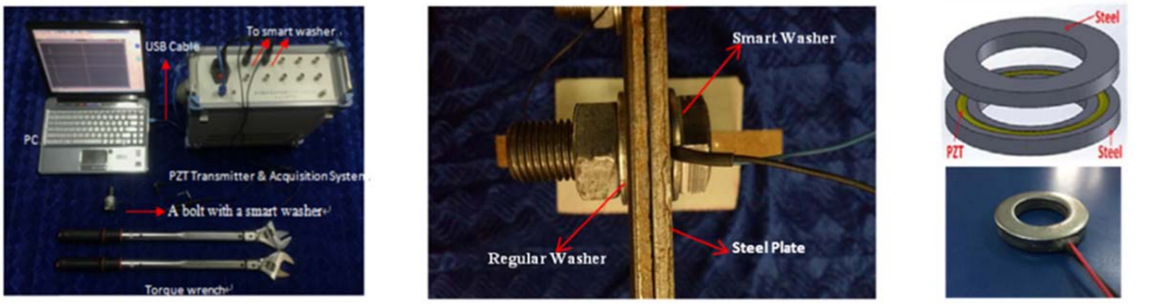
To compare the above two methods, two different amplitude waveforms which characterize the signals received by PZT with different aging effects are used. Figure 2(a) shows two waveforms A and B, where the amplitude of B is 0.5 times of A, which means the PZT losses 50% of its performance due to aging. The energies of signal A calculated by using equations (1) and (2) are shown in figure 2(b). For comparison, we also plot the energies of signal B calculated with equations (1) and (2), respectively. It can be seen that the energies using TWE method are quite different, which is not conclusive to the quantitative evaluation of bolt joint state. In other words, with the aging of PZT and decrease of PZT performance, the relationship between energy and bolt state should be re-calibrated. The amplitude of coda wave mainly depends on the excitation signal amplitude and connection state of bolt structure. To eliminate the effects of PZT aging, coda wave is normalized through the amplitude of the direct wave, and the magnitude of CWE only reflects the change of connection states. Therefore, the CWE of signal B calculated by using equation (2) is equal to the CWE of signal A. By comparison, we can find that the coda wave is more favorable to the quantitative evaluation of bolt joint state. The relationship between CWE and the connection state after the normalization obtained by calibration can be used for quantitative evaluation of the same type of bolt structure.

3. Experimental verification

3.1. Experimental setup and specimen

To validate the proposed method to evaluate the bolted connection state by CWE, monitoring experiments on bolt connection state are carried out. Figure 3 shows the experimental setup, including a pair of bolt and nut, a regular washer, a piezoceramic SW, two steel plates that are connected by the bolt and nut, a computer, a torque wrench, and a multifunctional PZT Transmitter and a data acquisition system (SC-HY-PZT2.0) which was manufactured by Jiangsu Sanchuan Intelligent Technology Co., Ltd in China. The multifunctional PZT Transmitter and Acquisition System has eight sampling channels, with the sampling frequency of 2.4 MHz, and can generate pulse signal and swept-frequency signal. In this experiment, a pulse signal with a width of 6.5 μs is selected. The bolt is used to apply a tightening force to connect two steel plates. The bolt outer diameter is 25 mm, inner diameter is 20 mm, and the steel plates are 5 mm thick. The PZT is encapsulated in the SW. As shown in figure 3(c), a groove was machined on the surface of one of the flat steel ring, and the PZT was embedded in the groove; the second metal ring was overlaid to guarantee the PZT would not be damaged by external forces.

The PZT ring has a diameter of 23.5 mm, an inner diameter of 21.5 mm, and a thickness of 1 mm. Figure 4 shows a schematic of PZT with the d33 mode. The poling direction is parallel to the three-axis. In order to provide enough mechanical protection for the PZT ring, the smart ring is



(a) Experimental devices (b) Bolts with Smart Washer (c) Smart Washer

Figure 3. Experimental platform for monitoring on bolt connection states.

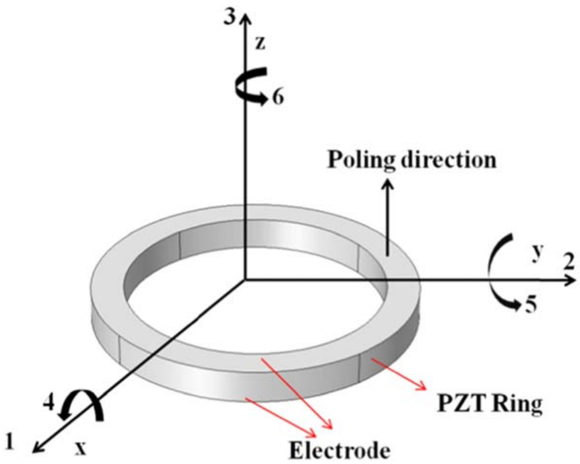


Figure 4. The poling direction of PZT ring.

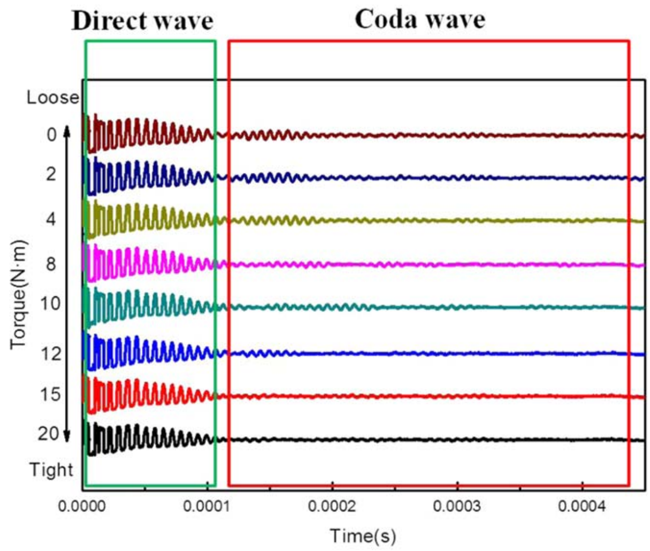


Figure 5. Experimental waveforms for the monitoring of bolt connection state.

fabricated by sandwiching the PZT ring between the two washers with an appropriate groove, as shown in figure 3(c).

3.2. Experimental procedure

The experimental steps to monitor the bolted connection state are listed below:

(1) In the bolt fully-loose state (at this time, the torque of the bolt is 0 N m), after exciting the pulse signal (12 V) with the width of 6.5 μs to the SW, and the data acquisition equipment is used to collect signals in the fully-loose state.
(2) Different torque values are applied to the bolt using a torque wrench to adjust the bolt connection state. Torque values range from 0 to 20 N m. The signals at different connection states are collected, and the CWE in different connection states is calculated by using equation (2).
(3) Steps (1) and (2) are repeated to obtain multiple sets of experimental data to check the repeatability of the proposed method. Through nonlinear curve fitting, the relationship of CWE with the variation of bolted connection states is obtained.

非线性拟合

4. Experimental results and discussion

Experimental waveforms of bolts in different connection states are shown in figure 5, and the eight waveforms correspond to the different connection states. As the bolt varies from the completely loose state to the fully tightened state, the amplitude of coda wave after direct wave decreases gradually.

Figure 6 shows the normalized CWE (the black line) of the waveforms show in figure 5. For comparison, the normalized CWEs in the other two groups of repeated experiments (the red and blue line, respectively) are also reported. It is clear from the figure that the three sets of experimental data have good consistency. When the bolt connection loosens, the CWE shows a declining trend. The tighter the bolted connection state, the smoother the declining trend. The consistency of the three sets of measuring data also indicates that the relationship between the calibrated state of bolted connection and the CWE can be applied to evaluate the connection state of the same type of the bolt. This is because the CWE calculated in this paper is relative to the direct wave,

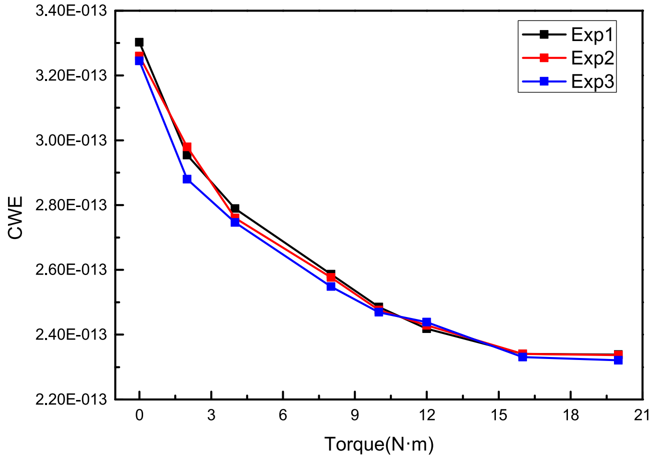


Figure 6. Coda wave energy for three sets of experimental data on bolted connection states.

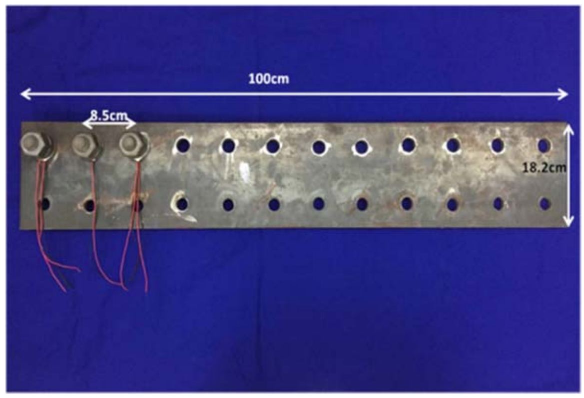


Figure 8. The bolt assembly.

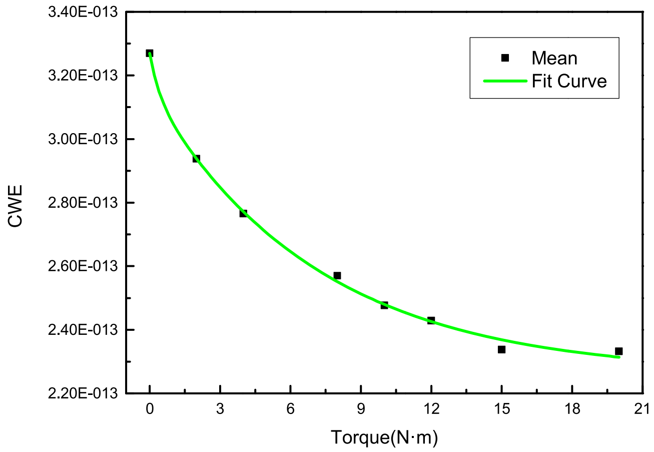


Figure 7. Comparison of average experimental results with nonlinear fitting results.

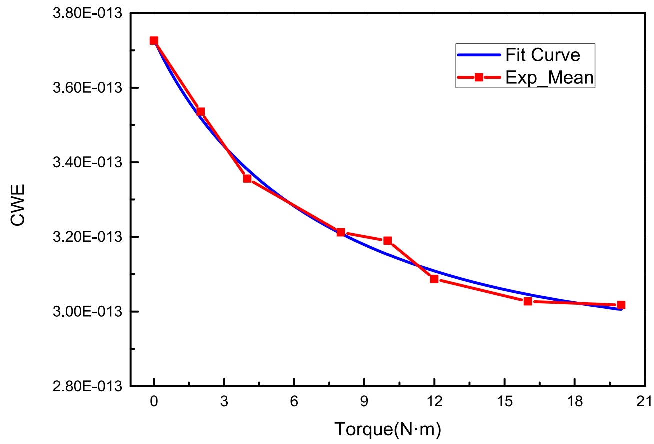


Figure 9. Comparison of the average experimental results of new bolt assembly with the nonlinear fitted results.

which only reflects the variation of connection structure states and is not influenced by the PZT aging effect.

The three sets of experimental data in figure 6 are averaged, and the curves obtained through nonlinear fitting (green line) are shown in figure 7. The functional relationship between the torque (x) and CWE (y) can be expressed as

$$y = y_0 + A_1(1 - e^{-x/k_1}) + A_2(1 - e^{-x/k_2}), \tag{3}$$

where $y_0 = 3.3 \times 10^{-13}$, $A_1 = -9 \times 10^{-14}$, $A_2 = -1.1 \times 10^{-14}$, $k_1 = 7.1$, and $k_2 = 0.42$. To verify the effectiveness of the proposed method on other bolt assemblies, another monitoring experiment on bolt connection state is carried out, as shown in figure 8. For the steel plate, its length is 1000 mm, its width is 182 mm, and its thickness is 5 mm. Three sets of experimental data are obtained and averaged, and the curves obtained through nonlinear fitting (blue line) are shown in figure 9, and curve fitting parameters are $y_0 = 3.73 \times 10^{-13}$, $A_1 = -6.498 \times 10^{-14}$, $A_2 = -1.46 \times 10^{-14}$, $k_1 = 9.1$, $k_2 = 2.43$. It is important to note that:

(1) If the intervals of the coda wave used for calculation are inconsistent, the parameters in the equation (3) will change (see the difference between figures 7 and 9). In this experiment, the computation interval for coda wave is [0.13 0.45] ms. The selection of the calculation interval is related to the characteristics of the signal. The starting value of the interval should be set after the direct wave, and the length of the calculation interval is generally 2–3 times of the duration of the direct wave signal.

(2) The function relationship in the equation (3) only reflect the bolt connection state of this experimental setup. For other types of bolt connections, new functional relationships shall be obtained through new calibrations.

拟合的曲线仅适用于本实验螺栓

To verify the effectiveness of this method in eliminating the effect of PZT aging, pulse signals with different magnitudes (7.2 V and 4.8 V, 6.5 μs pulse width) are sent to excite the PZT, and the measured signals are plotted in figure 10. For comparison, we also plot the pulse signal of 12 V and 6.5 μs pulse width. The experimental results with different pulse signals are shown in figure 11. The CWE with the pulse signals (7.2 and 4.8 V) are consistent with that of the pulse signal of 12 V. The above analyses demonstrate that the proposed method achieves accurate quantitative evaluation of the status of bolted connection by using coda wave in the presence of PZT transducer aging.

For implementations, the threshold selection is important to issue bolt loosening warning. As can be seen from the results of the experiment, when the bolt state tightens, the

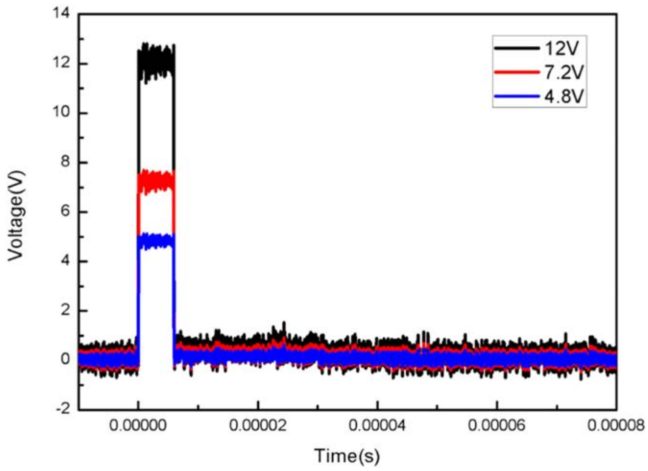


Figure 10. The measured pulse excitation signals.

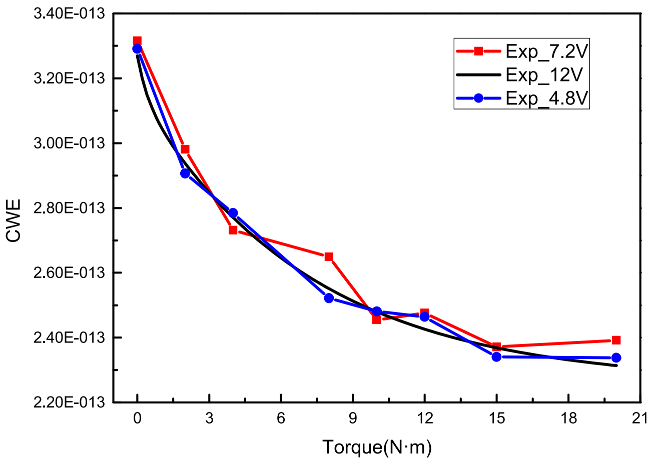


Figure 11. The experimental results with different magnitudes of the excitation signal.

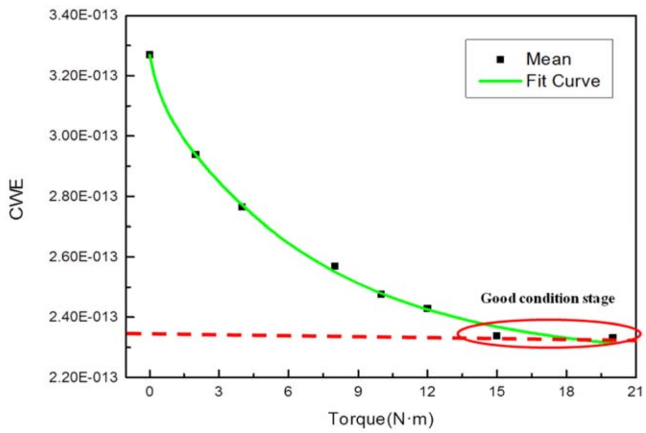


Figure 12. An example of the selection of a threshold to issue a warning.

CWE shows a declining trend. The tighter the bolted connection state is, the smoother the declining trend. The following is an example of the experimental data in figure 7. First, the trend line of bolt at different connection states are drawn, then the threshold can be set based on the CWE value of the bolt at the fully tightened state and the requirement. As an example, a selected threshold (red dotted line) is used to issue an early warning against bolt loosening, as shown in figure 12. Obviously, a higher value of the threshold can be chosen if there is a less requirement on the bolt loosening monitoring.

5. Conclusion

This study proposes an innovative method to monitor a bolted connection by using a single piezoceramic transducer enabled CWE. In this paper, a single Lead Zirconate Titanate (PZT) transducer, acting as both an actuator and a sensor, is used to transmit and receive stress wave signal. The stress wave signal consists of two parts, one is the direct wave whose amplitude is related to the excitation signal, and the other part is the backscatter wave (coda wave) produced by microscopically rough surfaces and the boundary along the interface of a bolt connection. Taking the advantage of its high sensitivity to small changes in material or structural heterogeneity, the proposed method employs coda wave to evaluate the changes of magnitude of the pre-tightening force on the bolt. The proposed CWE is normalized through the amplitude of direct wave only reflects the information of bolt connection states, eliminating the effect of PZT aging, and, furthermore, a functional relationship between the bolted connection looseness and the CWE is established to the quantitative evaluation of the bolted connection status. To verify the proposed method, in this study, experiments on a bolt connection using a single piezoceramic transducer are conducted. Experimental results show that the CWE decreases gradually when the connection changes from the fully looseness to completely tightness, demonstrating the validity of the proposed method to real-time monitor the looseness of a bolted connection. Compared with the existing ultrasonic energy method based on transmitted waves, the CWE method only needs a single piezoceramic transducer to realize monitoring of the bolt connection. The proposed method decreases the number of transducers and connecting lines, reducing the overall cost of bolted connection monitoring.

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References

[1] Caccese V, Mewer R and Senthil S 2004 Detection of bolt load loss in hybrid composite/metal bolted connections *Eng. Struct.* **26** 895–906

[2] Amerini F, Barbieri E, Meo M and Polimeno U 2010 Detecting loosening/tightening of clamped structures using nonlinear vibration techniques *Smart Mater. Struct.* **19** 085013

[3] Wang T, Song G, Wang Z and Li Y 2013 Proof-of-concept study of monitoring bolt connection status using a piezoelectric based active sensing method *Smart Mater. Struct.* **22** 1–5

[4] Wang Q, Yuan S and Qiu L 2007 Study on bolt debonding monitoring of composite joint based on time reversal method *J. Astronaut.* **28** 1719–23

[5] Jiang T, Wu Q, Wang L, Huo L and Song G 2018 Monitoring of bolt looseness-induced damage in steel truss arch structure using piezoceramic transducers *IEEE Sensors J.* **18** 6677–85

[6] Jhang K Y, Quan H H, Ha J and Kim N Y 2006 Estimation of clamping force in high-tension bolts through ultrasonic velocity measurement *Ultrasonics* **44** e1339–42

[7] Wang T, Song G, Liu S, Li Y and Xiao H 2013 Review of bolted connection monitoring *Int. J. Distrib. Sens. Netw.* **9** 871213

[8] Johnson G C, Holt A C and Cunningham B 1986 An ultrasonic method for determining axial stress in bolts *J. Test. Eval.* **14** 253–9

[9] Joshi S G and Pathare R G 1984 Ultrasonic instrument for measuring bolt stress *Ultrasonics* **22** 261–9

[10] Derek D, Andrei Z, Brandon A and Hakan C 2010 Damage detection in bolted space structures *J. Intell. Mater. Syst. Struct.* **21** 251–64

[11] Yasui H and Kawashima K 2000 Acoustoelastic measurement of bolt axial load with velocity ratio method *Proceedings WCNDT* **66** 16–21

[12] Chaki S, Corneloup G and Lillamand I 2007 Combination of longitudinal and transverse ultrasonic waves for *in situ* control of the tightening of bolts *J. Press. Vessel Technol.* **129** 383–90

[13] Amerini F and Meo M 2011 Structural health monitoring of bolted joints using linear and nonlinear acoustic/ultrasound methods *Struct. Health Monit.* **10** 659–72

[14] Shao J, Wang T, Yin H, Yang D and Li Y 2016 Bolt looseness detection based on piezoelectric impedance frequency shift *Appl. Sci.* **6** 1–11

[15] Song G, Gu H, Mo Y L, Hsu T T C and Dhonde H 2007 Concrete structural health monitoring using embedded piezoceramic transducers *Smart Mater. Struct.* **16** 959–68

[16] Jeannette R W, Gyuhae P and Farrar C R 2005 Integrated structural health assessment using piezoelectric active sensors *Shock Vib.* **12** 389–405

[17] Fromme P 2009 Structural health monitoring of plates with surface features using guided ultrasonic waves *Health Monitoring of Structural and Biological Systems Int. Society for Optics and Photonics* vol 7295, p 729517

[18] Kong Q, Robert R H, Silva P and Mo Y 2016 Cyclic crack monitoring of a reinforced concrete column under simulated pseudo-dynamic loading using piezoceramic-based smart aggregates *Appl. Sci.* **6** 341

[19] Vishnuvardhan J, Muralidharan A, Krishnamurthy C V and Balasubramanian K 2009 Structural health monitoring of anisotropic plates using ultrasonic guided wave STMR array patches *NDT E Int.* **42** 193–8

[20] Zhang W, Hao H, Wu J, Li J and Li C 2018 Detection of minor damage in structures with guided wave signals and nonlinear oscillator *Measurement* **122** 532–44

[21] Lin B and Giurgiutiu V 2014 Development of optical equipment for ultrasonic guided wave structural health monitoring *Proc. SPIE* **9062** 90620R

[22] Wilcox P D, Lee C K, Scholey J J, Friswell M I, Wisnom M R and Drinkwater B W 2006 Quantitative structural health monitoring using acoustic emission *Smart Structures and Materials 2006: Smart Structures and Integrated Systems.* vol 6173, p 61731K

[23] Huo L, Li C, Jiang T and Li H 2018 Feasibility study of steel bar corrosion monitoring using a piezoceramic transducer enabled time reversal method *Appl. Sci.* **8** 2304

[24] Jiang T, Kong Q, Wang W, Huo L and Song G 2016 Monitoring of grouting compactness in a post-tensioning tendon duct using piezoceramic transducers *Sensors* **16** 1343

[25] Wang G 2013 Analysis of bimorph piezoelectric beam energy harvesters using Timoshenko and Euler–Bernoulli beam theory *J. Intell. Mater. Syst. Struct.* **24** 226–39

[26] Luo M, Li W, Hei C and Song G 2016 Concrete infill monitoring in concrete-filled FRP tubes using a PZT-based ultrasonic time-of-flight method *Sensors* **16** 2083

[27] Xu Y, Luo M, Hei C and Song G 2018 Quantitative evaluation of compactness of concrete-filled fiber-reinforced polymer tubes using piezoceramic transducers and time difference of arrival *Smart Mater. Struct.* **27** 035023

[28] Liu T, Huang Y, Zou D, Teng J and Li B 2013 Exploratory study on water seepage monitoring of concrete structures using piezoceramic based smart aggregates *Smart Mater. Struct.* **22** 065002

[29] Huo L, Chen D, Kong Q, Li H and Song G 2017 Smart washer-a piezoceramic-based transducer to monitor looseness of bolted connection *Smart Mater. Struct.* **26** 025033

[30] Huo L, Chen D, Liang Y, Li H, Feng X and Song G 2017 Impedance based bolt pre-load monitoring using piezoceramic smart washer *Smart Mater. Struct.* **26** 057004

[31] Heyman J S A 1977 CW ultrasonic bolt-strain monitor *Exp. Mech.* **17** 183–7

[32] Joshi S G and Pathare R G 1984 Ultrasonic instrument for measuring bolt stress *Ultrasonics* **22** 270–4

[33] Kim N and Hong M 2009 Measurement of axial stress using mode-converted ultrasound *NDT&E Int.* **42** 164–9

[34] Han B, Wang Y, Dong S, Zhang L, Ding S, Yu X and Ou J 2015 Smart concretes and structures: A review *J. Intell. Mater. Syst. Struct.* **26** 1303–45

[35] Giurgiutiu V and Zagrai A 2005 Damage detection in thin plates and aerospace structures with the electro-mechanical impedance method *Struct. Health Monit.* **4** 99–118

[36] Liang C, Sun F and Rogers C A 1994 An impedance method for dynamic analysis of active material systems *J. Vib. Acoust.* **116** 120–8

[37] Liang C, Sun F and Rogers C A 1996 Electro-mechanical impedance modeling of active material systems *Smart Mater. Struct.* **5** 171–86

[38] Sevillano E, Sun R and Perera R 2016 Damage detection based on power dissipation measured with PZT sensors through the combination of electro-mechanical impedances and guided waves *Sensors* **16** 639

[39] Shi Y, Luo M, Li W and Song G 2018 Grout compactness monitoring of concrete-filled fiber-reinforced polymer tube using electromechanical impedance *Smart Mater. Struct.* **27** 055008

[40] An Y K and Hoon S 2012 Integrated impedance and guided wave based damage detection *Mech. Syst. Sig. Process.* **28** 50–62

[41] Yang J and Chang F K 2006 Detection of bolt loosening in C-C composite thermal protection panels: I. Diagnostic principle *Smart Mater. Struct.* **15** 581–90

[42] Yang J and Chang F K 2006 Detection of bolt loosening in C-C composite thermal protection panels: II. Experimental verification *Smart Mater. Struct.* **15** 591–9
[43] Wang F, Huo L and Song G 2018 A piezoelectric active sensing method for quantitative monitoring of bolt loosening using energy dissipation caused by tangential damping based on the fractal contact theory *Smart Mater. Struct.* **27** 015023
[44] Walker J and Basil E 1986 Lead zirconate titanate ceramics *US Patent* 4626369
[45] Shepard J F Jr *et al* 1999 Characterization and aging response of the d 31 piezoelectric coefficient of lead zirconate titanate thin films *J. Appl. Phys.* **85** 6711–6
[46] Wang T, Liu S, Shao J and Li Y 2016 Health monitoring of bolted joints using the time reversal method and piezoelectric transducers *Smart Mater. Struct.* **25** 025010
[47] Yin H, Wang T, Yang D, Liu S, Shao J and Li Y 2016 A smart washer for bolt looseness monitoring based on piezoelectric active sensing method *Appl. Sci.* **6** 320
[48] Payan C, Garnier V and Moysan J 2009 Determination of third order elastic constants in a complex solid applying coda wave interferometry *Appl. Phys. Lett.* **94** 011904
[49] Zhang Y *et al* 2017 Nonlinear coda wave interferometry for the global evaluation of damage levels in complex solids *Ultrasonics* **73** 245–52
[50] Shokouhi P *et al* 2017 Dynamic acoustoelastic testing of concrete with a coda-wave probe: comparison with standard linear and nonlinear ultrasonic techniques *Ultrasonics* **81** 59–65
[51] Aki K 1969 Analysis of the seismic coda of local earthquakes as scattered waves *J. Geophys. Res.* **74** 615–31
[52] Snieder R, Grĕt A, Douma H and Scales J 2002 Coda wave interferometry for estimating nonlinear behavior in seismic velocity *Science* **295** 2253–5
[53] Frankel A and Wennerberg L 1987 Energy-flux model of seismic coda: Separation of scattering andintrinsic attenuation *Bull. Seismol. Soc. Am.* **77** 1223–51
[54] Tang X, Li Z, Hei C and Su Y 2016 Elastic wave scattering to characterize heterogeneities in the borehole environment *Geophys. J. Int.* **205** 594–603
[55] Wu R and Aki K 1985 Elastic wave scattering by a random medium and the small scale inhomogeneities in the lithosphere *J. Geophys. Res.* **90** 10261–73
[56] Xie F, Zhuang C, Jiang H, Fan P and Ren Y 2016 Damage assessment of real-size T-beam from deficient prestressed concrete bridge using ultrasonic coda waves *IEEE Technol. Appl. Forum (FENDT)* pp 22–5
[57] Xie F, Li W and Zhang Y 2019 Monitoring of environmental loading effect on the steel with different plastic deformation by diffuse ultrasound *Struct. Health Monit.* **18** 602–9
[58] Planes T and Larose E 2013 A review of ultrasonic Coda wave interferometry in concrete *Cement Concr. Res.* **53** 248–55
[59] Sato H, Fehler M C and Maeda T 2012 *Seismic Wave Propagation and Scattering in the Heterogeneous Earth* 2nd edn (New York: Springer)
[60] Nishigami K 1991 A new inversion method of coda waveforms to determine spatial distribution of coda scatterers in the crust and uppermost mantle *Geophys. Res. Lett.* **18** 2225–8
[61] Aki K and Chouet B 1975 Origin of coda waves: source, attenuation and scattering effects *J. Geophys. Res.* **80** 3322–42
[62] Xie F, Ren Y, Zhou Y, Larose E and Baillet L 2018 Monitoring local changes in granite rock under biaxial test: a spatiotemporal imaging application with diffuse waves *J. Geophys. Res.* **123** 2214–7
[63] Hei C and Xiao Z 2019 Borehole elastic wave anisotropic scattering and application to hydraulic fracturing *J. Pet. Sci. Eng.* **183** 106405
[64] Lei H, Hei C, Luo M and Li Z 2019 The effects of near well heterogeneities on single-well imaging: numerical studies *Waves Random Complex Media* (https://doi.org/0.1080/17455030.2019.1663958)