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An anti-noise real-time cross-correlation method for bolted joint monitoring using piezoceramic transducers

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Abstract. Bolted joint connection is the most commonly used connection element in structures and devices. The loosening due to external dynamic loads cannot be observed and measured easily and may cause catastrophic loss especially in an extreme requirement and/or environment. In this paper, an innovative Real-time Cross-Correlation Method (RCCM) for monitoring of the bolted joint loosening was proposed. We apply time reversal process on stress wave propagation to obtain correlation signal. The correlation signal's peak amplitude represents the cross-correlation between the loosening state and the baseline working state; therefore, it can detect the state of loosening. Since the bolt states are uncorrelated with noise, the peak amplitude will not be affected by noise and disturbance while it increases SNR level and increases the measured signals' reliability. The correlation process is carried out online through physical wave propagation without any other post offline complicated analyses and calculations. We implemented the proposed RCCM on a single bolt/nut joint experimental device to quantitatively detect the loosening states successfully. After that we implemented the proposed method on a real large structure (reaction wall) with multiple bolted joint connections. Loosening indexes were built for both experiments to indicate the loosening states. Finally, we demonstrated the proposed method's great anti-noise and/or disturbance ability. In the instrumentation, we simply mounted Lead Zirconium Titanate (PZT) patches on the device/structure surface without any modifications of the bolted connection. The low-cost PZTs used as actuators and sensors for active sensing are easily extended to a sensing network for large scale bolted joint network monitoring.

Keywords: Real-time Cross Correlation Method (RCCM); bolted joint loosening detection; PZT; time reversal; stress wave propagation; active sensing

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1. Introduction

A bolted joint is one of the most widely used connection mechanisms in civil structures and mechanical devices. They can be applied to fix the precise camera in a satellite, secure a blowout preventer in high pressure and high temperature working environment at the bottom of the sea, and even fasten a high speed vehicle’s wheels. Once the bolted joint fails, it may cause a catastrophic disaster. Bolted joint failures are usually due to insufficient and excessive axis loads during installation or a loss of axis load caused by external dynamic loads in service. Therefore, it is very important to develop methods to detect and/or monitor the bolted joint loosening states.

The most current conventional practical techniques in industry for monitoring the bolted joint loosening states directly measure the stress between the connected pieces or the strain in the bolted joints. One method is to install a load cell in the connected pieces to measure the stress. This method is expensive and sometimes it is not possible to access the area to do modification. Another method is to embed a strain gauge into the bolt to measure the accurate strain of the bolt. This method could detect the axis load on the bolted joint directly. However, it is expensive and also requires modification of the bolt. Actually, all commercial techniques with direct measuring method require modifying the structures or bolts/joints, while the instrumentation is expensive and is limited to specific types of bolted joint connections, which could not widely be applied in practice. So an indirect measurement method without involving modification for embedding sensors arouses the enthusiasm of researchers, and several methods have been developed.

As a conventional nondestructive test method, the ultrasonic method is also widely applied in bolted joint loosening detection. As the ultrasonic wave propagation velocity along the bolt is dependent on the bolt axis stress, the ultrasonic method is feasible to detect the bolt stress in an indirect way. Heyman (1997) designed a CW Ultrasonic Bolt-strain Monitoring device in which he correlated the ultrasonic wave resonant frequency shift with the applied stress. By comparing the Time of Flight (TOF) of the ultrasonic wave propagation between an unstressed bolt and a stressed bolt, the wave propagation stress-dependent velocity and stress can be achieved to monitor the state of the bolt. The TOF can be detected by either the zero crossing method (Yasui and Kawashima 2000) or the phase locking method (Jhang *et al* 2006 and Tadolini 1990). The velocity ratio between longitudinal and transverse wave method was also proposed by Holt *et al.* without measuring the TOF (Johnson *et al.* 1986). However, the ultrasonic method has several limitations. The bolt ends must be flat and parallel, and its surface finish should be reasonable. Minimum bolt length is required for the detection, the bolt end size is important for mounting probes, and the bolt should be easy to access.

Vibration response analysis is widely used in structural damage detection. There are two major types of methods: modal analysis and wave propagation. In modal analysis, the vibration features are extracted to correlate with the damage or degradation. The major feature changes due to the damage are resonant frequency changes, mode shape shifts, modal damping and flexibility shifts. The damage or degradation will also change the wave propagation, especially in high frequencies. The propagated energy and the transmittance function from actuator to sensor are commonly used. When the bolt joint loosening states change, it will affect the system’s dynamic performance and wave propagation through the contact surface.

In vibration methods, we usually excite the structure and analyze the system’s response. TODD *et al.* (2004) assessed the modal property effectiveness in detecting bolted joint degradation. Huda *et al.* (2013) used the high power pulse laser to excite the bolted lap joint connection and he used accelerometers to measure the response. Finite element analysis was incorporated to verify the measured data to detect the bolted joint states using the modal analysis. Amerini *et al.* (2010) also applied modal analysis by using Power Spectrum Density to indicate the bolted joint loosening, and in another paper (Amerini and Meo 2011) he developed nonlinear methods including a harmonic and sideband modulation method while the linear acoustic moment method with energy changes was adopted. Caccese *et al.* (2004) applied a piezoceramic actuator to excite a hybrid composite/metal bolted connection while shear accelerometers and dynamic strain sensors measured the vibrations. Low frequency modal analysis, a high frequency transfer function between actuator and sensors, and transmittance functions between sensors were proposed to detect the single bolt joint loosening. Wang *et al.* (2013) used propagated energy to represent bolt lap joint states by simply applied PZT patches used as actuators and sensors. Nakahara *et al.* (2004) applied a thin plate with piezoelectric elements as a sensor between a bolt, a nut and washers. By analyzing the sensor modal characteristic, the local vibration mode could be obtained.

The PZT mechanical-electrical coupling effect could be used to detect host structure damage (Park *et al.* 2003, Giurgiutiu *et al.* 1999, and Ayres *et al.* 1998). The impedance analysis of PZT has been adopted by researchers to detect bolt joint loosening (Park *et al.* 2006, Peairs *et al.* 2004 and Ritdumrongkul *et al.* 2004). Since the electrical conductivity of the contact surface of the bolted joint is also stress dependent, some research has been conducted to prove the feasibility to monitor the bolt joint loosening states (Song *et al*. 1993, Argatov and Sevostianov 2010).

Cross correlation refers to the similarity of two signals. In a nondestructive ultrasonic test, cross correlation methods are widely used for determination of the time difference between different channels, which could determine the damage or interference locations (Yu and Giurgiutiu 2005 and Marioli *et al.* 1991). A damage index can also be built by using the correlation between healthy states and damaged states in structural health monitoring (Park *et al.* 2010). However, the correlation process is post calculated by a powerful computer which requires a great amount of computer memory, as well as a complicated digital signal algorithm.

In this paper, we proposed a real-time cross correlation method to monitor the bolted joint loosening states, which is a vibration based method. In the RCCM process, we first applied an impulse wave through a designed working state of a bolted joint as a baseline state, and then we applied the store baseline time reversal wave through any testing state of the bolted joint to obtain the response. The peak amplitude of the response represents the correlation between the testing loosening states and the baseline state. That is why we could apply the peak amplitude to detect the bolted joint loosening. The acquired peak amplitude from the data acquisition system is an already processed value through physical wave propagation. It does not require more complicated post analysis and the instrumentation is simple. Two PZT patches were mounted on the surfaces of the two separate parts that the lap bolted joint connected. Experiments on a single bolted joint model device and a real structure (reaction wall) with multiple bolted joints were conducted to verify the method's feasibility. The great ability of anti-noise and disturbance was also demonstrated.

2. RCCM principle in bolted joint loosening detection

As the schematic of the experimental setup with a single bolted joint in Fig. 1 shows, PZT patches A and B are mounted on the plate surface as actuator and sensor, respectively. RCCM includes two major successive processes: a baseline state auto-correlation process and a testing state cross-correlation process.

In the baseline process, the bolted joint is in the tightest state which is the working state. It includes two wave propagation processes.

In the first wave propagation process, a pulse denoted as $\delta(t)$ is generated by PZT A as the system input, while the system transfer function from PZT A to PZT B for this baseline state is denoted as *h(t)*. The corresponding *y(t)* received by PZT B is written as

$$y(t) = \delta(t) \otimes h(t) \tag{1}$$

where $\otimes$ represents the convolution operations.

We reverse *y(t)* in the time domain to obtain the time reversal signal *y(-t)*

$$y(-t) = \delta(-\mathrm{t}) \otimes h(-t) \tag{2}$$

In the second wave propagation process, the stored time reversal signal *y(-t)* is generated by PZT A again and PZT B receives the propagated wave $y^B(t)$ which is called the correlation signal. The wave propagates through the same channel as the first wave propagation process and the propagation transfer function is the same as *h(t),* therefore,

$$y^B(t) = y(-t) \otimes h(t) = \delta(-t) \otimes \left[h(-t) \otimes h(t)\right] \tag{3}$$

According to the correlation and convolution definition, Eq. (3) could be developed as

$$y^B(t) = \delta(-t) \otimes [h(t) \odot h(t)] \tag{4}$$

where $\odot$ denotes the correlation operator.

If the input pulse signal $\delta(-t)$ is an ideal impulse and it is symmetrical $\delta(-t) = \delta(t)$. The correlation signal $y^B(t)$ is the impulse response of $h(t) \odot h(t)$ and can be written as

$$y^B(t) = h(t) \odot h(t) = \int_{-\infty}^{+\infty} h(\tau)\, h(\tau - t) d\tau \tag{5}$$

From Eq. (5), we could see that the correlation signal is the auto correlation function of the baseline state's transfer function.

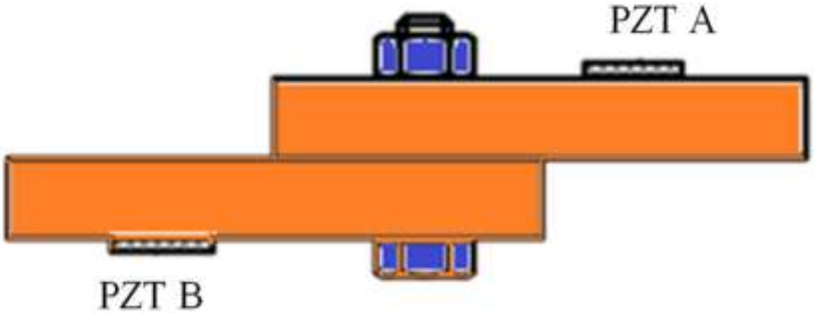


Fig. 1 Schematic of experimental setup with single bolted joint with PZT patches

In the detection process: after implementing the baseline process, the bolted joint is fastened in a testing state. We send the stored baseline time reversal signal *y(-t)* to the actuator PZT A. After wave propagation through this testing channel, whose transfer function can be denoted as $h^t(t)$, PZT B acquires the testing correlation signal $y^t(t)$, therefore

$$y^t(t) = y(-t) \otimes h^t(t) = \delta(-t) \otimes [h(-t) \otimes h^t(t)] = \delta(-t) \otimes [h(t) \odot h^t(t)] \quad (6)$$

From Eq. (6), $y^t(t)$ is found to be the impulse response of the system $h(t) \odot h^t(t)$ and it can be written as

$$y^t(t) = h(t) \odot h^t(t) = \int_{-\infty}^{+\infty} h(\tau)\, h^t(\tau - t) d\tau \quad (7)$$

From Eq. (7), it is obvious that the correlation signal $y^t(t)$ for the testing state is the correlation function between the transfer functions of the baseline state and testing state. So the peak amplitude in $y^t(t)$ represents the similarity between the testing state and baseline state. The baseline peak amplitude is the largest among the testing states peak amplitudes because it's the auto-correlation of the baseline. The smaller the peak amplitude is, the more uncorrelated with the baseline state the testing state is, therefore, the more loosened the bolted joint is.

3. Experimental results and discussions

Firstly, we performed experiments on a single lap bolted joint setup to verify the proposed method's feasibility in a narrow tightness range, then we implemented the experiment on a reaction wall with multiple bolted joints to detect the loosening of a specific bolt and show the ability for future application in a real structure in industry.

3.1 Single bolted joint experiment

3.1.1 Experimental setup

The experimental device is shown in Fig. 2. Two flat steel plates with dimensions of 101 mm×48 mm×11.5 mm were connected together by an M10 bolt connection. Two PZT patches with dimensions of 10 mm×10 mm×0.8 mm were mounted on the outer surfaces of the steel plates. PZT A on the top surface was connected to NI USB 6361 Board's analog output and was used as an actuator. PZT B on the bottom surface was connected to NI USB 6361 Board's analog input and was used as a sensor. Fig. 3 shows the experimental setup. The bolt connection was tightened by a digital torque wrench.

3.1.2 Experimental procedures

The bolt connection was tightened by a torque wrench with different torques, namely 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, and 80 N·m, to represent the loosened states. Under each torque condition, we applied our proposed RCCM to detect the bolted joint loosening. The detailed steps are as follows.

Step1: 80Nm of torque was applied on the bolted joint as a baseline state. A modulated Gaussian pulse with amplitude 10 V, center frequency 100kHz, and normalized bandwidth 2 was generated by USB 6361 m and was sent to PZT A. PZT B acquired the propagated waves, and then was reversed in the time domain which was called the reversal signal. We stored this reversal signal as a baseline signal which contained the wave propagation channel's information because an impulse response is the channel's transfer function. The baseline signal was amplified 500 times and was sent back to PZT A again, and then PZT B would receive the correlation signal. The peak amplitude of the correlation signal would be used to represent the state of 80 N·m.

Step2: 0 N·m torque was applied, which means that the bolted joint was totally loosened. We amplified the stored baseline signal 500 times and sent it back to actuator PZT A, and then PZT B would pick up the testing correlation signal. The peak amplitude of the correlation signal would be used to represent the state of 0 N·m.

Step3: Step 2 was repeated for torques of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70 and 75 N·m.

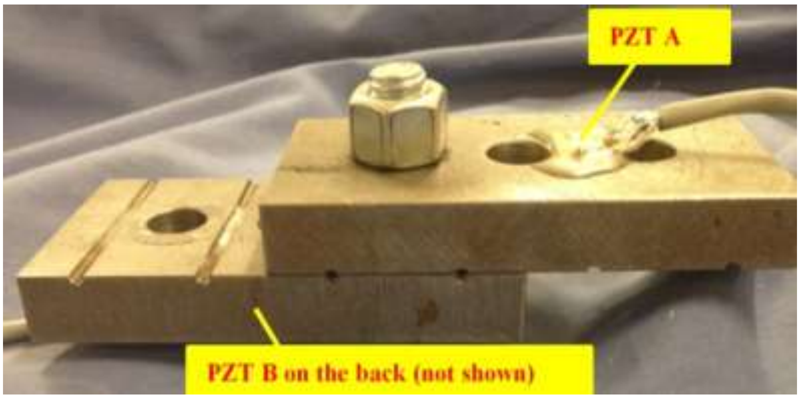


Fig. 2 Single bolted joint experimental setup

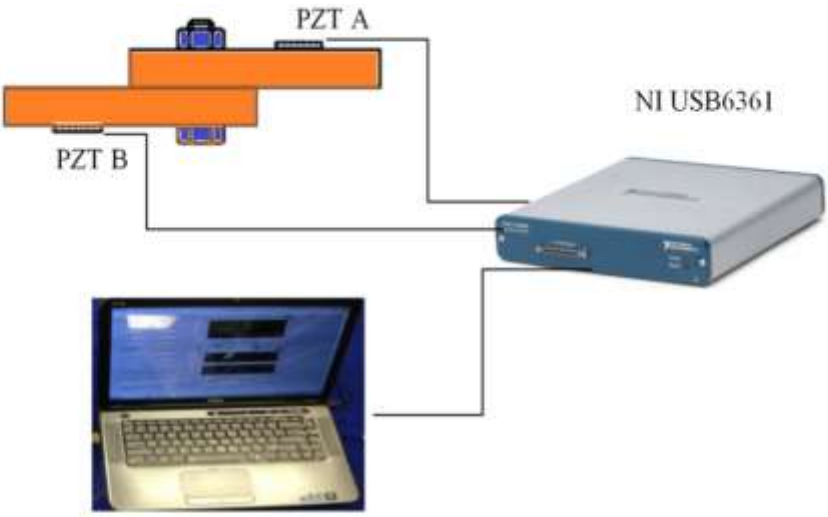
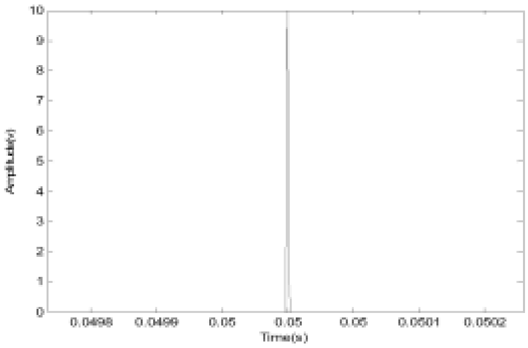
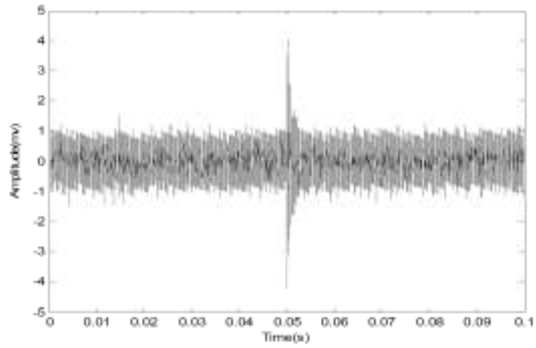


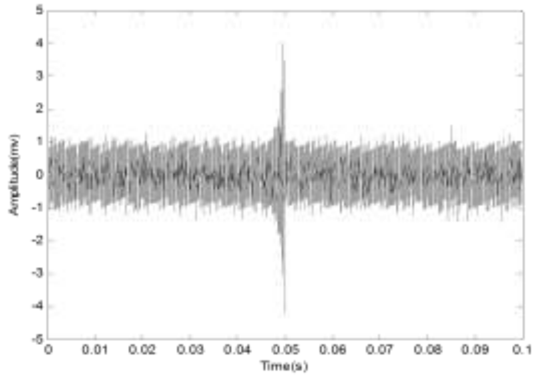
Fig. 3 Schematic of experiment instrumentation



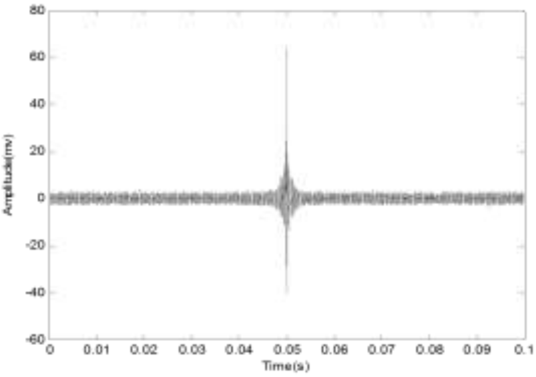
(a) Gaussian pulse input signal



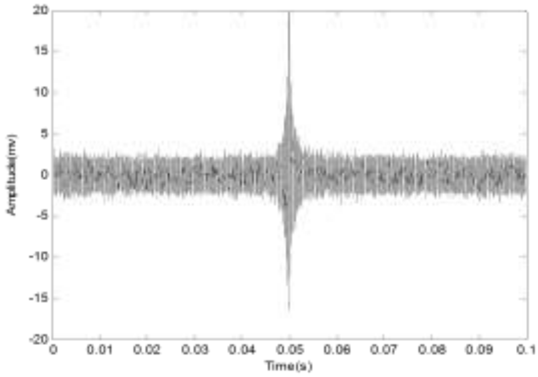
(b) Received signal for 80 N·m



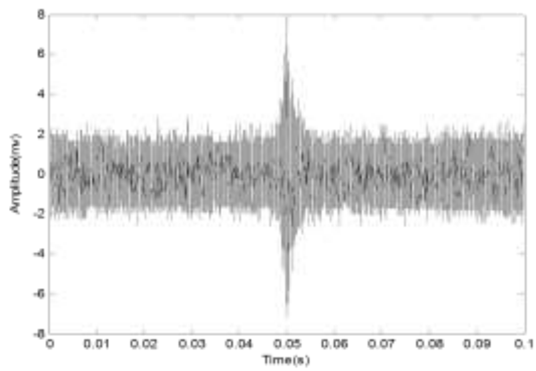
(c) Time reversal signal for 80 N·m



(d) Correlation signal for baseline under 80 N·m



(e) Correlation signal for 40 N·m



(f) Correlation signal for 20 N·m

Fig. 4 Signals in the detection processes at 80N·m, 40N·m and 20N·m states

3.1.3 Experimental results and discussions

RCCM process results were shown clearly in Fig. 4 by using the 80N·m state as a baseline, while 40 N·m and 20 N·m were used as testing states.

The state at the first torque of 80N·m was the baseline state. During the baseline process, the input signal was a Gaussian modulated pulse applied on PZT A as shown in Fig. 4(a). It is symmetrical and very short. Due to wave reflection, dispersion, and scattering during the wave propagation, the signal PZT B received contained multiple pulses, but the amplitudes were attenuated during the wave propagation for each pulse as shown in Fig. 4(b). This phenomenon is called the multipath effect. The received signal in Fig. 4(b) was reversed in the time domain to become the time reversal signal as shown in Fig. 4(c). This signal would be stored as the baseline signal. After amplifying the time reversal signal 500 times and applying it to the actuator PZT A, PZT B received the correlation signal as shown in Fig. 4(d). The peak amplitude shows the auto correlation results, which are the baseline indicator.

In the testing state of 40 N·m, the stored baseline signal in Fig. 4(c) was sent to actuator PZT A. The testing correlation signal was received by sensor PZT B as shown Fig. 4(e). It was seen that the peak amplitude dropped compared to the baseline state peak amplitude. Similarly, we got the testing correlation signal for the state of 20 N·m as shown in Fig. 4(f). The peak amplitude for this state of 20 N·m was much lower than that of 40 N·m. The correlation signal represents the cross correlation function between the testing channel transfer function and baseline testing channel. The peak amplitude, which is the maximum value of the cross correlation function, stands for the degree of similarity of the two channels. When the bolt loosening state is closer to the baseline state, the peak amplitude is closer to the baseline amplitude. The 40 N·m state is more similar as the baseline state of 80 N·m compared to the 20 N·m state.

The relationship between the peak amplitudes of the correlation signals for testing states and applied torque is shown in Fig. 5. When the torque was lower than 20 N·m, the bolted joint was very loose. These states were very dissimilar with the baseline state of 80N·m and the measured peak amplitudes were smaller than 10 mV. As the torques ranged from 25 to 70 N·m, the peak amplitudes increased smoothly from 14.7 mV to 37.7 mV as the applied torque increased. 75 N·m was much closer to the baseline so the peak amplitude was much closer to the baseline states.

Loosening index I was built by using Eq. (8)

$$I = 1 - \frac{A^t}{A^B} \tag{8}$$

where A^t *and* A^B are the peak amplitudes of the testing state and baseline state, respectively.

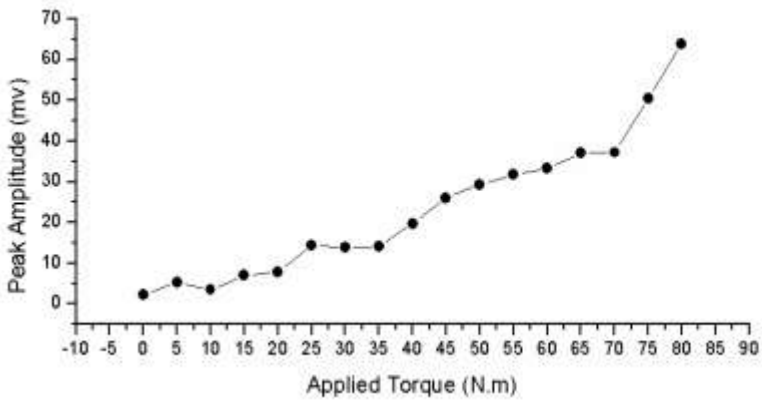


Fig. 5 Correlation signal peak amplitude under different applied torque

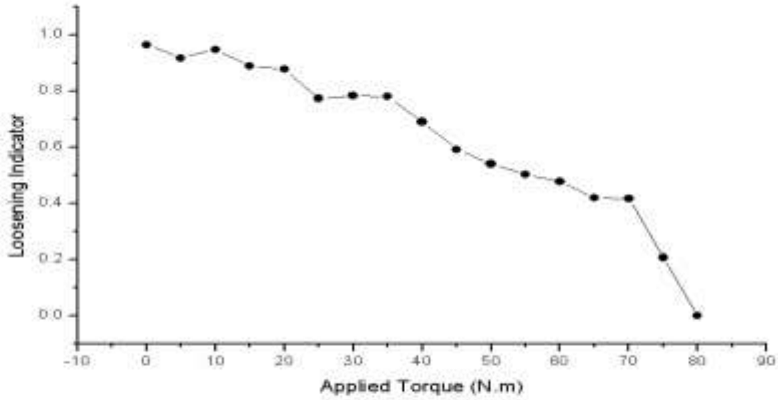


Fig. 6 Loosening index

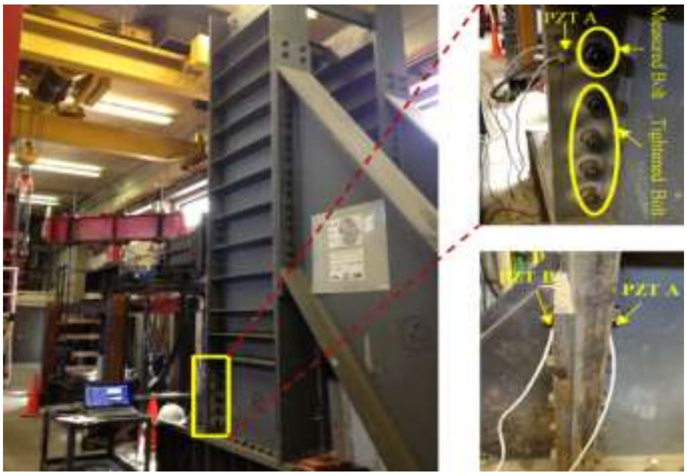


Fig. 7 Reaction wall as an experimental setup

As Fig. 6 shows, when the index is larger, the bolt-joint is more loosened. When the loosening index is above 0.8, the applied torque is below 20 N·m which corresponds to 25% of 80 N·m. When the bolt is very tight, within 90% of the working state of 80N·m, the index is less than 0.2.

3.2 Real structure experiment

We applied the proposed RCCM on a wall reaction structure with multiple lap bolted joints as shown in Fig. 7. When all the other bolted joints are tightened without any changes, we applied torques from 0 N·m to 680 N·m with an increment of 27.2 N·m on the top bolted joint. During the RCCM process, the input signal is a Gaussian modulated pulse with amplitude 3 V, center frequency 300 kHz, and normalized bandwidth 1. Before all signals were sent to the actuator, the signals were amplified 50 times by a wide frequency band (1MHZ) power amplifier Trek 2100HF.

As shown in Fig. 8, the peak amplitude was very small, below 20 mV (less than 20% of the baseline 103 mV) when the torque was below 163N·m (24% of 680 N·m), then the peak amplitude increased very linearly before the torque reached 544 N·m. After 544 N·m, the peak amplitude would not change much. In very loose states, the states are almost uncorrelated with the baseline tightest state; the correlation signal peak amplitude will be very small. When the bolted joint is tightened closer to the baseline states, the peak amplitude remains the same. Compared to the single bolted joint experiment, this range is much smoother like saturation, without a sharp jump. When the single bolt joint device was tightened around the baseline 80 N·m, the relative positions (rotation) of the steel plates may be altered (for 75 N·m and 70 N·m) from the original position as the steel plate was in small size and was without other boundary restrains. Therefore the states of 75 N·m and 70 N·m for a single bolted joint would be much different from the baseline 80N·m.

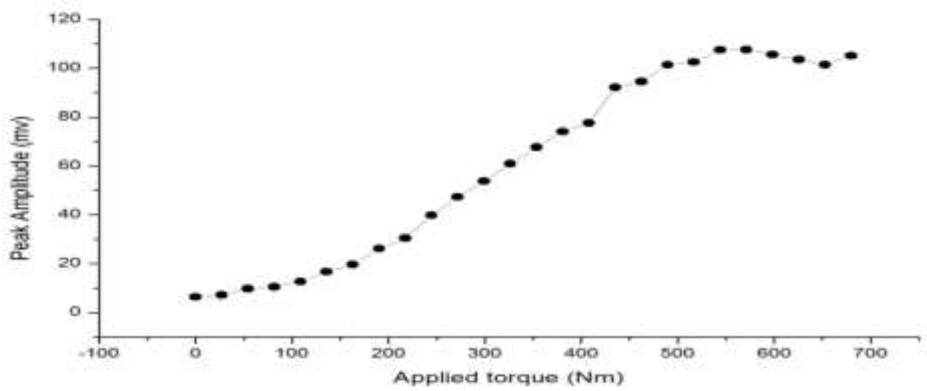


Fig. 8 Peak amplitude vs. applied torque on reaction wall

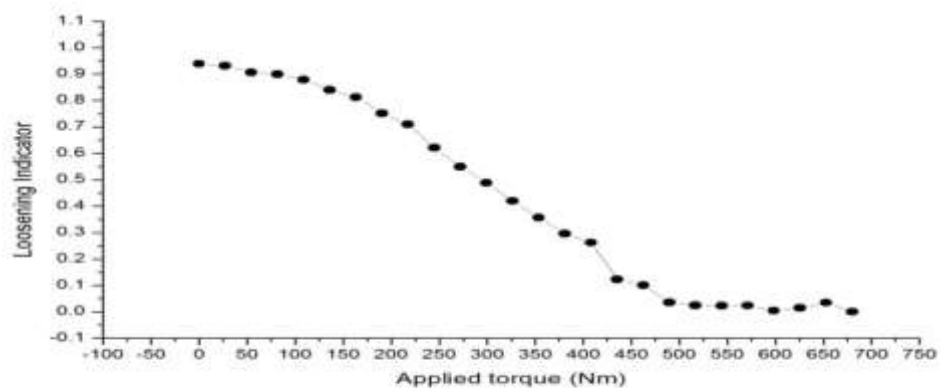
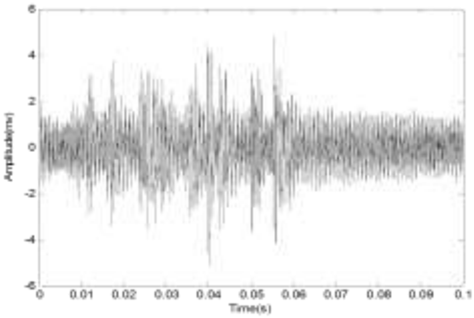
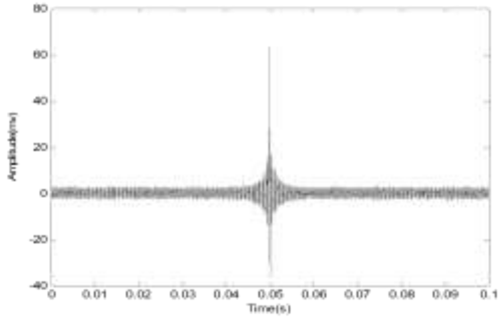


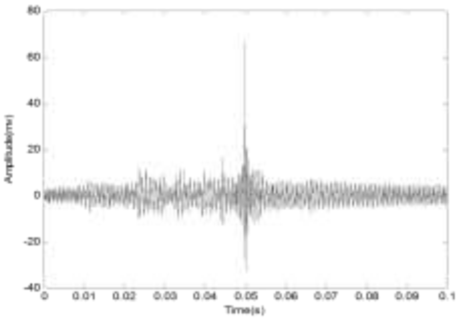
Fig. 9 Loosening index



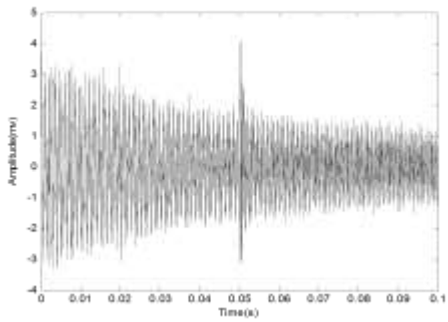
(a) Received signal with impact in first process



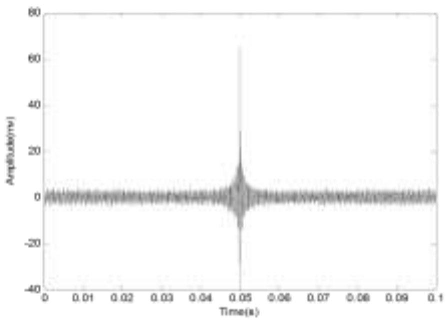
(b) Correlation signal with impact in first process



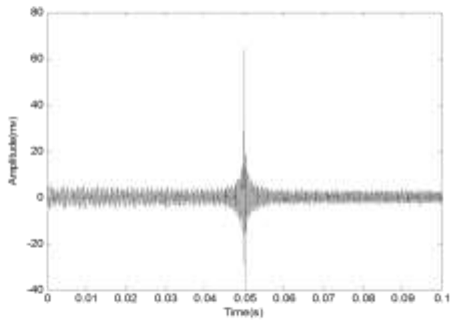
(c) Correlation signal with impact in both processes



(d) Received signal with rubbing in first process



(e) Correlation signal with rubbing in first process



(f) Correlation signal with rubbing in both processes

Fig. 10 Received signals and correlation signals with different noises under 80N·m

Due to the fixed boundary conditions of the reaction wall around the baseline state, undesired rotation of the steel plates become negligible, and the states become more alike. RCCM is highly sensitive to similarities, hence the sharp jump in the curve around the tightest state in single bolted joint experiment while a smooth curve was observed for reaction wall experiment. During the middle range of the torque in the reaction wall, the peak amplitude increased very linearly and smoothly, therefore it is very useful and indicates the bolt loosening states. The loosening state index was also built to indicate the loosening state in a range from 0 to 1 as shown in Fig. 9.

4. Anti-noise/disturbance ability of RCCM

Because the peak amplitude is the cross correlation representation between different states, noise or disturbance are uncorrelated with the system states. Therefore, the noise and disturbance will not affect the correlation peak amplitude and this proposed RCCM has great anti-noise ability. In this paper, we introduced great impact and rubbing vibration to the single bolted joint experimental apparatus during the RCCM process to demonstrate the proposed method's anti-disturbance ability.

The baseline process actually is the cross-correlation of the baseline state with itself, and the peak amplitude is the largest. We introduced impact and rubbing vibration by a pencil in the baseline process to demonstrate the anti-noise ability where the results and displays could be more obvious and easier to check.

In impact cases, when the structure was continuously impacted during the first wave propagation (Gaussian pulse) process, the received signal by PZT B was very noisy as shown in Fig. 10(a). The useful propagated wave from the pulse input was totally drowned out by the impact vibration waves. After we applied the time reversal noisy signal again to PZT A without impact in this second wave propagation process, the correlation signal that was again received by PZT B, as shown in Fig. 10(b), was almost the same as the situation without any impact during any process by comparison with Fig. 4(d). This means that the noise in the first wave propagation was eliminated in the second wave propagation process. We introduced impacts in both wave propagation processes as another case. As shown in Fig. 10(c), the correlation signal was noisy, but the peak amplitude still remained at 63.8mV.

Similarly, in rubbing cases, the received signal with continuous rubbing in the first wave propagation process is shown in Fig. 10(d). The correlation signals without rubbing and with rubbing in the second wave propagation process are shown in Figs. 10(e) and 10(f). The peak amplitude in both cases stayed the same as 63.8mV like the state without any disturbance.

In addition to the anti-noise ability, the peak amplitude itself was much greater than that of the noise. It increased the SNR level and the reliability of the measured signals. As Figs. 10(a) and 10(d) show, the useful received signals were almost drown in the introduced noise. Energy method (Wang *et al.* 2013) or modal analysis method (Caccese *et al.* 2004) using these noisy received signals may not be reliable since it is difficult to obtain the accurate energy and modal shape. On the contrary, the proposed method can work in such low SNR environments by focusing an obvious peak and rejecting noise.

5. Conclusions

In this paper, we proposed the RCCM in bolted joint loosening detection. The basic principle of the method to detect the loosening is the correlation between the testing state and the baseline working state. The way to find correlation is by using the time reversal technique during physical wave propagation which is very innovative and stable. The correlation signal representing the correlation function can be acquired directly by a data acquisition system without any more post analyses and calculations. The peak amplitude of the correlation signal which can indicate the bolted joint loosening states can be easily displayed in real time. The method also has a great anti-noise ability because usually the noise is uncorrelated with the bolt joint states and will not contribute to the peak amplitude in the correlation function. At same time, the method increases the SNR level, therefore increases the measured data's reliability in low SNR environment. Finally, the instrumentation we implemented on the experiment to demonstrate the proposed RCCM in bolt joint loosening detection is simple. The low-cost PZT patches used as actuator and sensor are easily extended as a sensing network for future large scale bolt joint network monitoring.

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