Research on identification and monitoring method of bolt connection loosening based on piezoresistive effect

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Abstract. Bolted connection is commonly used in the joint connection of engineering structures, and its connection reliability plays an important role in ensuring the service performance of engineering structures. In complex service environment, bolt connection is easy to lose. In order to identify and monitor bolt connection looseness, a bolt looseness monitoring device based on piezoresistive effect is designed and manufactured in this paper. The feasibility of the device is verified through flange bolt looseness identification test. The results show that the monitoring device can effectively identify the minor bolt loosening damage, and the identification results have good stability, and the bolt loosening can be deduced based on the variation of the conductance value. The bolting connection loosening monitoring method based on piezoresistivity effect proposed in this paper can provide a reference for the identification and monitoring of bolt loosening.

1. Introduction
Bolt connection is widely used in the field of engineering structure. It has the advantages of convenient disassembly and strong reliability. In order to ensure the quality of threaded connection, it is necessary to apply pre-tightening force to the bolts, and the screw fastening quality plays an important role in ensuring the structural force mode. Torque fastening method is a commonly used bolt fastening method, as shown in Figure. 1. Related studies show that only about 10% of the torque of torque fastening method is converted into clamping force. Therefore, bolt loosening is a common problem in engineering structures. As shown in Figure 2, on May 3, 2012, the bottom formwork of the hanging basks of a viaduct under construction in Wenling City suddenly collapsed, causing two workers to be injured. The primary reason was that the formwork fell after the bolts at the key parts became loose due to repeated use. Therefore, bolt loosening is a common damage of engineering structures, and has been increasingly widely concerned by scholars at home and abroad. Monitoring and identification of bolt loosening is a hot issue in the field of engineering structure research.
At present, there are many methods to identify bolt looseness. J.L. Shen et al.\textsuperscript{[1]} conducted a simulation study on the mechanical system composed of threaded connection as the research object, established a simplified dynamic model of threaded connection structure by using the simplified method, and identified the looseness fault by using the wavelet packet energy method. X.L. He et al.\textsuperscript{[2]} identified the bolt loosening of wind tower based on the vibration characteristics of tower drum. The measured test showed that, compared with other vibration characteristics, the first-order phase difference was more significantly affected by the loosening of flange bolt, and could better reflect the phenomenon of flange bolt loosening. Z.F. Cao et al.\textsuperscript{[3]} studied the identification method of bolt connector looseness in high-temperature vibration environment based on time-frequency analysis. It is found that the loosening state of the connection structure can be comprehensively evaluated based on the ratio of the amplitude of double frequency and the amplitude of fundamental frequency. D.M. Ai et al.\textsuperscript{[4]} proposed a damage identification method for bolt loosening of tunnel segment structure based on piezoelectric impedance, and quantified the damage by calculating the damage index RMSD. Its rate of change measured sensor sensitivity. C.C. Song et al.\textsuperscript{[5]} designed four kinds of special gaskets pasted with PZT material in different forms in order to realize the monitoring of bolt tightness. The experimental study showed that the method of using warped gaskets was more sensitive to bolt loosening. X.D. Xie et al.\textsuperscript{[6]} in order to eliminate the influence of temperature change on the guided wave propagation, Independent component analysis (ICA) is used to process guided wave signals, and it is found that the loose bolts can be successfully located and the influence of temperature change on guided wave propagation can be eliminated. In conclusion, the existing methods, such as those based on structural dynamic parameter changes, belong to the overall damage identification methods of the structure. It is basically necessary to carry out complex parameter identification on the collected detection data of the whole structure to obtain the structural damage information. This kind of method is not only difficult to accurately identify the connection state of each bolt, but also subject to environmental factors in actual use.

Piezoresistive effect is widely used in the manufacture of various sensors, S.T. Zhang et al.\textsuperscript{[7]} applied the flexible piezoresistive sensor to the stress monitoring of solid rocket engine interface. J.H. Yao\textsuperscript{[8]} proposed a sitting pose recognition method based on thin film pressure sensor set, and found that random forest tree algorithm had the highest recognition accuracy for the test set. G.H. Liu et al.\textsuperscript{[9]} proposed a pulse acquisition system based on flexible piezoresistive sensor for pulse detection, and proposed a fitting scheme based on least square method. Equation (1) is the relation expression of the distance $D$ between the resistor $R$ and the piezoresistive material\textsuperscript{[7]}:

$$R = \frac{V}{AJ} = \frac{h^2d}{Ae^2\sqrt{2m\lambda}} \exp\left(\frac{4\pi d}{h}\frac{\sqrt{2m\lambda}}{h}\right)$$ (1)
Where: \( J \) is the tunnel current density; \( V \) is the potential difference; \( E \) is electric quantity; \( M \) is the electron mass; \( H \) is Planck's constant; \( D \) is the distance between piezoresistive materials; \( \lambda \) is the energy constant; \( A \) is the cross-sectional area where the tunneling effect occurs. According to Equation (1), as the pressure acting on the piezoresistive material surface increases, the material spacing of the conductive medium \( D \) decreases, and its output resistance value \( R \) decreases accordingly\(^7\). To sum up, piezoresistive materials, as a sensing material widely used at present, can change the resistivity under a certain external force, and can effectively monitor the connection state of engineering structures reliably and effectively. At present, there are few literatures on the identification of bolt looseness by using piezoresistive materials. Therefore, this paper can carry out the identification and monitoring research on bolt looseness by identifying the change of the resistivity of piezoresistive materials.

2. Bolt loosening monitoring device

In order to apply piezoresistive materials to the identification and monitoring of bolt looseness, a kind of looseness monitoring device based on piezoresistive effect is designed and manufactured here. The physical diagram of the monitoring device is shown in Figure.3, including: 1-magnet, 2-brass plate, 3-silica gel sheet, 4-piezoresistive film. The brass plate is the protective shell, the piezoresistive film is the power sensitive element and the conversion element, the silica gel sheet is the buffer protective layer, and the upper and lower magnets are annular.

The installation position of piezoresistive monitoring device is shown in Figure. 4. First to install the original nut, then loose pressure resistance monitoring device installed, to install the locknut, when the bolt looseness, nut axial displacement occurs, so as to make the monitoring device to produce pressure change, leading to the internal pressure resistance film resistivity changes, through the resistance change of the detecting device can identify is loose or not, degree of loose. In this way, bolt loosening can be monitored and further loosening of bolts can be effectively prevented.

Arduino is a kind of programmable logic controller. The sensor control can be realized by writing programs through the Arduino IDE programming software and uploading them to the control board. The connection between Arduino and electronic components is relatively simple, and the circuit can be built by plugging and unplugging DuPont wires. This is shown in Figure 6. In this paper, Arduino control board is used to collect and store data, and data is read by relevant test software.
According to the original performance parameters of piezoresistive film, it can be seen that the relationship between resistance and pressure is a quadratic function by fitting the relationship curve between resistance and pressure, and the relationship between resistance and torque is expressed as:

$$R = 0.0006F^2 - 0.4434F + 100.256$$  \hspace{1cm} (2)

By fitting the change curve relationship between the conductivity and pressure of piezoresistive film, it can be seen that the relationship between the conductivity and pressure is a linear function, and the relationship between the conductivity and torque is expressed as:

$$G = 0.0001F + 0.0062$$  \hspace{1cm} (3)

In Equations (2) and (3), $R$ represents the resistance (kΩ), $G$ represents the conductance (kΩ$^{-1}$), and $F$ represents the loosening torque (N).

3. Bolt loosening identification test

In order to verify the feasibility of using piezoresistance looseness monitoring device for bolt looseness identification, an experimental study on bolt group looseness identification was carried out. As shown in Figure. 8, the model consists of a flange surface, a supporting Angle and a bottom diagonal brace. When making the flange bolt connection model here, the geometry or material similarity is not considered. The model is only used as the support platform for the loosening test, and 12 bolts represent the actual bolt group. In the test, the single bolt loosening test was carried out first, and then the loosening torque identification of 12 bolts was carried out. The test process is shown in Figure. 9.
As shown in Figure 10, the ratio of theoretical torque to measured torque is shown. The loose bolt is No.5 bolt, and the rest bolts are not loose. Due to the installation error of the test, there is also some initial stress in the loosening monitoring device corresponding to the loose bolt. Figure 11 shows that the identification error of the 12 bolts loosening torque is basically within 5%, and the maximum error is about 8%.

Figure 12 shows the variation curve of resistance and conductance of No.5 bolt tested in the test with loading time. It can be seen that the resistance decreases with the continuous loosening of the bolt, the conductance increases linearly and the resistance value decreases continuously until the bolt loosening reaches the maximum value of 5N·m. The device conductance value is about 0.062K Ω⁻¹ and resistance value is about 20kΩ.
4. Conclusion

In this paper, a bolt loosening monitoring device based on piezoresistive sensing effect is designed and only made. The feasibility of the loosening monitoring device and the stability of the monitoring data are verified through the bolt loosening identification test. It is expected to provide reference for identification and monitoring of bolt looseness. The main conclusions of this paper are as follows:

(1) The loosening monitoring device based on piezoresistive effect proposed in this paper can be used in bolt loosening monitoring and identification, and the identification results have higher accuracy and better stability.

(2) The conductance of piezoresistive monitoring device increases linearly with the increase of loosening torque. Coco can infer whether the bolt is loosening or not and the degree of loosening based on the change of conductance.

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