Research on the application of on-line monitoring technology for bolt axial force of wind turbine

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Abstract. During wind turbine operation, hub and pitch bearing connection bolts are constantly subject to alternating loads. The axial force of the bolts is an important factor affecting the normal operation of the wind operation. Real-time monitoring of residual axial force can timely feedback the operation of the wind turbine and then the health assessment of the fan structure can be realized. This paper introduces a monitoring system of axial force based on ultrasonic method for measuring bolt axial force. The system can realize the data acquisition of multiple bolts and multiple measuring points in the period. Then, we introduce the engineering application of the system and the corresponding data management system. Through the analysis of the monitoring data, scientific and accurate maintenance of the connection structure is realized, which reduces the operation cost and quality cost. This paper also tests the adaptability of the system to verify its accuracy and reliability at different temperatures.

1. Introduction

Bolt connection is widely used in aerospace, aviation, automobile, electric power and other fields. However, due to the improper loading of assembly axial force, external alternating load or other environmental factors, various failure modes such as looseness, crack and fatigue fracture may occur during the service of bolts, which will affect the health of the connection structure. Bolt looseness is one of the most important forms of bolt connection failure. The axial force of connecting bolt assembly is the key factor affecting bolt looseness, so the monitoring of bolt axial force has high engineering value and significance for the safety and reliability of products.

Bolt on-line monitoring technology has the ability of structure function integration, in-situ monitoring and real-time online diagnosis. At present, many methods have been applied to on-line monitoring technology of bolt axial force, such as resistance strain gauge measurement method, piezoresistive impedance method, ultrasonic method, chaotic ultrasonic excitation method (nonlinear) and so on. Since S. OKA discovered in 1940 that stress can affect the speed of ultrasonic propagation in solid, ultrasonic has been widely used in structural flaw detection. The force and residual stress can be measured by measuring sound velocity and propagation time. Interllifast, a German company, has designed a bolt with a built-in sensor, which combines the sensor with ultrasonic technology to measure the internal pressure of and determine the bolt tightening degree. Ultrasonic monitoring has the characteristics of fast response speed, high monitoring accuracy, simple and convenient operation. The application of ultrasonic monitoring in foreign engineering has been more mature, but at present, the application of bolt monitoring engineering in China is less, and most of them stay in theoretical research.

In this paper, based on ultrasonic monitoring technology and combined with the actual engineering situation, a set of bolt axial force online monitoring system is developed. Through the collection and
data management of the bolt axial force during service, scientific and accurate maintenance of the connection structure is realized. We also test the adaptability of the system to verify its accuracy and reliability at different temperatures.

2. On-line monitoring principle of axial force
When the bolt in a free state, there is no axial force inside the bolt, but in the fastening state, the bolt will deform due to the action, so the deformation of the bolt is \( \Delta L \). The bolt monitoring system calculates the axial force \( F \) according to the mathematical relationship between \( \Delta L \) and axial force \( F \), which is as follows:

\[
F = \frac{E \cdot S \cdot \Delta L}{L}
\]  

(1)

Where, \( F \) is the axial force of the bolt; \( E \) is the elastic modulus of bolt material; \( S \) is the cross-sectional area of the bolt; \( \Delta L \) is the deformation of the bolt; \( L \) is the clamping length of the bolt pair. According to the formula (1), the bolt monitoring system calculates the current smart bolt axial force \( F \) according to \( \Delta L \).

The bolt monitoring system transmits and receives the ultrasonic pulse electrical signal, measures and calculates the time difference between transmission and echo electrical signal. When the bolt is in free state, the time difference between transmitted and received electrical signals is \( T_0 \); when the bolt is tightened, the time difference between transmitted and received electrical signals is \( T_1 \). Thus, according to the relationship between the transmission time difference of the electrical signal and the deformation of the bolt, the deformation of the bolt is obtained:

\[
\Delta L = \frac{1}{2} \cdot (T_1 - T_0) \cdot v
\]  

(2)

Where, \( V \) is the propagation velocity of mechanical longitudinal waves in bolts. Finally, according to \( \Delta L \) and formula (1), the axial force of monitoring bolt under current state can be obtained by bolt monitoring system. The measurement principle diagram of bolt monitoring system is shown in Figure 1.

![Figure 1. Measurement principle of bolt monitoring system.](image)

3. Introduction of axial force monitoring system
The on-line monitoring method of axial force is to detect the bolt length through ultrasonic detector in real time. The change of bolt length is transmitted to industrial computer through electrical signal, and the electrical signal is converted into the axial force of bolt to realize on-line monitoring of bolt load. According to the requirements of engineering application, the bolt axial force monitoring system includes: bolt shaft force measuring instrument, signal splitter, industrial computer, software control system, data processing system and other key parts. The system architecture is shown in Figure 2.

3.1 Bolt axial force measuring instrument
Axial force measuring instrument of the bolt is the core of the axial force monitoring system. It is connected with the splitter. And it can excite and measure multiple specified bolts through the channel switching of the splitter. The data acquisition frequency is 2MH and the maximum measurement length is 1500mm. The axial force measuring instrument is also connected with the industrial computer through LAN interface. According to the instructions of the industrial computer, it can complete the measurement, related operation and return the corresponding data.

3.2 Signal splitter
The signal splitter can connect at least 12 test channels and realize the switching of 12 channels. The minimum switching time interval of each channel shall not be less than 5 seconds.

3.3 Software control system
The software control system has the function of setting ultrasonic transmitting and receiving parameters. It can realize the calibration of batch bolt ultrasonic system, complete the calibration curve of acoustic time difference and axial force, support the average calibration curve of multiple bolts, realize the contrast display of initial waveform and current waveform, carry out the function of waveform expansion and contraction, and complete the calibration and compensation of temperature coefficient of batch bolt. At the same time, the software control system can also set the polling interval and sampling rate of 12 channels, and store the monitoring data of 12 channels.

3.4 Industrial computer
The industrial computer communicates with the monitoring system through Modbus TCP protocol, so as to realize real-time data acquisition, axial force monitoring system control and other functions. Its information interaction relationship is shown in Figure 3. The collected data is transmitted by high-frequency FTP protocol.
3.5 Data processing system

Bolt ultrasonic on-line monitoring data processing system is an auxiliary tool of monitoring system, which can realize the collection, grouping and processing of monitoring data. The system stores the imported monitoring data according to the temperature, time, number and other conditions. It can realize the data processing between the target time and the temperature, and meet the needs of the staff for the detailed analysis, query and historical trace of the service condition of the monitoring bolt. The overall framework of on-line monitoring data processing system is shown in Figure 4.
Using the data processing software of the monitoring system, the change of axial force in a certain period of time and the parts of axial force of different bolts on the same flange can be queried. As shown in Figure 5, the large amount of data generated due to long-term monitoring can be processed efficiently and rapidly.

**Figure 5.** Schematic diagram of monitoring system data processing software.

### 4. Application cases

The system is installed on the connecting bolt of hub and pitch bearing in a wind power plant. Two bearing surfaces are tested, the total number of bolts is 120. After a long-term operation test, the grid connected operation is carried out, and the axial force of 120 bolts is monitored and stored in real time. The long-term monitoring results are shown in Figure 6.
4.1 Analysis of monitoring axial force changing with time

Figure 7 shows the fitting curve of typical monitoring data of No.1 bolt within 200 days. From this figure, it can be seen that no obvious downward trend has been found in the axial force of No. 1 bolt since the test. Therefore, the normal installation process can ensure the good performance of the bolts during the service period, and reduce the frequency of retightening according to the monitoring results.

![Figure 6. Long term monitoring results.](image)

**Figure 6.** Long term monitoring results.

![Figure 7. Fitting curve of typical monitoring data of No.1 bolt.](image)

**Figure 7.** Fitting curve of typical monitoring data of No.1 bolt.

Figure 8 shows the curve of bolt axial force changing with time in 24 h. The figure indicates that the axial dynamic load on the bolt is ± 5kN, which is about 1% of the axial force. From the perspective of fatigue strength check, it is far less than the fatigue limit stress. From the peak distance of the curve, the time of a cycle of bolt stress changes can be evaluated. For example, the cycle at this time is about 5s, and the fan operates at 12rpm.
4.2 Analysis of peak stagger in ultrasonic measurement

According to the monitoring results, the phenomenon of peak staggering is easy to occur during ultrasonic measurement. This is because in normal ultrasonic measurement, the time window is placed in the middle of the measurement signal waveform. So that when the waveform of the acquisition equipment moves, the equipment can also distinguish the position of the back shift characteristic peak, so as to calculate the time variation. However, if the position of the time window is close to the critical position of the waveform, the acquisition device will recognize the next call back feature as the reference position, resulting in the deviation of the measurement results.

Aiming at this problem, the function of automatic feature peak recognition has been optimized in subsequent products. The probability of peak staggering can be reduced to less than 90%. The risk of peak staggering caused by the waveform characteristics can be avoided by optimizing the excitation power and piezoelectric chip size.

Aiming at the problem of peak staggering of current test data, typical data are selected for analysis. It is found that for short-term peak staggering, the axial force deviation caused by peak staggering is regular. The difference of axial force before and after peak staggering is about 250kN. Therefore, this method can be used to correct the effect of peak staggering on the measurement results.

4.3 Influence of temperature on ultrasonic measurement results

Considering the influence of temperature on the speed of sound propagation, temperature compensation has been done automatically in the design of acquisition system. The experimental results show that the temperature balance for more than 2 hours can eliminate the influence of temperature change on bolt axial force.

According to the test results, there is no obvious linear relationship between bolt axial force and temperature. In general, the influence of temperature on the monitoring results of axial force can be ignored.

But the change of temperature in one day has a great influence on the monitoring results of axial force. As shown in Figure 9, the bolt axial force is relatively stable before 9:00 and after 21:00. Within one day, the average axial force changes by 1kN. From 9:00 to 20:00, the temperature changes by 3.7 °C, and the axial force changes by 7kN. In the daytime, the bolt axial force fluctuates greatly with the change of temperature, while at night, the bolt axial force fluctuates little with the change of temperature. The preliminary analysis is that the temperature probe is located at the head of the bolt, but the bolt has a certain length, and the flange surface will be blocked by sunlight, resulting in a large unbalanced temperature gradient between the bolt and the temperature sensor. As a result, the temperature compensation can’t reflect the real bolt temperature, thus affecting the axial force.

In order to reduce the influence of temperature gradient on the measurement results, the time interval with small temperature change rate at night can be selected to analyze the change trend of bolt stress.
Figure 9. Time varying curve of bolt axial force monitoring value on a certain day.

From the above monitoring results, the axial force of the monitoring bolt does not decrease significantly, which indicates that the normal installation process can ensure the good performance of the bolt during service period. According to the monitoring results, the frequency of bolt re-tightening can be reduced. The change of day and night temperature has a certain effect on the axial force of bolt. In order to reduce the difference of measurement results, we can select the time period with small temperature change rate at night to analyze the change trend of bolt stress, so as to reduce the influence of temperature gradient on measurement results.

5. Accuracy and reliability verification
The accuracy verification and environmental test are carried out for the possible application of the system. Figure 10 shows the results of M16 bolt accuracy verification test. The results show that the measurement error is less than 3% when the load of bolt is 50%. According to the possible environmental impact of the application situation, the low temperature, high temperature, salt fog, damp heat and vibration tests are carried out on the system. The host, splitter, probe and cable of the tested ultrasonic axial force measurement system can still work normally after high temperature, low temperature, vibration, salt spray, humidity and heat alternation, which further verifies the accuracy and reliability of the on-line axial force monitoring system.

Figure 10. Measurement accuracy percentage of axial force in online monitoring system of axial force.
6. Conclusion
In this paper, based on the ultrasonic monitoring technology and combined with the actual situation of the project, an on-line monitoring system of bolt axial force is developed. And the monitoring data results are analyzed. The adaptability of the system is tested to verify its accuracy and reliability at different temperatures. The summary is as follows:

(1) The whole system adopts ultrasonic method to monitor the bolt axial force directly, which has high measurement accuracy, simple operation, high reliability and meets the long-term monitoring requirements of the connecting structure.

(2) The system integrates data measurement, signal acquisition, high-frequency transmission, remote transmission and data processing. It realizes the functions of real-time data acquisition, long-term monitoring and unified data processing. It is convenient to conduct comprehensive analysis and research on the change of fastener axial force and environmental impact. Through the analysis of the long-term monitoring results, the scientific maintenance and precise maintenance of the connecting structure can be realized.

(3) From the above monitoring results, the monitoring bolt axial force has not significantly decreased, which shows that the normal installation process can ensure the good performance of the bolt in service. According to the monitoring results, the frequency of bolt retightening can be reduced. The change of day and night temperature has a certain effect on the axial force of bolt. In order to reduce the difference of measurement results, we can select the time period with small temperature change rate at night to analyze the change trend of bolt stress, so as to reduce the influence of temperature gradient on measurement results.

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