Safety monitoring method of vehicle bridge stress structure based on wireless sensing technology

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Abstract—In the safety monitoring of bridge stress structure, the influence of surrounding environment and noise interference will cause the change of monitoring node coverage and affect the monitoring accuracy. Based on wireless sensor technology, a safety monitoring method of vehicle bridge stress structure is proposed. The interpolation fitting method is used to calculate the stress value of the sensor, and the optimal layout of the sensor is determined with the minimum deflection transfer error as the objective function. Probability sensing model is used to establish wireless overlay network, and wireless sensing technology is used to collect monitoring data. Based on the monitoring data, the static and dynamic response equation is established to establish the finite element model of bridge stress structure. The first level early warning threshold is determined according to the monitoring data under the normal operation state of the bridge, and the second level early warning threshold is determined according to the most unfavorable load distribution of the finite element model, so as to complete the bridge safety monitoring. The experimental results show that the average deformation deviation of the monitoring method proposed in this paper is 0.26mm, which is 0.77mm and 1.22mm smaller than the monitoring methods based on machine vision and GPS differential positioning technology, indicating that the monitoring method in this paper is more accurate and meets the safety requirements of bridge engineering.

1. Introduction
With the development of society and the continuous progress of civil engineering technology, more and more long-span bridges have been built to meet the expanding traffic demand caused by social development, population flow and material transportation. The continuous completion of bridges benefits from the proposal of new design theories in the field of civil engineering, the discovery and synthesis of new materials, the improvement of construction monitoring, and sufficient financial support. The safety of bridges has always been an issue of great concern to the government, the engineering field and the public. As an important throat of urban and highway traffic, once a safety accident occurs, the bridge will cause traffic paralysis and other chain social problems [1]. In the history at home and abroad, large bridge collapse accidents caused by various reasons continue to occur. In order to evaluate the reliability of bridge structure safety, put forward bridge safety management and maintenance strategies, formulate bridge emergency measures and reduce the occurrence of catastrophic accidents, it is very important to carry out long-term on-line monitoring of bridge performance and safety status during its construction and operation.

In the past two decades, stress structure safety monitoring has become a research hotspot in the field of civil engineering. Bridge stress structure safety monitoring is to monitor, identify and evaluate the state changes of the monitored structure (including material properties, geometric properties of
structural system, boundary conditions and connection state of system), various loads and structural
dynamic response during structural service. By combining the monitoring data with the basic theory of
structural mechanics and finite element calculation method, the safety monitoring model is established
to realize the real-time and online evaluation of bridge [2]. Wireless sensor is widely used in the field of
condition monitoring because it can be reused into a network, high sensing accuracy, low processing
cost, absolute digital measurement and accurate positioning. Therefore, based on wireless sensor
technology, it proposes a vehicle bridge stress structure safety monitoring method, so as to obtain
bridge information, diagnose structural health status, and provide effective and reliable basis and
guidance for bridge maintenance and management decision-making.

2. Safety monitoring method of vehicle bridge stress structure based on wireless sensing
technology

2.1. Select the layout mode of bridge wireless sensor

Wireless sensor is widely used in bridge safety monitoring because of its own advantages. In order to
maximize the monitoring effect of sensors and consider from an economic point of view, how to
optimize the layout of sensors has become the key content of bridge structure safety monitoring. For a
long time, concrete has been considered as a material with good durability and corrosion resistance.
Improper proportioning of concrete materials during construction or improper on-site maintenance are
internal factors. External factors are mainly caused by uneven settlement of structure foundation,
external load or erosion and weathering of surrounding environment [3]. In this case, interpolation
fitting method is generally used, that is, points are arranged on the bridge structure first, and the sensor
stress values on the points are collected. The relationship between section deflection and bending
moment is as follows:

\[ \alpha = \int \frac{1}{\chi} \beta(u) \beta' du \]  (1)

In formula (1), \( \alpha \) represents the deflection of the control section; \( \chi \) represents the stiffness of the
bridge; \( \beta(u) \) represents the theoretical bending moment of unit load; \( u \) represents load; \( \beta' \)
represents the bending moment measured by the resistance strain gauge [5]. According to the
relationship between section deflection and bending moment of beam bridge, as long as the transfer
error of section deflection is minimized, that is, the minimum deflection transfer error is taken as the
objective function [6]. Assuming that the target parameters are determined by the directly measured
values, the maximum error value can be expressed as:

\[ \mu_{max} = \pm \left( \left| \frac{\partial \alpha}{\partial x_1} \right| \varepsilon_{x_1} + \left| \frac{\partial \alpha}{\partial x_2} \right| \varepsilon_{x_2} + \cdots + \left| \frac{\partial \alpha}{\partial x_m} \right| \varepsilon_{x_m} \right) \]  (2)

In formula (2), \( \mu_{max} \) represents the maximum error value; \( \varepsilon \) represents the error of the measured
value; \( m \) represents the total amount of measured data. For different deployment schemes, the
maximum error value of the objective function is different. According to the minimum error transfer
criterion, it is necessary to find all \( \mu_{max} \) minimum values, that is, the optimal layout scheme of the
sensor.

2.2. Collecting monitoring data based on wireless sensor technology

On the basis of determining the layout of bridge wireless sensors, the monitoring data are collected
based on wireless sensor technology. Through the research of sensor network coverage, we can
understand the current situation of wireless sensor networks, whether there are monitoring
abnormalities, whether there are coverage blind areas and so on. If it exists, the distribution of wireless
sensor network nodes in the monitoring area can be adjusted to make the wireless sensor nodes
effectively cover the target monitoring area, ensure that the wireless sensor nodes can communicate
with each other, and finally complete the tasks of monitoring data collection and information transmission \[7\]. Therefore, this paper uses probabilistic sensing model to establish wireless overlay network. It is assumed that the deployed nodes have the same performance parameters in a 2D plane target monitoring area. \[8\]. Then its coverage area is a circle with its own coordinate as the center and the perceived radius as the radius. Then the probability that a pixel is covered by a sensor node can be expressed as:

\[
p = \begin{cases} 
1 - \sqrt{(x_i - x_o)^2 + (y_i - y_o)^2} < r \\ 
0, \text{ otherwise}
\end{cases}
\]  

\( \text{(3)} \)

In formula (3), \( p \) represents the probability of event occurrence; \((x, y)\) represents pixel coordinates; \( i \) represents sensor node; \( o \) represents any point on the plane of the monitoring area; \( r \) represents the perceived radius \[9\]. The influence of surrounding environment and noise interference will cause the change of sensor node coverage, so the sensor node measurement model should show a certain probability characteristic distribution. In general, target monitoring points are sometimes perceived by multiple sensor nodes. In order to improve the measurement probability of sensor nodes, this paper uses the joint probability of sensing nodes. When the coverage of the node set needs to be optimized, determine the coverage of the function. Then the area coverage of the node set is expressed by the ratio of the area coverage of the node set to the area of the whole target monitoring area.

2.3. Construction of finite element model of bridge stress structure

The measured static and dynamic responses of the structure can reflect the mechanical characteristics of the structure. Selecting the static and dynamic characteristics as the correction target can effectively increase the evaluation basis of the model correction results and make the finite element model closer to the real situation. When combining static and dynamic force to modify the model, it is necessary to carry out modal analysis and calculation and static analysis and calculation respectively. Optimization with ANSYS optimization analysis module is often accompanied by a large number of finite element calculation processes. For the model modification of large-scale structures with large number of elements and complex calculation, the amount of calculation is too large. The effective order of modal parameters to be corrected in ANSYS may change, which may lead to the change of modal analysis order. According to the material grade, component size and boundary conditions in the structural design information, the initial finite element model is established by ANSYS. The main beam adopts solid unit Solid4_5. The main beam rib adopts plate shell element Shell63. The stay cable adopts the tie rod only unit Link10. Beam element Beam188 is adopted for cable tower and pier. The modified objective function of the finite element model of simultaneous static and dynamic forces is defined as:

\[
Y = \omega \left( \frac{f_1 - f_2}{f_2} \right) + \varphi \left( \frac{h_1 - h_2}{h_2} \right)
\]  

\( \text{(4)} \)

In formula (4), \( Y \) represents the modified objective function; \( \omega \) and \( \varphi \) represent the frequency and cable force weight coefficient, which is taken as 0.5 in this paper; \( f_1 \) and \( f_2 \) represent calculated and measured frequency values; \( h_1 \) and \( h_2 \) represent the calculated value and measured value of cable force. The parameters to be corrected mainly include material properties, structural dimensions and boundary conditions.

2.4. Design of structural safety monitoring algorithm for bridge stress

The purpose of bridge stress structure safety monitoring is to measure the environmental and working parameters, observe the static and dynamic characteristics, evaluate the state and safety, and give guiding bridge inspection conclusions and structural management and maintenance measures. On the premise of ensuring the safety of people's lives and property, effective measures are taken in time to avoid or reduce the losses caused by disasters, providing scientific safety management means for
bridge management departments. Therefore, it is particularly important to establish a safety monitoring algorithm which is sensitive to bridge structural damage and can quickly, scientifically and reasonably identify bridge diseases. The flow of bridge stress structure safety monitoring algorithm designed in this paper is shown in Figure 1.

As shown in Figure 1, safety monitoring is realized by setting an early warning threshold. In this paper, the bridge monitoring state is divided into three levels: normal state, primary early warning state and secondary early warning state. Combined with the actual situation, this paper selects the standard deviation of the average value of statistical samples plus or minus 5 times of samples as the upper and lower limits of the first-class early warning threshold of monitoring items. According to the above analysis, the mathematical expression of primary early warning index is shown in formula (5).

$$\vartheta = \eta \pm 5\epsilon$$ (5)

In formula (5), $\vartheta$ represents the level I early warning threshold; $\eta$ represents the average value of the sample; $\epsilon$ represents the standard deviation. The deflection change directly reflects the overall linear change of the bridge, and its change trend can characterize the bearing capacity of the bridge to a certain extent. In this paper, the deflection monitoring output value is the deflection change, which can be calculated by the following formula.

$$\Delta \alpha = (\alpha_t - \alpha_0) + (\hat{\alpha_t} - \hat{\alpha}_0)$$ (6)

In formula (6), $\Delta \alpha$ represents the calculated value of deflection measuring point; $t$ represents the measurement time; $\alpha_t$ and $\alpha_0$ represent the measured value and initial value of the measuring point; $\hat{\alpha}_t$ and $\hat{\alpha}_0$ represent the measured and initial values of the base point. So far, the design of vehicle bridge stress structure safety monitoring method based on wireless sensor technology has been completed.

3. Experiment

3.1. Experimental preparation

Based on wireless sensing technology, this paper puts forward a safety monitoring method of vehicle bridge stress structure. Taking a vehicle bridge in a city as an example, the bridge deflection is monitored. It has a total length of 1629.5m. It is designed according to the left-right separation type. The half width of the bridge is 12.128m, with a total of 50 holes. The span of the main bridge in the river is 50+100+170+170+100+50m, and the superstructure adopts prestressed variable section continuous box girder. 20#-22# pier top beam body shall be poured by pier side bracket, and other main beam sections shall be constructed by precast cantilever method. The bridge has been in operation for more than 20 years since its opening time. The mid span and quarter point deflection
measuring points are used to track the long-term deformation of the structure and the deflection deformation under the action of live load. The pier top position measuring points are used to track the settlement of the structural support and provide reference for other deflection measuring points.

3.2. Experimental results and analysis

In order to verify the test accuracy of the monitoring method proposed in this paper, manual leveling is carried out, and the results are taken as the actual measured values, and the deformation is compared with the monitoring results. At the same time, the bridge stress structure safety monitoring methods based on machine vision and GPS differential positioning technology are selected as the control group, which are compared with the monitoring methods based on wireless sensor technology in this paper. The cumulative deformation measurement results of different methods are shown in Table 1.

Table 1 Cumulative deformation measurement results

| Test point | Position   | Manual measurement (mm) | Method in this paper (mm) | Machine vision based method (mm) | Method based on GPS differential positioning (mm) |
|------------|------------|-------------------------|---------------------------|---------------------------------|-----------------------------------------------|
| 1          | 18# Pier top | 0.1                     | 0.2                       | 2.0                             | 1.8                                           |
| 2          | 19# Mid span | 3.9                     | 4.3                       | 5.6                             | 5.2                                           |
| 3          | 19# Pier top | 1.6                     | 1.8                       | 2.4                             | 2.3                                           |
| 4          | 20# Mid span | 2.1                     | 2.4                       | 2.8                             | 3.4                                           |
| 5          | 20# Pier top | 0.4                     | 0.7                       | 1.1                             | 1.3                                           |
| 6          | 21# Mid span | 0.3                     | 0.5                       | 1.2                             | 2.6                                           |
| 7          | 21# Pier top | 0.5                     | 0.7                       | 1.6                             | 2.4                                           |
| 8          | 22# Mid span | 3.1                     | 2.8                       | 4.2                             | 5.4                                           |
| 9          | 22# Pier top | 0.7                     | 0.3                       | 1.5                             | 1.8                                           |
| 10         | 23# Mid span | 1.2                     | 1.4                       | 1.8                             | 2.5                                           |

According to the measurement results in Table 1, there is a certain deviation between the bridge deformation obtained by the three methods and the actual value of manual leveling. Further compare the deviation between the monitored value and the actual value, and the results are shown in Figure 2.

![Figure 2 Comparison results of bridge disturbance deformation deviation](image)

According to the comparison results of bridge disturbance deformation deviation in Figure 2, the deformation deviation of the monitoring method proposed in this paper is significantly smaller than that of the monitoring methods based on machine vision and GPS differential positioning technology. Taking the average value of the monitoring deviation, the average deviation in this paper is 0.26mm,
which is 0.77mm and 1.22mm smaller than the monitoring methods based on machine vision and GPS differential positioning technology, indicating that the monitoring method in this paper is more accurate. Therefore, the disturbance monitoring effect of the method proposed in this paper is feasible, and the test effect can meet the application requirements of practical engineering.

4. Conclusion
In order to improve the anti-interference performance of the bridge structure safety inspection process, thereby improving the accuracy of the safety inspection. This paper presents a safety monitoring method of vehicle bridge force structure based on wireless sensing technology. This paper uses probabilistic perception model to establish a wireless coverage network, uses wireless perception technology to collect monitoring data, establishes static and dynamic response equations, and completes bridge safety monitoring. The test results show that the average deformation deviation of the monitoring method of this method is 0.26mm, the disturbance deformation monitoring deviation of this method is small, the monitoring effect is good, and it meets the actual needs of bridge engineering. However, there are still some imperfections in the method of this paper, so the later stage has the following prospects. In future research, it is necessary to further optimize the power supply mode of wireless sensor nodes and add new charging management technologies to make the system reasonable and sustainable.

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