Dynamic Geometry Monitoring System and Its Application in Sutong Bridge Construction

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Abstract  The construction period of large cable-stayed bridges is long, and the structure deformation is complicated. Any error during construction will potentially affect the cantilever alignments and the internal forces. In order to ensure safety during construction and to accurately determine the bridge deformation, consecutive dynamic monitoring is needed during the superstructure construction. This paper aims at the requirement of deformation monitoring during the Sutong Bridge construction, and introduces the realization and observing schemes of the GPS and georobot based on remote real-time dynamic geometrical deformation monitoring system, then researches the data processing methods and enumerates some of the application achievements. Long-term operation during the Sutong Bridge construction indicates that the system runs steadily and the results are reliable.

Keywords  dynamic geometry monitoring system; Sutong Bridge; GPS; construction

Introduction

The large cable-stayed bridge is a high static indeterminate structure and the construction process is complicated. Any error during construction will potentially deflect the alignments and internal forces and decrease the life and load capacity of the bridge after it is opened to traffic. In order to ensure safety during construction and to accurately determine the bridge deformation, consecutive dynamic monitoring is needed during the superstructure construction.

Total stations, accelerometers and displacement sensors are usually used for deformation monitoring of large structures. However, they cannot meet the requirements of consecutive, real-time and automatic dynamic monitoring of large bridges during construction because of their disadvantages, such as total stations needing a clear line of sight, data collected by accelerometer needing a double integration process to get displacements, and they cannot determine the static and quasi-static components, and the fact that the displacement sensor is a kind of touch sensor and it may be impossible to be used in some construction fields. The recent advances of modern measurement technology such as Global Positioning System (GPS) and robotic total station (georobot) bring new technical measures. The search
of literature indicates that GPS can be used to measure the deformations of large construction structures such as cable-stayed bridges, suspension bridges and high-rise buildings[1-7]. Several simulation trials have shown that GPS is capable of measuring displacement amplitudes above 2 mm and frequencies up to 50 Hz[7-8]. GPS based displacement monitoring systems have been used to monitor the health status of large bridges, such as the Guandong Humen Bridge and the three bridges of Tsing Ma Control Area, after they were opened to traffic and shown to be effective.

In this paper, the requirements of deformation monitoring for the superstructure construction of Sutong Bridge are outlined first. The architecture of the GPS and georobot based real-time dynamic geometric deformation monitoring system and the measurement schemes are introduced, data processing methods are discussed, and some initial results are analyzed.

1 Background

The Sutong Bridge lies between Nantong and Changshu in the east of Jiangsu province, China. The main bridge is a double-cable-plane, double-pylon steel box girder cable-stayed bridge with 1088 m central span and 62 m height. The bridge and its approaches are a six-lane expressway design, with a maximum speed of 100 km/h. It creates four world records for cable-stayed bridges: central span length (1088 m), bridge pylon tower height (300.4 m), stayed cable length (577 m), and pile groups scale (plane dimension: 112 m×48 m, depth: 125 m).

The bridge is located at the lower reaches of the Yangtze River in China, where the monsoon and diurnal thermal cycle effects are severe. All kinds of poor conditions cause the pylon towers, the cantilevers and the cables to displace and/or vibrate, which will affect the reliability and precision of the measurement results. Under this circumstance, an automated dynamic deformation monitoring system is proposed to exactly estimate the cantilever alignments and internal forces, to monitor the critical construction situation, and to estimate and forecast the poor state and guide the construction.

2 System Architecture

The monitoring system is a remote real-time dynamic deformation monitoring system developed by integrating GPS, georobots, data communication, and the Internet, and consists of two subsystems. It can work in all weather conditions and achieve real-time, high accuracy results automatically, which makes it easy to acquire data at nighttime and under abnormal weather conditions for further analysis.

2.1 Remote GPS based real-time dynamic monitoring subsystem

The subsystem consists of a GPS reference station, a total of 8 GPS monitoring points, an Internet data commutation system and a control center. Both the reference station and the monitoring points are equipped with dual-frequency GPS receivers. The reference station broadcasts GPS correction via the wireless local area network (WLAN) in a specified interval. The monitoring points automatically compute their antenna positions in real-time according to the received correction and send them to the control center with up to 10 Hz frequency. The control center management software analyzes the results and displays them on the computer screen immediately. All of the raw data and results are saved to the local database so that one can retrieve them for further analysis. The network structure of the subsystem is shown in Fig.1.

The reference station is located on top of a low building on the traffic dock of the construction site, which will shorten the distances from the monitoring points and improve the GPS precision. The control center is located in the courtyard of the project department. Two of the monitoring stations are mounted on top of the towers and the others are distributed at the same side over the bridge deck (small circles in Fig.1 denote 5 other monitoring points on the bridge deck). Their setting processes follow the girder construction as:

1) When the cantilever is constructed up to 200 m from the pylon towers, the first pair of monitoring points is fixed on the upriver side of the cantilevers.

2) The second pair of the monitoring points is set when the girder is constructed up to 300 m. They
keep standing on the front of the cantilever and move forward with the progress of cantilever construction. When the cantilever is constructed up to 400 m, the second pair is fixed.

3) As the cantilever is constructed forward, the third pair of monitoring points is set and moves forward with the cantilever till the closure segment construction. During this period, there are totally 6 GPS monitoring points on the bridge deck. Their deployment is shown in Fig.1.

![Fig.1 System network structure](image)

The data link of the subsystem is an ad hoc point-to-multipoint wireless network (11 m bandwidth) based on the spread spectrum techniques. For clear line of sight between each segment of the subsystem, a relay station is set on the top of the south pylon tower to improve the communication quality.

2.2 Georobot based dynamic deformation monitoring subsystem

Considering the requirements of the bridge deck deformation monitoring, the georobot based dynamic deformation monitoring subsystem works in the following two modes during the cantilever construction: one is called fixed-point tracking, and the other is specified period scanning. Prisms should be deployed on all the monitoring points so that the georobot can survey continuously during a mission.

For the first mode, the georobot automatically tracks each point at a specified time interval. It measures the 3D coordinates at a higher speed (up to 3 Hz) and saves the results into a memory card. A piece of software developed by the working group is used to analyze the data and output the equilibrium positions and dynamic characteristics of the monitoring points. This mode is suitable for deformation monitoring in dynamic environments.

For the second mode, the georobot scans the targets one after another automatically. Considering the vibration of the cantilever, it measures each point at least 4 circles within 2 minutes. The targets should be in a relatively stable state in order to ensure the synchronization of the observation results.

The scheme of specified period scanning using tri-dimensional coordinate method for the pylon tower deformation monitoring is shown in Fig.2. The georobot is set on the transition pier or the auxiliary pier. Two of the construction densified control points on the brackets inside the tower legs serve as backsight and check point. A total of 44 monitoring points are set on each tower.

The scheme of specified period scanning survey of the cantilever is shown in Fig.3. One of the construction densified control points inside the tower leg serves as the master station and the other as an aux-
iliary station. The monitoring points on both the central and side span are monitored in each work. 8

Fig.2  Periodic scan of georobot for bridge pylons

Fig.3  Periodic scan of georobot for bridge deck

Custom bridge axis coordinate system is determined by moving the origin of the independent coordinate system to an appointed point on the bridge axis or its extended line and rotating the x-axis of the independent coordinate system about the origin to the bridge axis. The relationship between the two coordinate systems can be determined by Eq.(1) as follows:

\[
\begin{pmatrix}
X_i \\
Y_i
\end{pmatrix} = \begin{pmatrix}
X_0 \\
Y_0
\end{pmatrix} + \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix} \begin{pmatrix}
x_i - x_0 \\
y_i - y_0
\end{pmatrix}
\]

where \(\theta\) denotes the angle of rotation, \((x_i, y_i)^T\) and \((x_0, y_0)^T\) are the independent coordinates of monitoring points and origin of the custom bridge axis coordinate system, \((X_0, Y_0)^T\) denotes the coordinate of the origin of the bridge axis coordinate system, \((X_i, Y_i)^T\) denotes the custom bridge axis coordinates of the monitoring points. The vertical component is computed by surface fitting. Coordinates from the above transformation process should be able to directly represent deformations in the longitudinal, lateral and vertical direction of the bridge. Results of georobots are referenced to the custom bridge axis coordinate system, which is convenient to compare them with the results of GPS monitoring points so as to improve the reliability of the systems. The \(x\) and \(y\) direction of the custom bridge axis coordinate system is shown in Fig.4.

Fig.4  Schematic layout of field on May 16, 2007

3  Data analysis

3.1 Unification of coordinate system

GPS results are referenced to World Geodetic System 1984 (WGS84), while the bridge construction coordinate is based on Beijing Geodetic Coordinate System 1954 (Beijing54). Data of GPS coordinates should be transformed to Beijing54[9].
3.2 Accuracy analysis

In order to estimate the accuracy of the GPS monitoring system, data collected by NO# and SO# on Jan 14, 2007 and Jan 19, 2007 are selected respectively, during which the effects of the influential factors (wind load, thermal effects, construction situation, etc.) are not obvious, and the results should reflect the true accuracy of the system. The monitoring points collected data at 0.1 s interval (10 Hz). Considering that the dynamic deformation of the monitoring points will distort the results more or less, a great deal of data occupying the whole days was utilized for statistical analysis. 1-min, 2-min, 5-min and 1-h data with 1 hour interval are chosen respectively for analysis and 24 groups of results for each series are obtained. Their mean values are listed in Table 1.

| Period | \( m_x \) (mm) | \( m_y \) (mm) | \( m_H \) (mm) |
|--------|----------------|----------------|----------------|
| NO#    |                |                |                |
| 1-min  | 3.6            | 2.8            | 8.4            |
| 2-min  | 4.0            | 3.0            | 9.2            |
| 5-min  | 4.4            | 3.4            | 10.3           |
| 1-h    | 4.9            | 4.3            | 13.2           |
| SO#    |                |                |                |
| 1-min  | 3.4            | 2.6            | 7.4            |
| 2-min  | 3.6            | 3.0            | 8.0            |
| 5-min  | 4.0            | 3.1            | 9.3            |
| 1-h    | 4.7            | 4.4            | 12.4           |

It can be seen from Table 1 that accuracy obtained from 1-min and 2-min data are better than ±5 mm in horizontal direction and ±10 mm in vertical direction. Compared with the results computed from 5-min and 1-h data, it is concluded that the mean square error decreases with the data length. It is because the monitoring points were always unstable and the distribution of the data tends to disperse, which will decrease the mean square error. To sum up, data selected is dispersed by the dynamic deformation of the monitoring points and the accuracy of the subsystem is actually better than the above results.

Theoretical and statistical analysis was conducted for the georobot subsystem. The results indicate that the positioning accuracy is better than ±5 mm.

3.3 Dynamic characteristics analysis

Vibration statuses (magnitudes and frequencies) are important parameters of safety and health of a bridge. As the spans of the bridges are increasing, the effects of wind loads to structures are being attached more importance. It is very important to understand that studies are needed for the partially complete structures as well as the completed structures. The performance of a structure under the effect of wind loads should be investigated during the various construction stages of the cable-stayed bridge. The sampling rate of GPS dynamic monitoring system is set at 10 Hz, which means that frequencies below 5 Hz can be extracted by performing spectrum analysis according to Nyquist’s Sampling Theorem. The Fast Fourier Transform (FFT) is a widely used and efficient algorithm for implementing Discrete Fourier Transform (DFT), which is used to transform discrete data from time domain to frequency domain. By performing FFT and comparing the extracted fundamental characteristics with that of other construction situation or abnormal weather conditions, the bridge health status can be evaluated, which provides critical information for construction control.

Take data collected on May 16, 2007 as an example. The cantilever was constructing section J31# at that time. Strong wind was blowing from approximately west-northwest and the wind direction varied from 283° to 293° and was relatively stable. The schematic layout of the field is shown in Fig.4 and the time series of wind velocity is shown in Fig.5. It should be noticed that it was adjusting cables during 18:00-19:30, so data collected during two periods of 16:00-17:00 and 20:30-21:30 was selected to compute dynamic characteristics that were not affected by external force. The results are shown in Fig.6. Data collected by GPS N3# and GPS NO# during 17:00-17:30 and 18:00-18:30 were also analyzed. All of the results are listed in Table 2.

| Period | GPS N3# | GPS NO# | Situation |
|--------|---------|---------|-----------|
| \( Y(Hz) \) | \( H(Hz) \) | \( X(Hz) \) |
| 1  | 0.090  | 0.091  | None      |
| 2  | 0.090  | 0.095  | None      |
| 3  | 0.092  | 0.095  | None      |
| 4  | 0.090  | 0.190  | Adjusting cables |

Results of Table 2 and Fig.6 indicate that:

1) During periods 1 and 2 of N3#, the fundamental frequencies of lateral direction are both 0.090 Hz and
the amplitudes are approximately 5 mm; in vertical direction, the frequencies are 0.194 and 0.195 respectively and the amplitudes are smaller than that of lateral direction. During these periods of N0#, the fundamental frequencies are both 0.191 Hz in longitudinal direction. There are no fundamental frequencies detected in longitudinal direction of N3#, lateral and vertical directions of N0# GPS monitoring points, and they are not listed here.

2) During period 2, there is a 1 Hz frequency (where the arrows point at) shown in the three directions, while this frequency is not shown in period 1. This phenomenon was possibly caused by the vibration of cables.

3) Comparing the results of period 1 and 2 with that of period 3 and 4, it is evident that wind loads and construction situation will cause the bridge to behave differently.

For other periods the same spectrum analysis was conducted and similar results were obtained. From this it can be seen that although the GPS data is noisy, the fundamental bridge frequencies can still be identified. Changes in the fundamental frequency of a bridge could indicate the health status of the bridge.

4 Discussion

The authors introduce a dynamic monitoring system designed for detecting the dynamics of civil structures. The architecture and layout scheme and data processing methods of this system are presented in the paper. Long-term operation during the Sutong Bridge construction indicates that the system operates very well. The main conclusions are as follows.

1) The system is capable of operating in all weather conditions and obtaining high accuracy results, which make it easy to collect precious data of the bridge during weather anomaly and at nighttime.

2) The accuracy of the GPS monitoring subsystem is within ±5 mm in the horizontal direction and ±10 mm in the vertical direction at the sampling rate of 10 Hz, which makes it possible to find the fundamental frequencies of the measured displacements and to clarify their dynamic characteristics.
3) Software was developed and embedded into the georobot subsystem, which makes it easy to operate in the two proposed modes. Long-term application indicates that the system runs steadily. The measured locating error of georobots was estimated to be within ±5 mm.

4) Dynamic characteristics of the bridge during a working situation are researched using data collected by the GPS subsystem. Results indicate that fundamental frequencies of the bridge are accurately obtained.

5) With two subsystems operating independently, the results of one subsystem will serve as a check for another, which realizes the objective of “double control” for the construction of Sutong Bridge.

This paper only demonstrates some initial results. It is concluded that the GPS and georobot based dynamic deformation monitoring system is reliable and can successfully monitor the geometric and dynamic deformations of cable-stayed bridges.

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