Large Structure Health Dynamic Monitoring Using GPS Technology

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Key words: Large Structure, Health Dynamic Monitor, Global Positioning System (GPS).

ABSTRACT

Structure health dynamic monitoring works, which measure key structure parameters systematically, provide valuable information in current evaluation of structure integrity, durability and reliability. Large structures, such as long bridges, towers and tall buildings, may vibrate and displace during the typhoon, temperature change, load change and earthquake. To measure the structural vibration and displacement some traditional measurement methods, such as accelerometer, laser interferometer and electronic distance measurement instrument, are adopted. These methods have some disadvantages. For example, accelerometer cannot measure the swing of total vibration of structure because acceleration cannot be obtained well and truly when structure moves slowly, laser interferometer and electronic distance measurement instrument are limited by climate condition, i.e. clear line of sight is the basic condition in which they can work.

Global Positioning System (GPS) technology not only overcome the limitation of climate, but also measure the structure displacement in three-dimensional directions. An mm-level accuracy can be obtained by using a differential GPS carrier-phase approach, and the sampling frequency of 10 Hz or even 20 Hz are now available from several GPS receivers. All these improvements provide a great opportunity to monitor dynamic charactristics of large structures in real-time or near real-time.

In this paper, we first briefly outline conventional methods for measuring structural vibration and displacement, then discuss the methodology of monitoring large structures by using GPS technology. Some cases of monitoring structures using GPS, such as long suspension bridges, high building are given. Monitoring data management schema and visualization contents are discussed by some examples. It put forward that the future trend is development ing a structures health monitoring system integrating GPS, Database, and visualization techniques under the Internet or Intranet.

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1. INTRODUCTION

Structure health dynamic monitoring works, which measure key structure parameters systematically, provide valuable information in current evaluation of structure integrity, durability and reliability. Large structures, such as long bridges, towers and tall buildings, may vibrate and displace during the typhoon, temperature change, load change and earthquake. To measure the structural vibration and displacement some traditional measurement methods, such as accelerometer, laser interferometer and electronic distance measurement instrument, are adopted. These methods have some disadvantages. For example, accelerometer cannot measure the swing of total vibration of structure because acceleration cannot be obtained well and truly when structure moves slowly, laser interferometer and electronic distance measurement instrument are limited by climate condition, i.e. clear line of sight is the basic condition in which they can work.

Global Positioning System (GPS) technology not only overcome the limitation of climate, but also measure the structure displacement in three-dimensional directions. An mm-level accuracy can be obtained by using a differential GPS carrier-phase approach, and the sampling frequency of 10 Hz or even 20 Hz are now available from several GPS receivers. All these improvements provide a great opportunity to monitor dynamic charactristics of large structures in real-time or near real-time.

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2. CONVENTIONAL MEASUREMENTS FOR MONITORING STRUCTURES

There are some conventional methods for measuring structural vibration or displacement. These methods include measurement with accelerometer, measurement with a laser interferometer and measurement with an electronic distance measurement instrument (Lovse, 1996).

Accelerometer measurement is the standard method of measuring structural vibration. It is very light, small size and thus have a minimal effect on the properties of the vibrating system. But it requires direct contact of the sensors with the structure, and wiring is also required to link the accelerometers to a central recording unit. The wiring can easily be damaged. Accelerometer cannot measure the swing of total vibration of structure because acceleration cannot be obtained well and truly when structure moves slowly.

The measurement of laser interferometer is used to measure the changes in distance between the interest point and the reference point by using laser interferometer. A prism or reflective

film must be mounted at the point of interest. The distance change versus time can be collected and be further analyzed to determine dominant frequencies and corresponding amplitudes. This method has the advantage of high accuracy, but it is difficult to catch the measure point when the shake or vibration of structures is too big.
Electronic distance measurement is similar the laser interferometer method. It can be carried out with much less expensive equipment. But the resolution of the changes in distance and the sampling rate are much lower than for a laser interferometer. For one electronic distance measurement instruments with a sampling rate of c Hz, it can only be used to collect the information with frequency of less than 0.5c Hz
Laser interferometer and electronic distance measurement instrument are limited by climate condition, i.e. clear line of sight is the basic condition in which they can work. In addition, they have some disadvantages, such as the measurements in different interest points are not synchronous, it is difficult to measure the bigger displacement, and it is difficult to get the observations in real time. In a word, all these traditional methods are limited, and not satisfied to the demands of monitoring dynamically large structures in the aspects of continuity, real-time and automatization.

3. CHARACTERISTIC OF GPS TECHNOLOGY

GPS technology has advanced significantly during the past decade. The accuracy of positioning is improving, the equipment is reducing in weight and size, the software has improved functionality, the system is more users friendly, and yet the cost of GPS is reducing. There are some advantages by using GPS technique to monitor vibration and displacement of large structures.
Firstly, GPS technology overcome the limitation of climate, GPS position work can be carried out all the day in despite of atrocious weather even if the rainstorm climate.
Secondly, GPS positioning belongs to satellite positioning. Differential GPS Real-Time Kinematic (RTK) positioning can be carried out as long as the interest point can receive the signals coming from 5 satellites and the differential signal transmitting from the reference benchmark. It is not necessary that there should be sighted between different interest points. The measurement values at different interest points are absolute.
Thirdly, GPS technology can measure the structure displacement in three-direction. Displacement measurement by using GPS technology has a high degree of automatization. The works from receiving signal, catching satellite to achieving Real-Time Kinematic differential displacement can be carried out automatically by instrument.
Lastly, GPS positioning has the characteristics of high positioning speed and precision. An mm-level accuracy can be obtained by using a differential GPS carrier-phase approach. GPS receiver with sampling frequency 10 Hz or even 20 Hz are now available from several manufacturers, and GPS data processing method is improved and perfected.
In summary, all these improvements provide a great opportunity to monitor dynamic charactristics of large structures in real-time or near real-time by using GPS technology.

4. MONITOR THEORY AND DATA PROCESS

Because of the vibration and displacement of the structures are smaller, so a high accuracy GPS location method should be adopted when monitoring large structures by using GPS technology.To obtain mm-level accuracy, a differential GPS carrier-phase approach can be used. The specific differential technique was the double-difference technique, which eliminates the satellite and receiver clock errors, reduces orbital and atmospheric errors.For the vibration range of rigidity structures is small, it is difficult to monitor rigidity structures by GPS. GPS are in common used to monitor the flexible structures, such as long-span cable-supported bridges, high buildings and so on.

4.1 Differential GPS

Differential GPS (DGPS) is a technique that data from a receiver at a known location is used to correct the data from a receiver at an unknown location. Differential corrections can be applied in either real-time or by post-processing. Since most of the errors in GPS are common to users in a wide area, the DGPS-corrected solution is significantly more accurate than a normal GPS solution.

Differential GPS Real-Time Kinematic (RTK) positioning can be carried out as long as the interest point can receive the signals coming from 5 satellites and the differential signal transmiting from the reference benchmark.

In Reference and remote station, the data collection should be synchronous for 15 to 20 minutes at least so as to carry out difference GPS.

4.2 Composing of monitor system

Monitor system of structures is consisted of GPS reference station, remote stations, communication system, and monitor central, see figure 1. A GPS reference station tracks all GPS satellites that are in view at its location, and all antennas in remote stations simultaneously received satellite signals from several satellites. At least four satellites are required to obtain accurate positioning. At the reference station, the difference information received from the satellites is transmitted to the remote stations in real time by using the cable of the communication system. In the remote station, the signal received from the satellites and the difference information from the reference station is received, and the remote station coordinates in three-dimensional can be calculated by carrying out the real time difference processing using GPS software. The coordinates are then transmitted to the GPS monitoring center, and are further processed so as to get the structures' displacements, rotation angle in a special direction. Cable-suspension bridges, for example, the displacements in three directions-longitudinal, lateral, and vertical is calculated in general. All these displacements are stored into database so as to make health assessment about the structures in future.

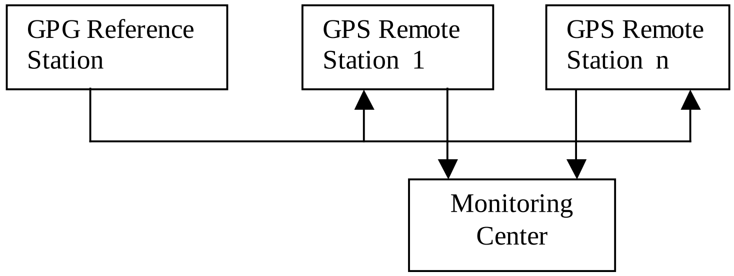

Figure 1 Graph of monitoring system composing

4.3 Selection of reference points and remote points

Because of atmospheric and orbital errors increases with the distance between the reference and the remote station, it is possible to set up the reference station at a relatively short distance from the remote station. At present case, when the distance was 1 km or less the effect of atmospheric and orbital errors are expected to be at or below the millimeter level. More than 5 degree above the horizon there should be no structures keep out the satellite signal or no reflective structures around, so as to reducing the errors of multipath.

The selection of the remote station is related to the importance, deformation size, and the captured information of the structures. In general, the remote station should be located at the interest points, the biggest deformation points or the feature points of structure. A long-span cable supported bridge, for example, the remote points are located at the middle of the bridge deck, one fourth of the bridge deck or on the top of the bridge tower. The middle bridge deck would, theoretically, experience the greatest displacement.

4.4 Data processing

The objectives of monitoring is to obtain the displacements of the interest points in special directions-vertical, lateral and longitudinal, and further analyses the relation of displacement versus temperature, relation of diplacement versus wind velocity, and relation of diplacement versus load of structures and so on. The data processing include coordinates transform, spectral analyses, data extract and structures health assessment etc.

Because of the coordinates obtained by GPS technology belongs to WGS-84 coordinate system, the coordinates should be transformed into coordinates in structural coornate system. Thus the displacements in the axial direction of structures and the time-range curve of structures can be obtained, and it is convenient to monitor the displacement of interest points real-time. Analyzing the vibration frequency and amplitude so as to diagnose soundness of structures. Spectral analyses could be conducted using the disperse speedness Fourier transform method. By spectral analyses, we can get the power spectral densities in different direction, such as lateral and vertical directions.

As the rough data collected from the monitoring system are often huge in volume, it is difficult to store these accumulating data. How to find an extract the useful information hiding in the masses of these unanalyzed data so as to reduce the data volume to an acceptable size for storage is a challenging issue.

Assessing the structural condition and evaluating the structural safety and serviceability, based on the monitored information, is one of the desired objectives of a monitoring system.

5. SOME CASES OF MONITORING LARGE STRUCTURES

There are some successful cases which monitoring the large structures using GPS, such as Calgary Tower in Canada, Humber bridge of UK, Akashi Kaikyo Bridge in Japan, Three cable-supported bridges of Hong Kong, and Humen suspension and Diwan Building in China, and so on.

Dynamic deformation monitoring has been done for Calgary Tower Calgary, Alberta, Canada, using differential GPS carrier-phase approach in 1993 (Loves, 1995). The top of the tower is approximately 160m above the ground level. One GPS receiver at the reference station located on a tripod on the roof of low-risk apartment building situated approximately 1 km north of the tower, and two GPS receivers on the tower (one is backup). Data collection frequency is 10 Hz about 15 min on the morning of November 19,1993. The monitoring results show that the frequency of north-south and east-west movement is about 0.3 Hz, the north-south amplitude is approximately ±15mm and the east-west amplitude is approximately ±5mm.

Humber bridge in UK was monitored using Kinematic GPS (Ashkenazi,1997). The Humber bridge is located across the Humber estuary on the east coast of England. Consisting of three sections, in an approximately north-south direction, the bridge spans 2220 m, supported by two towers 155.5 m high. The real-time monitoring of a bridge by 'Kinematic GPS' was carried out by putting individual GPS antennas on strategic points on the bridge deck (midspan) and the support towers, and continuously positioning these relative to a reference receiver. The latter was situated 1.5 km away from the bridge, and was considered as a fixed three-dimensional benchmark. The equipment used for the Humber bridge monitoring experiment consisted of two Ashtech Z-II dual-frequency GPS receivers, a pair of Racal Delta Link II UHF telemetry links and a real-time version of Ashtech's PNAV processing software run on a Pentium-90 laptop PC. The objectives of this work is to monitor the displacement of the bridge deck at midspan in the axial directions of the bridge, and the displacement of support tower in the north-south, east-west and vertical directions.

Akashi Kaikyo Bridge in Japan with a center span length of 1991 meters, has been installed an advanced monitoring system (Fujino, 2000). In this system GPS technology is using to determine the coordinates at 3 point, the middle of the center span, one of tower top and anchorage, and further calculate the displacements in the axial direction. Determination of configuration of the bridge under temperature change is made using GPS. In addition to GPS measurement, temperature was also measured at the corresponding points so as to obtain the relationship of temperature to displacement. The objective of the monitoring is to ensure the traffic safety and their structural soundness.

In Hong Kong of China, there are three cable-supported bridges, namely, Tsing Ma Bridge (TMB), Kap Shui Mun Bridge (KSMB) and Ting Kua Bridge (TMB) in Tsing Ma Control Area (TMCA). Structural health monitoring by using GPS technology has been implemented in the three bridges (Wong, 2000). The GPS monitor system is composed of four sub-systems, namely, GPG surveying system, information collection system, information processing and analyses system, and system running and control system. GPS receivers are

located mainly on the two sides of the bridge body and the top of the bridge tower. There are 27 positions set up GPS receivers and the sampling frequency is 10 Hz. The three-dimensional coordinates obtained through the difference GPS real time Kinematic are transferred to the information processing and analyses system synchronously by the information collection system. The objectives are to monitor the instantaneous displacements of the bridge body and the bridge tower in real time, and further calculate the stress of main structures and assess the carrying capability, working status and enduring capability.
In the mainland of China, as respect of monitoring structures displacements by using GPS technology, there are some successful cases such as Humen suspension bridge real time monitoring (Xu, 2001), Diwang building displacement monitoring (Guo,1997). The Humen suspension bridge has a span of 1538.5 m. For monitoring the bridge working status in real time under the typhoon, traffic loads and temperature, there are 7 GPS remote stations located on the position of middle, one fourth and one eighth of the bridge. The sampling frequency is 5 Hz. The bridge safety monitoring work beginning on May 2000, and the practice shows that the monitored displacement obtained by GPS surveying could be used for bridge safety analyses. The Diwang building is 324.95 m high. The remote station was located on the top of itself and the reference station located on a lower building about 500m away on the south-west direction. The dynamic displacement and vibration frequency were measured by GPS while it was attached by typhoon. The result shows that the location accuracy reaches ±5mm, vibration frequency is 0.1-10Hz.

6. MANAGEMENT AND VISUALIZATION OF MONITORING DATA

In the long-term structures monitoring system, as the rough data collected from the monitoring system are too huge in volume to store these accumulating data. A special measure should be adopted to store the rough data. In addition, some data coming from the data processing and data analyses system should be managed efficiently too. Database is a good tool for managing huge data. The better method to manage the monitoring data is to create dynamic database. The data in the dynamic database should be updated automatically with a regular interval, i.e. the existing data in the database could be backup and be replaced regularly by new data. For data share, a database based on Internet or Intranet should be adopted, such as SQL Server database management system. For the huge rough data, the creating database scheme that one days' monitoring data creating a daily database has some advantages. For example, it is very convenient to create database, database backup and restore, and retrieve data from database. Based on the above ideas we created successfully the database for monitoring data at the Ting Kua Bridge in TMCA of Hong Kong.
Visualization is a powerful means to explain huge data. In the real time monitoring system of structures, the visualization of monitoring data could reflect the dynamic change situation of the structures more clearly. Different observation has different visualization methods. There are some data need to be visualized, such as graphs of daily fluctuation of temperature and displacement in three-dimensional, graph of variations of the displacement over a certain period in the axial direction of the structures, relationship graph of temperature to displacement, relationship graph of loading to displacement and so on. In the long suspension bridge monitoring system, the status graph of the bridge deck displacement in vertical direction is very useful to view the bridge change under the different loads in real time.

7. CONCLUSION

With the development of GPS technology, the accuracy of positioning is improving distinctly. GPS technology has some advantages comparing the conventional monitoring methods in structures monitoring. GPS technology overcome the limitation of climate, and can work all the day in despite of atrocious weather even if the rainstorm climate. An mm-level accuracy can be obtained by using a differential GPS carrier-phase approach, and the sampling frequency of 10 Hz or even 20 Hz are now available from several GPS receivers. Three-dimentional coordinates can be obtained continuously by using GPS surveying. All these improvements provide a great opportunity to monitor dynamic charactristics of large structures in real-time or near real-time. Developing a structures health monitoring system integrating GPS, Database, and visualization technique under the Internet or Intranet is the future objective.

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REFERENCES

Ashkenazi V., and Roberts G.W., (1997), Experimental monitoring of the Humber bridge using GPS, Proc., Instn. of Civ. Engrs, 120, Nov., 178-182

Fang Q., Yuan J.P. Zheng E., (1999), Satellite positioning and navigation foundation, Xian: Southwest industry university press

Fujino Y., Murata M., Okano S., Takeguchi M., (2000), Monitoring system of the Akashi Kailkyo Bridge and displacement measurement using GPS, Proceedings of SPIE Vol. 3995,229-235

Guo J.J, Sang R.B, Guo S.J, Xie B.T, Bai T., (1997), Bigbuilding displacement monitoring with GPS, , Geotechnical investigation & surveying, 1997(3), 48-51

Lovse J.W., Tesky W.F., Lachapelle G., etc, (1995), Dynamic deformation monitoring of tall structure using GPS technology, Journal of Surveying Engineering, Vol. 121(1), 16~22

Wong K.Y., Lau C.K., Filint A.R., (2000), Planning and implementation of the structural health monitoring system for cable-supported bridges in Hong Kong, Proceeding of SPIE Vol.3395, 266-276

Wong K.Y., Wen J.L.,Chen W.E., Lau C.K.,(2000), Application of GPG in bridge structure health monitoring, Proceeding of fourteenth China bridge science conference,827-839

Xu L., Gu J.J, Dai L.J. Lu Y.C., (2001)Humen bridge diplacement real time monitoring data anlyses based on GPS, Geotechnical investigation & surveying, 2001(1), 48-49

BIOGRAPHICAL NOTES

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