MONITORING THE DYNAMIC CHARACTERISTICS OF TALL BUILDINGS BY GPS TECHNIQUE

LUO Zhicai
CHEN Yongqi
LIU Yanxiong

KEY WORDS  kinematic GPS technology; dynamic characteristics; tall buildings; auto-regressive spectral analysis

ABSTRACT  Dynamic characteristics of large structures, such as tall buildings, long-span suspension, cable-stayed bridges and tall chimneys, are key to assess their drift and stress conditions. The dynamic characteristics of large structures are difficult to measure directly under the condition of earthquakes or strong winds using traditional techniques such as laser collimator, total station and accelerometers. Therefore there is a great need for developing new method or technique for this purpose. Recent advances in Global Positioning System (GPS) technology provide a great opportunity to monitor long-period changes of structures reliably. GPS receivers capable to gauge the motion at the centimeter or sub-centimeter level with sampling frequency 10Hz or even 20 Hz are now available from several manufacturers. To the authors’ knowledge, the capability of identifying dynamic characteristics from GPS observations has not been widely verified. For the feasibility study on using kinematic GPS technology to identify the dynamic characteristics of tall buildings, some experiments were conducted in a simulative environment. This paper discusses in detail the experiment device, and the ways through them GPS data are recorded, processed and analyzed. With post-processing version of NovAtel’s Softsurv software and auto-regressive (AR) spectral analysis method, relative displacements and corresponding vibrating frequencies have been derived from GPS observations. The results indicate that the dynamic characteristics can be identified accurately by kinematic GPS technology.

1 Introduction

Dynamic characteristics of large structures, such as tall buildings, long-span suspension, cable-stayed bridges and tall chimneys, including relative displacements and vibrating frequencies, are key to assess their drift and stress conditions. These structures are difficult to measure directly, especially under the condition of earthquakes or strong wind/typhoon. In general, accelerometers are the most common instruments used to monitor the response of structural systems, but displacement measuring requires processing by double integration. The integration process cannot be automated because of the following requirements of signal processing: (a) choice of filters and baseline correction (the constants of integration), and (b) substantial judgments when anomalies exist in the records. Consequently, this process can lead to errors in the calculation of velocities and displacements so measurements with accelerometer can not be used to discover displacements at the centimeter level in real-time.
or near real-time. Other traditional methods, like laser collimator and total station, can be also applied to measure displacements at very high precision, but can not work properly during earthquakes or strong winds/typhoons, and in most cases do not work in real-time or near real-time. Until recently, there are no efficient or feasible methods to measure displacements during an earthquake or severe wind. Therefore, there is a great need for developing a new method or technique to monitor the dynamic characteristics of large structures precisely in real-time or near real-time under bad conditions.

Fortunately, recent advances in Global Positioning System (GPS) technology enable above-mentioned long-period changes of structures to be reliably monitored. GPS receivers with a capability of resolving motion at the centimeter or sub-centimeter level and sampling frequency 10 Hz or even 20 Hz are now available from several manufacturers. That provides a great opportunity to monitor long-period changes of structures reliably, and will be very useful for structural health monitoring purposes.

Xu et al. (1998) established the GPS automatic surveying system to monitor the deformation of Geheyan Dam, and demonstrated that the accuracy of horizontal component can arrive at 1.0 mm and 1.5 mm of vertical component (1 ~ 2 hours solution). Guo and Ge (1997) derived preliminary results including relative displacements and frequencies of Diwang tower from GPS observations under the condition of strong winds in Shenzhen, China. Ashkenazi et al. (1997) obtained the initial exciting results for monitoring the movements of bridges by GPS. All these results demonstrated that GPS can monitor the response of large structures at sub-centimeter level. But to the authors' best knowledge, the capability of identifying dynamic characteristics from GPS observations has not been widely verified. In this paper some experiments in a simulative environment are described for feasibility study on using kinematic GPS technology to identify the dynamic characteristics of tall buildings. The methods for processing GPS data and analyzing the results are then discussed.

2 Simulating and monitoring dynamic characteristics of tall buildings

2.1 Experimental equipment

The experimental equipment consists of GPS receivers NovAtel-Outrider-DL-RT2 dual frequency GPS receivers with sampling frequency of 10 Hz and vibrating unit which is composed of power amplifier, signal generator, signal analyzer, regulator, exciter, displacement sensor, mass block and rigid beam or elastic beam (see Fig. 1(a) and (b)), it can generate simple harmonic vibration or damped simple harmonic vibration with known vibrating frequency and amplitude. The intrinsic frequency of the vibrating unit is determined by the mass of GPS antenna, the material and geometrical dimensions (length, width and height) of rigid or elastic beam. Fig. 1 (a) and Fig. 1 (b) display the working principle of the vibrating unit, where Fig. 1(a) is suitable for GPS test with vibrating frequency above 1Hz, and Fig. 1(b) below 1Hz.

2.2 Simulating dynamic characteristics

In general, the majority of large structures such as tall buildings are flexible steel framed structures whose fundamental period (T, in seconds) can be approximated with the empirical formula $T = 0.1 N$, where $N$ is the number of stories of a building. Considering other factors, the vibrating or swaying frequency of tall buildings is almost in the range of 0.1 ~ 10 Hz. Moreover, the movement (swaying) of tall buildings is of a simple harmonic nature, due to wind loading or earthquake, as well as the vertical movement or lateral movement of bridges due to traffic loading. To investigate the feasibility of identifying dynamic characteristics of tall buildings by kinematic GPS technology, we designed a series of vibrating status with different simple harmonic nature, but only two typical sets with vibrating parameter (frequency and amplitude) are listed in Table 1 for horizontal and vertical vibration respectively. In practice, the movement of tall buildings is very complicated, so only following two simple and typical cases are taken into consideration.
Case 1 The swaying of tall buildings satisfies following simple harmonic equation

\[ y = A \sin(2\pi ft + \varphi_0) \] (1)

where \( y \) is displacement; \( A \) amplitude; \( f \) frequency; \( t \) time and \( \varphi_0 \) initial phase. And provided the changes of amplitude and frequency by external force decreased or increased suddenly during the swaying of tall buildings, which corresponds to case 1 listed in Table 1.

Case 2 The swaying of tall buildings satisfies following damped simple harmonic equation

\[ y = Ae^{-\alpha(t-r)}\sin(2\pi f(t - \tau)) \] (2)

where \( \alpha \) is damped coefficient; \( r \) initial time, and other quantities have the same meanings as those in Eq. (1). This case corresponds to case 2 listed in Table 1, and simulates the case that external force disappeared suddenly during the swaying of tall buildings.

2.3 Monitoring dynamic characteristics

To minimize the influence of external environmental factors, the experiments were conducted in an open area with little multi-path effect. Two NovAtel-Outrider-DL RT2 GPS receivers were used. One GPS antenna was mounted at the middle of elastic beam (see Fig. 1 (a)) or at the tip of rigid beam (see Fig. 1 (b)), which is used as rover station. And the other one is located about 10 m away from the rover station, which is called as fixed station. Sampling frequency is 10 Hz, a minimum of five satellites and cut-off elevation 10( are selected, and about ten minutes GPS observations are recorded for every vibrating status. In addition, all experiments were carried out only in sunny day or cloudy day due to the restriction of working condition for the vibrating device.

3 Data processing and analysis

3.1 Methods of data processing

3.1.1 GPS baseline solution

NovAtel’s Softsurv software was used for processing the GPS observations. Then the relative displacements in every epoch for each vibrating status are obtained. NovAtel’s Softsurv is powerful processing tool capable of computing relative positions with sub-centimeter or centimeter-level accuracy in less than ten minutes if the following conditions are ready: (1) dual-frequency, full-wavelength data, (2) PDOP<4, (3) a low multi-path field environment, (4) a minimum of five satellites and preferably six or more satellites and (5) a minimum number of cycle slips caused by obstructions. Its
major advantage is the ability to resolve or fix the carrier-phase integer ambiguities while the receiver is in motion or on-the-fly with dual frequency data. Unlike standard kinematic processing, it does not require a static initialization or an antenna swap to solve the ambiguities and does not require the field operator to return to a known point if lock on the satellites is lost while the receiver is moving from point to point. To display clearly the change of relative displacements from GPS observations for every vibrating status, Fig. 2 (a), (c), (e) and (g) are given only in some short period.

![Fig. 2 Relative displacements from GPS and corresponding normalized auto-regressive spectra for various vibrating status](image)

**3.1.2 Auto-regressive spectral analysis**

To detect the dynamic characteristics of tall buildings implied in the relative displacements from GPS observations, auto-regressive spectral analysis method is employed in this paper. Auto-regressive (AR) model for time series data \( x_n (n = 1, 2, \ldots, N) \) is described as

\[
x_n = \sum_{i=1}^{p} a_i x_{n-i} + e_i
\]

where \( a_i \) is the coefficient of the AR model, \( e_i \) white noise and \( p \) is the order for the AR model determined by the FPE or AIC criteria presented by Akaike (1973). The coefficients are derived by
the Yule-Walker equation consisting of autocorrelation estimates with different time lags of the data series \( x_n \).

Eq. (3) can be obtained from Burg algorithm or Marple algorithm. The Marple algorithm can provide more precise estimates of frequencies and can decrease the splitting of spectral peaks (Zheng and Luo, 1992). Thus, we use the Marple algorithm for carrying out the AR spectral analysis in this paper. The results obtained by AR spectral analysis are summarized in Table 1. Fig. 2 (b), (d), (f) and (h) show the normalized AR spectra for every vibrating status.

### 3.2 Analysis of results

The left part of Fig. 2 ((a), (c), (e) and (g)) clearly show the motion of rover station and time-history of relative displacements from GPS observations, and the right part ((b), (d), (f) and (h)) correspond their normalized auto-regressive spectra. It can be directly perceived from these figures that the simulated dynamic characteristics of tall buildings can be measured by kinematic GPS technology. Moreover, for the same sampling frequency, the higher the vibrating frequency, the worse the form of wave. This illustrates that the sampling frequency of GPS receiver should be as high as possible to measure the detail movements of tall buildings. From Fig. 2 (a) and (g) it can be seen that the amplitude for the same vibrating frequency is not very stable, this is caused by the noise of vibrating unit, noise of GPS observations, wind loading and other environmental factors, so the value of amplitude provided by vibrating unit is an average value.

Table 1 summarized the spectral analysis results. The column “Known” and “Estimated” are the value supplied by vibrating unit and derived from GPS observations respectively. From this table we can see that a very precise frequency can be derived from GPS data, but the higher the vibrating frequency, the larger the error of amplitude and frequency. This also indicated that the sampling frequency of GPS receiver should be as high as possible to measure the detailed dynamic characteristics of tall buildings. Moreover, the estimated frequency for horizontal and vertical component is of almost same accuracy, but the derived amplitude of horizontal component is slightly better than that of vertical component. We can conclude that accurate dynamic characteristics such as relative displacements and low frequencies can be determined by kinematic GPS technology.

### Table 1 Spectral analysis results of various vibrating status

| Vibrating status | Amplitude/mm | Frequency /Hz | Known | Estimated | Relative error | Known | Estimated | Relative error |
|------------------|--------------|---------------|-------|-----------|--------------|-------|-----------|--------------|
|                  | Known       | Estimated     | Relative error | Known       | Estimated     | Relative error |
| Horizontal       | 80.0        | 78.5          | 1.9%  | 0.20       | 0.1999       | 5.0x10^-4 |
| Case 1           | 49.8        | 48.8          | 2.0%  | 0.40       | 0.3997       | 7.5x10^-4 |
| Case 2           | 100.0       | 97.4          | 2.6%  | 1.062      | 1.0629       | 8.5x10^-4 |
| Vertical         | 49.0        | 47.9          | 2.2%  | 0.20       | 0.1999       | 5.0x10^-4 |
| Case 1           | 79.3        | 77.4          | 2.4%  | 0.40       | 0.3997       | 7.5x10^-4 |
| Case 2           | 80.0        | 77.5          | 3.1%  | 1.287      | 1.2785       | 6.6x10^-3 |

### 4 Conclusions

Accurate low frequency dynamic characteristics of tall buildings can be determined by kinematic GPS technology. In general, vibrating or swaying frequency of tall buildings can be derived from GPS observations provided that the sampling frequency meets sampling theorem. To obtain accurate dynamic characteristics of tall buildings, the sampling frequency should be preferably higher. This capability also allows reliable monitoring of long-period large structure changes such as dam, tall chimney and suspension or long-span bridges, especially under the condition of typhoon, earthquake and flood. Its advantage is that the movements of large structures can be measured in real-time or near real-time and with sufficient accuracy. Furthermore, with future advances in GPS technology and improvements in sampling capability, it will be possible to monitor
short-period structures as well.

Considering the practical purposes, following points should be taken into account.

1) The sampling frequency of GPS receiver should be as high as possible, so that the detailed movements of tall buildings can be measured accurately.

2) To obtain reliable results, at least two GPS reference stations (fixed station) should be set up, as well as at some key monitoring points.

3) Measuring methods have to be developed to reduce the multi-path effects.

4) Program or scheme should be developed to permanently deploy GPS units for monitoring tall buildings, and to assess and mitigate the effects on structures of the natural hazards such as typhoon, flood and earthquake.

5) GPS automatic monitoring and early-warning system should be established, which have the functions of GPS data collecting, data transmitting, data processing and analyzing, deformation analyzing, early-warning, etc.

Acknowledgements

We are grateful to Mr. Mannars T. C. Chan, Mannars Chan & Associates, for supplying NovAtel-Outrider-DL-RT2 GPS receivers. We also express our deep gratitude to Prof. Zhou Chuangan and Mr. Xu Qinghua, both from the Institute of Vibrating Engineering, Nanjing University of Aeronautics and Astronautics, for designing the vibrating unit for our GPS test.

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