Measurement of wind-induced response of buildings using RTK-GPS

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Abstract

Accelerometers have been used for field measurements of wind-induced responses of buildings. However, wind-induced response consists of a static component, i.e. a mean value, and a dynamic fluctuating component. The static component is difficult to measure by accelerometers. An RTK-GPS (Leica MC1000) has a nominal accuracy of $7 \pm 1$ cm + 1 ppm for horizontal displacements and $7 \pm 2$ cm + 2 ppm for vertical displacements with a sampling rate of 10 Hz. This study aims to demonstrate the feasibility of RTK-GPS for wind-induced response measurements and its efficiency in measuring the displacement of a full-scale tower.

As the first experiment, the accuracy of Real-Time Kinematic-Global Positioning System (RTK-GPS) in measuring sinusoidal displacements was examined, using an electronic exciter. When the vibration frequency was lower than 2 Hz and the vibration amplitude was larger than 2 cm, RTK-GPS results seemed to closely follow the actual displacement.

The efficiency of RTK-GPS was then demonstrated in the full-scale measurement of an actual steel tower. Based on the feasibility study of RTK-GPS for measuring wind-induced responses of buildings, the responses with amplitudes larger than 2 cm and natural frequencies lower than 2 Hz can be detected by RTK-GPS.

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1. Introduction

Accelerometers have been used for field measurements of wind-induced responses of buildings. However, wind-induced response consists of a static component, i.e. a mean value, and a dynamic fluctuating component. The static component is difficult to measure by accelerometers. Čelebi [1] proposed to use Real-Time Kinematic-Global Positioning System (RTK-GPS) for measurements of responses of buildings. An RTK-GPS (Leica MC1000) has a nominal accuracy of $\pm 1\text{ cm} +1\text{ ppm}$ for horizontal displacements and $\pm 2\text{ cm} +2\text{ ppm}$ for vertical displacements with a sampling rate of 10 Hz [2,3]. Considering the static component and the first mode predominance for wind-induced responses, GPS is better for wind-induced response measurements. The objectives of this paper are to study the feasibility of RTK-GPS for wind-induced response measurements and to demonstrate its efficiency in measuring the displacement of a full-scale tower.

2. RTK-GPS

Fig. 1 shows the outline of the response measurement using RTK-GPS. GPS surveys the distance from a certain point on the earth to a GPS satellite by measuring the exact traveling time of the electric wave transmitted from the satellite to an antenna at the measuring position. GPS generally requires 4 satellites to obtain the information of 3 components of the position ($X, Y, Z$) and the time. However, RTK-GPS requires one more satellite for real-time high-frequency (10 Hz) measurements. There are many causes for errors, e.g. position dilution of precision (PDOP), clock and orbit errors of satellites, ionosphere and troposphere delays, multi-path and so

![Fig. 1. Response measurement by RTK-GPS.](image-url)
on. However, if two antennas relatively close to each other in the global scale receive the same electric waves from the same satellites simultaneously, the error sources may be the same. Therefore, if the position of one of the two points, i.e. reference point, is fixed and exactly known, the error of the GPS survey can be accurately detected at any moment. If the error information obtained at the reference point is immediately transmitted as a correction signal to the other point, i.e. moving measuring point, the error of the position survey of the measuring point can be minimized. This is the outline of the position survey by RTK-GPS.

3. Accuracy of RTK-GPS

Before the full-scale measurement of the response of an actual tower, the basic characteristics of RTK-GPS were examined.

The background noise of the RTK-GPS survey was first examined. The GPS antenna not only at the reference point but also at the measuring point was fixed on the roof of a rigid 3-story RC building on the TIP campus. Fig. 2 shows an example of a 10 min locus of the RTK-GPS signals for X and Y directions at the stationary measuring point. Although the measuring point was not moving, the X and Y signals fluctuated in the ranges of about ±1 cm for the X direction and ±1.5 cm for the Y direction. Fig. 3 shows an example of the 10 min mean of the stationary point. The 10 min mean value fluctuated ±5 mm. The error can be thought to result from the background noise of the measuring system using RTK-GPS. It should be noted that the background noise was influenced by PDOP, which depends on the geometrical arrangement of the satellites.

The accuracy of RTK-GPS in measuring sinusoidal displacements was next examined, using an electronic exciter. Fig. 4 shows the set up of the sinusoidal vibration tests. A GPS antenna was mounted on the exciter, and a wire displacement transducer was set to measure the actual displacement. Table 1 shows the ranges of amplitude and frequency for the sinusoidal vibration tests. Figs. 5 and 6 compare the

Fig. 2. Example of fluctuation of RTK-GPS outputs for a stationary point (10 min).
Fig. 4. Sinusoidal vibration tests using an exciter.

Table 1
Amplitude and frequency ranges for sinusoidal vibration tests

<table>
<thead>
<tr>
<th>Frequency: $f$ (Hz)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude: $Y$ (cm)</td>
<td>0.3</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 5. Comparison of RTK-GPS output and actual displacement by wire displacement transducer ($Y = 2$ cm): (a) $f = 0.5$ Hz; (b) $f = 1$ Hz; (c) $f = 3$ Hz and (d) $f = 4$ Hz.
temporal variations of the displacements measured by RTK-GPS and the wire displacement transducer. When the vibration frequency was lower than 2 Hz and the vibration amplitude was larger than 2 cm, RTK-GPS results seemed to closely follow the actual displacement.


Fig. 7 shows a 1.6 m high elastic model with 5 lumped masses. The elastic model can vibrate with along-wind, across-wind and torsional components. A GPS antenna and accelerometers were set on the top of the model. The lowest natural frequency and the damping ratio of the model were 1.32 Hz and 1.52%, respectively. Fig. 8 compares the temporal variations of the across-wind displacement by RTK-GPS and its acceleration by the accelerometer. Considering the lowest natural frequency of 1.32 Hz, the displacement amplitude of 2 cm almost corresponds to 140 cm/s², and the displacement measured by RTK-GPS agrees closely with the acceleration records.

5. Measurements of wind-induced responses of an actual tower

As shown in Fig. 9, an anemometer, an RTK-GPS antenna and the accelerometers were set on the top of a 108 m high steel tower, and another RTK-GPS antenna as the reference point was set on the top of a rigid 16 m high RC building located next to the tower. Fig. 10 shows an example of the temporal variation of the response of
the tower in the $Y$-direction, which coincides with the wind direction $N$ during a typhoon. The RTK-GPS data is the sum of the static displacement of about 4 cm and the fluctuating component with a dominant frequency equal to the lowest natural frequency, 0.57 Hz. The acceleration record seems to correspond closely to the
Fig. 9. A 108 m high steel tower for full scale.

Fig. 10. Example of temporal variations of wind-induced responses of actual steel tower during a typhoon: (a) RTK-GPS (Y-dir.) and (b) accelerometer (Y-dir.).
fluctuating component of the displacement by RTK-GPS. Fig. 11 shows the temporal variation of the wind and the response data every 10 min during the typhoon. The wind direction was almost $N$, which corresponds to the $Y$-direction, when the typhoon was approaching and the wind speed was increasing before reaching its maximum mean wind speed of 19 m/s. For the RTK-GPS data shown in Fig. 11(d), only the records obtained under the conditions of the PDOP less than 2.5 were analyzed. The acceleration data $\sigma_{\text{ACC}}$ shown in Fig. 11(c) varies following the variation of wind speed shown in Fig. 11(b), and the displacement by RTK-GPS, $\sigma_{\text{DIS},Y}$, also follows the variation of $\sigma_{\text{ACC}}$. Fig. 12 shows the variation of the mean

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**Fig. 11.** Temporal variations of 10 min mean values of wind speed and responses of the tower: (a) Wind direction (most frequent value); (b) wind speed; (c) standard deviation of tip acceleration ($Y$-dir.) by the accelerometer and (d) standard deviation of tip displacement ($Y$-dir.) by RTK-GPS.

**Fig. 12.** Variation of 10 min mean tip displacement ($Y$-dir.) of the tower by RTK-GPS with 10 min mean wind speed.
displacement by RTK-GPS to the 10 min mean wind speed. The mean displacement increases almost in proportion to the square of the mean wind speed in the higher wind speed range. Fig. 13 shows the power spectrum densities of the tip responses. The power spectral density of the acceleration was converted to that of displacement multiplied by $(2\pi f)^{-4}$ for comparison with the displacement by RTK-GPS. Both spectra have a peak at 0.57 Hz corresponding the lowest natural frequency of the tower, although that of the displacement by RTK-GPS shows almost constant energy at the lower and higher sides of the natural frequency, which is attributed to the background noise of RTK-GPS.

The characteristics of vibration are estimated by the RD technique. Fig. 14 shows the free vibration wave obtained by the RD technique. From these free vibration waves, damping ratio and lowest natural frequency are estimated using the least-squares method. Both the lowest natural frequencies are 0.57 Hz. The damping ratio for acceleration signal is 0.94% and for RTK-GPS signal is 0.87%.

Since RTK-GPS measurement system can measure the static displacement, the deformation of the tower caused by heat stress can also be measured. Fig. 15 shows the deformation of the tower caused by heat stress. The day used for analysis was a calm and fine weather day. The marker means 1 h averaged data. Before sunrise, top of the tower did not move. However, after sunrise, top of the tower moved to NW direction by about 4 cm. Top of the tower moved in almost circular shape in the daytime, and returned to zero point after sunset.
Fig. 14. Free vibration wave obtained by the RD technique.

Fig. 15. Deformation of the tower caused by heat stress.
6. Concluding remarks

In this paper, we investigated the basic characteristic of RTK-GPS and applicability of RTK-GPS measurement system. We could obtain the following conclusions:

- RTK-GPS can measure the total displacement, not only its dynamic component but also the static component.
- GPS is available for response measurements under the following conditions:
  - Natural Frequency is smaller than 2 Hz.
  - Tip displacement is larger than 2 cm.
- In full-scale measurement, a static component of along-wind direction can be measured about 4 cm in Typhoon.
- The characteristics of vibration can be estimated not only for accelerometer signal but also for RTK-GPS signals.
- The deformation of the tower caused by heat stress can measure about 4 cm for maximum deformation using the RTK-GPS measurement system.

References