Effectiveness of GPS technology in monitoring of traffic-induced response of highway steel bridge

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Abstract. Despite some disadvantages, regarding the limited accuracy, the Global Positioning System (GPS) is widely used in monitoring of long-span bridges. This paper is concerned with the analysis of the capabilities and limitations of the use of the GPS technology in monitoring of semi-static and dynamic vertical responses of a highway steel cable-stayed bridge excited by traffic loads. The field test was conducted on the Maxau Rhine Bridge, located over the Rhine River near Karlsruhe, Germany. The so-called baseline method with the Post-Processing mode was applied using two units Leica Viva GS15. The basic characteristics of the GPS background noise before and after filtering were examined in the time and frequency domain. The natural frequencies of the bridge were extracted based on the vertical dynamic displacements recorded in the mid-span of the bridge using GPS and accelerometer. It was shown that the GPS receivers were able to measure only two primary modal frequencies of the bridge. The obtained experimental results proved that the GPS system is an efficient tool in measuring the vertical semi-static displacements of the bridge with satisfactory accuracy. Moreover, GPS is capable of tracking the vertical vibrations of long-period bridges to a few millimeters.

1. Introduction

Nowadays, the technology of Global Positioning System (GPS) became an alternative technique to monitor the semi-static and dynamic displacements of long-span cable-stayed or suspension bridges due to various ambient excitations, e.g. [1-3], and, based on it, to detect the potential structural damage of such structures, e.g. [4]. This is due to some important advantages of the GPS technology. Among other, the continuous long-term monitoring using GPS can be automated and performed regardless of the weather and visibility conditions. Moreover, the GPS system is able to measure structural displacements simultaneously in three directions, i.e. in two horizontal and one vertical directions. Due to the geometry of the satellite constellation the measurement accuracy in the vertical direction is about twice smaller than in the horizontal direction. Besides these advantages, the GPS measurement accuracy is susceptible to several kinds of error sources such as the noise of the GPS signals, limited data sampling rate, multipath effect, and GPS signals shielding effect due to shielding of a certain area of the sky by local obstacles. Recent advances in the sampling capability of the GPS technology allow us to monitor the total response of long-period engineering structures with 20 Hz, or even with 50÷100 Hz. Despite the constantly developing technology of GPS receivers the following question
arises: what is currently the effectiveness of the GPS technology in monitoring of bridge deformations?

This paper is concerned with the analysis of the capabilities and limitations of the use of the GPS technology in monitoring of semi-static and dynamic vertical responses of a highway steel cable-stayed bridge excited by daily traffic loads. The field test was conducted on the Maxau Rhine Bridge, located over the Rhine River near Karlsruhe, Germany. Two units Leica Viva GS15 as reference and rover units were applied, tracked the satellite signals at the data frequency equal to 20 Hz. The basic characteristics of the GPS background noise were examined in the time and frequency domain. The natural frequencies of the bridge were identified based on the recorded vertical dynamic displacements of the bridge. It was shown that the GPS receivers were able to measure only two primary modal frequencies of the bridge. To validate the GPS results, the dynamic response of the bridge was also recorded by an uniaxial accelerometer type PCB 3711E112G with the sampling rate of 200 Hz. In order to improve the measurement accuracy of the bridge deformations by GPS technology the filtering procedure using the eighth-order Type 1 Chebyshev band-pass digital filter with a selected pass-band frequency was adopted. The obtained experimental results proved that the GPS system is an efficient tool in measuring the vertical semi-static displacements of the bridge with satisfactory accuracy, and that GPS is capable of tracking the vertical vibrations of long-period bridges excited by traffic loads to a few millimeters.

2. GPS vertical background noise

The basic characteristics of GPS background noise was examined based on a static test using two GPS Leica Viva GS15 receivers. In the test the Kinematic On the Fly (KOF) method was applied in the Post-Processing Kinematic Mode (PPK-GPS) to determine the baseline (3D-vector) between two GPS units, i.e. reference and rover receivers. Both receivers were fixed in a stable position on concrete pillars at a distance of 15 m away from each other. One should be aware that increasing the distance between the rover and reference GPS units to several hundred meters does not affect the accuracy of measurements [5]. The static test was carried out with the sampling rate of 20 Hz in good GPS conditions. It means that a clear view to the sky on both GPS units was ensured and a good satellite configuration was prevailing defined by so-called the Geometric Dilution of Precision (GDOP) factor changing in the range from 1.7 to 3.7. The number of available satellites was 7-10.

The representative time series of the background noise \( B_V(t) \) of GPS system in the vertical direction recorded during a time interval of 33 min and 20 s (2000 seconds) are given in Fig. 1. Since the measured baseline between two GPS receivers was unchanged in time, it was assumed that any measured deviations from the expected baseline were considered as the signal background noise. For \( B_V(t) \) the statistical characteristics were calculated and are also given in Fig. 1.

\( B_V(t) \) was analyzed by the Fast Fourier Transform (FFT) and its Power Spectral Density (PSD) function is presented in Fig. 2. It is shown that \( B_V(t) \) contains two components, i.e. (1) the low-frequency noise component \( L_V(t) \), visible as a non-stationary trend with the dominant noise energy corresponding to the frequency range limited to 0.05 Hz, and (2) the high-frequency noise component \( R_V(t) \), visible as a random noise with the frequency over 0.05 Hz and the spectrum close to the white noise type spectrum. In this case the values of the spectrum are in the range between \( 10^{-6} \) and \( 10^{-5} \) m²/s.

![Figure 1. Time series of vertical background noise \( B_V(t) \) of GPS system recorded during measurements of the position of a stationary point over 33 min and 20 s (2000 seconds).](image-url)
Hence, the GPS background noise $B_V(t)$ can be expressed as follows:

$$B_V(t) = L_V(t) + R_V(t)$$  \hspace{1cm} (1)$$

where $L_V(t)$ is the low-frequency noise of GPS system, $R_V(t)$ is the high-frequency noise of GPS system, and $t$ is the time tracked according to the inverse of the sampling rate of GPS system.

In the baseline method the $L_V(t)$ component is mainly caused by the changing number of available satellites, their geometrical configurations and multipath effect appearing during the measurements. The $R_V(t)$ component is mainly caused by the noise of the GPS signals. In order to study the effect of two mentioned components, i.e. $L_V(t)$ and $R_V(t)$ on the GPS measurement accuracy, $B_V(t)$ was filtered using the eighth-order Type 1 Chebyshev high-pass digital filter with pass frequency range below or over 0.05 Hz, respectively. The obtained both $L_V(t)$ and $R_V(t)$ components and their statistical characteristics are shown in Fig. 3. $L_V(t)$ is changeable between -5.8 and 8.7 mm, while $R_V(t)$ between -11.8 and 8.9 mm with the standard deviation of 1.9 mm. Such the accuracy level determines the sensitivity threshold of the used GPS receivers in monitoring of the quasi-static and dynamic structural displacements.

3. Maxau Rhine Bridge and experimental set-up
The considered cable-stayed Maxau Rhine Bridge is located over the Rhine River near Karlsruhe in Germany. The bridge carries highway traffic along the Federal highway B10 with two three-lane carriageways, footpath and bicycle lanes on both sides. The design traffic velocity is 80 km/h.

The streamlined box girder of the bridge is made of steel with the total length of 292 m, width of 35.3 m, and deck depth of 3.0 m. The bridge comprises two continuous spans with lengths of 175.2
and 116.8 m, supported by a single rectangular 48.0 m tall (above a concrete pillar) pylon made of steel. The cross-section of the pylon is a box-type and has a rectangular shape with outer dimensions of 2.6x2.0 m. The pylon is founded on a reinforced concrete 24.7 m tall central pillar. The longitudinal layout of six stay cables is made in a semi-fan type system. All suspension cables are arranged in two layers in a flat rectangle and consist of 18 steel strands, each with a diameter of 82 mm. The general view and longitudinal section of the Maxau Rhine Bridge with the most important dimensions are shown in Fig. 4(a-b).

The purpose of the test was to measure the vertical response of the bridge, i.e. the semi-static and dynamic displacements caused by daily traffic loads using both GPS technology and accelerometer and, based on it, to investigate the natural frequencies of the bridge. The second goal of the field test was to investigate the capabilities and limitations of the use of the GPS technology in monitoring of the semi-static and dynamic vertical responses of the bridge.

The field test was carried out on June 16, 2016. The KOF method was applied using GPS Leica Viva GS15 equipment with two dual-frequency receivers temporarily installed as a reference and rover units. The reference receiver was mounted on a tripod about 250 m northeastern from the bridge. The rover receiver was located in the mid-span of the main span of the bridge and was installed on the handrail of the existing railing at the footpath lane on the south side. The position and installation way of the GPS rover receiver on the railing of the bridge are shown in Fig. 4(b-c). The measurements were carried out using the baseline method in which both GPS receivers tracked the satellite signals simultaneously with the same data frequency equal to 20 Hz. This frequency rate is appropriate to analyze dynamic displacements of the Maxau Rhine Bridge with an expected dominating frequency of about 0.5 Hz. The bridge displacements were processed using the PPK-GPS mode. During GPS monitoring the quality of satellite constellation geometry was favorable and was very similar to the conditions of the static test, described in Section 2. The GDOP factor was changed in the range from 1.7 to 2.9, while the number of available satellites was 7÷10. During the field test the air temperature was constant with the value of 11°C, while full cloudiness and windless period were observed. In such conditions the wind and solar radiation influence were negligible.

Figure 4. Maxau Rhine Bridge over the Rhine River near Karlsruhe, Germany: (a) general view, (b) longitudinal section with main dimensions and position of the GPS rover receiver, and (c) installation way of the GPS rover receiver on the barrier rail of the bridge.

To validate the GPS results, the dynamic response of the bridge was also recorded by an uniaxial accelerometer type PCB 3711E112G with the sampling rate of 200 Hz. The sensor was located inside the box girder of the bridge below the outside position of the GPS rover receiver. The high sensitivity accelerometer was based on the Micro-Electro-Mechanical System technology. The measurement
range of the sensor was ±2 g, the frequency range 0–400 Hz, the broadband resolution 0.1 mg rms in 0.5 to 100 Hz bandwidth, and the spectral noise 15 μg/√Hz in 1 to 100 Hz bandwidth. Such sensitivity is adequate for studying dynamic behaviour of the considered bridge.

4. Measurement results and their analysis

Fig. 5(a) depicts the total vertical displacements of the bridge under daily traffic conditions recorded using GPS system in the mid-span of the bridge. The field test was performed over 33 min and 20 s with the sampling rate of 20 Hz. Fig. 5(b-c) shows two components of the measured vertical displacements, i.e. the low-frequency component, namely the semi-static component, and the high-frequency component, namely the dynamic component of the bridge displacements. Both components were extracted from the total displacements by applying adequate post-processing filtering procedure using the eighth-order Type 1 Chebyshev high-pass digital filter with pass frequency range below or over 0.20 Hz, respectively. The semi-static component was caused mainly by the weight of moving vehicles, especially heavy vehicles, while the dynamic component was caused by the dynamic effects due to moving vehicles, random characteristics of the pavement roughness and bridge-vehicle interaction impact. The recorded bridge displacements, depicted in Fig. 5, were related to the position of the measurement point in a static equilibrium of the bridge (dotted line). This position was determined based on the geometrical data of the bridge without taking into account any external loads.

![Graph](image)

**Figure 5.** Vertical displacements of the bridge due to daily traffic loads, recorded using GPS system in the mid-span of the bridge on June 16, 2016 over 33 min and 20 s with the sampling rate of 20 Hz: (a) total displacements, (b) semi-static and (c) dynamic components of the displacements.

Regarding the static equilibrium the measured maximum semi-static displacement of the bridge was 78 mm with the mean value of 23 mm, while the amplitude of the dynamic displacement was ±16 mm with the standard deviation of 2.6 mm. It should be noticed that both measured components of the bridge displacements were significantly greater than the sensitivity threshold of GPS system recognized in Section 2 (see Fig. 3). However, one should be aware that the measured bridge responses are always overlaid by the background noise of GPS system.
Fig. 6 shows the vertical vibrations of the bridge due to daily traffic loads, recorded using GPS system in the mid-span in an enlarged time scale, during 180 s-interval, corresponding to the fragments indicated in Fig. 5(c). In this figure it is obviously visible that the measured dynamic response is disturbed by the GPS background noise. The displacements shown in Fig. 5(c) were analyzed by the FFT. The PSD function was estimated for the total length of interval time series of recorded displacements. Fig. 7 shows the PSDs of the recorded vertical displacements of the bridge and the GPS vertical background noise $B_V(t)$, as depicted in Fig. 2. The PSD of the measured bridge displacement is dominated by two well-separated peaks with $f_1 = 0.520 \text{ Hz} \ (T_1 = 1.923 \text{ s})$ and $f_2 = 1.012 \text{ Hz} \ (T_2 = 0.988 \text{ s})$, representing two primary natural frequencies of the considered bridge in the vertical direction. Because of the limited nominal measurement accuracy of GPS technology higher natural frequencies were not detected. Based on the analysis of PSD, the limit frequency of the semi-static components of the bridge displacements was identified as 0.2 Hz.

![Figure 6](image1.png)

**Figure 6.** Vertical dynamic displacements of the bridge due to daily traffic loads, recorded using GPS system in the mid-span in an enlarged time scale corresponding to the fragments indicated in Fig. 5(c).

![Figure 7](image2.png)

**Figure 7.** PSDs of recorded vertical dynamic displacements of the bridge by the GPS system and vertical background noise $B_V(t)$ of GPS system.

To validate the GPS results, the PSD of vertical accelerations of the bridge excited by traffic loads was determined and depicted in Fig. 8. The accelerations were recorded in the mid-span of the bridge on June 16, 2016 over 33 min and 20 s with the sampling rate of 200 Hz. A total of eight modal frequencies of the bridge were identified within the frequency range of 0÷4 Hz. The identified two primary modal frequencies of the bridge using the GPS system match well with those identified using the accelerometer. The maximum frequency difference was about 1.3%. Based on the analysis of the PSD of the bridge accelerations the frequency components of traffic excitations were also recognized within the frequency range of 8÷16 Hz. Thereby, it could be concluded that the modal frequencies of bridges can be satisfactorily identified when the clear separation between natural frequencies of structure and vehicle excitations is observed.

5. Improvement of GPS measurement accuracy by filtering process

In order to increase the measurement accuracy of the vertical dynamic displacements of the bridge using GPS technology the filtering procedure using the eighth-order Type I Chebyshev band-pass
Figure 8. PSD of vertical accelerations of the bridge due to daily traffic loads, recorded using the accelerometer in the mid-span of the bridge on June 16, 2016 over 33 min and 20 s with the sampling rate of 200 Hz.

digital filter with a selected pass-band frequency was adopted. Since two primary mode frequencies of the bridge were extracted on the PSD (see Fig. 7), a band-pass filtering process may reduce significantly the GPS background noise. For the considered dynamic displacements the filter pass-band range of 0.4÷1.1 Hz was selected to cover two identified modal frequencies of the bridge. The efficiency of the proposed filtering process to de-noise the GPS data was validated in the papers [6,7].

Fig. 9 depicts the high-frequency component $R_V(t)$ of GPS background noise (see Fig. 3b) after band-pass filtering process, denoted as $F_V(t)$. The pass-band filtering process leads to a fourfold reduction of high-frequency GPS noise. In this case the accuracy of de-noised vertical dynamic displacements is about ±3 mm with the standard deviation of 0.5 mm. The dynamic displacements of the bridge (see Fig. 5c) after filtering process using the eighth-order Type 1 Chebyshev band-pass filter with pass-band 0.4÷1.1 Hz and pass-band ripple 1 dB are shown in Fig. 10. Fig. 11 depicts the PSDs of filtered bridge displacements and the GPS background noise $F_V(t)$ for the time series shown in Figs 10(a) and 9, respectively.

Figure 9. Filtered high-frequency component $R_V(t)$ of GPS background noise.

Figure 10. (a) Filtered dynamic component of the vertical displacements of the bridge and (b) the filtered dynamic displacements in an enlarged time scale corresponding to the fragments indicated in Fig. 10(a).
6. Concluding remarks

The major outcome of the present study clearly proved that the GPS technology could detect the semi-static and dynamic components of the bridge response in the vertical direction under daily traffic excitations. The obtained results confirmed that the maximum values of the measured bridge displacements are significantly greater than the accuracy limit of the GPS system in the vertical direction. Based on the results of a static test using two GPS Leica Viva GS15 units it was found that the GPS measurement accuracy in the vertical direction was about ±9 mm for the low-frequency component (the noise frequency below 0.05 Hz), and ±12 mm for the high-frequency component (the noise frequency over 0.05 Hz). The filtering process using the eighth-order Type 1 Chebyshev band-pass digital filter with pass-band 0.4÷1.1 Hz and passband ripple 1 dB improved the measurement accuracy of the vertical dynamic displacements to ±3 mm.

The measured maximum semi-static component of the bridge displacements in the vertical direction due to the daily traffic loads was about 80 mm, while the amplitude of the dynamic displacements was about 16 mm. Based on the recorded bridge displacements using the GPS system two primary natural frequencies of the bridge could be extracted from FFT analysis, i.e. \( f_1 = 0.520 \) Hz and \( f_2 = 1.012 \) Hz. These frequencies match well with those detected using the accelerometer.

References

[1] Vazquez G E, Gaxiola-Camacho J R, Bennett R, Guzman-Acevedo G M and Gaxiola-Camacho I E 2017 Structural evaluation of dynamic and semi-static displacements of the Juarez Bridge using GPS technology Measurement 110 pp 146-153

[2] Han H, Wang J, Meng X and Liu H 2016 Analysis of the dynamic response of a long span bridge using GPS/accelerometer/anemometer under typhoon loading Engineering Structures 122 pp 238-250

[3] Yi T-H, Li H-N and Gu M 2013 Experimental assessment of high-rate GPS receivers for deformation monitoring of bridge Measurement 46 pp 420-432

[4] Miao C, Wang M, Tian H, Feng Z and Chen C 2015 Damage alarming of long-span suspension bridge based on GPS-RTK monitoring Journal of Central South University 22 pp 2800-2808

[5] Breuer P, Chmielewski T, Górski P and Konopka E 2002 Application of GPS technology to measurements of displacements of high-rise structures due to weak winds Journal of Wind Engineering and Industrial Aerodynamic 90 pp 223-230

[6] Górski P 2015 Investigation of dynamic characteristics of tall industrial chimney based on GPS measurements using Random Decrement Method Engineering Structures 83 pp 30-49

[7] Górski P 2017 Dynamic characteristic of tall industrial chimney estimated from GPS measurement and frequency domain decomposition Engineering Structures 148 pp 277-292