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An investigation of using high rate GNSS data in structural monitoring process

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Summary. This paper introduces results of investigation carried on by The Applied Geomatics Section in Military University of Technology. Research includes possibilities of monitoring dynamic behavior of a constructions using high rate GNSS data. Results of laboratory and two bridges tests are described below. Way of compute data and used software (TRACK MIT) are also shown in this paper.

INTRODUCTION

For about twelve years scientists from couple of world famous universities (ION 2003-2006) have been working on using GPS data to detect deformations of big structures like tall buildings, long bridges or dams. As they say, they success. Main elements of monitoring system includes high sample rate GNSS receivers and software able to calculate phase measurements to sub centimeter values.

The Applied Geomatics Section Military University of Technology began studies to develop reliable method of structure health monitoring using GPS phase observations. Whole project includes laboratory and bridges trials. Result of two bridges measurement projects are introduce in this paper: «im. Obrońców Modlina 1939» in Zakroczym and Siekierkowski Bridge in Warsaw (fig. 1).

Fig. 1 – Bridges location.

The whole project starts with hanged platform movement detection using 10Hz, post-processing data (fig. 2a, b). Next platform test utilized spring element to impute harmonic, high frequency loading (fig. 2c).

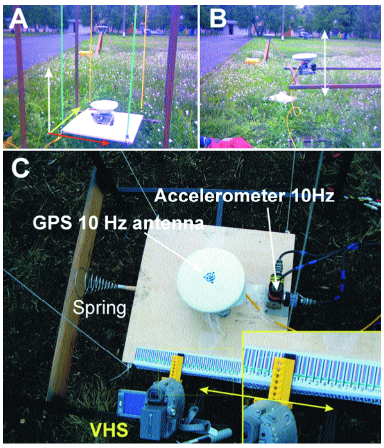

Fig. 2a) First test, first construction mode. b) First test, second construction mode. c) Second test.

During first laboratory test, free-hanged platform was used. Construction allowed to compute movements in 3 directions: $\approx N$, $\approx E$ and H. Measuring session included several types of dynamic forcing in 3D: big amplitude and low frequency, small amplitude and low frequency, small amplitude and high frequency. For vertical coordinates, only few deflections (seen on figure 2, H coordinate, as 5 cm picks) ware induced because second construction mode was used for only vertical movement detection.

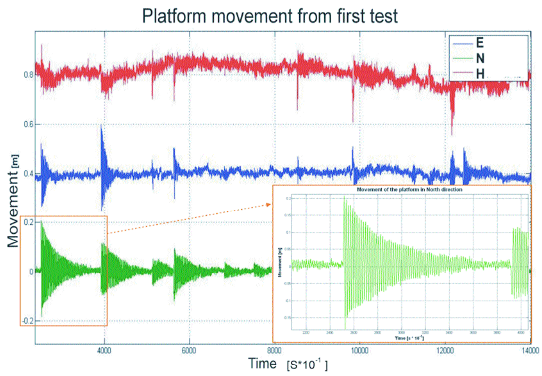

Fig. 3 – Results of kinematic intrusion during first platform test, first construction mode.

Second construction mode allowed for initiate vertical movements with different frequency. Furthermore, reaction of framed structure under loading and its relaxation movement were investigating. Three perturbations in beginning of fig. 3 describes this kind of intrusions.

First platform test in both construction modes showed promising results but did not give other movement data to compare with GPS. This was main premise to carry out second platform test. This time despite of GPS receiver, accelerometer and camera data were used.

The main task of using accelerometer was to get information about oscillation frequency of the platform. Fig. 5 describes results of Fast Fourier Transformation computed for three different, 20 seconds periods including GPS (North and East direction) and accelerometer data. It can be easily seen that two main movement frequencies are detected: 1.4 Hz and 2.2 Hz.

Thanks to cooperation with The Road and Bridge Management and The Warsaw Geodesy Company, it was possible to get permission to make first bridge test in Zakroczym. Investigated construction has 6 spans: two 75.0 m long and four 95.0 m long (fig. 6). Trial started at 3 p.m. and contained 5 hours of measurements. During this time loading of the construction is mainly caused by single trucks (42 t) crossing the bridge. Five geodetic GPS receivers were used: two 20 Hz receivers across second span, two 10 Hz receivers across third span and one 20 Hz as a reference station.

Video camera situated between second and third span captured type o vehicles crossing the bridge. Five hours movie and GPS data synchronization enables to figure out what kind of vehicle cause such deformations.

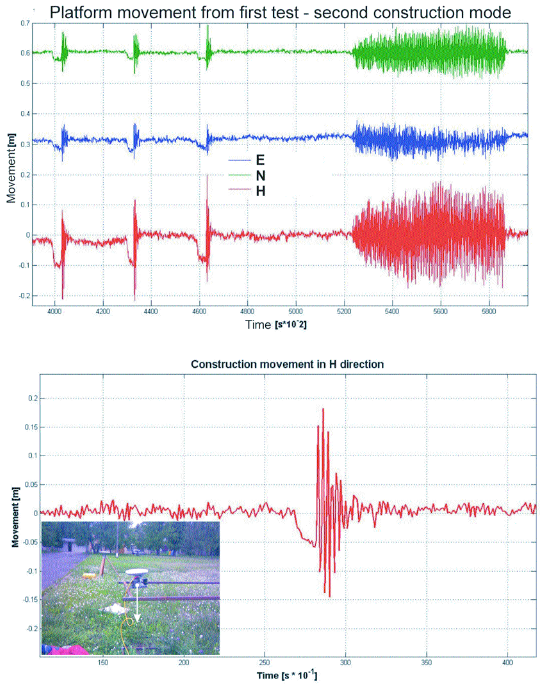

Fig. 4 – Results of kinematic intrusion during first platform test, second construction mode.

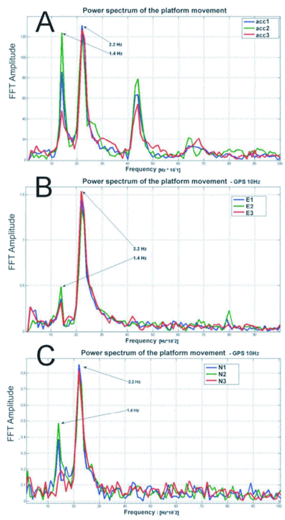

Fig. 5 – Construction movement frequency (three independent time series): A - Accelerometer; B - GPS East direction; C - GPS North direction.

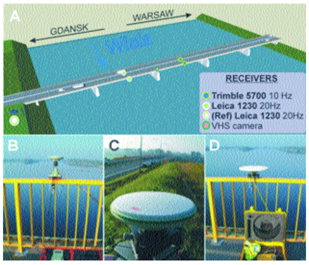

Fig. 6 – A) Receivers localization; B) Leica 1230 (20Hz); C) Reference Station Leica 1230 (20Hz); D) Trimble 5700 (10Hz).

To calculate results, all collected GPS data were converted to the RINEX format and split to 1 hour files. To get best result, precise ephemeris were used. Test with using rapid and ultra-rapid ephemeris didn't afford satisfying results because distance between receivers and reference station was about 150m.

Analysis process contained two steps. In first, GPS data and stability of kinematic solution were investigated. In second step, results were referred to the bridge construction. This interdisciplinary attitude engaged physics, bridge and geodesy specialists in this project.

Two characteristic cases are described below. In first, single cargo car load is analyzed, second shows set of heavy cars passing through the bridge.

Fig. 6 shows absolute high displacement caused by cargo cars pass the bridge. Truck entering can be clearly detected. Deflections increases to 2-3 cm and it was the most often value for cargo car (42 tons) type. Figure describes real deflection curve progress caused by 30 t loading car moving with speed of 97.7 km/h (1 and 2). Truck speed was recognized by distance between Leica and Trimble receivers (95 m). Fig. 7 also shows detected displacement caused by two trucks (3), rated 30 tons each. Cars were moving trough the bridge with speed of 72.8 km/h, distance between trucks was about 20 m.

Fig. 8 illustrates deflation recorded by Trimble 5700 situated on both sides of the road. It can be easily notice that left side of the road goes up when trucks cross the bridge. Right side goes down in the same time. Result shows possibility of detection not only vertical movements of construction, but also torsions of each element.

Next bridge trial have been carried on during 25 September night. Five hours data was collected from 3 to 8 a.m.. This campaign included apart of Military Academy of Technology crew (The Applied Geomatics Section), The Warsaw Geodesy Company with special participation of The Road and Bridge Management. Thanks to cooperation of these entities, nine GPS receivers could be used: two Trimble 5700 (10Hz) and seven Leica 1230 (20Hz). Two from seven Leica receivers were used as reference. Movement detectors (GPS receivers) ware located across middle part of the main span and also on the top of each pylon (fig. 9). Authors assumed that pylons movement can be detected during intensive load of the main span.

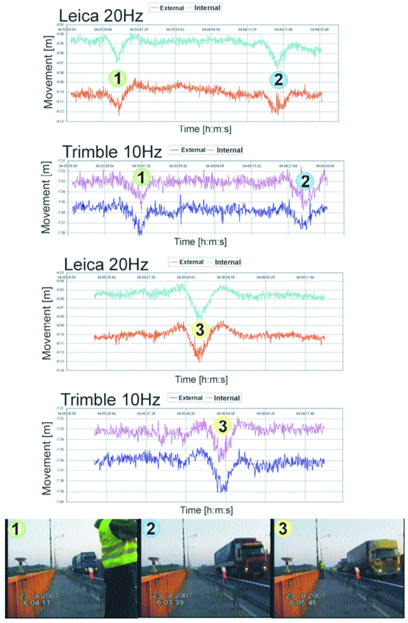

Fig. 7 – Sample results of the Zakroczym Bridge trial.

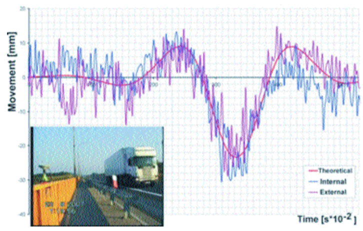

Fig. 8 – Detection of torsions of the road caused by truck crossing by at one side of the road.

Time of the event was assigned for midnight hours when the main load of the construction is caused by single cargo trucks. To precise identify extortions, three video cameras were located in trial field.

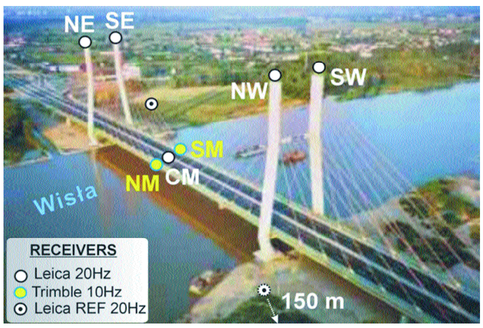

Fig. 9 – Receivers localization.

Siekierkowski Bridge is the second longest suspension bridge in Poland. Main span of the Siekierkowski bridge is 250 meters long. Suspended part of the construction has total length 500 meters. Dimensions of the main parts of the bridge are shown on fig. 10.

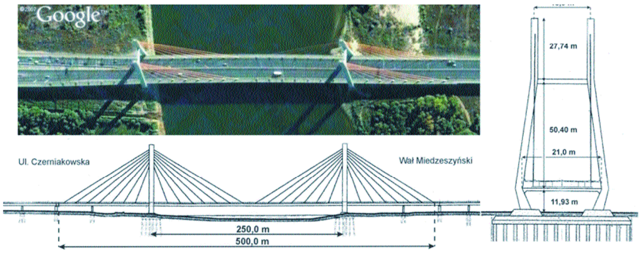

Fig. 10 – Siekierkowski bridge dimensions.

Sample results of campaign are described below. First plot from the top describes detection of vertical movement of the main span caused by two cargo cars crossing the bridge one after another (fig. 11 A). Two plots below shows change of distance between opposite pylons. Effect of construction work can be easily seen. When main span is forced by dynamic loading, distance between opposite pylons is visibly decreasing. Fig. 10 B shows similar situation.

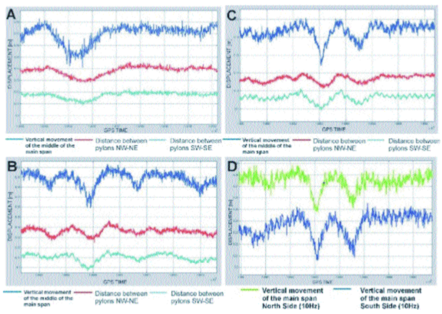

Fig. 11 – Construction elements displacement detected by 20Hz (A, B, C) and 10 Hz (D) receivers.

Fig. 11 C shows the same displacement caused by set of cargo cars. First, set of two trucks were moving through the bridge. Six seconds later, another set of two truck were passing through. Vehicles were going from the different sides, so loading of the main span was quite uniform what is confirmed by data from 10 Hz receivers located in external sides of the road (fig. 11 D).

Fast Fourier Transformation allowed to get information about main frequencies of the Siekierkowski Bridge. The main detected frequency is 0.931 Hz (fig. 12). It is quite similar to 0.95 Hz value computed during inspection tests with known loading. Values seems different because test done with GPS were taken during normal traffic loading, without closing object. Another frequency taken from horizontal movements of pylons NWNE shows the same value of 1.27Hz as previous tests taken with geotechnical instruments. Fig. 12 almost shows different movement frequencies of South and North side of the bridge.

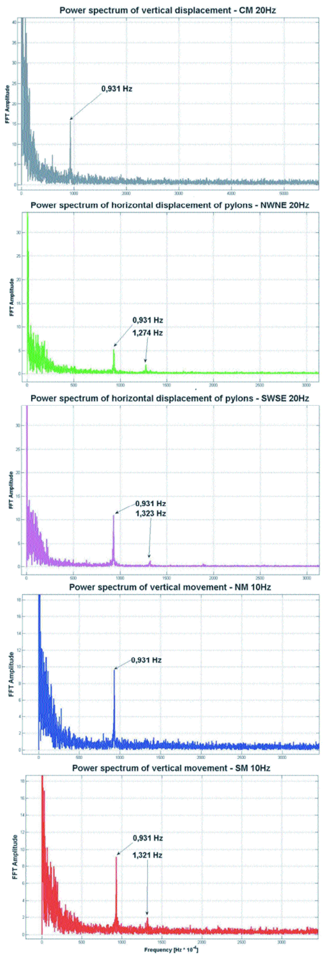

Fig. 12 – Power spectrum of vertical and horizontal movement of the bridge.

To compute data TRACK application was used. Trajectory Calculation with Kalman Filter have been used primarily to work with 1Hz data. Authors have changed algorithms to read 10Hz and 20Hz data so high sample rate information could be compute. Kalman filtering is used in TRACK software to get antenna position with centimeter accuracy using GPS, ephemeredes and atmospheric information.

This filtering technique was brought by Rudolf Kalman. It is a recursive filter that estimates the state of dynamic system of noisy measurements. The state of the system is often represented as a vector.

Kalman filters are applied to linear dynamic systems with discrete values in time.They are modeled on a Markov chain built on linear operators perturbed by Gaussian noise. At each discrete time increment, a linear operator is applied to the state to generate the new state, with noise mixed in, and optionally information from the controls on the system if they are known. Then, another linear operator mixed with more noise generates the visible outputs from the hidden state (fig. 13).

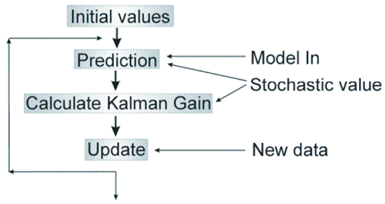

Fig. 13 – Diagram of the Kalman Filter Processing.

Using this method needs to correct modeling not only measurements but also process. Authors assumed that every brand of GNSS receiver can be use. TRACK software works with universal GNSS date format: RINEX 2.1 and 3.0 so above assumption is execute.

Same method was exposed in Military University of Technology. Laboratory trials with known parameters of extortion confirmed totally usefulness of this technique - method of measurements and calculating algorithms - for big construction monitoring like bridges, buildings or dams.

CONCLUSIONS

Results show that using this method authors are able to monitor construction behavior. GPS technology enable to:

– get information about dynamic behavior of construction caused by exterior loading caused by traffic, extreme weather conditions and other dangerous extortions like earth quake;

– detect overload trucks inducing adverse micro-breaks in elements of a construction;

– get real information about eccentric construction overload (what can be seen on fig. 7) when one side of the road (construction) is load and the other is not.

– collected data from permanent, long-term observations can help to bridge servicing crew to rationalize outlay related with support good condition of the construction;

– permanent GPS RTK (NRTK – ASG-EUPOS) installation could be simple, reliable and fast source of information about normal and abnormal behavior of the construction in real time.

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