57

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ANALYSIS OF DYNAMIC LOAD OF SIMPLE BEAMS USING GEODETIC AND GEOTECHNICAL SENSORS IN LABORATORY CONDITIONS

Abstract

In this paper, the analysis of the dynamic load of the beam using geodetic and geotechnical sensors was performed. From the group of geodetic sensors, GPS/GNSS receivers were used, while from the group of geotechnical sensors, an accelerometer was used. The measurements were performed in laboratory conditions, and the experiment itself was designed so that the measurements from several series were independent of each other. For the experiment, a construction was made on which all sensors are mounted, which ensures their smooth operation in real time, as well as the setting of different loads. Based on the obtained measurement results, the analysis was performed and conclusions were drawn, as well as the directions of future development.

Keywords: GNSS, accelerometer, beam load, deformation detection

АНАЛИЗА ДИНАМИЧКОГ ОПТЕРЕЋЕЊА ПРОСТЕ ГРЕДЕ ПРИМЕНОМ ГЕОДЕТСКИХ И ГЕОТЕХНИЧКИХ СЕНЗОРА У ЛАБОРАТОРИЈСКИМ УСЛОВИМА

Сажетак

У оквиру овог рада извршена је анализа динамичког оптерећења греде применом геодетских и геотехничких сензора. Из групе геодетских сензора коришћени су GPS/GNSS пријемници, док је из групе геотехничких сензора коришћен акцелерометар. Мерења су извршена у лабораторијским условима, а сам експеримент је осмишљен тако да мерења из више серија буду међусобно независна. За експеримент је израђена конструкција на коју су монтирани сви сензори, а која обезбеђује њихов несметан рад у реалном времену, као и поставку различитих оптерећења. На основу добијених резултата мерења извршена је анализа и донети закључци као и правци будућег развоја.

Кључне ријечи: GNSS, акцелерометар, оптерећење греде, детекција деформација

1. INTRODUCTION

Geodetic and geotechnical sensors are being applied in monitoring of various objects (such as dams, bridges and other constructions) and terrain (e.g. landslides) more and more. In this paper we analyzed the application of these sensors on bridge model in laboratory conditions.

Different types of deformations are inevitable due to material ageing, ecological erosion of the bridge, as well as to increased load by vehicles [1]. Large span bridges are susceptible to external influences, such as strong winds [2, 3], quakes [4], traffic load and temperature changes [5, 6]. Monitoring of dynamic deformations and assessment of bridge condition in real-time are important for providing the load capacity, durability and construction safety, alarming in cases of danger and in prevention of material damage and casualties in extreme conditions [7]. This task, known as Structural Health Monitoring (SHM), is done using different sensors in order to early detect and later mitigate potential damage of the object.

In general sensors can be divided into three groups: geodetic (GNSS/GPS receivers, robotic total stations, etc.), geotechnical (accelerometers, piezometers, extensometers, inclinometers, etc.) and other sensors (temperature, humidity, anemometers, etc.). In this paper GNSS receiver and accelerometers were used. History of development of SHM based on GPS and some examples are described in [8]. GPS-based SHM has evolved from static into dynamic system, and different data processing strategies have been developed as well [8].

GPS provides a great potential for bridge monitoring. Being a very useful sensor follows from several facts [9, 10]:

- Measured values are mutually independent;
- GPS receiver can operate continuously, during day or night-time, regardless of weather conditions;
- High-precision positioning;
- Short observation time;
- Static and dynamic 3D coordinates can be determined concurrently;
- Error cannot be accumulated;
- Receivers are easy to handle.

The development of techniques for dynamic monitoring of bridge movements caused by wind, traffic and temperature changes is described in [9]. Integration of GPS and other sensors for dynamic monitoring is analyzed, e.g. integration of GPS and accelerometers, GPS and robotic total stations. Besides, problems appearing in dynamic monitoring with GPS-based systems are examined (bad satellite geometry, tropospheric and ionospheres delays). Dynamic tests on a series of sine input waves with various frequencies are analyzed in [11]. The results show that the ability to track the signal (oscillations, vibrations) with frequency lower than 2Hz and amplitude higher than 2cm is very good. In this paper, an analysis of the monitoring of the bridge with dynamic loads is conducted. Measurements are done using GPS receivers at the highest frequency, while accelerometer measurements are used as a reference values.

2. SENSORS

In our experiment a combination of geodetic and geotechnical sensors is used. From geotechnical group an accelerometer is used and from geodetic group GPS receivers. Characteristics of used sensors are given in following sections.

2.1. GPS/GNSS RECEIVERS

Global Navigation Satellite System (GNSS) is a satellite navigation system used to determine the position of certain location. It provides reliable data on space and time in all weather conditions, anywhere on Earth or close to Earth, provided that the signal from at least four satellites can be tracked simultaneously. One of basic requirements that have to be met is that there are no obstacles between the satellites and the receiver.

Currently there are several satellite systems, including [12]:

- Global Positioning System (GPS),
- Glonass,
- Galileo,
- Compass, etc.

If the receiver can register signals from all available systems it is called GNSS receiver, although manufacturers do not always follow this convention (e.g. Leica GS15 GNSS receiver cannot register Compass signal, Table 1). Using more systems provides higher accuracy of the measurement [13].

Positioning methods can be static, fast-static, post-processing kinematic (PPK), real-time kinematic (RTK), etc. In this paper a post-processing kinematic method is used. It requires two receivers of similar characteristics. One receiver is a base station that is static during the measurement. Other receiver, called rover is moving during the measurement. The position of the rover is determined relative to the base station. This way measurement errors are greatly reduced. Since base station and rover are very close to each other (few meters), clock errors and atmospheric delays can be neglected [9].

Receivers used in this experiment are Leica GS15 (Fig. 1a) and Trimble R8s (Fig. 1b). Trimble R8s is used as a base station, while Leica GS15 is used as a rover. Rover is rigidly attached to the object, so that there is no movement relative to the object. Trimble R8s has 440 channels and can receive signals from GPS, GLONASS, Galileo, Compass and QZSS satellites [14].

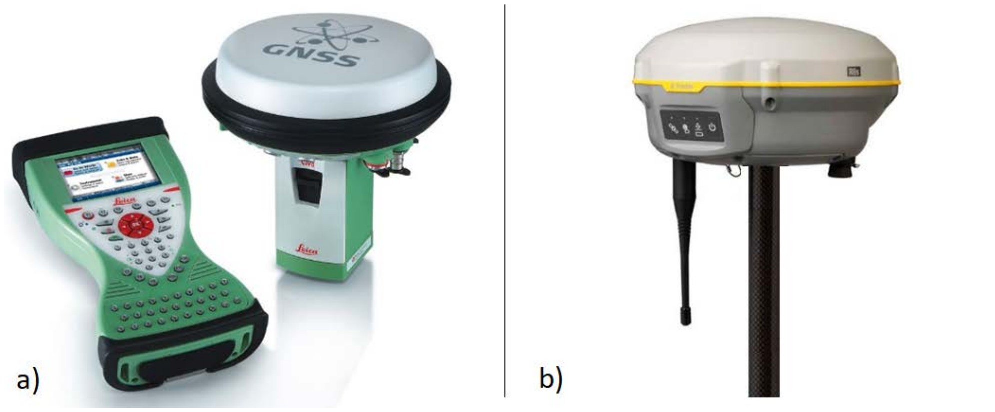

Figure 1. *Leica GS15 receiver and Leica CS15 controller (a), TrimbleR8s receiver (b)*

Characteristics of used receivers are given in Table 1.

Table 1.Leica GS15 and Trimble R8s specifications

	***Leica GS15* [15]**	***Trimble R8s* [14, 16]**
Satellite signals	• GPS: L1, L2, L2C, L5 • GLONASS: L1, L2 • Galileo (Test): GIOVE-A, GIOVE-B • Galileo: E1, E5a, E5b, Alt-BOC • BeiDou: B1, B2 • SBAS: Waas, Egnos, Gagan, Msas, Qzss	GPS: L1C/A, L1C, L2C, L2E, L5 GLONASS: L1C/A, L1P, L2C/A, L2P, L3 SBAS: L1C/A, L5 (for SBAS satellites that support L5) Galileo: E1, E5A, E5B BeiDou (COMPASS): B1, B2 SBAS: QZSS, WAAS, EGNOS, GAGAN
Maximum measurement frequency	20Hz	10Hz
Positioning performance	Post-processing kinematic H . . . 8 mm + 1 ppm RMS V . . . 15 mm + 1 ppm RMS	Post-processing kinematic H . . . . 8 mm + 1 ppm RMS V . . . 15 mm + 1 ppm RMS

2.2. ACCELEROMETER

Accelerometer is geotechnical sensor used for precise measurements of oscillations (acceleration) [17]. According to the number of measurement axes they can be single, two and three-axis. In this experiment the two-axis accelerometer ADXL203 is used (Fig. 2).

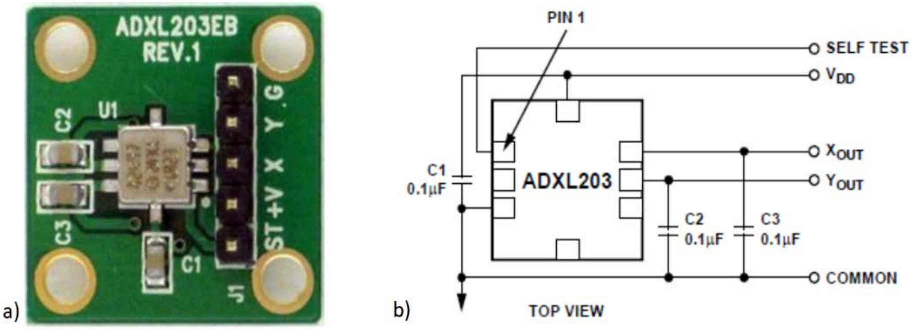

Figure 2. *ADXL203 accelerometer (a); ADXL203ED schematic (b)*

Accelerometer's sensitivity is inversely proportional to the square of the first resonant frequency [18]. Most important parameters from ADXL203EB datasheet are given in Table 2.

Table 2.ADXL203EB specification

	Value
Measurement scale	± 1.7g
Linearity	± 0.2% FS
Sensitivity	1000mV/g
Bandwidth	50Hz
Supply voltage	3-6V
Output voltage at 0g	2.5V (supply 5V)

3. EXPERIMENTAL SETUP

An experiment is conducted in laboratory environment to simulate the dynamic load of a single beam (bridge segment/entire bridge). As stated in previous sections GNSS receivers and accelerometer are used, as well as additional equipment. In order to obtain the best possible GNSS signal reception the experiment is conducted on the roof of building of Science and Technology Park (STP) in Novi Sad.

Construction used in experiment is consisted of a wooden beam, 1.30m long, 0.20m wide and 0.008m thick. On one end it is fixed using clamp (Fig. 3b), while the other end is leaned on the desk. Accelerometer is firmly attached to a piece of steel pipe (rectangular cross section), and then to the beam using screws (Fig. 3a). Leica GS15 receiver is placed on the beam using tribrach and carrier. This provides the centering error not greater than 0.2mm. Tribrach is firmly attached to the beam using the screw. On the part of screw beneath the beam a cut is made to enable the placement of the load bellow the beam (Fig. 4).

Base station, Trimble R8s receiver, is mounted on a 2m long carbon pole, fixed using bipod and placed in the close vicinity of the construction. Different scenarios of beam loading are simulated combining weights of 1kg and 2kg.

Figure 3. *Accelerometer, tribrach and GNSS receiver carrier (a), construction with beam and sensors (b)*

Schematic of beam construction with installed sensors is given in Fig. 4.

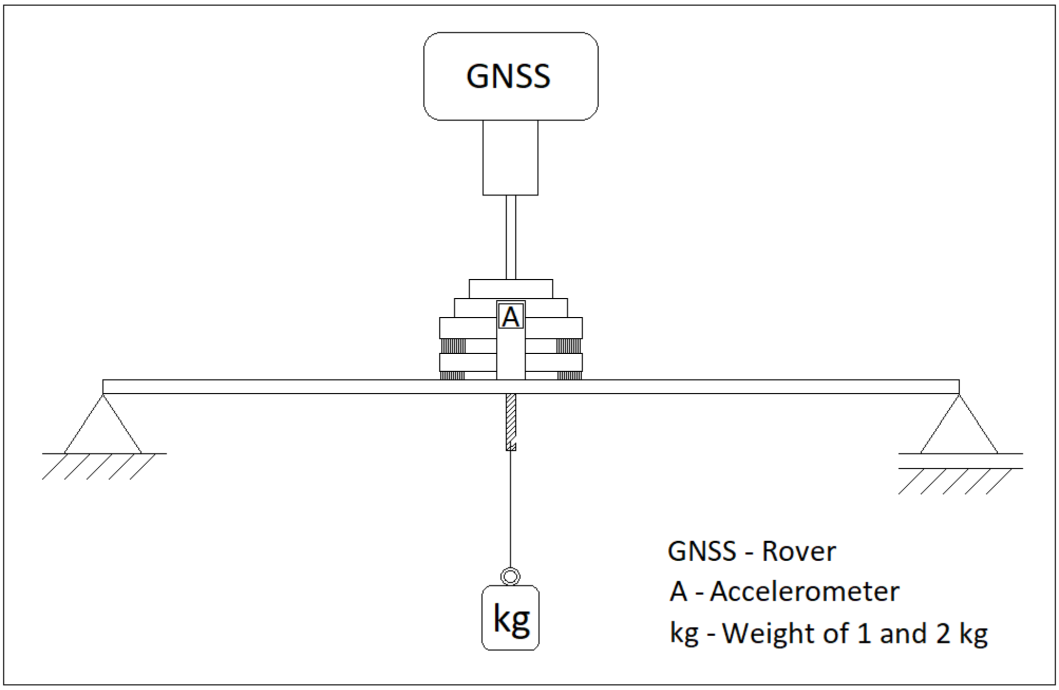

Figure 4. *Beam, sensors and load*

4. MEASUREMENTS

Experiment includes two series of independent measurements, with different beam loads. Before each measurement the beam is loaded using the weight which is placed bellow the center point of the beam. Non-elastic thread is used to attach the weight. This way controlled dynamic loading of the beam is obtained. Considering that the weight is hung before the measurement the force is applied to the beam, i.e. the beam is statically loaded.

First series of measurements involved releasing the 1kg weight from 30cm height. Controlled release is obtained using two threads, one of which (the shorter one) is cut. This way the loading of the beam is retained. After the oscillations disappear the beam settles down in its initial state (steady state). Next measurement is conducted after the weight is taken down, threads replaced, and the weight hung again. The fixed end of the beam is checked after each measurement. Main parameters of the measurements are given in Table 3.

Table 3.Measurements setups

Height [cm]	Weight [kg]	GNSS measurement frequency [Hz]
30	1	20
30	2	20

Oscillations induced by different loads are registered using sensors measuring 20 times per second, i.e. 20Hz. Both GNSS receivers enable this rate of measurement. Accelerometer is installed with one axis being vertical, i.e. aligned to Z-axis.

Data obtained from accelerometer represent the acceleration of the beam center point along the Z axis every 0.05s (20Hz), while GNSS data represent the displacement of the center point from its initial position along the Z axis in meters. In order to compare the data, GNSS results are recalculated to acceleration using well known equations [19].

5. RESULTS AND DISCUSSION

Considering that ADXL203 accelerometers provides much higher rate of measurement compared to GNSS receiver, data obtained with this sensor are taken for reference values within this experiment.

Also, it has to be mentioned that all GNSS measurements have fixed solutions, which provides highest accuracy in given environment.
The first test includes loading the beam using 1kg weight free falling from the height of 30cm. The moment of cutting the thread can clearly be seen in Fig. 5. Immediately after this moment the highest value of acceleration amplitude is reached (measured by both accelerometer and GNSS) and afterwards it gradually decays. Values of global maximum and minimum amplitude are approximately equal by both sensors, while local values can be significantly different at various time instances. Accelerometer data show that the beam returns into its rest state in approximately 5 seconds after the loading is applied.

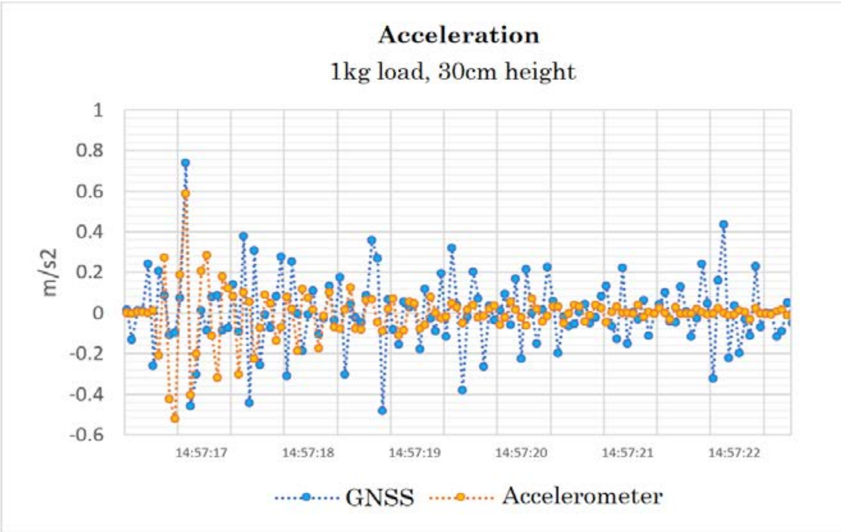

Figure 5. *Measured acceleration, 1kg load, 30cm height*

Results obtained within the second independent measurement are shown in Fig. 6. Here the beam is loaded with the 2kg weight, at the height of 30cm. In this data maximum value can be seen in the early phase of the measurement. Positive peaks have similar values at both sensors, but the negative peak in GNSS data is significantly higher (in absolute terms) than the negative peak in accelerometer data.
It can be seen that by both accelerometer and GNSS oscillations are detected, but they are more obvious in the curve derived from accelerometer data. These data also show that the beam returns into its rest state in approximately 6 seconds. However, besides global maximum and minimum, in GNSS data local maximum and minimum values are obtained. Therefore it is difficult to determine the moment when the beam returns into its steady state based on GNSS data.

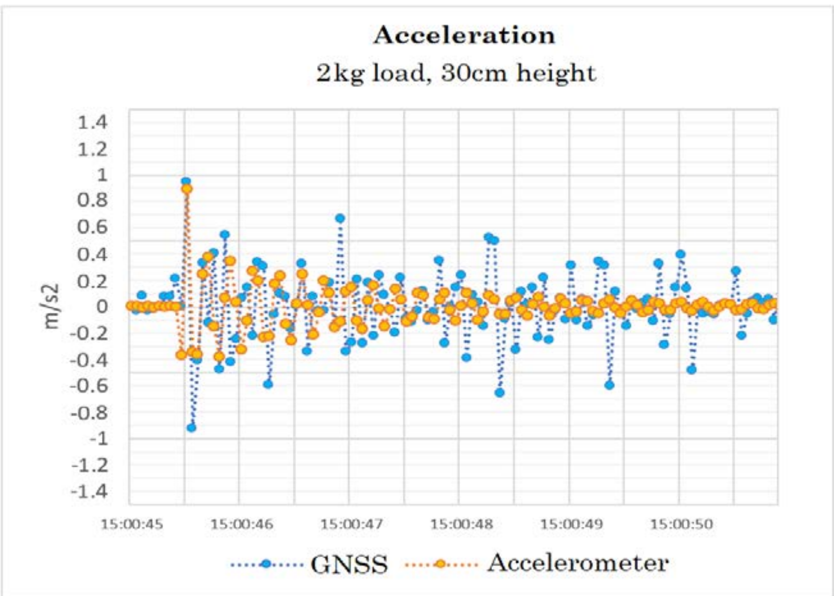

Figure 6. *Measured acceleration, 2kg load, 30cm height*

Measurement results show that smaller differences are in the case of loading the beam with 2kg weight. Before steady state is established, only in few moments the deviation is larger than 0.2m/s^2 (1kg weight) and 0.4m/s^2 (2kg weight). The biggest issue is in the steady state where GNSS data show that there is still some movement. This can be troublesome in the case of small amplitude oscillations. Longer duration and higher amplitude of oscillations could help to overcome this problem. Global maximum coincides well in both cases. The differences are 18% (1kg weight) and 9% (2kg weight). On the other hand, global minimum coincided better in the case of 1kg weight (8% difference) than in the case of 2kg weight (39% difference). Considering values for both cases the acceleration amplitude is almost twice bigger when the load is doubled. Taken that into account the biggest difference in global minimum should have been present in accelerometer measurements. A new experiment could show whether increasing the measurement rate would correct this issue or not.

6. CONCLUSIONS

Complex structures such as bridges, tall buildings, tunnels etc., require the usage of both geodetic and geotechnical sensors for successful monitoring. In this paper an experiment is conducted simulating controlled dynamic loading of a basic bridge element. Geodetic and geotechnical sensors are placed in the middle of the beam and they continuously measure the displacement (GNSS receiver) and acceleration (accelerometer). Measurements are done in two series, loading the beam with different weights. GNSS receiver is set to its highest measurement rate (20Hz) and all observations have fixed solutions. Even though its measurement rate can be higher the rate for accelerometer is also set to 20Hz in order to provide more adequate comparison. For the same reason the values obtained with GNSS receiver (displacement) are converted to accelerations.

Results obtained in the experiment show that, if 20Hz measurement rate is applied, it is possible to utilize GNSS receiver for displacement measurement in dynamic tests. With 2kg load similar values of global maximum and minimum are measured with both sensors. In both accelerometer measurement series, the transient process and the moment of entering the steady state are clearly visible. This moment is less visible in GNSS measurements, especially when amplitudes are lower. This is a consequence of the error in height measurement in the rest state, which influences the acceleration. More base stations can increase the accuracy of GNSS measurement.

Further experiments could include more elastic or longer beam in order to achieve higher oscillation amplitudes. Heavier loads can be applied as well. Also, an algorithm to filter GNSS data, such as AFEC [12], could be utilized.

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