EXAMINATION OF ENGINEERING CONSTRUCTION KINEMATICS USING RTK GPS

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1. INTRODUCTION

The article discusses the applicability of real time GPS measurements to monitoring of engineering objects, especially of their vibration. It was the main objective during the examination of an exemplary structure – a pedestrian footbridge in Tylmanowa (southern Poland).
At least basic knowledge of mechanical theory problems is indispensable in planning of such experiment. The expected magnitude and frequency of movements should be known for proper selection of measurement method. Though the real time kinematic (RTK) technique was used in the test, other methods are also mentioned. The main part of this article contains description of measurements of the Tylmanowa footbridge vibration. The data gathered during the experiment were carefully analyzed. Basing on results of the analysis, the detected bridge answer to test loads and forced swing, are described. The mathematical model of vibration was found using the Least Squares Spectral Analysis invented by Prof. Petr Vaníček (Vaníček, 1971), an alternative model to the (Fast) Fourier Transformation.

2. TECHNIQUES FOR MONITORING OF STRUCTURES DEFORMATIONS AND DISPLACEMENTS

Exploitation of building objects often leads to appearance of displacements and deformations. Periodical or continuous measurements are needed to provide their operational safety. The most important tall structures are:

- **industrial and multi-floored buildings,**
- **factory chimneys,**
- **masts and towers,**
- **wind energy turbines,**
- **bridges, especially suspension bridges and their pylons.**

Engineering object deformations can be classified into two groups: long-term movements and short-term dynamic vibration. The technology of examination of these effects depends on tested object construction specificity, environmental conditions and required accuracy.
During observations it is necessary to define the time between consecutive measurements, both in the case of the long-term and dynamic deformations. The proper selection of observation frequency should ensure reliable representation of the object changes in time. The results should be obviously related to a stable, stationary coordinate system.

There are many technologies applicable to deformation examination. Widely used are:

- **surveying techniques:**
  - **classic (precision leveling, networks with distances and angles),**
  - **photogrammetry and laser scanning,**
  - **satellite (GNSS, radar interferometry).**
  - **physical measurements, based on different kinds of sensors (e.g. inclinometers, extensometers, accelerometers etc.).**

The main advantage of the classic surveying techniques are results obtained with the highest precision. However, this high accuracy may be disturbed by unfavourable environmental conditions. Apart from that, the data are being gathered quite slowly and the visibility between instrument and observed points must be secured.
The photogrammetric techniques have an important advantage of making measurements based on simultaneous photographs from various directions, so a series of object images is obtained, representing consecutive stages of its deformation or movement.
In recent years the satellite measuring systems gained popularity as movement monitoring tools for different building objects. Coordinates, acquired with subcentimetre precision, are precisely defined in time. For huge engineering objects, deformation monitoring is very important to obtain the global representation of movements which occurred in whole object. Satellite observations are not dependent on weather conditions. The great advantage, especially for fast variable movements examination, is the high data recording frequency, which at present allows detection of vibration frequencies up to 50 Hz. The drawback of GPS measuring is the accuracy of vertical positioning, about 2÷3 times worse than horizontal. A solution for this problem may consist in joining of different technologies, e.g. precision leveling of points positioned by satellites.
Physical sensors, such as inclinometers and extensometers, allow measurements of slow deformations. To monitor forced dynamic movements, accelerometer is the widely applied device. This sensor is able to measure acceleration from 1 to 10^6 g, where g means the acceleration of gravity. Moreover, two or three components of acceleration vector may be measured at the same time. Very high frequency of recording data (up to 200 Hz) is useful to objects dynamics examination. In opposition to the surveying techniques, acceleration measuring is independent of electromagnetic waves propagation, what allows to avoid disturbances caused by refraction, radio interference, ground-based objects and weather conditions.

3. SHORT-TERM VIBRATION MEASURING

Short-term object vibration is mainly caused by weather conditions, seismic movements and influences of industry or transport. Such displacements are monitored for lengthwise-shaped objects like tall buildings, chimneys, towers, masts and also bridge pylons and spans. Measurements of deflection variable in time let to characterize dynamic answer of object.
High building objects are often susceptible to wind and sun influence and ground vibration caused by industry. Their construction design has to respect these factors. Especially important for building safety is evaluation whether the forcing vibration frequency is different from object eigenfrequency. Dynamic intensification occurs when difference between these values approaches zero. It may bring resonance effect and risky construction weakening.

4. FOOTBRIDGE EXAMINATION

The main purpose of the footbridge examination was verifying RTK measurements to monitoring of short-term dynamic vibration. The basic demands are: high precision positioning (better than 1 cm) and high frequency of data gathering (10 Hz and more). According to the Nyquist-Shannon sampling theorem, the continuous signal can be restored from discrete signal if it was sampled with the frequency at least twice more than the spectral frequency. RTK receivers satisfy this requirement.
The examined object was one of the pedestrian footbridges in Tylmanowa crossing the Dunajec river, called in (Michałowski, 2002; Michałowski, 2003) as Tylmanowa II. Two frame construction pylons are 17.8 m high. Suspension cables have parallel configuration and suspenders are in W-configuration (the Jawerth truss). The center span is 81 m long and 1.6 m wide. Measurements of object vibration were carried out on April 20th, 2007.

Fig. 1. Tylmanowa footbridge (view from the northern side).

Equipment using for this experiment was:
- **as reference stations: SR399 and SR530 Leica receivers, both with AT503 choke ring antennas,**
- **on the deck of footbridge: three SR530 Leica receivers with AT502 geodetic antennas.**

Works began at 10 a.m. Two reference stations were set on the southern side of the object (points R and S). The initial observations, when one receiver was located in the midpoint of the span, were used to check the recorded signal noise level in this place. The footbridge stood then motionless. The noise was computed as root mean square of deflections from receiver average position. For 30 minutes period it was about 5 mm for horizontal position and 20 mm for height.
Basing on the almanac for the test day, time period with the optimal satellite configuration was chosen. Number of usable GPS satellites was 7÷8 during whole test and the GDOP coefficient varied from 1.9 to 2.3.

Table 1. Intervals of vibration measurement

Interval number		I	II	III	IV
Time		12:02÷12:07	12:16÷12:21	12:40÷12:52	12:57÷13:06
Locali-zation	Receiver S	S	S	S	S
	Receiver A	¼	3/4	¾	1/2 left
	Receiver B	½	1/2	½	½
	Receiver C	R	R	¼	¼

Vibration measurement were carried out in four time intervals (table 1), each with different localization of receivers. The receivers were working in the RTK mode, gathering data with 10 Hz frequency. Antennas installed on 1-metre poles were fastened to the southern handrail. The pictorial sketch showing receivers layout is presented in Figure 2. Bridge vibration was forced by test participants in various ways.

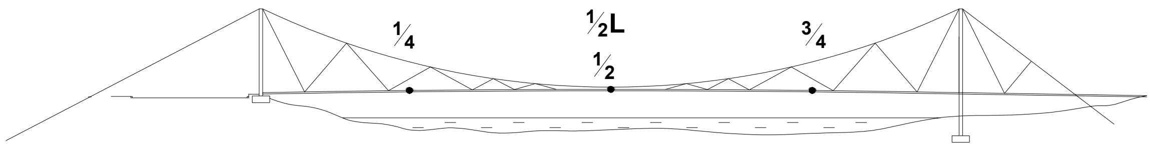

Fig. 2. Receivers layout on the footbridge deck.

5. EXAMINATION RESULTS

Surveying data were processed using the Leica Geo Office software v. 4.0. Base points coordinates were calculated in EUREF-89 coordinates system, referring to permanent stations KRAW, NTAR and SACZ, which belong to the local, provincial system of real time precise positioning (MSPP: Małopolski System Pozycjonowania Precyzyjnego). The computed horizontal coordinates were transformed from the EUREF-89 to the national coordinate system "2000" (the 7th zone) and then to a local coordinate system proper for the footbridge: the X-axis direction was compatible with the bridge longitudinal axis. This was also the direction of longitudinal vibration, not discussed in this paper. Lateral horizontal vibration was described after Y coordinate changes analysis. Ellipsoidal heights were converted to normal heights, using the precise geoid model of Prof. Osada. They were used for vertical vibration computation. Graphs below demonstrate obtained vibration. The 1-metre displacement value on the vertical axis marks the average position of the examined point. As the time unit 0.1 sec interval was assumed.

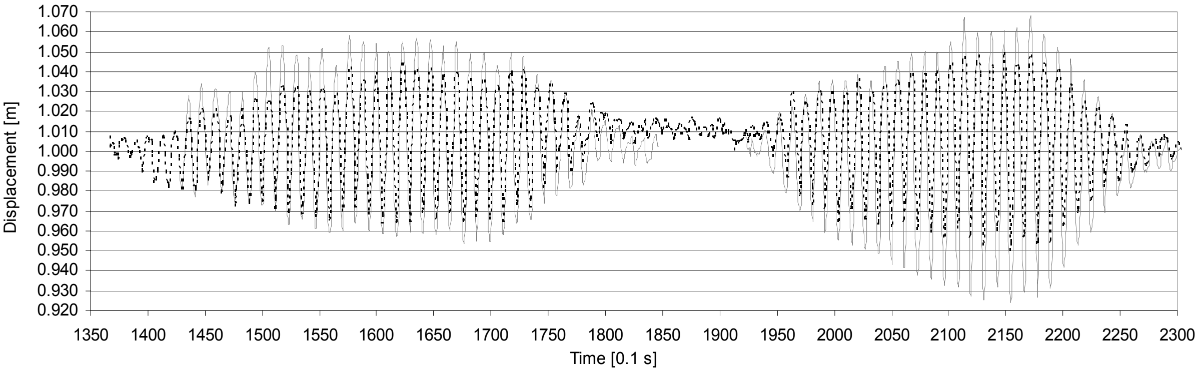

Fig. 3. Example of observed horizontal vibration.

Figure 3 shows an example of forced horizontal vibration. Two receivers were set on the deck – one in a quarter length and second in a half length. Their movements are presented by the black dotted line and gray continuous line respectively. Vibration amplitude recorded by the first receiver was about 4÷5 cm and by the second – about 5÷6 cm. The greatest horizontal amplitude reached during the test on the deck middle was about 7 cm. For the sake of weak susceptibility of this footbridge to vertical movements, the recorded vertical vibration has maximally 2 cm amplitude.

6. ANALYSIS OF ENGINEERING OBJECTS VIBRATION

Vibration observed at an examined point has a representation as a continuous time series. The result of recording point positions with a predetermined frequency is a discrete time series, i.e. signal given by sampling the continuous signal.
In practice, the Discrete Fourier Transform is computed using dedicated algorithms. The most popular algorithm is the Fast Fourier Transformation (FFT). However, the results given in (Kraska & Letkiewicz, 2001) show that this algorithm approximates the observed time series worse than the Least Squares Spectral Analysis (LSSA), invented by Prof. Vaníček (Vaníček, 1971).
A few time intervals were put to the analysis using program based on the LSSA algorithm (Wells et al., 1985). As the model used does not account for damping, intervals with almost constant amplitude were analyzed. As an example a chosen part of interval from Figure 3 is shown below.

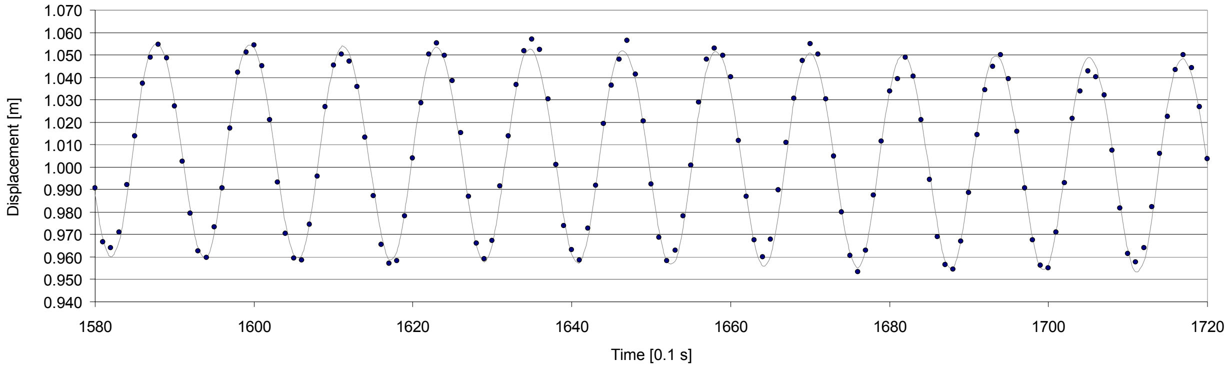

Fig. 4. Discrete time series approximated by the model continuous time series.

Coefficients of the continuous time series equation shown on Figure 4 were obtained from a LSSA computer program. The equation can be written in the form (unit of t = 0.1 sec):

$$f(t) = 1.09561 - 0.0000541219 \cdot t - 0.00320890 \cdot \cos\frac{2\pi t}{11.74} + 0.0476867 \cdot \sin\frac{2\pi t}{11.74} +$$
$$+ 0.00156756 \cdot \cos\frac{2\pi t}{5.87} + 0.00104769 \cdot \sin\frac{2\pi t}{5.87} =$$
$$= 1.09561 - 0.0000541219 \cdot t + 0.0477945 \cdot \cos\left(\frac{2\pi t}{11.74} - 1.50361\right) +$$
$$+ 0.00188544 \cdot \cos\left(\frac{2\pi t}{5.87} + 0.589172\right)$$

7. SUMMARY

Stages of test:

- **gathering of considerable amount of observing data, i.e. variable in time vibrating points coordinates – with high frequency recording,**
- **presentation of obtained time series on lateral and vertical displacement graphs,**
- **selection of intervals with distinct vibration without significant influence of damping,**
- **application of Least Squares Spectral Analysis to determine the footbridge eigenfrequency in selected time intervals.**

In table 2 vibration frequencies, acquired from the same kind of forcing but different measuring techniques, are compared. Results of RTK GPS method are in fact identical to Dr Michałowski's results, obtained with the use of accelerometers (Michałowski, 2002; Michałowski, 2003).

Table 2. Comparison of results

Frequency, amplitude	RTK GPS results				Michałowski's results (accelerometers)	
	Series 1		Series 2		Series I	Series II
	Rec. A	Rec. B	Rec. A	Rec. B		
f_1 A_1	0.85 Hz 0.036 m	0.85 Hz 0.048 m	0.86 Hz 0.045 m	0.86 Hz 0.066 m	0.88 Hz	0.83 Hz
f_2 A_2	1.70 Hz 0.002 m	1.71 Hz 0.002 m	1.71 Hz 0.003 m	0.96 Hz 0.002 m	1.76 Hz	1.71 Hz
f_3 A_3				0.75 Hz 0.002 m		2.54 Hz
f_4 A_4						5.08 Hz
f_5 A_5						5.96 Hz

The decrease of frequency, suggested in series 1 results, may be either an effect of applied kind of forcing or of construction stiffness decrease. In series 2, recorded by receiver B, besides the fundamental frequency it was not possible to determine other vibration periods unambiguously. Frequencies higher than 5 Hz are not detectable with the measurement technique applied.
During calculation, presence of periods close to the identified ones was observed. It is possible that these frequencies are an artifact, brought by the lack of estimation of damping parameters in model applied.

The test carried out on the Tylmanowa footbridge confirms the usefulness of RTK GPS measurements to testing of vibrating engineering objects kinematics. The applied recording with 10 Hz frequency facilitated satisfactory results. However, detection of frequencies higher than 5 Hz with the modern receivers, capable of recording with at 20÷100 Hz, will bring more information.

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