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IDENTIFICATION OF MULTIPLE OSCILLATION FREQUENCIES WITH GPS, BASED ON EXPERIMENTAL EVIDENCE AND ANALYSIS IN THE FREQUENCY DOMAIN

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Abstract: A serious limitation in the use of GPS in the monitoring of important structures like bridges, and especially in the identification of their modal frequencies, is whether this geodetic sensor can identify more than one modal frequency. In order to contribute in the solution of this problem, we made a large number of experiments with a linear oscillator of predetermined characteristics and with three degrees of freedom and max displacements up to 3.4cm. A GPS receiver was mounted on the sliding mass most remote from the generator and was recording simultaneously with another receiver in nearby, stable position, both sampling at 20Hz rate. Experiments were made with different excitation frequencies, up to 4Hz, either constant or linearly increasing from 0.05 to 4Hz. Recorded displacements were analyzed in the frequency domain using least-squares software, suitable for the spectral analysis of short and non-equi-spaced time series. From the spectral analysis it was revealed that GPS records can determine accurately the excitation frequency and the significant modal frequencies of the oscillating mass even when the excitation frequency is not constant or the time series are very short (50-60 observations). These results are very promising for they were obtained from signals a few seconds long and with very small amplitude. The conclusion is therefore that GPS can identify multiple frequencies, including transient and modal ones in real structures, especially in flexible ones, in which the oscillation amplitude is larger than those tested and this leads to a higher signal-to noise value.

1. INTRODUCTION

In the last years, after the pioneering studies of Lovse et al. (1995) and Ashkenazi and Roberts (1997) and others who used GPS to measure oscillations of major structures and of Celebi and Sanli (2002), Kijewski et al., (2206) and of others who assessed the potential of this technique, GPS appears to be a promising solution for the study and monitoring of semi-static and dynamic displacement of flexible structures. However, GPS has been mainly applied and tested for flexible structures with relative low (<1-2 Hz) modal frequencies.

Since the recording frequency of modern GPS is 20 Hz with a tendency to increase, an arising question is whether GPS can be used in the monitoring of high frequency oscillations (>1-2 Hz) and estimation of multiple modal frequencies in a single displacement record.

In an effort to contribute in answering this question, we made a number of experiments to assess the accuracy of GPS for the estimation of oscillation frequency using an experimental technique based on an oscillation device. Particularly, we tested the tolerance of GPS (1) in recording oscillation of frequencies up to 4 Hz, in order to cover a wider range of civil engineering structures (not only flexible ones) and (2) in recording oscillations with several degrees of freedom.

The output of this study indicates that GPS may be used for the structural monitoring of relatively stiff engineering structures and can identify modal frequencies up to 4 Hz.

2. METHODOLOGY AND EXPERIMENTS

2.1. Methodology

Our study was based on generated experiments of horizontal, uni-axial sinusoidal oscillations of known characteristics recording simultaneously the variations of the 3-D coordinates of the moving mass-oscillator with GPS. The resulting time series were analyzed, and computed results were compared with the real (predetermined) values of the amplitude and of the dominant frequency of the oscillation. Experiments were repeated several times for the same and for various combinations of the oscillation characteristics (frequency, amplitude, characteristics of the experiment). Hence, we could define statistically the *accuracy* of the method to determine amplitude and dominant frequency of oscillations (i.e. how much the estimates are close to the corresponding real values; Nickitopoulou et al., 2007). This methodology has been followed for the assessment of the accuracy of GPS and RTS in monitoring oscillation by using the single degree of freedom mode of the device, as well (Psimoulis and Stiros 2007; Psimoulis and Stiros, 2008). In this paper, only the analysis of the oscillation frequency will be presented.
Thus this study was focused on determination of (1) oscillation frequencies higher (up to 4 Hz) than those were examined until now, and (2) modal frequencies of oscillators with several degrees of freedom. It should be noted that although experiments were based on linear movements, they could control 3-D kinematics and spectral characteristics, as is analyzed below.

2.2. Experiments

Experiments were based on an apparatus permitting computer-controlled oscillations and a pair of dual frequency GPS instruments (TOPCON Javad Legacy E receivers and Legacy-H antennas). The rover receiver was mounted on top of the oscillating part of the apparatus, while the base receiver was operating in a nearby static position (a few tens of meters away) recording at the same frequency (20Hz).

The experimental apparatus (ECP Systems Model 210a; Fig. 1) consists of a PC used to define the oscillation characteristics (frequency, amplitude, duration), of a controller converting the digital signal to analog and transferring it to the oscillator and of an oscillator composed by a servo-motor which can generate linear oscillations with pre-determined characteristics (frequency, amplitude, duration). The oscillator includes three wagons sliding on a straight rail connected each other by springs, with the first wagon connected through a steady bar with the servo-motor. Thus, a three-degree of freedom system was formed, with the GPS antenna mounted on the third wagon (Fig. 1).

The modal frequencies f of the oscillator could be analytically computed based on the equation

$$[K]-\omega^2[\mathrm{M}]=0 \tag{1}$$

where [K] and [M] are the matrices of the stiffness and of the mass of the oscillator, respectively, and $\omega=2\pi/f$. Computed modal frequencies, however, may deviate from real values up to 0.1 Hz, mainly due to uncertainties of the stiffness of the springs.

The GPS time series of each oscillation can be analyzed in three parts (Fig. 2): (1) a short oscillation at the beginning corresponding to the superimposition of the harmonic (steady oscillation) and a rapidly attenuating oscillation (due to the high damping ratio ~15%) lasting

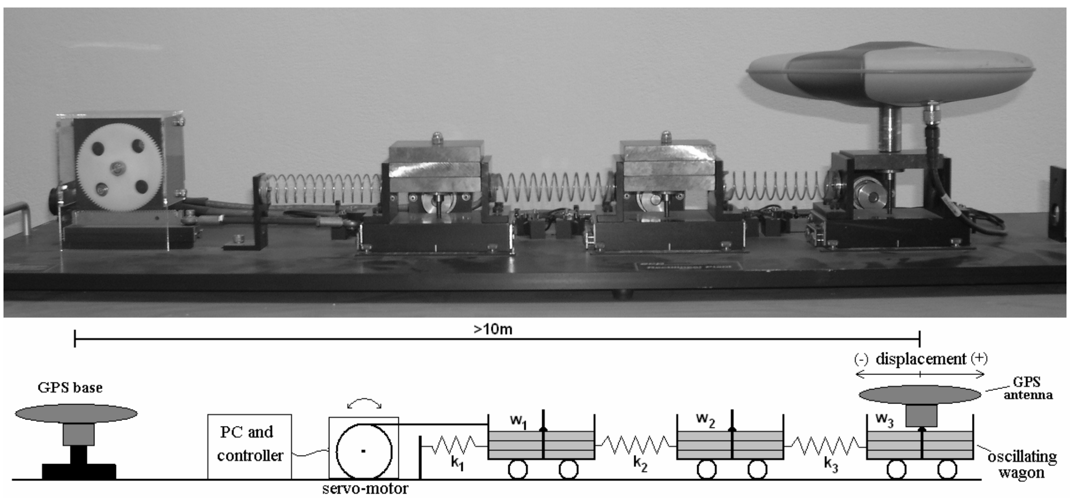

Figure 1 - A photo of a part of the oscillation device and a sketch describing the instrumentation used in our three-degree of freedom oscillation experiments. The GPS rover antenna is settled on the third wagon. All the wagons (w_1, w_2, w_3) are connected with springs (k_1, k_2, k_3).

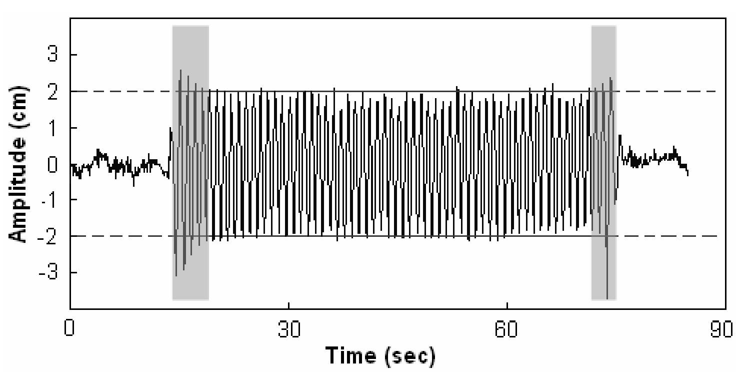

Figure 2 - A representative GPS time series of the oscillation displacements indicating with the two gray zones the initial and the final parts of the time series and the middle part corresponding to the steady oscillation

for few cycles (transient oscillation). (2) The middle part (the major part of the time series) corresponding to the harmonic oscillation with the constant preset oscillation frequency (excitation frequency) and amplitude (steady oscillation) and (3) a very short oscillation (1-2 cycles) at the end of the time series corresponding to the necessary procedure to stop the oscillation.

The maximum oscillation amplitude was 3 cm and it depended on the oscillation frequency. Thus for an oscillation frequency higher than 4 Hz, the corresponding amplitude was very small (<4 mm) and difficult to be identified by GPS. For this reason the examined oscillation frequencies were in the range of 0.05-4 Hz, which covers the oscillation characteristics of most relatively rigid engineering structures, and not only long suspension bridges and high-rise buildings.

3. TIMESERIES ANALYSIS

3.1. Preliminary analysis

At a first step recorded 3-D coordinates were transformed into a local coordinate system using a standard linear transformation (see Chan et al. 2006). The origin of this new coordinate system was calculated as the mean value of coordinates recorded in each experiment and corresponded to the equilibrium point of the oscillating wagon, while the x-axis corresponded to the oscillation axis. Given that the real movement was linear, displacements along x-axis represented the oscillation signal and those along the y and z-axes noise of measumerens. At a second step, very few outliers were found and where excluded from the GPS time series. However the exclusion of data from the time series caused discontinuities in the time series, providing problems in their spectral analysis.

3.2. Spectral analysis

Gaps in the GPS records are mainly due to (1) instrument function interruption (i.e. power outages), (2) malfunction of the connection between antennas and receivers (especially in cases of long connection cables) and (3) signal defects due to poor satellite availability. The cases of discontinuities due to exclusion of outliers are very few. The time series containing gaps cannot be treated with FFT spectral techniques, which requires continuous and equidistant data. Usual remedies such as division of the time series into shorter continuous data sets or adding interpolated values to fill the gaps have the disadvantage that they ignore information of longer period signals or induce additional noise, respectively.

For this reason alternative spectral analysis technique was adopted, the Normperiod Code (Pytharouli and Stiros, 2008), which is based on the Lomb Normalized Periodogram (LNP). This technique is based on the fitting of sinusoidal equations in observations using the Least Square method (LSQR) and can analyze non-equidistant and discontinuous data, as well as short time series, providing simultaneously estimates of the statistical significant of the computed peaks.

4. ANALYSIS RESULTS

4.1. Study case: constant oscillation frequency

Based on the Normperiod code the GPS time series which corresponded to the oscillations of the constant excitation frequency were analysed. These time series corresponded to the oscillation of a three-degree of freedom oscillator excited by a constant frequency. Each time series was separated in two parts: the initial part (including the transient oscillation) and the middle part (corresponding to the steady oscillation). Spectral analysis for each one of these parts separately and for the whole time series was made. In Figure 3 representative spectra of LNP analysis of 1, 2, 3 and 4 Hz are presented.

From these spectra it is obvious that in all cases the oscillation frequency was clearly identified. For the cases of steady and of whole time series, identification of excitation frequencies was very accurate (maximum difference from the preset one 0.003 Hz). On the contrary, from the analysis of the transient oscillation, this identification was less accurate (maximum difference 0.025Hz), which was expected due to the small number of observation (about 50 observations). In these spectra, smaller peaks, below the 95% confidence level,

Modal Frequency	Predicted frequency (Hz)	Computed frequency (Hz)
First	0.73	0.78
Second	2.33	2.33
Third	3.89	3.69

Table 1: Modal frequencies predicted by modal analysis and estimated based on GPS data

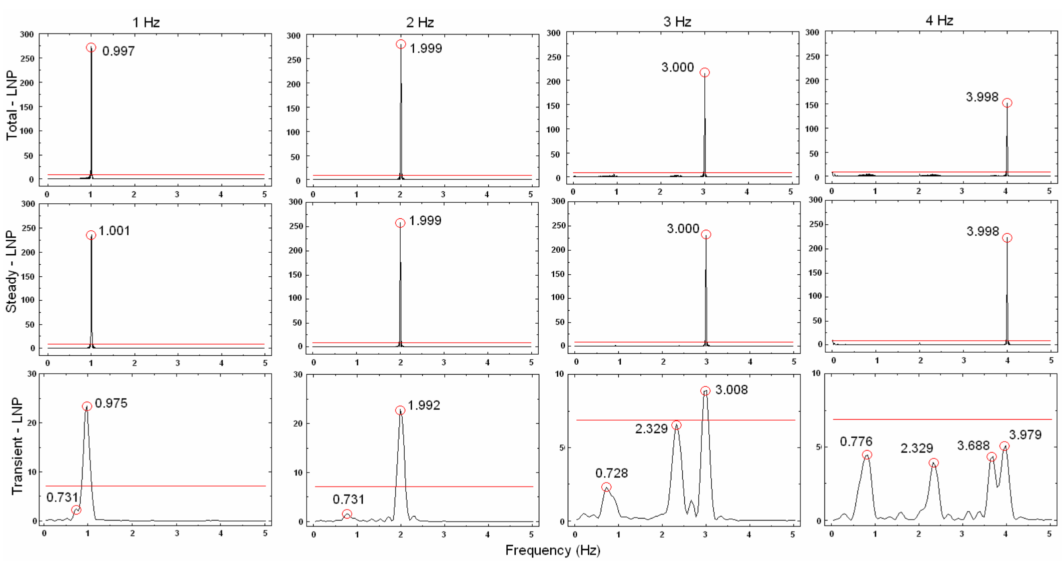

Figure 3 - Spectra of GPS time series of representative experiments for constant excitation of 1, 2, 3 and 4 Hz. The first row corresponds to the spectra of the whole time series, the second

row to the middle (steady) part and the third to the initial part (transient). The horizontal line corresponds to the 95% confidence level.

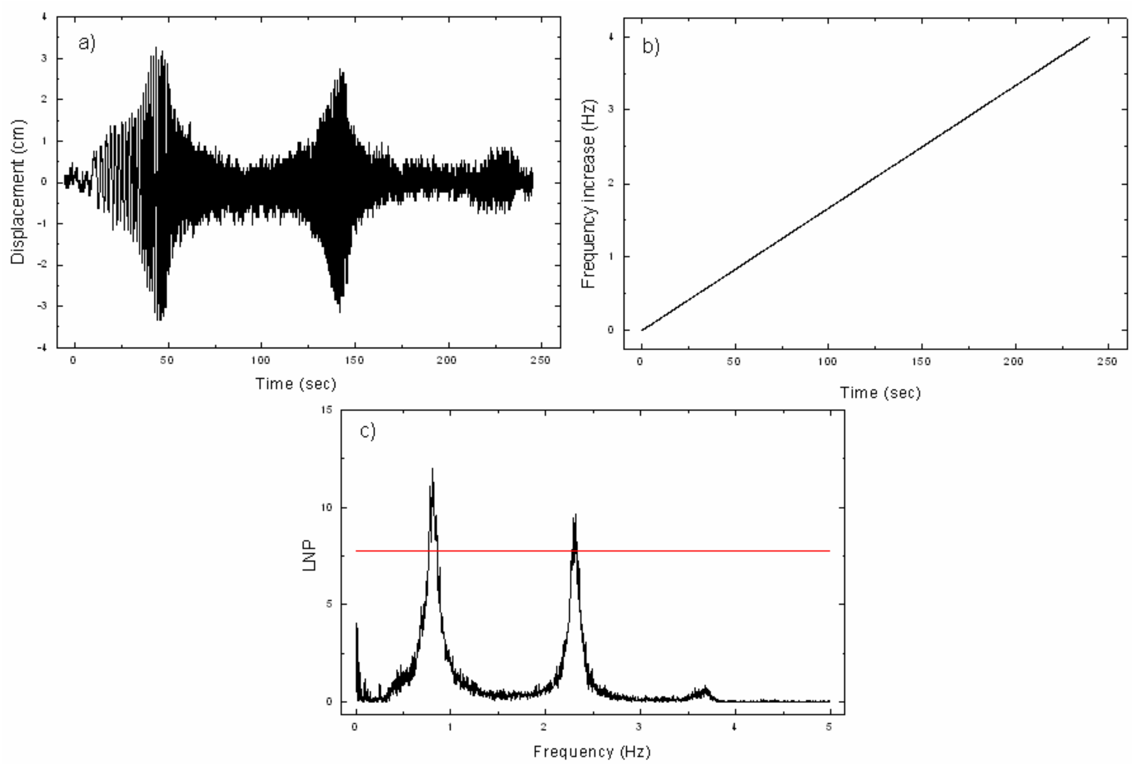

Figure 4 - Results of an experiment with three degrees of oscillation and frequency increasing linearly from 0.05 Hz to 4 Hz in 4 minutes. (a) Displacement, (b) real oscillation frequency and (c) computed frequencies using the Normperiod Code (LNP spectrogram). Three displacement peaks are observed in the displacement diagram, indicative of resonance. The two lower modal frequencies are clearly shown in the LNP spectrogram, while the third one is shown as a minor peak.

corresponding to the modal frequencies of the oscillator were also detected. These peaks become clear with increasing excitation frequency (≥3 Hz), and their accuracy depends on participation of each modal frequency in the oscillation movement. These estimated modal frequencies were compared with the analytically computed ones and it was observed that, the first two modal frequencies coincided with the computed ones, while a relatively large difference is observed in the third mode (0.2Hz); this is expected because the corresponding amplitude was slightly above the uncertainty error of GPS and time series were too short (50-60 observations).

4.2. Study case: linearly increasing oscillation frequency

The frequency in this experiment was increasing linearly from 0.05 to 4 Hz in 4 minutes and the response of the oscillator was maximized when the excitation frequency was close to the modal frequencies as it was expected because of resonance (Fig.4). From the diagrams of the excitation frequency and the response of the oscillator versus time it appeared that, as is expected, the maximum response was observed for excitation frequency close to the modals frequencies; only in the case of the third modal frequency the response was small (<1cm), probably because this modal frequency is not significant for the oscillator response. Analysis of the time series using the Normperiod Code revealed three frequencies, two of practically coincide with the real input first and the second modal frequency. For the third modal frequency there was a ~0.2 Hz deviation, probably due to the small response of the oscillator (Fig. 4a), leading to displacements slightly above the uncertainty level of GPS.

5. DISCUSSION AND CONCLUSION

The systematic experiments of oscillations with three-degree of freedom and the spectra analysis of the corresponding GPS time series, both for constant and linearly increasing excitation proved that:

1. Analysis of GPS records can identify oscillation frequencies up to 4 Hz, covering the range of the main modal frequencies not only of flexible, but also for rigid civil engineering structures
2. The increase of the excitation frequency does not seem to affect significantly the accuracy of the frequency determination
3. Using the Normperiod code, an alternative to FFT based on least-squares, it is possible to readily analyse discontinuous data, a common case in GPS records, and it was proved that the determination of the frequency was accurate even very short time series (up to 50-60 data only)
4. GPS proved to be suitable for the identification of the modal frequencies of structures with modal frequencies >1-2 Hz, and this broadens the range of the structures which can be GPS monitored.

Acknowledgments

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