Investigating the ability of high-rate GNSS-PPP for determining the vibration modes of engineering structures: small scale model experiment

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Key words: *Kinematic PPP; GNSS; Structural Health Monitoring; FEM*

ABSTRACT

This study evaluates the performance of the Precise Point Positioning method using Global Navigation Satellite System measurements (GNSS-PPP) for monitoring vibration modes of shear type buildings excited by harmonic ground motions and hammer tests. For experimental testing, the shear type lumped-mass building system is represented by a specially designed metal frame model, resembling a three story building, which was excited on a small scale shaking table. The excitation protocols applied were harmonic motions with different frequencies and amplitudes. The metal model has special deformation plates at the column tips to prevent the nonlinear rotations and out-of-plane motions for the entire system. The fundamental vibration periods of the model structure were computed by a Finite Element Mathematical (FEM) model, which were compared with the position variations determined by GNSS-PPP. Two GNSS receivers were mounted on top of the model structure on the line perpendicular to the motion axis to measure the rotation motion. The GNSS data comprised dual-frequency observations with a 10 Hz sampling rate. GNSS-derived positioning was obtained by processing the data using a post-mission kinematic PPP method with fixed phase ambiguities. Analysis of the characteristics of the vibration frequencies showed that the high-rate GNSS PPP method can capture the frequencies of first motion mode of shear type structural response when compared with the FEM output. Results demonstrate the efficiency of the high-rate GNSS PPP method in monitoring first motion mode of a natural frequency.

I. INTRODUCTION

High Rate Global Navigation Satellite Systems (GNSS) method has been widely used to detect dynamic displacements of an engineering structures stimulated by loads such as wind, earthquake and traffic. For the determination of dynamic displacements in engineering structures, high rate GNSS receivers in the range of 1-100 Hz and the relative GNSS positioning method, which requires simultaneous measurements with at least two GNSS receivers, have been successfully used as a complementary sensor to monitor engineering structures, such as high-rise buildings, skyscrapers, towers and long and short span cable suspended bridges, for the past two decades (Çelebi 2000; Breuer et al. 2008; Park et al. 2008; Yigit et al. 2010; Roberts et. Al. 2004; Moschas and Stiros 2011). The detection performance of the displacement movements of this method is sub-cm level of precision in the horizontal components and cm level in the vertical component (Gikas and Daskalakis, 2008).

Thanks to the availability of precise satellite orbit and clock correction products, which is produced by GNSS (Global Navigation Satellite System) services such as the international GNSS Service (IGS), position information is obtained using the precision point positioning (PPP) method. PPP can accurately determine the position information with a single GNSS receiver without the need for another reference receiver and obtain accuracy at the cm to dm level (Zumberge et al., 1997; Kouba and Heroux, 2001). The rapid developments in the PPP methods and improved capabilities, encourages a new research motivation to examine whether the PPP method has accessed the positioning performance that can be achieved by the GNSS relative positioning technique.

PPP method provides a great advantage compared to the relative positioning method, due to the fact that it does not require any reference receiver. However, the PPP method requires products such as precise satellite orbit information, satellite clock error corrections, and modelling solid earth tides to determine precise position information. In addition, the conventional PPP method takes a long time to achieve a stable ambiguity float solution for the cm-level positioning accuracy (El-Mowafy et al. 2016). In recent years, PPP with ambiguity resolution (PPP-AR) has been developed to improve the accuracy of the estimated coordinates and to shorten the convergence period. Three PPP main integer ambiguity resolution methods has been introduced, namely the single difference between satellites method, the integer phase clock model and the decoupled clock model (Shi & Gao 2014).

In case of large (mega) earthquakes, due to the lack of a fixed point condition for the relative method, the earthquake-induced displacements cannot be determined by the relative method. Hence, it is clear that the relative Kinematic GNSS positioning technique will fail to capture the absolute displacement movements (Shu et al., 2017). Kouba's (2003) demonstrated that seismic waves produced by large earthquakes can be detected by PPP technique at 1 Hz frequency. In order to demonstrate the applicability of GNSS-PPP method at 50 Hz in the determination of seismic waves, a series of experiments were conducted by Xu et. al. (2013). They found that high frequency PPP method captured seismic waves with accuracy of 2-4 mm in the horizontal component and sub-cm level in the vertical component. In addition to geoseismic studies, the performance of Kinematic-PPP technique was also analyzed in terms of structural health monitoring in several studies (Moschas et al., 2014, Yigit, 2016; Yigit and Gurlek, 2017, Kaloop et al, 2018). In these studies, PPP-derived time series were compared with the relative GNSS Positioning-derived ones. The results of these studies demonstrated that high-rate kinematic PPP method can accurately capture horizontal and vertical displacements. Recently, the Real-time GPS-PPP method has been applied to real bridge monitoring, and PPP-derived results were compared with the relative positioning results (Tang et al. 2017). They found that Real-time PPP can be used as an alternative method to the relative method for large structure monitoring.

While conventional PPP with float-ambiguity resolution has been extensively tested for structural health monitoring in previous studies, in this study, performance of GNSS-PPP-AR method is investigated in terms of accurate determination of vibration frequency of an engineering structure. For this purpose, a series of free vibration experiments have been carried out using a small scale model structure and 10 Hz GNSS receivers. GNSS data were processed using PPP-AR method. In this contribution, the basics of PPP are first introduced. Then, small scale model structure and its Finite Element Model (FEM), experimental setup and GNSS data processing are briefly described. Following that, the obtained results are presented and discussed. Finally, conclusions and future works are drawn.

II. Basics of PPP Model

Although the basis of the PPP method were set in 1976, the date on which its use started in in engineering measurements was early 2000's when precise ephemeris and clock correction information was available as products The traditional PPP method is used in post-processing, where dual-frequency measurements are used to eliminate the first-order ionosphere error. The observation equations for code and carrier phase observations of the traditional PPP method can be written as follows (El-Mowafy et al., 2011; Yigit et al., 2013):

$$P_{IF}^{s} + c\tilde{d}t^{s} = \rho^{s} + c\tilde{d}t_{r} + T^{s} + \varepsilon_{P_{I^{s}F}} \quad (1)$$

$$\phi_{IF}^{s} + c\tilde{d}t^{s} = \rho^{s} + c\tilde{d}t_{r} + T^{s} + \lambda_{IF}\tilde{N}_{IF}^{s} + \varepsilon_{\phi_{I^{s}F}} \quad (2)$$

The expression $\lambda_{IF}\tilde{N}_{IF}^{s}$ represents ambiguity.

III. Small Scale model structure

The dynamic tests on the used three-story small-scale model in our experiment were conducted on a shake-table, illustrated in Figure 1. The small-scale model is a shear type structure with steel columns and aluminum plates. The model height and weight is 150 cm (each story is 50 cm) and 21.2 kgf, respectively, excluding the GNSS receivers and tribrach. The column ends are made of rectangular 5 mm thick aluminum connection plates to limit the out-of-plane movement during the tests. The numerical vibration frequencies calculated through the Finite Element Model analysis were 3.33 Hz, 4.65 Hz and 4.73 Hz for the first three modes, respectively.

Figure 1. Small Scale Model on the shake table

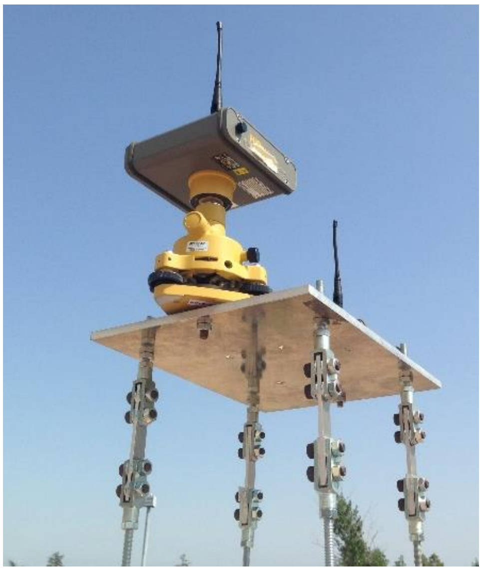

Figure 2. GNSS receivers attached on the structure model (GNSS 1 and GNSS 2 with tribrach are on right and left side, respectively)

IV. EXPERIMENT AND GNSS DATA PROCESSING

A. *Description of the Experiment*

In this study, two dual-frequency Topcon ™ HiPer-Pro GNSS were used. Two GNSS receivers were mounted on the top of the model structure (depicted in Figure 2). The experiment was carried out in February 2018 at the Gebze Technical University campus, Turkey. The natural frequency of model structures calculated from FE model were taken as references in order to evaluate the measured and estimated natural frequency obtained by using PPP-AR method. Both GPS and GLONASS data were collected. Eight GPS and seven GLONASS satellites were visible – on average - during the experiment. The data was collected with a 10° satellite cut off angle at 10 Hz (0.1 sec.) sampling rate.

B. *GNSS data processing*

The data of both GNSS receivers were processed in the post-processing kinematic PPP mode using the modernized version of CSRS-PPP software developed by the NRCan GSD (Geodetic Survey Division of the Natural Resource Canada), since CSRS-PPP software is capable of processing data sampled at 1 Hz and higher. The CSRS-PPP software uses different GNSS orbit and clock products (ultra-rapid, rapid and IGS-Final) depending on the time of a user's RINEX data submission and the epoch of the last observation in users' dataset (Mireault et al., 2008). In this study, IGS final products was used for processing. The IGS-Final products are currently available 13 days after the last observation.

The coordinates obtained from the solution of CSRS-PPP software cannot be used directly in structural health monitoring as their coordinates are expressed in the International Terrestrial Reference Frame (ITRF). Hence, The coordinates from CSRS-PPP software were converted to the local topocentric Cartesian system and then projected to movement directions of the shake table using a similarity transformation (Yigit, 2016).

V. RESULTS AND DISCUSSION

Several dynamic tests were conducted but due to the space limitation, only two of them are presented as a representative example. The top floor response time-histories under the two vibration cases are depicted in Figure 3. The time-series of forced and free vibration responses of the model structure were filtered with a moving average method to remove the long-period components.

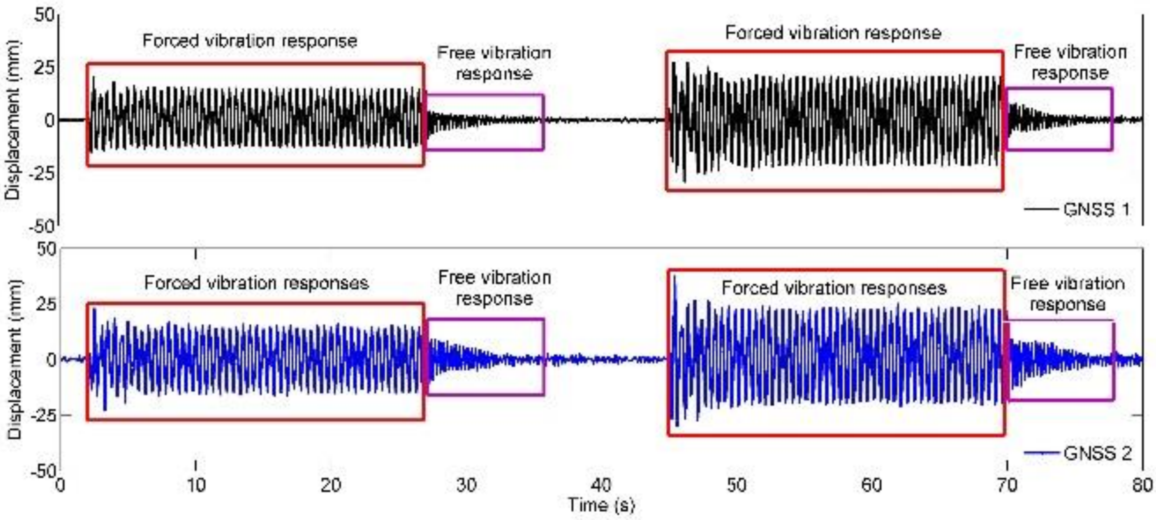

Figure 3. Time series of forced and free vibration responses of the model structure (first and second case selected for this study)

The response of the dynamic motions has four phases, namely static, transient, steady-state and free-vibration motions. There would be a static-equilibrium under gravity forces if no lateral force acts on the model structure. The dynamic force initially disturbs the structure causing a change from the static to dynamic movement in the transient response phase. Following the short-lasting transient motion, the steady-state response occurs as long as the dynamic action exists. The moment dynamic action (harmonic ground motion) diminishes, the model structure starts a the free-vibration motion with no external disturbance. The time period of the free-vibration is dependent on the inherent damping. All the response phases of the model structure are clearly visible in the time series obtained from analysis of the change of the attached GNSS antenna positions obtained from the PPP-AR method (Figure 3). The natural vibration characteristics are solitude in the free-vibration phase. Thus, the free-vibration response data was scrutinized in this paper. The duration of the free-vibration phase is calculated approximately as 10 seconds based on results from both FEM and GNSS measurements.

The time-histories of the free-vibration phase and the corresponding Fast Fourier Transform (FFT) Spectrum are depicted in Figure 4. The FFT spectrum clearly indicates that the free-vibration frequencies observed from both test cases are identical, which is 3.41Hz, whereas the amplitudes are slightly different, determined as 1.9mm and 3.2mm, . Similar observation is also possible for the second vibration test results, shown in Figure 5, the vibration frequencies of FFT spectrum are 3.41 while the amplitudes are 2.2 and 4.1mm, respectively.

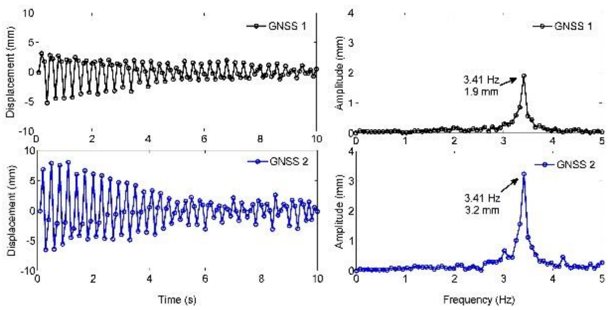

Figure 4. Time series and FFT spectrum of free vibration responses of the structure model after stopping the ground motion (first case)

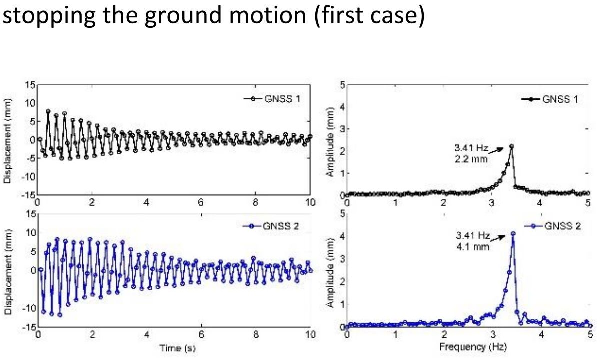

Figure 5. Time series and FFT spectrum of free vibration responses of the model structure after stopping ground motion (second case)

The symmetry and the uniform mass distribution of the system would create a transition dominant vibration mode. However, the amplitudes of the signal captured by GNSS receiver 2 are slightly larger than GNSS receiver 1. These indicate that the model structure has a slight rotational motion in addition to the transition movement in the excitation direction. This is the result of test setup strategy where GNSS receiver 2 is not directly mounted on the top floor plate of the model but to a tribrach (see Figure 2). The additional mass of the tribrach was intended to create intentional torsional response of the structure. Both FFT spectrums having identical dominant frequencies with different amplitudes prove that the strategy is accomplished successfully.

The common practice in the dynamic tests is the application of an impulsive force to the specimen, known as hammer test. The impulsive force vibrates a broad band response while the natural frequency emerges. Figure 6 shows the time series and its FFT spectrum of the hammer test where the similar observations are possible in the dominant frequency and the different amplitudes.

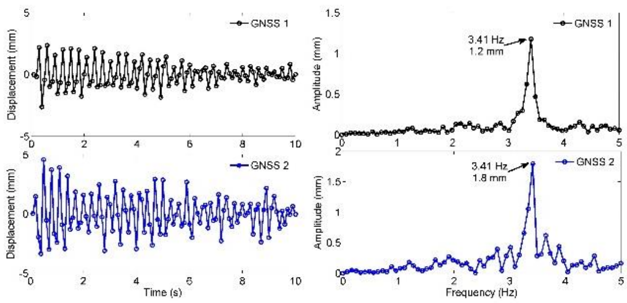

Figure 6. Hammer test: time series and FFT spectrum of free vibration responses of the structure model

Results show that the PPP-AR-derived natural frequency of the model structures is in good agreement with that of the FEM-derived natural frequency with a slight difference of approximately 0.08 Hz. This difference might be due to the effect of the uncertainties of the measurement conditions (temperature, wind etc.), which cannot be included in to the FEM analysis.

VI. CONCLUSION AND FUTURE WORK

In this study, the performance of the PPP-AR method is assessed in monitoring the vibration modes of shear type buildings excited by harmonic ground motions and hammer test. The fundamental vibration frequency estimated by GNSS-PPP-AR was compared with FEM-computed frequency. The high-rate GNSS PPP-AR method can be used in the determination of the frequencies of the first couple of motion modes of shear type structural. The difference in vibration mode values between GNSS-derived and FEM-computed is only 0.08 Hz, which might be due to the effect of the uncertainties those cannot be included in to the FEM analysis such as inherent damping and mass-distribution. Since the sampling rate of GNSS receivers used in this study is 10 Hz, only the first vibration mode of the small-scale structure was estimated successfully. To extend the measurements of the higher vibration modes, new tests using higher sampling frequency GNSS receivers are planned in the near future.

VII. Acknowledgements

The first author would like to thank The Scientific and Technological Research Council of Turkey (TUBITAK) Science fellowships and Grant Programs Department for awarding him a grant to perform a research on High-rate GNSS-PPP Method for GNSS seismology and Structural Health Monitoring Applications including this study at School of Earth and Planetary Sciences, Curtin University, Australia. The authors would also like to thank the Natural Resources Canada for providing CSRS-PPP service.

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