Engineering Structures 148 (2017) 277–292

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic characteristic of tall industrial chimney estimated from GPS measurement and frequency domain decomposition

Piotr Górski

Faculty of Civil Engineering and Architecture, Opole University of Technology, Katowicka 48, Opole 45-061, Poland

ARTICLE INFO

Article history:
Received 4 February 2017
Revised 25 May 2017
Accepted 26 June 2017

Keywords:
Tall chimney
Full-scale measurement
GPS
Background noise
Dynamic characteristics
Frequency Domain Decomposition

ABSTRACT

This paper is concerned with the analysis of the capabilities and limitations of the use of horizontal dynamic displacements measured by the Global Positioning System (GPS) technology along a vertical profile of a tall industrial chimney under wind excitations to investigate its dynamic characteristics, i.e. the natural frequencies, mode shapes and structural damping ratios. The analysis was performed using Frequency Domain Decomposition (FDD) approach. The basic characteristics of the background noise of GPS technology are examined in the time and frequency domain based on the result of a static test. The field tests were conducted on the chimney, located in Belchatow Power Plant in Poland, using three GPS rover units. The GPS units were installed at three levels of the chimney to measure its horizontal deformation along a vertical profile due to the wind. The GPS receivers were able to measure only the first natural frequency of the chimney. The reasons of the harmful multipath and shielding effects and their influence on the reliability of the measurement results were explained. In order to mitigate the spectral leakage effects as well as to improve the accuracy of damping ratio estimation the windowing procedure was adopted with a selected number of samples L_N, determining the duration of a window function. The influence of the L_N number on the damping ratio estimation was examined and suitable L_N number was recommended. The dynamic characteristics of the chimney were investigated based on the dynamic wind response considered in selected directions in the horizontal plane. The obtained experimental results were compared with the predicted values derived from the finite element analysis as well as with the experimental results based on a measured tip displacement of the chimney by GPS technique using Random Decrement Method. It was shown that the structural dynamic characteristics as well as displacement monitoring of tall slender structures under wind excitations can be effectively determined based on GPS measurements at various levels along the vertical profile.

1. Introduction

In recent years the GPS technology has been widely used in measuring and monitoring static, quasi-static and dynamic responses of long-period civil engineering structures such as tall buildings, industrial chimneys, TV towers, long span cable-supported or suspension bridges, and other tall structures, exposed to gust-winds, combined influence of solar radiation and daily air-temperature variations, earthquakes, traffic loads, settlement of the groundwork and other actions. The main reason of such tendency is the improvement of GPS data processing, the development of an analytical method as well as the appearance of the high sampling rate of GPS receivers, currently 10–20 Hz or even 50–100 Hz. The use of the GPS system provides other advantages which are very appreciated in the continuous long-term monitoring of civil structures behaviour, i.e. the monitoring can be automated and, unlike optional optical methods like the laser interferometer, multi-waveform radars or robotic theodolites, regardless of the weather and visibility conditions. The GPS system is also able to measure simultaneously in three directions, i.e. in two horizontal and one vertical directions, the static and quasi-static component of the structural displacements.

Besides the advantages mentioned above, the GPS technology has also some limitations. The GPS satellite signals as well as the measurement accuracy of GPS technology is susceptible to several kinds of error sources such as the atmospheric effects, i.e. the ionosphere and troposphere effects, the GPS receiver noise and its data sampling rate, the imperfect orbits of satellites, the error of the mutual geometry of the satellite constellation (usually evaluated by the GDOP factor so-called the Geometric Dilution of Precision). For this reason, the GPS measurement accuracy is changeable continuously during a twenty-four hours. All of the mentioned error

E-mail address: p.gorski@po.opole.pl

http://dx.doi.org/10.1016/j.engstruct.2017.06.066
0141-0296/

sources give only a little uncertainty in the GPS measurements. Another two troublesome effects could also decrease the GPS measurement accuracy or even seriously decrease a reliability and effectiveness of the monitoring using the GPS system. These problems are: (1) the multipath effect, caused by the falsified or reflected satellite signals from any local obstructions, and (2) the GPS satellite signals shielding effect due to shielding of the certain area of the sky by local obstacles. The second occurrence does not matter, if a remaining number of the available satellites is sufficient. In practise, in order to overcome the above two problems in full-scale measurements of tall structures the GPS units are installed in measurement points located at the top of these structures. Unfortunately, such a feature of the GPS system is a serious limitation in monitoring of the structural response in the vertical profile of tall structures.

In the literature, there exist many papers concerning the calibration tests conducted to assess the GPS accuracy and its limitations. Among others, the measurement accuracy of monitoring GPS system was studied by Breuer et al. [1,2], Chan et al. [3], Moschas and Stiros [4], Nickitopoulou et al. [5], Psimoulis et al. [6] and Tamura et al. [7]. The major outcome of the most recent studies proved that the GPS technology, advanced to record with 10 samples per second, could detect the dynamic displacements accurately if the dominant frequency of structural vibration is in the range between 0.05 Hz and 4.0 Hz, and simultaneously the vibration amplitude is not smaller than ±0.5 cm in the horizontal plane and ±1.0 cm in the vertical direction. Very few structures have natural frequencies below 0.05 Hz so quasi-static components below 0.05 Hz due to the wind and the combined influence of the solar radiation and the daily air-temperature variations can be removed by a filtering procedure to leave the dynamic component [8]. In order to examine the quasi-static component of the displacements the filtering procedure could not be used. For this reason, in recent years, the GPS system is a very useful tool in measuring the dynamic displacements of full-scale long-period civil engineering structures, e.g. [9–16]. However, according to the author knowledge, in the existing literature, there are known applications of the GPS receivers for dynamic monitoring usually in the measurement points located near the top of tall structures. Therefore, currently, it is very advisable and valuable to conduct further studies in order to evaluate the possibility of the structural deformation monitoring using the GPS technology along the vertical profile of tall structures in full scale and, based on this, the investigation of dynamic characteristics of the structures.

The most appropriate way to investigate the actual dynamic characteristics of existing tall slender structures is to perform an ambient modal analysis, called an output-only modal analysis. Such an analysis does not require controlled, expensive and heavy excitation devices as well as measurements of excitation forces acting on the structure. In this case the natural and environmental excitations, like a wind action, are presented and measurements of the structural response are needed only. However, in the ambient modal analysis some estimation techniques should be applied. The review of these techniques in both the time and frequency domain is presented in the papers [17,18]. In the past years, many estimation approaches were developed, such as Logarithmic Decrement Method [19], Random Decrement Method [20], Hilbert Transform Method [21], Hilbert-Huang Transform Method [22], Stochastic Subspace Identification (SSI) [23], Half Power Method [24], Frequency Domain Decomposition Method (FDD) [25], Enhanced Frequency Domain Decomposition Method (EFDD) [26], Collocation Method [27] and Wavelet Transform Method [28]. In the presented study, the efficiency of the FDD for the investigation of the natural frequencies and corresponding mode shapes, and the EFDD for the estimation of the modal damping ratios (as a fraction of critical damping) were considered.

2. Outline of paper

The primary aim of this paper is the analysis of the capability and limitations of the use of horizontal dynamic displacements measured by the GPS technology along a vertical profile of the tall industrial chimney to investigate its dynamic characteristics. In the first part of this paper the basic characteristics of a background noise of GPS technology are examined in both the time and frequency domain, based on the results of a static test using two GPS Leica 1200 receivers. Using the filtering process the accuracy of the dynamic displacement monitoring in good GPS conditions for a structure with the fundamental frequency over 0.05 Hz was identified. The chimney is located in Belchatow Power Plant in Poland. The field tests were conducted on the chimney using three GPS rover receivers simultaneously. The GPS units were installed at three levels of the chimney to measure its horizontal deformation along a vertical profile due to the wind. The GPS receivers were able to measure only the first natural frequency of the chimney. The reasons of the occurrences of the harmful multipath and shielding effects and their influence on the reliability of measurement results were explained. In order to mitigate the spectral leakage effects as well as to improve the accuracy of damping ratio estimation the windowing procedure was adopted using the Hanning time-window function with a selected number of samples L_N, determining the duration of a window function. The influence of the L_N number was examined on the damping ratio estimation. It was shown that the damping ratio is significantly affected by the L_N number and a reliable evaluation of the damping ratio needs a sufficient large number of samples L_N. In the case of the analyzed chimney response the L_N number was recommended. The dynamic characteristics of the chimney, i.e. the natural frequencies, mode shapes and structural damping ratios, were investigated based on the dynamic wind response measured by GPS technology using the FDD and EFDD approaches. The results delivered some important practical information. The damping ratio values were evaluated in four directions in the horizontal plane, in which the recorded response was considered. It was shown that the considered directions of the response have no significant influence on the results. The natural vibration frequencies and mode shapes of the chimney, assuming the flexibility of soil, were evaluated through the application of the finite element method based on a three dimensional finite element model of the chimney. The obtained experimental results using FDD were compared with the predicted values derived from the numerical analysis as well as with an experimental results based on tip displacements of the chimney measured over 2 h by GPS technique using RDM, presented in the paper [8]. It was found that the results are very similar. Thus, it was shown that the structural dynamic characteristics and horizontal displacement monitoring of tall slender structures under wind excitations can be effectively determined based on GPS measurements at various levels along a vertical profile of the structure. Consequently, it was shown that the GPS measurements can provide relevant data which could be used for the procedure of the calculation model verification at a design stage, the calculation model updating, the dynamic response prediction, the assessment of the technical state or structural health monitoring of tall slender structures. According to the author knowledge this paper presents the first instance of the dynamic characteristics investigation based on the horizontal displacement measured by three GPS receivers mounted at three levels along the vertical profile of the tall industrial chimney excited by the wind.

3. Analysis of GPS background noise

In order to examine the influence of GPS background noise on the measurement results a static test with two GPS Leica 1200