GNSS and Earth Observation for Structural Health Monitoring (GeoSHM) of the Forth Road Bridge

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ABSTRACT: The modelling of the typical response and the dynamic characteristics of long-span bridges and their connection with the loading of the bridge are difficult tasks, due to the continuous vibration caused by various types of loading (i.e. traffic, wind, temperature, etc.). Under the framework of GeoSHM (GNSS and Earth Observation for Structural Health Monitoring) Demo project, the monitoring of the response of the Forth Road Bridge is currently based on four GNSS receivers and an anemometer, aiming to study the response and its correlation with the different type of loading effects (traffic, etc.) and the environmental conditions (wind, temperature, etc.). A data strategy is being developed, focusing to create a data base, through which it can be expressed the variation of the response through the daily, weekly cycles and the corresponding environmental conditions. Through this data strategy potential alarming events can be detected, due to extreme loading or response conditions, followed by the management and archiving of the data. The GNSS data of the last 1.5 years have been analysed and archived, and part of their results are presented in the current study.

1 INTRODUCTION

There has been a great interest in the recent years for the monitoring of the structure response, as the latter is being used for the design of structures (Bardakis and Fardis, 2011) and the estimation of the structural health conditions, leading to the timely and cost-effective maintenance of the structure (Meo et al., 2006; Meng et al., 2007; Koo et al., 2013; Psimoulis and Stiros, 2013; Yu et al., 2014; Moschas and Stiros, 2014). Until the last decade, the structure monitoring was based mainly on accelerometers, strain gauges, etc., providing mainly the frequencies of the structure motion and the corresponding strain. However, the introduction of the geodetic sensors and mainly GPS contributed significantly to the estimation of the global displacement monitoring of the structure in a Cartesian coordinate system, independent of the structure (Psimoulis and Stiros, 2012).

Apart from the GPS, and recently the Global Navigation Satellite Systems (GNSS), which is used as a main geodetic approach for the bridge monitoring (Roberts et al., 2004; Meng et al., 2007), other geodetic techniques, such as Robotic Total Station (Psimoulis and Stiros, 2012; Psimoulis and Stiros, 2013), interferometric radar (Dei et al., 2009; Gentile, 2010), combination of Total Station with camera (Charalambous et al., 2015) and pseudolites (Meng et al., 2004) have been recently introduced for more accurate estimation of the structure displacement. All the above geodetic techniques have different advantages and limitations for monitoring long- and short-period deflection of structures, resulting many times in their combined use to overcome their drawbacks and estimate reliably the structure response (Moschas et al., 2013). However, there are only a few cases where the geodetic techniques have been used for permanent monitoring system,

with GPS technique being the most common technique and the case of Tsing Ma Bridge, being the most representative example (Wong et al., 2001).
Under the Integrated Application Promotion (IAP) scheme of the European Space Agency (ESA), the GeoSHM consortium was created, aiming to create the GeoSHM system, where GNSS and Earth Observation (EO) technologies (i.e. InSAR, etc.) are integrated with other broadly used sensors (such as accelerometers, anemometers, etc.) for the monitoring of long-span bridges. The GeoSHM Feasibility Study aimed on the investigation of the use of GNSS and EO data and led to the GeoSHM Demo Project, which started in March 2016 and will last for two years, which focuses on the development of a smart data strategy, where the data of the different sensors will be combined and produce an efficient, reliable and accurate output, which will reflect the response of the key-nodes of the bridge and identify potential atypical behaviour. In the framework of the GeoSHM projects, a small monitoring network has been installed on the Forth Road Bridge, in Scotland, using it as a case study for the evaluation of the GeoSHM system. Currently, the monitoring system is being expanded by adding more sensors (such as accelerometers, tiltmeters, GNSS receivers, weather stations, etc.) in more locations, aiming to improve the monitoring performance. For the moment, there are available GNSS and anemometer data of three nodes on the bridge for the last 1.5 year, and more data are continuously recorded, based on the data strategy being developed and improved.
In the current study, it is presented the preliminary results of the data strategy which has been developed for the analysis of the GNSS data, for a short period (i.e. month), aiming to express the bridge response due to different type of loading and environmental conditions (temperature, wind, etc.), and identify the typical behaviour of the bridge response. The response of the mid-span is presented during August of 2016, where the temperature variation is significant during the day, and where an incident of strong-wind occurred one of the monitoring days.

2 GNSS MONITORING OF FORTH ROAD BRIDGE

The monitoring system which has been deployed for the monitoring of the Forth Road Bridge currently consists of four GNSS receivers and two anemometers. One of the GNSS receiver (SHM1) is used as the reference station located in a distance about 1 km from the bridge, forming short baseline with the other three GNSS receivers, which are installed on the bridge. More specifically, the GNSS station SHM4 is located on the west side of the southern tower of the bridge, while the SHM2 and SHM3 GNSS stations are located at the midspan, installed on 4m tall masts in order to limit the multipath impact produced by the passing vehicles (Figure 1). All the GNSS receivers are Leica GM30, recording in 10Hz sampling rate, while the anemometers are recording in 20Hz sampling rate. The GNSS records are downloaded and processed a dedicated server for the GeoSHM project, using Leica Spider and Geoffice software, resulting finally to the GPS coordinates (North, East and Up) of the three GNSS stations on the bridge. The GNSS coordinates are then transformed into bridge coordinate system, expressing the displacement of the three points in the longitudinal, lateral and vertical axis of the bridge.

Figure 1. The Forth Road Bridge from the GNSS reference station (SHM1). The position of the GNSS station at the South Tower (SHM4) is indicated.

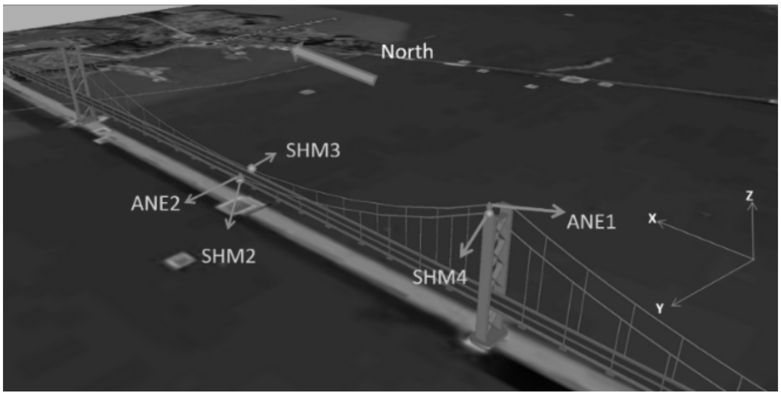

Figure 2. The GNSS stations and the anemometers deployed for the monitoring of the Forth Road Bridge.

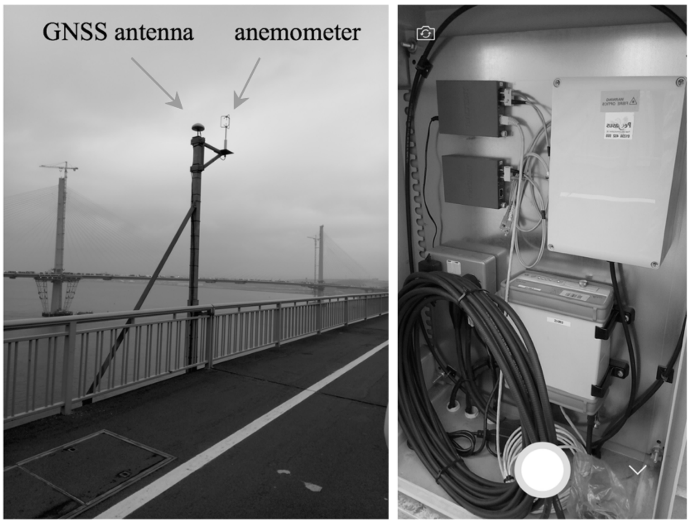

Figure 3. (left) The western GNSS station of the mid-span of the Forth Road Bridge. The GNSS antenna is installed on the rigid mast to limit the multipath from the passing vehicles. (right) The GNSS station, where the GNSS receivers is connected with power supply and internet access.

3 ANALYSIS OF GNSS TIME SERIES

The displacement of each GNSS station is used as the input for the estimation of the response of two key-nodes of the Forth Road Bridge: the south tower and the midspan. More specifically, the displacement of SHM2 and SHM3 are combined to compute the mean longitudinal, lateral, vertical responses and rotation of the deck of the midspan, based on the given geometry of the cross-section and that the SHM2 and SHM3 stations are on the same cross-section of the deck. Furthermore, to average the displacement time series of the two GNSS stations of the mid-span improves the accuracy of the final response, as potential site-specific GNSS errors, such as multipath effect, will be limited. Regarding, the monitoring of the South Tower, since there is only one GNSS station, the response of that point is being used to estimate the deflection of the Tower.

In the framework of the data strategy of GeoSHM, there has been developed a methodology which aims to specify the main characteristics of the bridge response (amplitude, modal frequencies) and correlate them with the bridge loading and the environmental conditions. More specifically, for each estimated component (longitudinal, lateral, vertical and rotation) the mean values are computed, and the standard deviations and the corresponding frequencies for every 10-minute period are also estimated. The mean value is being used to estimate the long-period behaviour of the bridge, while the standard deviation represents the short-period response due to dynamic load, etc. The frequencies of the time series are expected to reveal the main modal frequencies of the bridge. Likewise, the same statistical values are computed for the wind (amplitude and direction) and the temperature in order to correlate the response of the bridge with the environmental condition and identify potential short- or long-term typical relationship of the bridge response with any of the two environmental conditions.

4 RESULTS OF BRIDGE RESPONSE DUE TO WIND AND TEMPERATURE

In Figure 4 are presented the vertical response of the midspan for the period between 20/07/2016 and 21/08/2016, computed as the 10-min mean average of the vertical displacement from SHM2 and SHM3 and the corresponding standard deviation of the 10-min response. It is obvious the daily cycle on the vertical response of the midspan due to the variation of the temperature and the traffic. From the plot of the standard deviation is clear that during weekend, the standard deviation, which expresses the dynamic response, is reduced roughly by 40-50% (i.e. σ=15-16cm during week days is reduced to σ=8-9cm in weekend), indicating the significant impact of traffic in the response of the vertical component, and standard deviation for the 10 minutes interval.

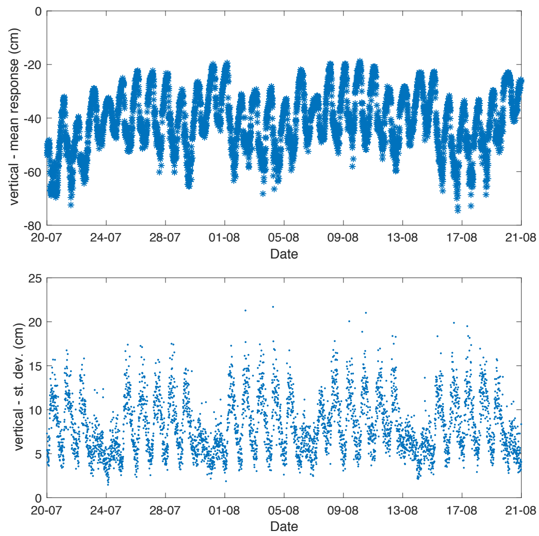

Figure 4. (up) The 10-min mean response and (bottom) the 10-min standard deviation of the vertical component for the midspan of the Forth Road Bridge, for the period 20/07/2016 – 21/08/2016. It is clear the daily cycle in both plots and the reduction of the standard deviation during weekends due to the limited traffic load.

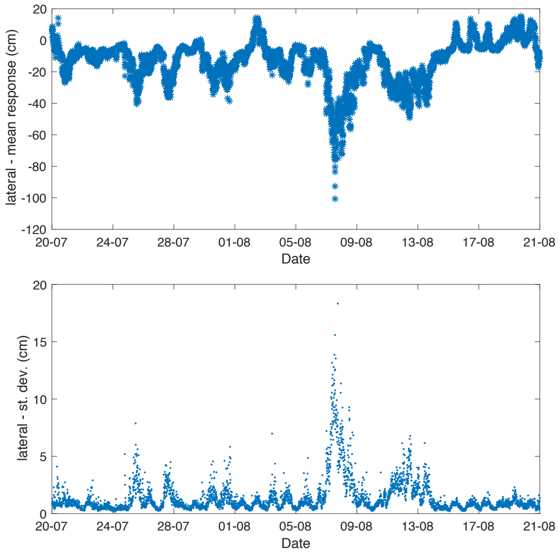

Figure 5. (up) The 10-min mean response and (bottom) the 10-min standard deviation of the lateral component for the midspan of Forth Road Bridge, for the period 20/07/2016 – 21/08/2016. It is clear the absence of daily cycle and the impact of the strong wind load, which can produce lateral response up to 1m.

Likewise, the mean response and the standard deviation of the lateral component of the midspan for the same time period, reveals that the daily cycle is not the dominant and that the mean response and the standard deviation have similar pattern, expressing basically the response due to the wind load. For instance, it is clear, that there is a strong wind event on 7th and 8th August 2016, where the mean response exceeded the one meter. From the standard deviation plot is clear that during period of weak wind load, the standard deviation ranges between 2-3cm, but for strong wind events, it may exceed the 15cm, reaching values similar to that due to traffic load.

By focusing on the mean response of the first days of August 2016, including a weekend (6th and 7th August) and an event of strong wind (7th August), we can identify that there is a daily cycle only on the vertical component, while on the lateral component, we can identify the impact of the strong-wind event, which is also evident also on the longitudinal response of the bridge, resulting a mean response of up to 2-3 cm (Figure 5). The rotation of the deck seems to vary mainly on weekdays, without having a specific pattern, indicating that it is the result of the traffic load, fluctuating randomly depending on the current traffic conditions.

However, by examining the corresponding 10-min standard deviation of the specific time period, it can be observed clearly the diurnal cycle apart from the vertical component, also in the longitudinal and rotation component, indicating that the dynamic response of bridge depends on the traffic which varies during the day. Furthermore, for the period from 1st to 5th August, where the wind load is low, there is also indication of the diurnal cycle in the lateral component, which though is significant lower than that of the vertical component. Also, it is important that for the two days of the weekend (6th and 7th August), where the main difference is the strong wind on the 7th August, it seems that the standard deviation, which reflects the dynamic response, is slightly higher for the three components, vertical, longitudinal, rotation, proving that the strong-wind produced dynamic vibration not only on the lateral component, which coincided with the wind direction, but also on all the axes of deck at the midspan.

Regarding the spectral analysis of the lateral, vertical and rotation component for the same time period, it is clear the the main modal frequency of each component varies with time in a range of $\pm 0.02 Hz$, with the largest variation in the lateral component (Figure 6). The lowest modal frequency corresponds to the lateral component (mean value 0.069Hz), which also seems to follow a diurnal cycle pattern, indicating that this could be probably be affected by the temperature variation and the traffic load.

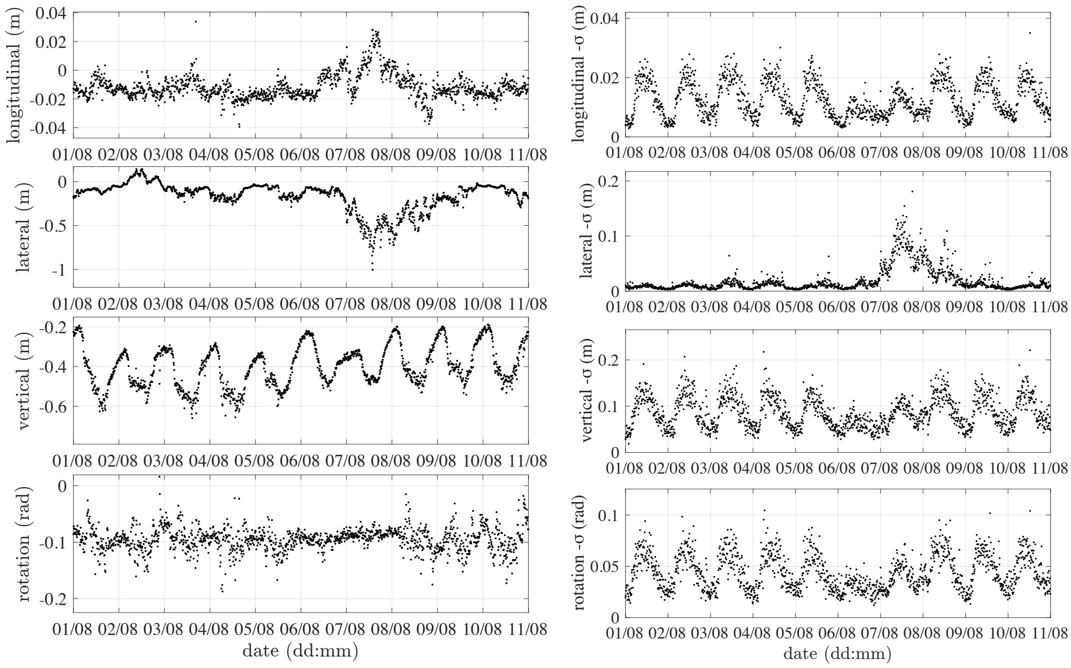

Figure 5. (left) The 10-min mean response and (right) the 10-min standard deviation of the four component (longitudinal, lateral, vertical, rotation) at the midspan of Forth Road Bridge, for the period 01/08/2016 – 11/08/2016.

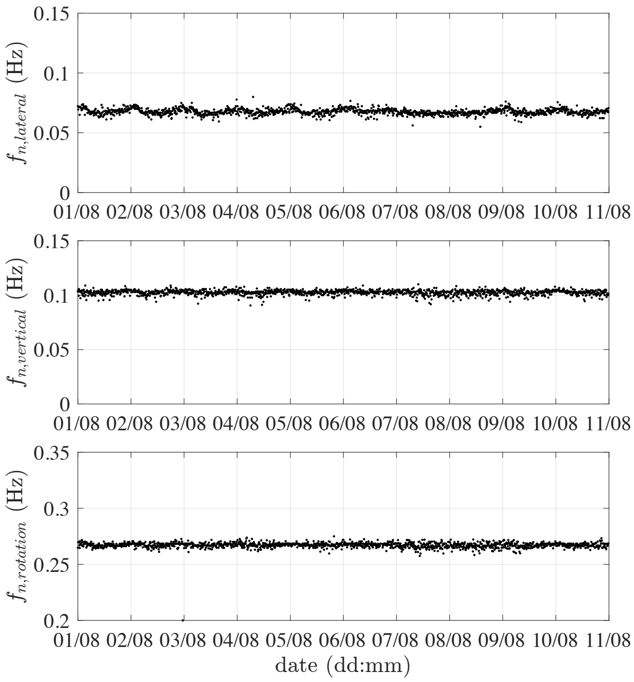

Figure 6. The main modal frequencies of the (up) lateral, (middle) vertical and (bottom) rotation component of the midspan of Forth Road Bridge, for the 10-min time periods, for the period 01/08/2016 – 11/08/2016.

5 CONCLUSIONS

The current study presents the first results of the GeoSHM system data strategy, using the Forth Road Bridge, as the case study. From the first results of the limited available data (GNSS records only from three rover points on the bridge) indicate the current developed data can lead to some helpful and reliable outcome of the behaviour of the bridge, how the main short- or long-period response of the bridge correlates with the three main type of loads (traffic, wind, temperature) and which type of load is dominant for the different components of the bridge response. It shows clear diurnal impact of the temperature and the traffic load and how this is limited during weekends, and how the wind load affects mainly the lateral component. It is also evident the variation of the modal frequencies during the day time and illustrates how this depends on the current environmental (temperature) and traffic conditions. Further intensive investigation needs to be conducted by using longer period of data, covering for at least a 2-year period, and including data from more points of the bridge (quarter-span, towers) and more sensors (accelerometers, etc.) to derive more clear correlation between the response of the bridge and the different type of loads. Finally, the main aim is also the determination of the weights of the significance of each type of load for the different components of the bridge response.

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