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Structural Health Monitoring System using GPS for Sustainable Bridges

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ABSTRACT

Monitoring concepts for structural systems have been subjected to a rapid development process. They have become more and more important in the intervention planning on new and existing structures. This paper presents an efficient approach to assessing the bridge Serviceability based on deflection data from structural health monitoring for sustainable bridges. A case study of the proposed approach is provided on an existing highway bridge in Mansoura, Egypt. GPS monitoring system is used to monitor the movement components of bridge. The de-noised wavelet method is used to extract the semi-static bridge movement and FFT is used to extract the frequency modes for the dynamic bridge. From the analysis results, it can be shown that the bridge behavior is safe in time and frequency domains. Also, the serviceability analysis of the bridges movements according to the ASSHTO specification show that the bridge movement is safe under existing traffic loads.

1 INTRODUCTION

Structural health monitoring (SHM) of a bridge can provide abundant information on bridge component conditions and system performance. What is needed is an efficient method to collect data from a structure in-service and process the data to evaluate key performance measures, such as serviceability, reliability, and durability [1]. Nevertheless, the greatest challenge in an efficient SHM design is how to integrate the monitored data into bridge management systems in order to achieve the goals of SHM. In general, the objectives of SHM include that the potential structural damage detect, the remaining service life of a structure predict and the maintenance decision database provide.

Depending on the goals of SHM, the procedures to analyze identical sets of the monitored data may be different. Therefore, it is crucial to develop an objective-oriented methodology to effectively process the monitored data. During the last decade, modern concepts for monitoring and maintenance programs of engineering structures have been developed [2, 3 and 4]. These studies are essential; however, they do not provide comprehensive information on how the measured data associated with an existing monitoring system can be used in a serviceability assessment method.

The Global Positioning System (GPS), nowadays, has been used for many civilian applications besides navigation. Beside the survey engineering GPS applications, the structural deformation monitoring is also a high precision GPS application, where points of interest on engineering structures are monitored to centimeter level accuracy and in real time if required [5]. Another study identified the goal of structural monitoring is to gain knowledge of the integrity of in-service structures on a continuous real-time basis [6].

Filtering and smoothing in the context of dynamic systems refers to a Bayesian methodology for computing posterior distributions of the latent state based on a history of noisy measurements. Other Researchers studied the de-noising GPS data based wavelet and Kalman filter, in this study used wavelet de-noising based on integration of feature extraction and low-pass filter to reconstruct the filter signal, then applying the Kalman filter to improve the high quality filter signals; from this method, they found that these methods have a very important significance in improving the accuracy GPS data processing and expanding the application range of GPS service [7]. Others applied the wavelet de-noise method with improved threshold function to optimize the GPS/INS navigation signals, in this study used the Translation invariant threshold wavelet noise reduction method reduces threshold to the signals with noise after translating, then reverses translation of de-noised signals and gets the processed signals[8].

Scheduled maintenance and periodic inspections offer only limited knowledge of structural condition, and these methods are costly in terms of extensive labor and downtime [6]. However, advances in sensing technologies, material and structural damage characterization, and monitoring diagnostic technologies enabled the integration of distributed sensors for real-time inspection and damage detection. Thus, the essence of structural health monitoring is the development of autonomous systems for the continuous monitoring, inspection and damage detection of structures with minimum labor involvement.

2 BRIDGE DESCRIPTION AND GPS MONITORING SYSTEM DESIGN

Mansoura Bridge is one of three important bridges that crosses the Nile River (Damietta branch) in Mansoura city, Egypt and was constructed in 1991. This bridge is connecting Mansoura, Damietta and Tanta cities. The total length of the bridge is 2037.5 m with a 270.0 m over the Nile River; the total width of the bridge is 24.0 m, two vehicle lanes for traffic on each direction and two pedestrian walkways (Fig. 1). The part of the bridge over the Nile consists of five spans with a maximum span of 80.0 m two spans of 50.0 m and two spans of 45.0 m.

The data presented in this paper were collected using two GPS (rover) receivers clamped at the center of the longest (mid) span (80.00 m) to study the deformation of bridge deck. This point is located on the top of the handrail of the sidewalk of the bridge, as shown in Fig. 1. The measurement system used is a real time kinematic (RTK) GPS. The base GPS, rover GPS and radio unit are used to collect raw data at rate of one Hz (Fig. 1). The measuring condition was favorable for the receiver and free of any obstructions at 15^{o} angle view of the horizon and at least four satellites were tracked continuously. The time observation for each rover point is one hour, approximately. The GPS base receiver, recording also at one Hz, was placed approximately 3.6 Km away from the bridge at stable ground, as shown in Fig. 1.

The data collected were pre-processed using GPS-Trimble software. The output of the GPS software was the time series of instantaneous Cartesian coordinates of the rover receiver in the WGS84 coordinate system. A local bridge coordinate system was established to be used in the analysis and evaluation of the observed data. The azimuth of the bridge is 5^{o} 18’ 59.76’’ (calculated from the data). Herein, the X-data represents the displacement changes along the longitudinal direction of the bridge, the Y-data represents the displacement changes along the transverse direction of the bridge and the Z-data represents the relative displacement change a long the altitude direction of the bridge.

Figure 1: Mansoura Bridge and GPS monitoring system design

3 MONITORING DATA ANALYSIS

To analyze the monitoring deformation of bridge, the filtration of GPS data monitoring must be first done. The time and frequency domains are main methods are used to study the health state of structures. In this study used de-noised method based on wavelet transform (WT) to filter and analyze time domain for the GPS data and used Fast Fourier Transform (FFT) to analyze the GPS data in frequency domains.

3.1 De-noised GPS monitoring data

Wavelet analysis is a strong tool to eliminate GPS noises according to the noise characteristics [9]. Donoho [10] and Aminghafari et al. [11] are proposed a method for reconstructing signals based on de-noised method of the observation data (x) from correlated noise as:

$$x_i = f(t_i) + \sigma z_i \qquad i = 0, \ldots \ldots, n-1 \qquad (1)$$

where, f is deterministic and is the signal to be recovered, $t_i = {}^{i}/_{n}$, $z_i \sim N(0,1)$ is a Gaussian whit noise, and σ is a noise level. Our interpretation of the term de-noising is that one's goal is to optimize the mean-square error

$$n^{-1} E\|\hat{f} - f\|^2_{l^2_n} = n^{-1} \sum_{i=0}^{n-1} E(\hat{f}(i/n) - f(i/n))^2 \qquad (2)$$

Subject to the side condition that:

with high probability; $\hat{f}$ is at least as smooth as f (3)

Our rationale for the side condition (1) is this: many statistical techniques simply optimize the mean-squared error. This demands a trade-off between bias and variance which keeps the two terms of about the same order of magnitude. Donoho [10] proposed three steps for a threshold procedure for recovering signals from noisy observation as follow: apply the interval-adapted pyramidal filtering algorithm of Cohen et al. [12] to the measured data, obtaining empirical wavelet coefficients. In this study, the method of a soft threshold eliminating noise processing is used also; and used it to process the high frequency coefficients to be zero in the decomposed signal constructions of wavelet analysis, and some scale or different scale signal components with these coefficients in the GPS data time series are all eliminated. Then, the signals are reconstructed to analyze their spectrum features.

In this section, the de-noising wavelet model based on discrete wavelet transform (DWT) is used at calculated level with Symlets mother wavelet (N=12). The output smoothed GPS data is obtained using the wavelet coefficients based on soft universal threshold with defined parameter for the threshold scaling used dependent estimation of level noise [12, 13]. About forty minutes continuous measurement of GPS used in this study. The observations of the three directions are plotted in Fig. 2. The original displacement history measurements in X, Y and Z directions of the bridge are extracted using wavelet de-noising process. The trend components in the series were investigated from the obtained data within de-noising process analysis. The trend component in the series represents the long-term changes related to time and it can be defined by a polynomial function in the time domain. From Fig. 2, it is found that the de-noised signal has high correlation with the original signal; the correlation between the real data and de-noised GPS observation is 0.98 for the three directions. It means that this method is suitable to remove the observed GPS noises. In addition, it can be seen that the maximum and minimum residuals between the original and de-noised signals are 13.83, 16.91; 36.78 and -16.71, -9.91, -24.60 mm, in the X, Y and Z directions, respectively. This indicated that the vibration noise and dynamic movement component for the Z direction is higher than other directions.

As well as, it can be seen that the de-noising processing caused an increase in the signals accuracy. In addition, it can be seen that the standard deviation for the original observations are: 11.1, 9.0, 14.6 mm whereas for the de-noised signals are: 10.5, 8.5, 13.3 mm. The results have shown that noises can effectively be removed and the useful signals can be extracted from original signals with wavelet de-noised analysis as shown in Fig. 2. From Fig. 3, it can be seen that the X, Y and Z-directions displacement of the bridge deck show no correlation between the three directions displacements. In addition, the maximum displacement in the X, Y and Z-directions are: 25.2, 16.6, 37.3 mm, respectively. Whereas, the minimum displacements are: -23.9, -24.2, -42.8 mm in the X, Y and Z-directions, respectively. From these results, it can be seen that the semi-static deformation of bridge deck is small and safe.

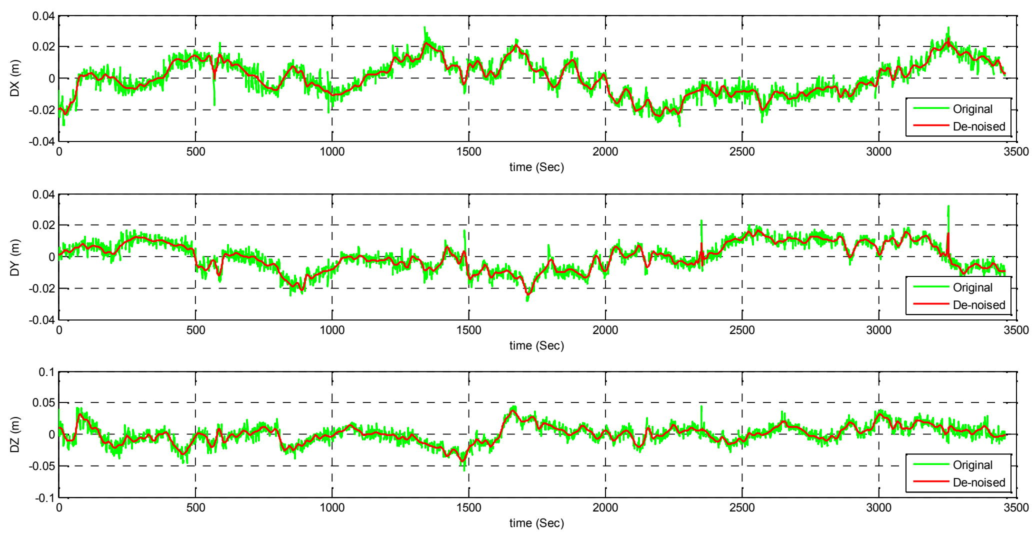

Figure 2: Time series GPS observation and de-noised signals

4 FREQUENCY DOMAIN ANALYSIS

As per examining Figs. 3 a, b and c, the apparent calculated frequency based on band pass filter for the original GPS observations and converted into acceleration, which contains the dynamic component frequency bridge deck modes. In addition, the high power spectrum is apparent; dynamic for the frequency movement directions are equal, approximately. Also, it can be seen that the correlation between the frequency domains in the three dimensions is high during the monitoring time, approximately. The results, also, show the significant dominant high frequency of the apparent displacement in the X, Y and Z directions are close to 0.19 Hz. The frequency modes of the structure can be extracted from dynamic displacement, as shown in Fig. 3.

The first to five frequency modes are 0.082, 0.12, 0.15, 0.17 and 0.19 Hz. From these results, it can be concluded that the bridge movement under affecting loads in frequency domain is, also, safe.

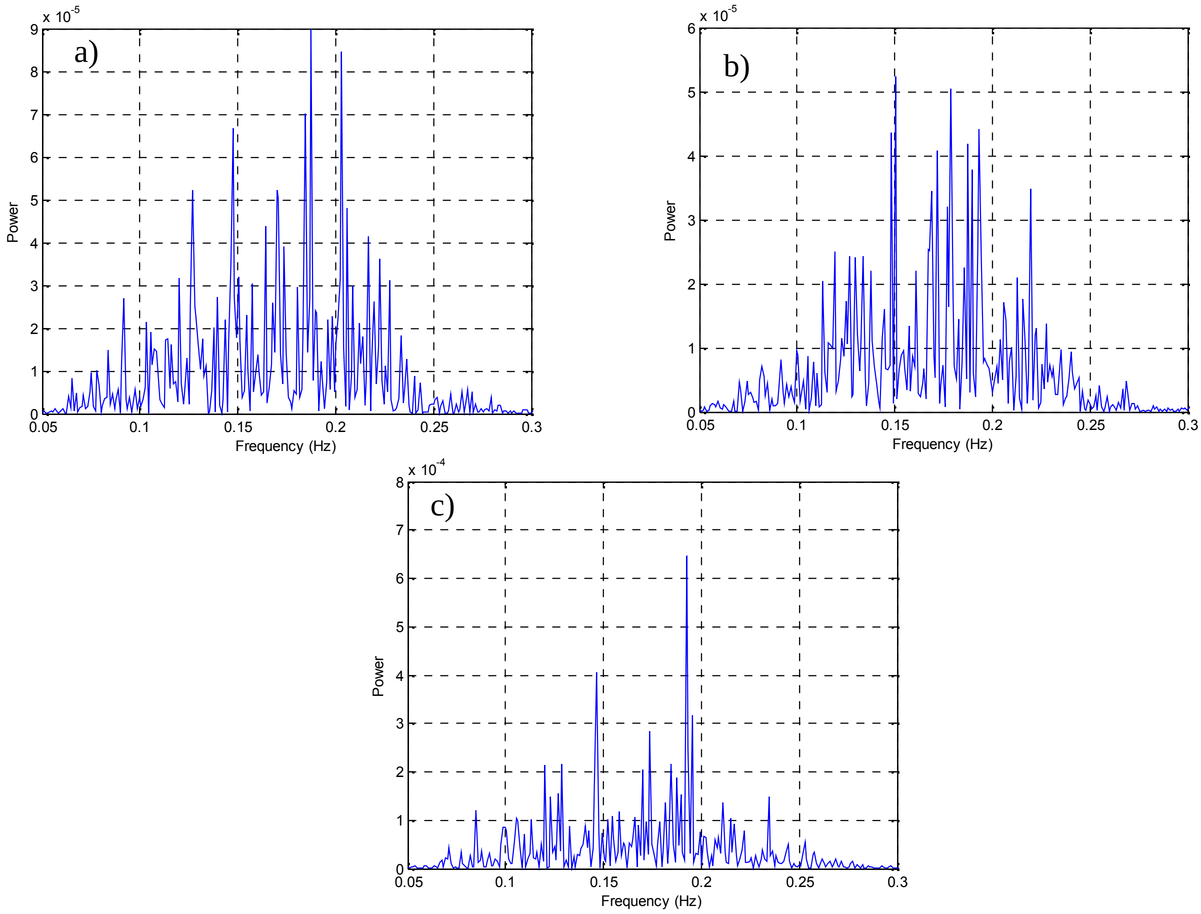

Figure 3: Frequency modes of bridge deck movements (a) X, (b) Y and (c) Z- directions

5 BRIDGE SERVICEABILITY RATING BASED ON SHM DATA TO MAINTAIN SUSTAINABILITY

Sustainability is now recognized as a key issue which much be addressed in the design, construction and lifelong maintenance of civil engineering structures. SHM of a bridge can provide valuable data on bridge component conditions and system performance that provide the database for optimal maintenance decision process in order to avoid costly replacement and increase sustainability. Serviceability limit states usually relate to satisfactory performance and correspond to excessive deflection, vibration and cracks. Serviceability analysis is used to describe the existing condition of a bridge's deck. While the importance of bridge health monitoring applications becomes more and more appreciated, current bridge management practice includes mostly visual inspection methods. Visual inspections include a great deal of uncertainty, since they are mostly limited by the indications at the surface and damage occurring inside the structure which can easily be overlooked. Accuracy of visual inspections depends largely on the experience and expertise of the inspector. Recent studies show that these inspections are, also, prone to high subjectivity. Instrumentation of bridges such as GPS can reduce these uncertainties considerably and lead to development of more realistic and accurate prediction models, enhancing the efficiency of bridge management practices. However, there are some issues to be resolved such as evaluation, storage and management of data as well as development of specifications for recommended health monitoring procedures.

In this study, the serviceability limit is defined in terms of deflection of Bridge's deck at any time, δ (t), in the design life. If the deflection exceeds the code requirement (δ_{all}) a serviceability failure is assumed to occur. It is also assumed that replacement or rehabilitation works must be conducted before deck reaching its deflection limit. The limit states usually define the various ways in which a structure fails to satisfy these basic requirements. To mathematically present the condition of structural members towards its limits at particular time, buffer functions, F(t), measured in percentage for each limit and then formulated accordingly to:

$$F_{\delta}(t) = (\delta_{all} - \delta (t)) / \delta_{all} \quad (4)$$

Four performance condition states, Good (G), Satisfactory (S), Fair (F), and Poor (P) are assigned to the percentage range of the deflection as mentioned above, respectively. Minimum acceptable criteria for Good (G_{min}), Satisfactory (S_{min}), and Fair (F_{min}) conditions are also needed to be defined [14].

$$\Omega_j = \begin{cases} G & F_\delta(t) \geq G_{min} \\ S & S_{min} \leq F_\delta(t) < G_{min} \\ F & F_{min} \leq F_\delta(t) < S_{min} \\ P & F_\delta(t) < F_{min} \end{cases}$$

(5)

Where Ω denote the set of possible deflection limit states. For example for the serviceability deflection limit at j = 1:

$$\Omega_1 = \begin{cases} G & F_\delta(t) \geq 15\% \\ S & 10\% \leq F_\delta(t) < 15\% \\ F & 5\% \leq F_\delta(t) < 10\% \\ P & F_\delta(t) < 5\% \end{cases}$$

(6)

According to the ASSHTO specification, highway bridges consisting of simple or continuous spans should be designed so that deflection due to live load plus impact should not exceed 1⁄800 the span. For bridges available to pedestrians in urban areas, this deflection should be limited to 1⁄1000 the span. For cantilevers, the deflection should generally not exceed 1⁄300 the cantilever arm or 1⁄375 where pedestrian traffic may be carried.

Based on the observed GPS filtered data of Mansoura Bridge, the nominal average deflections according to observed GPS data and the corresponding deflection limit states it was found that $F_{\delta}(t)$ more than 15% for all observation so, it can be concluded that the bridge movement is safe. In other words, no maintenance works will be needed under current bridge condition.

6 CONCLUSIONS

This paper presents an approach to use monitoring data for assessment of structural systems with respect to serviceability limit states in order to increase the sustainability of bridges. The proposed approach was implemented by using the actual SHM data collected from an existing Mansoura highway bridge. The following conclusions can be drawn from this study.

1) From the GPS monitoring and analysis observations, it can be seen that the bridge movement components in semi-static and dynamic components are safe under existing loads.
2) The proposed approach can effectively assess the bridge system performance using the SHM data collected from existing bridges. The bridges are studied with respect to serviceability limit states only using GPS. The purpose is to study the bridge movement which may reflect excessive deflection, vibration and cracks on bridge. More instrumentation are needed to study reliability, and durability of bridges such as strain gauges, accelerometers, temperature sensors and other instruments that provide more information about bridge condition.
3) From the analysis results, it can be shown that Mansoura bridge behavior is safe in time and frequency domains. Also, the serviceability analysis of the bridge movements according to the ASSHTO specification show that the bridge movement is safe under existing traffic loads.

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