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Wavelet based multi-step filtering method for bridge health monitoring using GPS and accelerometer

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Abstract. Effective monitoring, reliable data analysis, and rational data interpretations are challenges for engineers who are specialized in bridge health monitoring. This paper demonstrates how to use the Global Positioning System (GPS) and accelerometer data to accurately extract static and quasi-static displacements of the bridge induced by ambient effects. To eliminate the disadvantages of the two separate units, based on the characteristics of the bias terms derived from the GPS and accelerometer respectively, a wavelet based multi-step filtering method by combining the merits of the continuous wavelet transform (CWT) with the discrete stationary wavelet transform (SWT) is proposed so as to address the GPS deformation monitoring application more efficiently. The field measurements are carried out on an existing suspension bridge under the normal operation without any traffic interference. Experimental results showed that the frequencies and absolute displacements of the bridge can be accurate extracted by the proposed method. The integration of GPS and accelerometer can be used as a reliable tool to characterize the dynamic behavior of large structures such as suspension bridges undergoing environmental loads.

Keywords: suspension bridge; deformation monitoring; global positioning system; wavelet transform

1. Introduction

Bridge engineers require precise and reliable instruments to resolve their concerns about static, quasi-static and dynamic displacements of the bridges induced by ambient effects such as earthquakes, temperature, wind, traffic load and their combination (Yi *et al*. 2010). Traditionally, monitoring the dynamic behavior of bridges mainly relied on measurements made by instruments from accelerometer sensors deployed on the structure. The accelerometers have been proven useful to identify the modal frequency, which allow precise readings at rates of up to 1,000 Hz. However, only the relative displacement (there is no way to recover the static or quasi-static displacement from the acceleration) can be obtained possibly in theory by a double integration process of acceleration response since the integration process is problematic for two reasons: firstly, the process results in two constants of integration that cannot be determined, implying that only part of

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the response can be fully recovered; and secondly, the integration itself is inaccurate due to the accelerations are contaminated by "drift" error.

It is therefore necessary to adopt a new system which can measure directly the position coordinates of the bridge in order to assess its safety according to the displacement thresholds reached or the changed dynamic characteristics. The worldwide availability of Global Positioning System (GPS) signal coverage provides a great opportunity to monitor, in real-time, the both static and dynamic displacement behavior of bridge under different loading conditions. Feasible studies related to the application of GPS for displacement response measurements of bridge include those by Ge *et al*. (2000), Tamura *et al*. (2002), Roberts *et al*. (2004), Kijewski-Correa *et al*. (2006), Chan *et al*. (2006), Nickitopoulou *et al*. (2006), Psimoulis *et al*. (2008), along with many other examples in the literature. Henrik *et al*. (2002), Schaal *et al*. (2009), Moschas and Strios (2011) applied temporarily the installed GPS units to measure bridge vibration caused by the pedestrians. Among others, Ashkenazi *et al*. (1997), Nakamura (2000), Xu *et al*. (2002), Meo *et al*. (2006), applied the GPS technology to measure displacement responses of long-span cable supported bridges under the wind gust. In addition, Wong (2004), Xu *et al*. (2009), Kashima *et al*. (2001), Watson *et al*. (2007) applied the GPS technology to study the displacement responses of bridges subject to continuous temperature variations primarily due to the solar radiation and ambient air temperature. Although the GPS may offer bridge monitoring solutions both in static and in dynamic by use of the real-time kinematic (RTK) mode, it has its own limitations. A GPS measurement distinguishes from that of classical monitoring instruments due to the presence of so many corrupting sources. For example, the measurement accuracy can be affected by several types of biases such as the orbital bias, atmospheric biases, multipath disturbance and receiver noise, and also depends strongly on the number and geometric distribution of the available satellites. A double-differencing technique is commonly used for constructing the functional model as it can eliminate or reduce many of the troublesome GPS biases. However, some unmodelled biases still remain in the GPS observations, even after such data differencing. Timely and correct filtering of the monitored GPS data has become an essential request to improved quality control, safer system operations, and reduction in the number of false alarms. Without proper pretreatment, the necessary interpretation is difficult, even not impossible.

To overcome the abovementioned shortfall, efforts have been made in recent years to use an integrated monitoring system consisting of dual frequency GPS receivers and triaxial accelerometers for the detection of the dynamic behaviors of bridges and other structures. Roberts *et al*. (2004) carried out a trial on a suspension footbridge situated over the River Trent in Nottingham using a special cage to mount the GPS antenna and triaxial accelerometer to test the properties of the bridge, experimental results showed that through the use of the hybrid system, the 50% improvement over a GPS alone system could be obtained. Also on the Wilford Bridge, Meng *et al*. (2007) performed a forced vibration test excited by more than 30 people, and the responses were recorded by the GPS and triaxial accelerometers synchronously. After data analysis, they found that the amplitude of resampled 10 Hz acceleration was slightly higher than that derived acceleration from the GPS coordinate time series. An integrated system comprising of the RTK GPS and accelerometers were installed on a steel tower by the Li *et al*. (2006), with the objective of assessing full-scale structural responses by exploiting the complementary characteristics of GPS and accelerometer sensors, and they found that the two sensors did have some overlapping capability in the band between 0.2 and 2 Hz, i.e., whatever was picked up by the accelerometer would also be picked up by the RTK-GPS. This overlap could provide redundancy within the integrated system which enabled robust quality assurance. Smyth and Wu (2007) proposed a

Kalman filtering and smoothing technique, which was capable of dealing with multi-rate estimates, had been investigated to accurately estimate the velocity and displacement from noise contaminated measurements of acceleration and displacement, which were gathered by the accelerometer and GPS receivers, respectively. Moschas and Stiros (2011) proposed a novel multi-step filtering procedure which constrained and tested by independent accelerometer data, permitted to de-noise the noisy GPS recordings of the oscillations of a stiff pedestrian bridge and determine its oscillation amplitude and modal frequency. This unique research revealed that the GPS could measure the displacement history and the modal frequencies of rather stiff structures for the first time, far exceeding current limits of the method assumed so far, i.e. modal frequencies up to ~1 Hz and displacements 10~20 mm. These results have important implications in enhancing the GPS-based structural health monitoring (SHM) of engineering structures. Psimoulis, and Stiros (2012) presented a computer-based algorithm on the basis of supervised learning techniques and subsequent validation through additional experiments. This algorithm permits to estimate the mean amplitude of small-scale (up to few mm), high frequency (even above 4 Hz) oscillations. This is very important for practicing engineers and researchers because till recently such geodetic records are usually regarded below the noise level and not useful for structural studies.

To address the problems encountered when using the GPS alone in a bridge deflection monitoring system, based on the characteristics of the bias terms derived from the GPS and accelerometer respectively, the authors in this paper present a multi-step filtering method based on the wavelet transform (WT) to eliminate the disadvantages of the two separate units so as to address the GPS deformation monitoring application more efficiently. The basic idea is derived from the Chebyssev filtering used by Moschas and Stiros (2011) and the empirical band-pass filter proposed by Psimoulis and Stiros (2012). The remainder of this paper is organized as follows: Section 2 describes the main difficulties in filtering GPS-derived coordinates and the proposed wavelet based multi-step filtering method. A real structural monitoring experiment on a large-scale suspension bridge is presented in the third section, the monitoring system architecture, experimental procedure, coordinate transformation algorithm, as well as data analysis results are all introduced in this section. Concluding remarks and some recommendations are given in the last section.

2. Wavelet based multi-step filtering method

2.1 Discussion on main difficulties in filtering GPS-derived coordinates

Eliminating the influences from the various noises is a tough task in the GPS signal processing. There are generally four factors need to be considered.

Firstly, as aforementioned, some unmodelled biases still remain in the GPS observations after using carrier phase-based differential positioning techniques. Han and Rizos (1997) found that major sources of GPS errors by frequency band within the range of frequencies important for deformation monitoring on large structures are: 1) atmosphere: 0.00005-0.0008 Hz; 2) multipath: 0.0008-0.01 Hz; and 3) receiver system noise: 0.0008-0.02 Hz. Furthermore, there is also noise of an unknown source in the frequencies ranging from very flow (direct current, DC) to 10 Hz. According to this study, the GPS bias terms such as multipath and ionospheric delay behave like low frequency noise and the measurement noise as high frequency noise. Hence, the GPS bias terms contain many frequency components which are distributed almost along the whole frequency band and a high frequency resolution is needed to identify them (i.e., simple low-pass, high-pass, band-pass, or band-stop filters will not works well). In addition, the probability density functions (PDF) of the GPS bias studied by Kijewski-Correa and Kochly (2007) revealed its non-Gaussian nature that makes the filtering of signals even more complicated, though in some regions the Gaussian distribution may provides a conservative measure of the spread of the background noise.

Secondly, changes in load, boundary conditions, temperature and humidity have significant effects on the underlying modal characteristics of large bridge because the shifts of these environmental conditions will affect the overall stiffness, mass and damping of the bridge. Wahab and Roeck (1997) conducted dynamic tests for a prestressed concrete bridge in spring and in winter, and observed changes of 4% to 5% in the natural frequencies. For another example, concrete bridges in the United Kingdom during the damp weather were reported to absorb considerable amount of moisture, which thus increased their masses and altered their natural frequencies (Sohn *et al*. 1999). These indicates that the bridge under ambient excitation is a kind of time-varying system which may makes the measured structural natural frequencies and GPS bias terms mixed together more. Therefore, it is essential to consider the variability of the modal parameters for developing a reliable and robust GPS monitoring data filtering method.

Thirdly, the typical GPS-RTK 20 Hz GPS receiver's sampling rate limits its capability in detecting certain high modal signals of bridges (although higher rates receivers are now possible, sampling only at the maximum of 100 Hz are available). Therefore, in order to provide high frequency information along with the capability of measuring low frequencies for bridge health monitoring applications, acceleration records, which have been proved with little noise sources, should be adopted as the complementary data.

Lastly, although the parameter identification of a large bridge using ambient vibrations has emerged as a convenient alternative in terms of safety, cost and simplicity, several difficulties arise as the statistical properties of the unknown inputs play a significant role in the success or failure of the identification. Thus, the methodologies, which are capable of identifying modal parameters of bridge when the ambient excitation is unknown, should be carefully selected.

In brief, due to the frequency nature of a large-scale bridge and ambient observation scenarios, the GPS data are always contaminated by various kinds of noise and the traditionally spectrum approach sometimes cannot be directly applied for extracting the frequencies in the time-varying case. Without the support from the accelerometer and nonstationary signals filtering technique, it is difficult to obtain the desired monitoring results.

2.2 Proposed filtering procedure via wavelet

As known, the WT is a new tool for signal analysis that made possible to provide insight into the character of transient signals through time-frequency maps of the time variant spectral decomposition, in which the traditional approaches miss. Therefore, the WT can be used to filter the monitoring data, locate and identify intermittent response feature and the evolution of coupled responses of the bridge that depend greatly on the ambient effects. Combining the merits of the continuous wavelet transform (CWT) with the discrete stationary wavelet transform (SWT) and based on the understanding of various influencing factors as discussed previously, a wavelet based multi-step filtering method is proposed to dynamic measurement data from the accelerometer and GPS to reduce background noise. The proposed procedure mainly includes two steps:

Step (1): Instantaneous modal parameter extraction by the CWT

As the dynamic properties of the bridge is time varying, the CWT is adopted to identify the instantaneous frequencies so as to accurately separate the GPS signal form noise. Two points of main feature make the CWT particularly attractive to adopt here. Firstly, the vibration modes of the bridge can be automatically decoupled in most cases where the natural frequencies are not too close, which is allowed for an accurate extraction of the instantaneous frequencies and damping parameters. Secondly, the essential information is contained in a small subset of the CWT, namely in the maxima lines and ridges (Kijewski-correa and Pirnia 2007). For the ridges, the modal parameters of the decoupled modes can be accurately extracted.

Because the CWT based modal parameter identification technique relies on structural free responses like the first step in this study, the Natural Excitation Technique (NExT) is adopted to estimate the free response. The NExT assumes that the unknown excitation be weakly stationary, broad-band, and uncorrelated to prior system responses (It had been proved that even in the case of band limited ambient vibrations with questionable stationarity, reliable free responses could also be obtained.) (Giraldo *et al*. 2009). Under these conditions, the dynamic equation of the bridge can be manipulated to obtain as follows

$$\mathrm{M}\ddot{R}_{\ddot{X}\ddot{X}_i}(\tau) + \mathrm{C}\dot{R}_{\ddot{X}\ddot{X}_i}(\tau) + \mathrm{K}R_{\ddot{X}\ddot{X}_i}(\tau) = 0 \tag{1}$$

Where M, C , and K are matrices defining the mass, damping and stiffness of the bridge; $R(\cdot)$ denotes the vector of correlation functions, and $\ddot{X}(t)$ and $\ddot{X}_i(t)$ mean the accelerations from two sensors of the bridge. Eq.(1) shows that the cross-correlation function of the responses of the bridge with a reference signal $X_i(t)$ satisfies the homogeneous differential equation of motion and can be treated as free response.

The CWT based modal identification from the free vibration response is founded on the development of the complex analytical signal, taking the form of an exponential function given by

$$z(t) = A(t)e^{i\phi(t)} \tag{2}$$

where $A(t)$ and $\phi(t)$ are the time-varying amplitude and phase, respectively.

Thereby, the concept of instantaneous frequency as the time-varying derivative of the phase is

$$f(t) = \frac{1}{2\pi}\frac{d}{dt}\phi(t) \tag{3}$$

Thus, the phase of the complex-valued analytical function provides a simple method to identify the time-varying frequency of the bridge. In the case of free vibration decaying curves, the oscillator responds at the damped natural frequency ω_D, and the time-varying amplitude term takes the form of an exponential, decaying based on the system natural frequency $\omega_n = 2\pi\ f_n$ and damping ξ ($\omega_D \approx \omega_n$, for lightly damped systems)

$$z(t) = (A_0 e^{-\xi\omega_n t})e^{i(\omega_D t + \theta)} \tag{4}$$

where A_0 is the initial amplitude value and θ denotes the phase shift.

Note that this complex analytic signal would typically be generated by

$$z(t) = x(t) + iH[x(t)] \tag{5}$$

where $x(t)$ means the original signal and $H[\cdot]$ represents the Hilbert transform.

The square of the modulus of the WT can be interpreted as an energy density distribution over the (a,b) time-scale plane. The energy of a signal is mainly concentrated on the time-scale plane around the ridges of the WT. These locations where the frequency of the scaled wavelet coincides with the local frequency of the signal, are denoted by

$$a_r(b) = \frac{\omega_0}{\phi'(b)} = \frac{2\pi f_0}{f_i(b)} \tag{6}$$

where $\phi'(b)$ implies the derivative of the phase and ω_0 (or f_0) is the central frequency of the parent wavelet, i.e. the frequency on which the Fourier Transform of the parent wavelet focuses.

Note that Eq. (6) illustrates that the scales corresponding to the ridges, a_r, can be directly used to identify the instantaneous frequency. The wavelet coefficients along these ridges form the wavelet skeleton.

The WT is a linear representation of a signal. Thus, it follows that for a given N functions x_i and N complex values $a_i (i = 1,2,..., N)$

$$(W_g \sum_{i=1}^{N} \alpha_i x_i)(a,b) = \sum_{i=1}^{N} \alpha_i (W_g x_i)(a,b) \tag{7}$$

This property is convenient for the analysis of multi-component signals. In the simplest structural identification problem of free vibration, the system has a distinguishable enveloped sinusoidal behavior given by

$$h(t) = A_0 e^{-\xi\omega_n t} \cos(\omega_n \sqrt{1-\xi^2}\, t) = A_0 e^{-\xi\omega_n t} \cos(\omega_D t) \tag{8}$$

where A_0 denotes the initial displacement condition and θ represents the phase shift.

The analytic signal is then

$$z(t) = A_0 e^{-\xi\omega_n t + i\omega_D t} \tag{9}$$

The amplitude function is given by

$$A(t) = |z(t)| = A_0 e^{-\xi\omega_n t} \tag{10}$$

with phase described by

$$\phi(t) = \angle z(t) = \omega_D t \tag{11}$$

Thus, the damped natural frequency can also be determined from the derivative of the phase. Assuming a lightly damped system, where $\omega_D \approx \omega_n$, the damping can be determined from Eq. (10).

As discussed, for a particular class of parent wavelet, the ridge scales, or frequencies corresponding to the local maxima of the wavelet transform, could provide an estimate of the instantaneous frequency of the system. Extracting these ridge coordinates provides a pinpoint estimate of the instantaneous frequency of the system. There are countless mother wavelets and the choice of the mother wavelet is theoretically arbitrary, but it is critical and important in practice, because it may affects the performance of the technique. The Morlet wavelet is adopted here due to its unique analogs to the Fourier transform and its direct relationship between the wavelet scale a and Fourier frequency f : the two are inversely related via the Morlet wavelet's central frequency $f_0 (f = f_0 / a)$. This central frequency parameter dictates the time and frequency resolution of the wavelet, as well as its ability to separate closely spaced modes.

Step (2): Filtering the GPS measurements by the SWT

After accurate identification of the range and the time limits of modal frequencies of the bridge from the acceleration, a SWT based filter to denoise the GPS recordings is adopted in the critical interval around the real modal frequency to obtain the reconstructed, minimum bias waveform of the bridge oscillation. The SWT is adopted instead of conventional discrete wavelet transform (DWT) due to it uses upsampling at each level of decomposition that causes redundancy. The redundancy will increase the elements per scale and location at coarse scales. In term of denoising, there is an advantage in having more orientations than necessary at coarse scales. Hence, it is better in noisy GPS signal processing.

The SWT decomposition process can be described by Eqs. (12) and (13). A GPS signal, *Z*, is projected onto a dyadically spaced set of scales (spaced using a base of 2, i.e., scale= 2^j), or levels (level $j = \log_2(scale2^j)$), using a set of level dependent quadrature mirror decomposition filters, h_j and g_j, that have respective band-pass and low-pass properties specific to each wavelet base (Mallat 1998). The broad scale, or approximate coefficients, a_j, are convolved separately with g_j and h_j. This process splits the a_j frequency information roughly in half, partitioning into a set of fine scale, or detail coefficients, d_{j+1}, and a coarser set of approximation coefficients, a_{j+1}. During the next level of processing, a zero is placed in between each consecutive value found in the g_j and h_j filters (i.e., up-sampling by two) to achieve the g_{j+1} and h_{j+1} filters. This procedure can be iteratively continued until the desired level of decomposition, $j = J$, is obtained. Note that the algorithm is initiated by setting $a_0 = Z$.

$$a_{j+1}(k) = \sum_n h_j(n-k) a_j(k) \tag{12}$$

$$d_{j+1}(k) = \sum_n g_j(n-k) a_j(k) \tag{13}$$

The a_j coefficients can be reconstructed from a_{j+1} and d_{j+1} by convolving each with the respective reconstruction filter, $h_j(-n)$ or $g_j(-n)$, and summing (Eq. (14)). Note that each reconstruction filter is also level dependent and includes 2^{j-1} zeros between each filter coefficients. This process can be iteratively continued until the original signal, Z, is recovered.

$$a_j(k) = \sum_n h_j(k-n) a_{j+1}(n) + \sum_n g_j(k-n) d_{j+1}(n) \tag{14}$$

What needs to be mentioned is that the response of a slender bridge to wind loading may contain contributions from the fundamental mode and any number of higher modes depending on how the turbulent structure of the wind changes in time. Thus, the identified modal frequencies by the CWT may be intermittent. In this case, the band pass/stop filter may be adopted in each level of the SWT details coefficients to extract the real response of the bridge. The above denoising procedure can be described as: the SWT is used to decompose the input GPS noisy signal into N levels of the approximations and detailed coefficients. Next, a thresholding procedure and a band stop filter are applied to the coefficients in this domain in an attempt to discriminate between those that represent the signal and those that represent the noise. Finally, the inverse WT is used to reconstruct the signal in the time domain, but with smaller noise content. The wavelet de-noising depends on a great number of processing parameters. Since a quantitative criterion for selecting the mother wavelet to filtering the data is not available, here it is restricted to the Daubechies wavelet by trial and error. In the experiments listed below, the Daubechies 4 (db4) wavelet was found to perform better in preserving fine signal details. As soft-thresholding has slightly smooth property for a signal and better quality than hard-thresholding in most of application (Liu *et al*. 2011), the soft-thresholding is applied here.

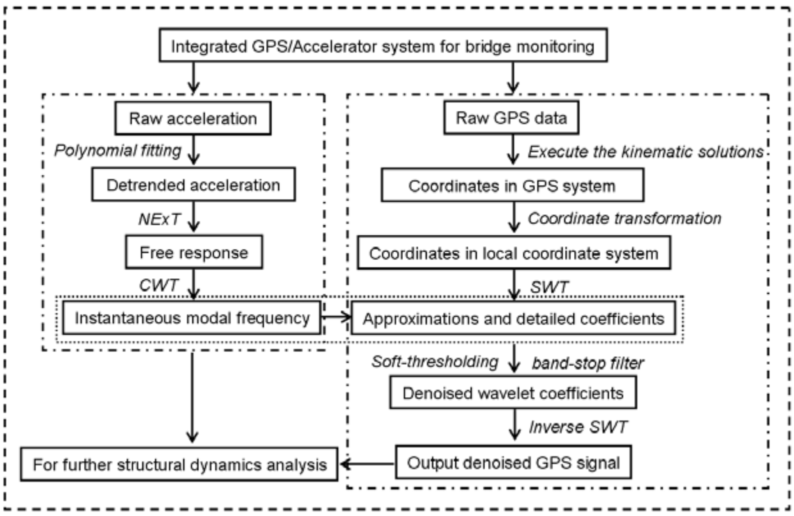


Fig. 1 Flowchart of the proposed multi-step filtering method

Fig. 1 shows the detailed procedure for the proposed filtering algorithm that is fully implemented with the commercial software of MATLAB (MathWorks, Natick, MA, USA) for Windows version 7.4. The MATLAB Toolbox for wavelets 4.0 is used for the library of wavelet filter coefficients.

3. Real-time monitoring experiments

3.1 Description of practical bridge

To confirm technical feasibility of the proposed method, the Dalian BeiDa Bridge pictured in Fig. 2 (a) was selected as a test case because of its large deflections under normal environmental loading. The bridge is a suspension bridge with a three-span simply-supporting stiffened truss with an overall length of 230 m (48 m+132 m+48 m), having two side walks and two lanes of 12 m wide. The height of the towers is 35 m with 17 m above the bridge deck. The bridge has two main cables, each including 37 bundles of wire ropes with a diameter of 42 mm (Yi *et al*. 2010).

The bridge was started to be constructed in 1984, and formally open to the traffic in 1987. In its more than 20 years service life, it has inevitably undergone deterioration and damage due to various factors such as too large operating load (i.e., wind load, live load), sun radiation and daily air temperature variation, environmental erosion, fatigue. Its structural failure could be catastrophic not only with financial loss, but also social impact. Hence, a full-scale measurement of the dynamic characteristics is of particular importance to provide the validation of the former design procedures and an assurance of acceptable behavior of this bridge.

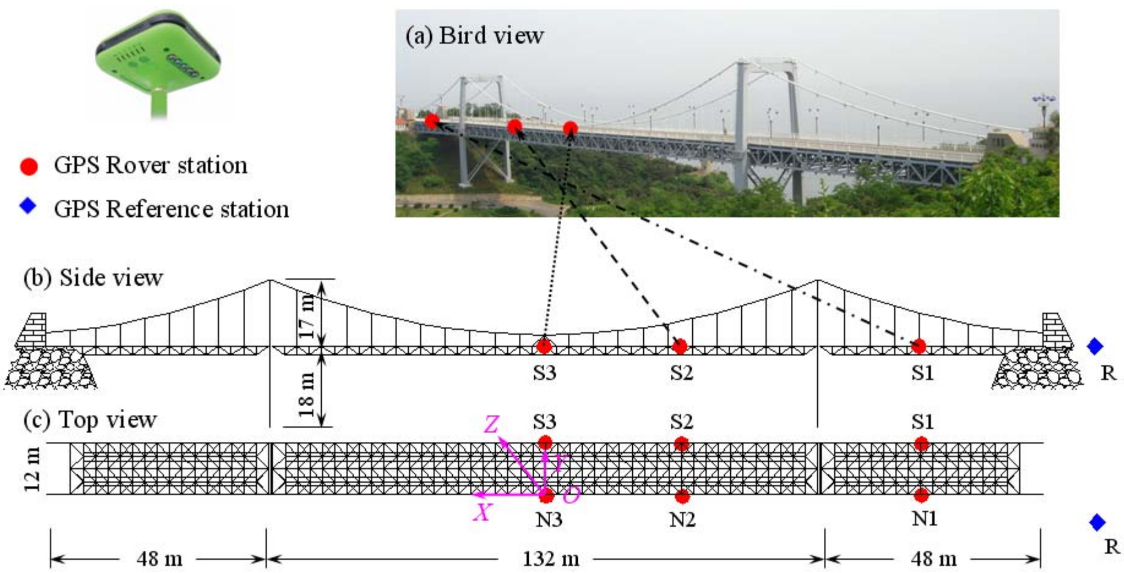


Fig. 2 Distribution of GPS receivers in Dalian BeiDa Bridge

3.2 System architecture and experimental procedure

Figs .2(b) and (c) illustrate the diagram of system architecture and GPS receiver layout for the bridge monitoring experiment made on October, 2010. Considering that Cantieni gave the statistical distribution of fundamental frequencies for 224 highway bridges in Switzerland. The fundamental frequencies of about 56 tested bridges were higher than 10 Hz (Cantieni 1983). Thus, the GPS system was composed of three TRIUMPH-1 GPS receivers with a sampling rate of 20 Hz, made by the JAVAD GNSS, Inc., USA. One reference station was set up on the bank of the river, on a point whose coordinates were well established from previous trials, as shown in Fig. 3(a). Other two rover receivers were located at the center of a side span (S1, N1), at the 1/4 main span (S2, N2) and at the center of the main span (S3, N3) (Fig. 3(b)), respectively, where the typical movement was expected. During the experiment, a kind of U-shaped clamp with a measuring rod was used to fix the receiver on the bridge handrail. Because the reference and rover GPS receivers were close to each other, signals recorded by each of them were affected by identical atmospheric effects, and hence many common systematic errors could be obliterated. From a multipath perspective, the measuring conditions were also favorable for the receiver, which was free of obstructions of the view of the horizon (except suspender cable of the bridge) and 8-9 satellites could be tracked continuously.

(a) GPS reference station

(b) GPS rover station

Fig. 3 Typical GPS sensory system being used during trials on the Dalian BeiDa Bridge

A postprocessing scheme was adopted where positioning data at both the reference and rover installations were recorded directly to the receiver's internal memory up to 2048MB and then be downloaded via the USB 2.0 ports to an off-site postprocessing PC to determine final position estimates for the rover off line. This configuration allows user flexibility in changing various postprocessing parameters, e.g., ionospheric model, stochastic model, and tropospheric model, settings that cannot be revisited if the data is processed in real time.

In addition to the GPS receivers, the bridge movement was recorded by a kind of LC0161A-type triaxial accelerometer with the sensitivity of 1000 mV/g, made by Lance Technologies Inc., USA, recording at a rate of 100 Hz. The accelerometers located near the GPS rover receivers were directly placed on the pavement due to the limited access to the actual floor beams (Fig. 4(a)). Three accelerometers were used in the experiments: two were moveable, and one was fixed as the reference accelerometer. A reference location was selected according to the information obtained from the mode shapes of the preliminary FE model. The acceleration data acquisition system consists of both hardware and software. In this monitoring system, the NI cRIO-9014 PXI platform was used as hardware (Fig. 4(b)) and the LabVIEW, a product of NI Inc., USA, was selected to be the software to write the program for the collection of accelerometer signals.

(a) Accelerometer mounted on the deck

(b) Data acquisition system

Fig. 4 Typical accelerometer and data acquisition system being used during trials on the Dalian BeiDa Bridge

The experiment started from the east side and progressed to the west side of the bridge. Once the data were collected in one setup, the GPS rover receivers and moveable accelerometers were shifted to the next station while the base stations remained stationary. This sequence was repeated 2 times to obtain ambient vibration measurements on all stations. The ambient vibration measurements were simultaneously recorded for 10 min for all channels.

3.3 GPS coordinate computations and transformations

The carrier phase data from both L_1 and L_2 frequencies were processed using a kinematic solution and GrafNav V8.10 (Waypoint Products Group, NovAtel Inc., Canada) post-processing GPS software for Windows version 6.02; using a 15° elevation mask and conventional models (double difference, fixed solutions, and a Goad & Goodman Troposphere model). In order to compare the results from the accelerometer measurement results, the dynamic trajectory in the GPS coordinate system (World Geodetic System 1984, i.e., WGS-84) was then transformed into the bridge local coordinate system (X, Y, Z) using the rotation matrix

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ N \\ H \end{bmatrix} \tag{15}$$

$$\alpha = \tan^{-1}\left(\frac{N_{\text{mean(ref)}} - N_{\text{mean(rov)}}}{E_{\text{mean(ref)}} - E_{\text{mean(rov)}}} \right) \tag{16}$$

where a is the azimuth of the bridge main axis in the local coordinate system, which is calculated from the mean coordinates of both the reference (ref) and the rover (rov) stations; E, N and H are the plane easting, northing coordinates and orthometric height, respectively.

In this local coordinate system, the X axis shows the traffic direction (span direction), the Y axis shows the lateral direction and the Z axis gives the vertical direction of the bridge (see Fig. 2(c)).

3.4 Data analysis results

Since the bridge remained open to traffic during the trial, only some special cases were selected to analyze. Thus, it’s very difficult for us to select ideal monitoring data long enough covering intervals of excitation and of no excitation before and after it. Here, the vertical displacements instead of the horizontal displacements are selected to analyze the bridge vibration. The basic reason is that the GPS receivers are much less sensitive and accurate in vertical than in horizontal coordinates and the approach proposed in this paper can be extended to horizontal displacements with much more accurate results. Fig. 5(a) shows a typical vertical acceleration of the bridge measured by accelerometer located on point N3. Before the modal parameter identification was performed, the measured data were first detrended to remove DC-component that could badly influence the identification results. This was accomplished by removing the best straight-line fit linear trend from the full duration of accelerations. The instantaneous frequencies identified from ridges that extracted from the wavelet modulus are provided in Fig. 5(b). In consideration of the GPS receiver’s sampling rate is 20 Hz, here only the identified frequencies below 10 Hz are given. It can be seen from Fig. 5(b) that the maxima take on from the lowest value in the vicinity of 0.68 Hz to the highest value in the vicinity of 9.73 Hz and the ridges revealed up to eight local maxima (0.68 Hz, 1.02 Hz, 1.42 Hz, 1.76 Hz, 3.94 Hz, 5.23 Hz, 7.42 Hz, 9.73 Hz) that usually display a kind of intermittent and accompanies the dominant presence of the straight lines because the measured bridge is time-invariant during the testing. The intervals don’t display modal frequencies that are characterized by noise, which can be removed using the band pass/stop filter. It is verified that wavelet instantaneous frequency estimates really serve as a “microscope” for studying the evolution of multiple harmonic components within the response. The relative contribution of each mode may vary significantly or the total bridge response may suddenly increase for apparently the same mean wind speed due to instantaneous changes in the distribution of energy at different frequencies. Such a response behavior cannot be identified through classical spectral techniques, while the CWT is ideal for such an analysis.

Fig. 6(a) (black dot line) shows 100-second-long time series of the GPS measured displacement in the vertical direction. Fig. 7 presents the band-passed time histories in order of decreasing frequency using the SWT based filterbank. This figure unfolds the response time history into a very revealing display of the time-scale representation. Note the different scales on the plots for the filtered processes, indicating relative contribution in that frequency band. The right column levels 1 through five are five frequency bands, with level 1 containing energy from one half the cutoff frequency up to the cutoff (20Hz). Level 2 contains energy from 1/4 to 1/2 of cutoff, and so on. Levels 2 through 5 contain all eight modes of bridge response, with the fundamental and second modes in the 5th level, the third and fourth modes in the 4th level, the fifth mode in level 3, and the sixth, seventh and the highest modes in level 2. The reduction of noise in the measured signal can be accomplished by altering wavelet coefficients according to the identified modal frequencies and modal frequency intervals obtained form the CWT results. In addition, since the frequency resolution available in each level is limited (scale= 2^j), particularly in the high frequency range, the selected band pass/stop filter can be adopted in critical interval around the real modal frequency of the each level of the SWT details coefficients to extract the real and transient response of the bridge. Fig. 6(a) shows the good performance of the proposed method for improving the signal and suppressing the noise. The left bottom level 5 contains the static and quasi-static displacement. From the extracted displacement in Fig. 6(b), it can be identified that the maximum displacements fluctuate between -0.0436 and -0.0152 m, indicating significant static and quasi-static movements corresponding to the maximum acceleration indicated in Fig. 5(a).

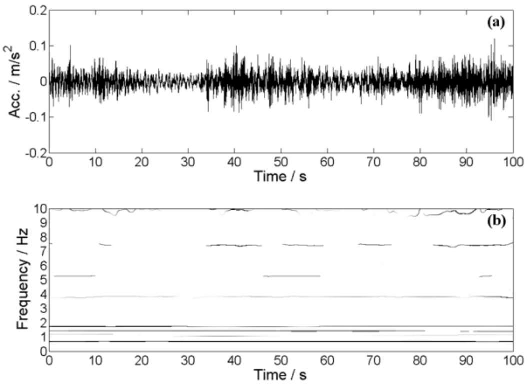


Fig. 5 Raw and processed acceleration data: (a) Vertical acceleration of the bridge and (b) Identified instantaneous frequencies with CWT.

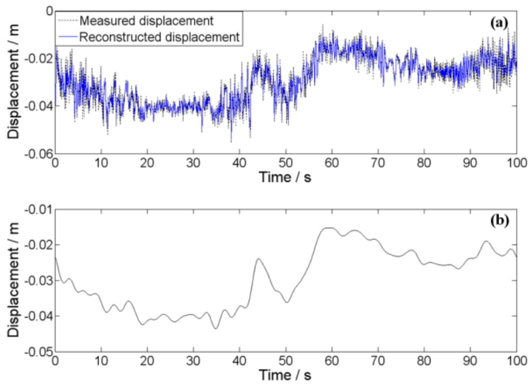


Fig. 6 Raw and processed GPS data: (a) Measured and reconstructed vertical displacement and (b) Extracted static and quasi-static displacement.

As known, it is very hard to compare the displacements obtained from the GPS and accelerometer quantitatively because the static and quasi-static displacements are missing from the accelerometer derived results, since there is no way to determine the integration constant. In addition, according to the finding of Stiros (2008), double numerical integration of accelerometer data will leads to very noisy results. Thus, the simple way to assess the quality of the GPS measured displacements is to compute accelerations from the GPS data and compare them with observed acceleration data. Using a double numerical differentiation procedure, the time series of acceleration corresponding to the data of Fig. 6(a) is computed and plotted in Fig.8. These data correspond to a 20 Hz sampling rate which is apparently not directly comparable with the acceleration recordings at a 100 Hz sampling rate. For this reason, the observed acceleration data were resampled to 20 Hz. From the Fig. 8, it can be found that the resampled accelerometer data seem a little different from the initial recordings (Fig. 5). Their main difference is that the smaller peak acceleration values in the resampled accelerogram that is due to the low-frequency sampling will leads to a loss of certain cycles of oscillation and of high-frequency high-amplitude events.

Comparing the acceleration time series between that derived using extracted GPS resonant displacement and the resampled 20 Hz acceleration of the accelerometer, it can be inferred the real resonant component is well marked, and is evidently distinct from the signals before and after filtering. Although the acceleration obtained by double differencing the displacement is slightly different from either resampled acceleration or the original acceleration of an accelerometer, the results are satisfactory on the whole when it takes into account there are some noise existing in the resampled or original acceleration. In addition, it's clear that the measured fluctuations in Fig. 5 and Fig. 6 contain real acceleration displacements of the bridge and not ordinary noise that can be verified from the Fig. 8 that the performance of the two sensors are comparable with each other, this proves that the measured signal are real displacement since the noise is random.

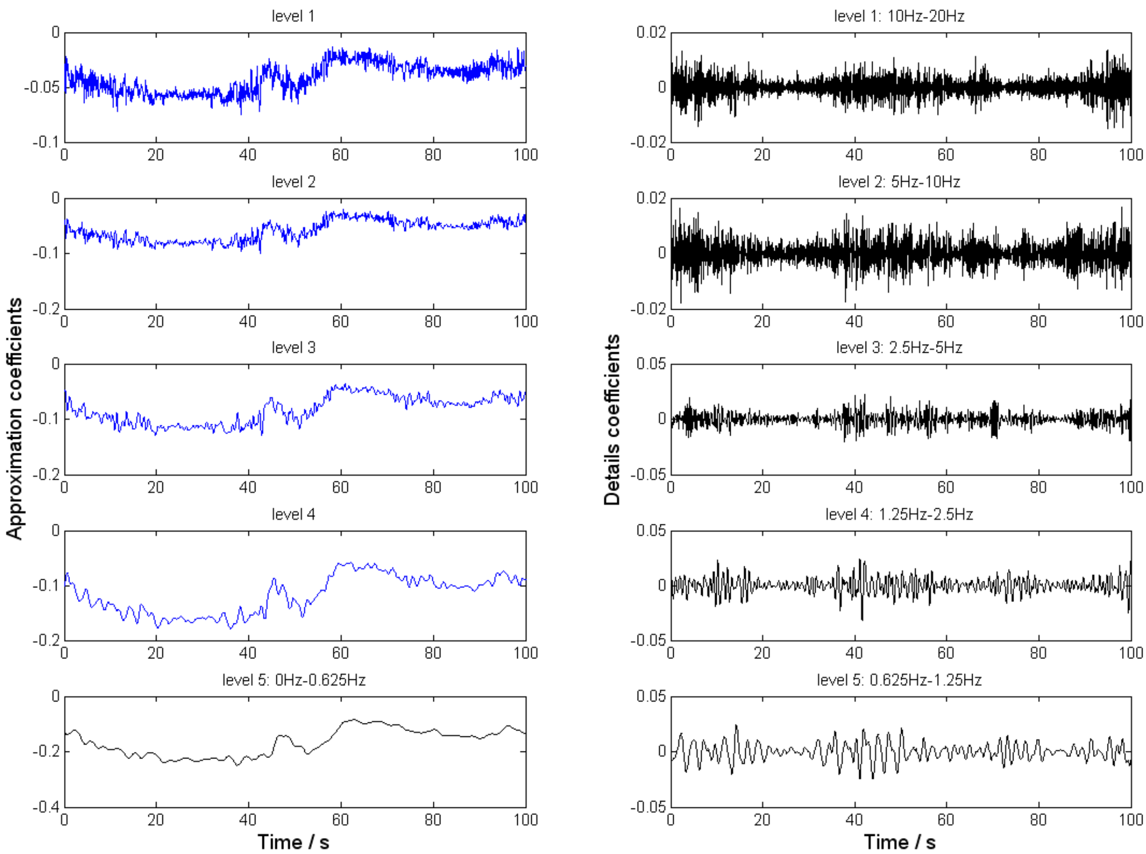
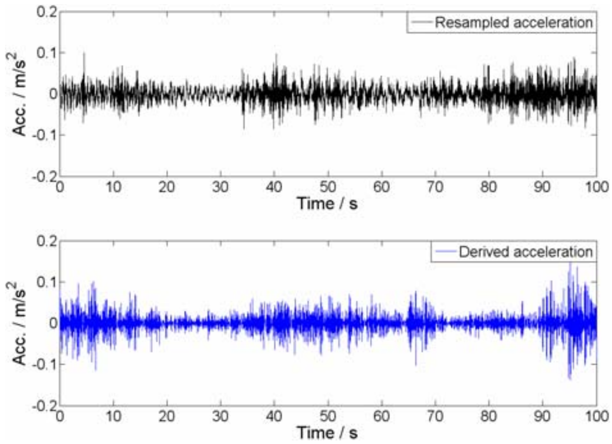
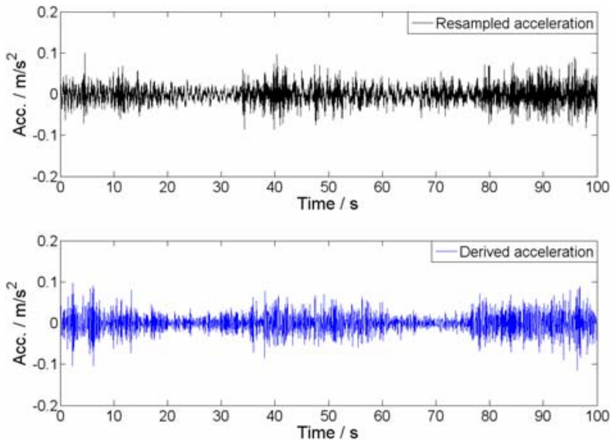


Fig. 7 The obtained approximations and details stationary wavelet coefficients of the measured GPS signal using SWT: The figure unfolds the response time history into a very revealing display of the time-scale representation. Note the different scales on the plots for the filtered processes, indicating relative contribution in that frequency band.



(a) Before filtering



(b) After filtering

Fig. 8 Resampled acceleration versus derived acceleration using extracted GPS resonant displacement

4. Conclusions

It's known that the bridge response to ambient loads is very complicated, which mainly consists of three components: a static component due to mean force; a quasi-static component due to low-frequency force fluctuations; and a resonant component due to force fluctuations near the first mode and any number of higher modes of bridge. This paper demonstrates how to use the GPS and accelerometer data to extract real displacement amplitude and resonant response from the noisy data of a large-scale suspension bridge induced by ambient effects. The main difficulties in filtering GPS-derived coordinates are summarized and discussed in detail. To support data analysis, a wavelet based multi-step filtering approach consisting of the CWT-based instantaneous frequency identification method and SWT-based filtering algorithm is developed, which skillfully uses the accelerometer as an objective, accurate and independent constraint to the analysis of the data of the GPS receiver. The filtered GPS coordinate time series are differenced to output accelerations and these values match well with those of real acceleration data from the accelerometer. It's proved that the GPS and accelerometer technology are complementary each other, and the integration of the two systems results in a hybrid arrangement that may eliminate the disadvantages of the two separate units. The proposed filtering approach has many advantages over using the GPS data alone, and can accurately gather both the magnitude of the deflections and the frequencies, both of which are important in obtaining knowledge about the health of the bridge.

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