Filtered-based GPS structural vibration monitoring methods and comparison of their performances

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Abstract

The purpose of GPS structural vibration monitoring is to obtain information on the frequency and amplitude of vibrations based on GPS observations that are often affected by various errors. Filters are frequently used to improve GPS accuracy and to retrieve vibration signals from GPS observational series. This paper studies the performances of four commonly used filters, i.e., Vondrak, wavelet, adaptive FIR and Kalman filters, for such applications. Controlled experiments are carried out and the results show that the capability of GPS in tracking structural dynamics and complex signals can be improved with any of the filters. The performances of Vondrak and wavelet filters are almost the same and superior to the adaptive FIR and Kalman filters. Recommendations are given for the selection of filters and filter parameters for different situations based on an analysis of the advantages and disadvantages of each of the filters.

1. Introduction

Global Positioning System (GPS) technology has in the past two decades been widely used in monitoring the vibration responses of large-scale structures, such as high-rise buildings and long suspension bridges (Lovse et al., 1995; Brown et al., 1999; Ogaja et al., 2001; Li et al., 2006), owing to its advantages of high accuracy, all meteorological conditions and no requirements of inter-visibility between measuring points over the traditional methods. However, the GPS accuracy for response measurement depends on many factors such as atmospheric reflection and delay, satellite geometry, multipath effects and GPS data processing techniques. For achieving high-precision GPS measurements at the sub-centimeter to millimeter level, it is therefore necessary to employ an appropriate data processing approaches which can efficiently deal with the variety of error sources in structural vibration monitoring.

In practice, the baseline between a reference and a monitored station is generally short (e.g. within several kilometers) when GPS is applied to structural monitoring. Therefore, the satellite and receiver clock biases can be eliminated and the distance-dependent errors (ionospheric and tropospheric refraction and delays, and orbital errors) can be largely removed by using the double-differenced observations. The resulting data of dynamic monitoring primarily consist of GPS multipath disturbance, random noise and vibrations. Filter-based methods are often used to separate signals from noise due to their distinct time-frequency characteristics. For example, the random noise exists all through the GPS observations and exhibit a high frequency feature; whereas the structural vibration signal has a local distribution in the frequency domain. The researchers found that typical structural vibrations range from 10 mm to 200 mm in amplitudes and from 0.1 Hz to 10 Hz in frequencies (Lovse et al., 1995). Thus the vibrations are low frequency relative to the random noise.

GPS multipath occurs when signals traveling from a satellite to receiver propagate via two or more paths due to reflections or diffractions from nearby obstacles such as buildings, trees or fences, thus degrading the accuracy of both code and carrier-phase measurements (Leick, 2004). The effects of multipath signals on carrier phase can amount to 1/4 of the GPS signal wavelength (or around 5 cm for L1 measurement) (Georgiadou and Kleusberg, 1988). Due to the choke ring antenna (Tranquilla et al. 1989) and the GPS receiver-internal correlation techniques, such as narrow correlator spacing technology (van Dierendonck et al. 1992), MEDLL (van Nee 1992; Townsend et al. 1995) and strobe and edge correlator (Garin et al. 1996), perform more satisfactorily on mitigating multipath with medium and long delay, the short-delay multipath caused by close-by reflectors (e.g. less than 30 m) becomes the dominant error source in GPS deformation monitoring (Braasch and van Dierendonck 1999; Ray et al. 2001; Weill 2003).

The typical multipath periods are considered from several decades sec to several decades min after multipath mitigation of hardware-based techniques (Huang et al., 2005). The multipath disturbance is also low frequency relative to the random noise, but may fall in the same frequency range as the vibration signal. The time-frequency analysis performance of filters is consequently a crucial element in extracting the high-precision signals of vibration.

Several filter-based approaches have been developed to extract or eliminate multipath effects, such as Vondrak filter (Zheng et al., 2005; Zhong et al., in press) with a good signal resolution at the signal truncation frequency band, wavelet filter (Ogaja et al., 2001; Huang et al., 2001) with a local characteristic of time domain and frequency domain, adaptive finite impulse response (FIR) filter (Kinawi et al., 2002; Chan et al., 2005) with a capability of adjusting filter parameters, and Kalman filter (Nce and Sahin, 2000; Tor, 2002) which predicts and updates a new state vector using observation vectors. Despite these filters are able to improve GPS accuracy to different extent, much remains uncertain about which filter has superior performance when retrieving vibration signals from GPS observational series. In this paper we will present the merits and deficiencies of the four filters mentioned above in such aspects of precision improvement, selection of filter parameters and computation efficiency based on the results of comparative tests.

2. GPS Observational Tests

To assess the accuracy of GPS for its application to structural vibration monitoring, a motion simulation table (see Fig. 1) is developed as a test bed to achieve the theoretical frequencies and amplitudes of the vibration signals. It consists of a movable platform, two servomotors, two ball screws, an electronic control system, a 16-channel data acquisition system, a power terminal box, a supporting frame, and a desktop for motion control and data acquisition.

Fig. 1 Motion simulation table

For time synchronization between the GPS and the motion simulation table, a GPS receiver (Ashtech GG24) is connected to the computer to synchronize the computer clock to atomic clock. The precision servomotors control the ball screws through the electronic control system and the ball screws drive the movable platform simulating various types of motions in the horizontal direction. The motion simulation table is able to generate sinusoidal wave, circular wave, random noise and any other waves defined by input wave time histories in two perpendicular directions with an amplitude accuracy of better than 0.1 mm.

GPS observations were conducted on a test site in Pak Shek Kok enclosed by Science Park and Chinese University of Hong Kong. Two Leica 9500 dual-frequency GPS receivers and two AT202/302 antennae were used with a baseline length of about 11 m from 30 to 31 January 2004 at a sampling rate of 10 Hz. The cut-off elevation angle for GPS observations is 15º.

In the test, one antenna was attached to the movable platform of the motion simulation table as rover station and another was fixed on a tripod as reference station. Both GPS antennae were kept still for an hour to precisely determine the position of the platform relative to the reference station before the simulated vibrations were introduced on the first day; while they were remained motionless during the second day's test.

To get better insight into the performance of aforementioned four filters in GPS application to structural vibration monitoring, coordinate series with and without applying the filtering are compared. The computation processes are as follows:

Firstly, obtain the so-called raw double-difference (DD) vibration series. It can be estimated by differencing the DD phase observations and their calculated values from the coordinates of reference station, satellite orbits and table on an epoch-by-epoch basis.

Secondly, extract the vibration signals. The filtered raw DD vibration series are supposed to involve the vibrations as the multipath disturbance and observational noise have been filtered out already.

Finally, calculate the position estimates before and after filtering based on a single-epoch algorithm (Xiong et al., 2005) and compare them with the theoretical values of the simulated vibrations. In the study, we use an *X*, *Y* and *H* coordinate system where *X* and *Y* refer to the Easting and Northing directions in a Universal Transverse Mercator (UTM) system; while *H* to the ellipsoidal height. For easy interpretation, the mean coordinates have been removed from the coordinate time series when presenting the results in the diagrams.

2.1 Test 1

The simulated vibrations are circular motion with frequency and amplitude being 0.075 Hz and 2 mm, respectively. The visible satellites are 6 and 2400-second duration of data collection is used in the analysis. Figure 2 shows the raw and filtered DD vibration series and their difference series taking the satellite pair PRNs 11~8 as an example.

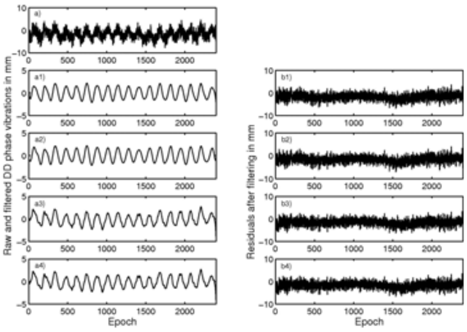

Fig. 2 Raw a) and filtered DD vibration series a1) ~ a4), and their difference series b1) ~ b4) for Vondrak, wavelet, adaptive FIR and Kalman filters respectively (Test 1)

The result in Fig. 2 indicates that the four filters can separate the vibration signals from multipath and noise, but the Vondrak and wavelet filtered data series are smoother than the two latters. The comparisons of position estimates before and after filtering and theoretical vibration values in the *X*, *Y* and *H* directions are shown in Fig. 3.

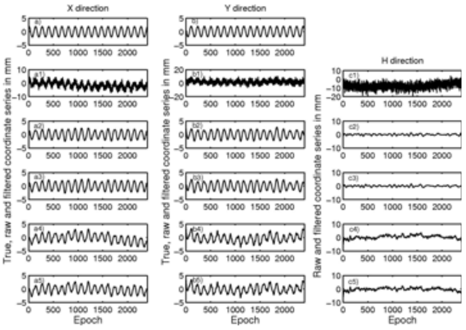

Fig. 3 Comparisons of position estimates before and after filtering and theoretical vibrations (Test 1): theoretical vibrations a) and b); original positions a1), b1) and c1); filtered positions a2) ~ a5), b2) ~ b5) and c2) ~ c5) with the Vondrak, wavelet, adaptive FIR and Kalman filters

It is seen from Fig. 3 that the filtered position estimates after the adaptive FIR and Kalman filtering contain not only vibrations but additional signals with long period compared to those of two former filters. It is considered that the signals may be caused by the residual multipath effects and tropospheric delay. The result manifests that the GPS accuracy of tracking dynamic displacement can reach 2 mm after the filtering.

2.2 Test 2

Simulated circular motion with frequency of 0.5 Hz and amplitude of 20 mm is used in this test. Five satellites are visible and 2400-epoch observations are collected. Due to the limited space, the original and filtered position estimates and theoretical vibrations are not illustrated herein. The comparison of their contributions to GPS accuracy will be given in Sect. 3.

2.3 Test 3

To simulate the real structural vibrations, the motion with frequency varying from 0.025 to 0.5 Hz and amplitude of 0 to 18 mm is employed. Six visible satellites and 2400-epoch observational data are used in this test. For clarity, the former 800-epoch position estimates before and after filtering and the theoretical vibration values are depicted in Fig. 4.

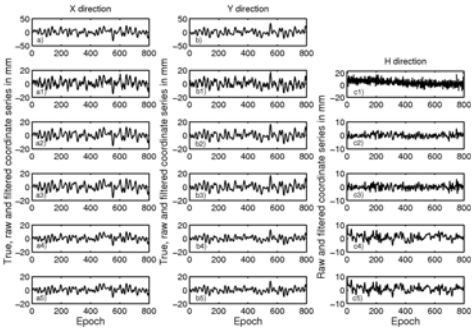

Fig. 4 Same as Fig. 3, except for Test 3

The test result in Fig. 4 shows that the measurement accuracy of GPS for complex signals with varying frequencies can be improved with any of the filters.

3. Comparison of Precision

To evaluate quantificationally the capability of filtering method for vibration extraction, we difference the GPS determined (either original or filtered) positions and the theoretical vibrations based on an epoch-by-epoch estimation and then calculate their standard deviation (STD) values. Table 1 lists the minimum of detectable vibrations calculated by 3 times STD (at the 99.7% confidence level) with and without applying the four filtering methods. The GPS accuracy improvement can be obtained by comparing the STD values of position estimates before and after filtering (see Table 2).

Table 1 Minimum detectable vibrations before and after filtering at the 99.7 % confidence level in all three directions (unit: mm)

	Test 1			Test 2			Test 3		
	X	*Y*	*H*	*X*	*Y*	*H*	*X*	*Y*	*H*
Before	6.3	8.6	9.9	8.5	7.2	13.3	5.1	10.3	18.7
Vondrak	0.9	1.1	1.5	5.8	4.2	4.3	2.4	2.2	4.8
Wavelet	0.9	1.0	1.5	6.1	5.4	3.0	2.6	2.4	5.4
FIR	2.7	2.6	3.7	7.3	5.4	9.1	4.4	5.4	7.6
Kalman	1.9	2.3	3.1	7.7	5.0	10.3	4.8	5.2	7.4

It is seen from Table 1 that the minimum detectable vibrations before the filtering range from 5.1 to 18.7 mm; while the values are from 0.9 to 5.8 mm after the Vondrak filtering is applied, 0.9 ~ 6.1 mm after wavelet filtering, 2.6 ~ 9.1 mm and 1.9 ~ 10.3 mm with the adaptive FIR and Kalman filtering methods, respectively.

Table 2 GPS accuracy improvement by four filtering methods in all three directions (unit: %)

	Test 1			Test 2			Test 3		
	X	*Y*	*H*	*X*	*Y*	*H*	*X*	*Y*	*H*
Vondrak	86	87	85	32	41	68	54	79	74
Wavelet	85	88	85	28	25	77	49	77	71
FIR	58	70	63	14	25	31	14	47	59
Kalman	70	74	68	10	30	23	6	49	61

It can be seen from Table 2 that the accuracy improvements by both Vondrak and wavelet are greater than those of the two latter methods. Especially for Test 3 with multi-frequency and multi-amplitude signals, the average contributions to GPS accuracy of the two latters are about 19 %, 62 % and 83 % of those of the two formers for the *X*, *Y* and *H* directions.

The results in Tables 1 and 2 indicate that the GPS accuracy for structural vibration monitoring can be improved by the four filtering methods. For the Vondrak and wavelet filters, the minimum detectable vibrations and accuracy contributions are almost the same and significantly better than those of the adaptive FIR and Kalman filters.

4. Comparison of Filtering Method

The distinct fundamentals (e.g., frequency response) or algorithms of each filtering method result in the different procedures and parameters for vibration extraction. Here we will analyze the advantages and disadvantages of each of the filters with respect to selection of filter parameters and computation efficiency.

4.1 Vondrak Filtering

In this study, we apply the Vondrak bandpass numerical filter to extract the vibrations. It can be implemented by giving the central frequency f_0 and rangeΔf of the bandpass frequency band (Vondrak, 1977). Two cases to be considered are as follows (Zhong et al., in press).

Case 1: If a signal with dominant natural frequency exists in the observational data series or there is a signal with certain frequency to be extracted, in this case we select the range$\Delta f > 0$ to maintain the amplitude of the vibration signal. Also, the central frequency f_0 may be known based on the design of the structure or can be determined based on time-frequency analysis by applying, e.g., the Fast Fourier Transform (FFT).

Case 2: If the distribution of signals with dominant frequencies fall over a frequency range, the cut-off frequencies f_1 and f_2 ($f_1 > f_2$) at the two ends of the frequency range can be chosen and the values of f_0 andΔf can be then estimated.

In summary, extracting the vibrations with the Vondrak bandpass filtering is not only easy to implement but computationally efficient without calculation iteration.

4.2 Wavelet Filtering

The procedure of vibration extraction by using the wavelet filtering proceeds in three steps (Teolis, 1998): decomposition, coefficients thresholding and reconstruction. In this analysis, the discrete Meyer wavelet is selected as the wavelet basis due to its good overall performance; the non-signal levels are regarded as noise levels and then rejected (threshold is set to zero) in the filtering (Xiong et al., 2005).

Although the noise rapidly decreases with the increase of decomposition levels, the success of wavelet-based vibration extraction depends on the estimation of vibration signal levels requiring the aid of time-frequency analysis or a prior knowledge of structure design and central frequency of each level (see Table 3).

Table 3 Central frequency of discrete Meyer wavelet with sampling rate of 10 Hz

Level	1	2	3	4	5	6	7	8	9
Freq.(Hz)	3.361	1.680	0.840	0.420	0.210	0.105	0.053	0.026	0.013

In conclusion, the wavelet filtering has the same advantages as the Vondrak. However, when the signals (e.g., multipath) in the observational data series fall in the same frequency range as the vibration signals, the parameter selection for both Vondrak and wavelet filters becomes challenging. In this situation, more complicated techniques (not discussed herein) are required for most of the filters to separate the vibrations.

4.3 Adaptive FIR & Kalman Filtering

Adaptive FIR and Kalman filters have the capability of continuously adjusting and updating the filter coefficients by adaptive algorithms based on the previous obtainable parameters to improve or optimize their performances (Ifeachor and Jervis, 1993). It is therefore feasible to apply them to GPS deformation monitoring where the GPS noise and deformation signals tend to fall in the same range of frequencies, and the noise is varying in time (Ge et al., 2000; Tor, 2002). However, when the two filtering techniques are applied to signal extraction, two GPS observational data series, both static and dynamic, with the same length are required simultaneously to mitigate the multipath disturbance (Chan et al., 2005).

For the adaptive FIR filtering, we use the recursive least squares (RLS) adaptive algorithm of the autoregression (AR) model in this study. Although it’s fast convergence rate, the RLS adaptive algorithm is fairly computationally demanding.

Despite its elegant derivation and often excellent performance, the Kalman filter has two drawbacks: erroneous a priori assumptions which may distort the result of filtering, and heavy computational burden which limits its utility in high-rate real time applications.

5. Conclusion and Discussion

Four commonly used filters, such as Vondrak, wavelet, adaptive FIR and Kalman, have been applied to GPS carrier phase measurements for vibration separation, based on the analysis of time-frequency characteristics of GPS multipath disturbance, observational noise and vibrations. The following conclusions can be drawn by comparing the performances of the filters:

(1) Utilizing the filtering technique can improve the GPS measurement accuracy of tracking structural dynamics up to 2 mm and complex signals with varying frequencies.

(2) The Vondrak and wavelet filters are significantly superior to the adaptive FIR and Kalman filters using the controlled experiments in this paper. The minimum detectable vibrations of 0.9 to 6.0 mm and accuracy contributions are almost the same for the two former methods. The average contributions to GPS accuracy of 56 %, 66 % and 77 % can be obtained for the three directions after applying the two formers.

(3) Compared to the adaptive FIR and Kalman filters, the implementations of both Vondrak and wavelet filtering techniques require neither prior assumptions nor static GPS observations, but are computationally efficient.

Recommendations are given here for the selection of proper filter and filter parameters for different situations in structural vibration monitoring. To analyze a vibration signal with certain frequency, the Vondrak filter can be used avoiding the estimation of vibration signal levels of wavelet transform. In this case, we can choose the frequency to be analyzed as the central frequency f_0 and range$\Delta f = 0.1$. To analyze signals falling over a frequency range, either the wavelet or the Vondrak filter can be employed.

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