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Research Article

Cross-correlation analysis of wind speeds and displacements of a long-span bridge with GNSS under extreme wind conditions

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Abstract

Nowadays, real-time bridge deformation monitoring has attracted more attention, due to huge civil engineering structures, such as long-span bridges, which are susceptible to dynamic deflection caused by various loadings. Hence, precise dynamic response measurement becomes necessary to make structure monitoring more reliable and accurate. Currently, Global Navigation Satellite System (GNSS) positioning technology is commonly used in this field to detect the dynamic displacement of long-span bridges. According to this, real-time data was collected from the Forth Road Bridge to observe the dynamic response of long-span bridges under extreme wind load conditions. This article has also verified the data processing technique of the real-time bridge deformation monitoring system. Compared with other monitoring methods, this method, with GPS and anemometer, has features of high frequency with low lag. After data synchronization and post-processing, the variation of wind speed and deflection of the main bridge span over time were obtained. Background noise was eliminated by the embedded software and the lowpass filter. Finally, according to the cross-correlation analysis, the relationship between wind speed and bridge displacement has been found, and the deflection in the y-axis has the largest correlation coefficient.

1. Introduction

In contemporary society, bridges have become more and more vital all over the world. They not only connect two places and allow transport between them, but also play crucial roles in economic ties. With the development of construction technologies and materials, the number of modern bridges with longer spans has continued to grow at a rapid pace in recent years. However, long-span bridges also cause many problems for bridge engineers, as they are more susceptible to ambient stimulations, such as earthquakes, traffic loadings, temperature effects, and strong winds (Han et al., 2016). In this article, the effects of strong winds on long-span bridges will be the research focus. Time series and cross-correlation analysis have been conducted in order to understand the dynamic response of long-span bridges. The analysis on the aeroelastic stability could be seen as useful guidance as a matter of improving the bridge's wind-resistance

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performance. Moreover, it is very important to build an online bridge monitoring system to identify the real-time health conditions of the bridge.

Precise monitoring of dynamic displacement characteristics is critical to evaluating the structural integrity of bridges. Nowadays, Global Navigation Satellite System (GNSS) and Global Positioning System (GPS) have been widely utilized to monitor the dynamic responses of civil engineering structures because of their good reliability in measuring absolute 3D quasi-static and dynamic displacement (Quan et al., 2015). Actually, the global positioning system (GPS) was first used by the military as a US Department of Defense (USDoD) satellite-based positioning system, and was then applied for civil use after the accuracy was degraded (Brown et al., 2006).

As a powerful tool for monitoring, GPS has several advantages over other positioning technologies; for example, the ability to make measurements in most weather conditions, high signal capture frequency with low lag, easily processed and synchronized data, no marks or targets needed to be set on site, and measurability over long baselines. Moreover, it has a long service life and is convenient to maintain. GNSS can build up its own GPS time series, which also provides a standard of time for other instruments such as anemometers and accelerometers. In order to obtain cases of the actual application of GPS technique on long-span bridges, a series of trials have been conducted, such as the Forth Road Bridge, London Millennium Bridge, and Wilford suspension bridge in the UK (Meng et al., 2007).

The technology of bridge health monitoring systems with GNSS has undergone rapid development over recent years. The data has been comprehensively analyzed and the accuracy collected has been improved, starting initially from a few centimeters to what is now a few millimeters. First, Meo et al. (2002) used GPS to identify parameters like damping coefficients, natural frequencies, and shapes of medium-span suspension bridges by using wavelet transforms. Then, Hristopulos (2006) found that GPS can not only measure the dynamic displacements of cable-stayed bridges and other flexible structures, but can also be used to monitor stable structures with higher sampling rates. With a sampling rate of up to 100 Hz, it enables us to measure the deformations and determine the high frequencies of bridges by using a high-rate GPS receiver. Due to the rapid growth of current Global Navigation Satellite System (GNSS) technology, the dynamic displacements can be identified with higher accuracy by using multimode GNSS data. Later and Psimoulis (2008) researched the potential of GPS to identify multi-dominant frequencies of civil engineering structures excited by various loads using least-square based spectral analysis and wavelet techniques. Finally, Breuer et al. (2002) found a method to monitor the wind-induced deflection of the Stuttgart TV Tower by using GPS. It showed that the GPS can measure dynamic wind responses, not only the dynamic fluctuating component, but also the static component.

GPS has its inherent limitations, which could lead to difficulties in offering highly precise and robust positioning data for bridge health monitoring. The limitations include multipath effects, satellite visibility conditions, uncorrected tropospheric delays, and reliance on communications for real-time applications. Moreover, the accuracy of the vertical component is usually three times worse than the horizontal component.

In this article, in order to establish an extensive monitoring system, multimode sensors were applied to obtain accurate dynamic displacements of the Forth Road Bridge in Edinburgh and Fife, Scotland. It aimed to verify the method’s feasibility by combining the GNSS with anemometers to monitor the dynamic response of a long-span bridge under extreme wind conditions and optimize the routine of data postprocessing to eliminate various error sources such as multipath effects and background noises. Finally, the relationship between wind speed and bridge deflection was found after synchronizing the wind speed and displacement data in all three axes of directions.

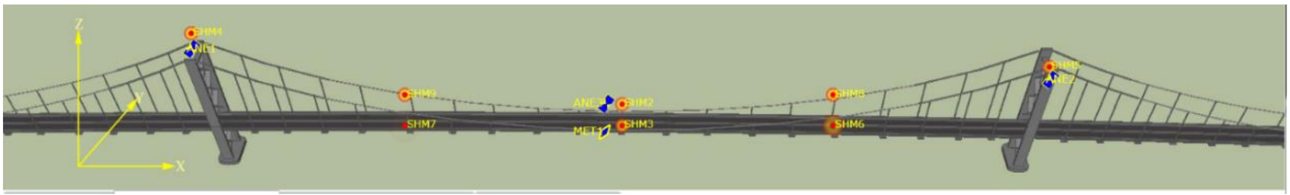
2. The structural health monitoring system of Forth Road Bridge

2.1 Composition of the SHM system

The Forth Road Bridge is a suspension bridge that spans the Firth of Forth and connects Edinburgh to Fife. It was first constructed in 1958 and was opened in 1964. It is a two-tower cable-stayed suspension bridge with a length of 2,512 m and a width of 33 m. The longest span between the two 156 m high pylons is 1006 m long. It has a two-lane carriageway with two cycle/footpaths (Theforthbridges.org, 2017).

Since the bridge has to withstand a variety of loadings, including temperature, urban traffic, and wind, a real-time structural health monitoring (SHM) system was suggested to be established in order to evaluate the reliability and integrity of the bridge. The SHM system at Forth Road Bridge includes 9 GPS reference stations, 3 anemometers, and 1 multifunctional weather observing station (MET). There are seven Leica GR10 (SHM1-7), two Panda DP318 (SHM8-9), and three GILL WindMaster Pro 3-Axis Anemometers among this equipment. **Figure 1** clearly shows the local bridge coordinate system and instrument allocation for the bridge deflection monitoring. It is clear that SHM4 and ANE1 are set up at the top of the left pylon, and SHM5 and ANE2 are located on the right pylon, while the others are installed in the main span between the two pylons. MET is used to measure the ambient environment, such as temperature, humidity, and wind.

(a)



(b)

Figure 1 Local bridge coordinate system; (a) plain view, (b) ariel view, and sensor positions.

2.2 Development of the SHM system

This SHM system was first set up in September of 2014. After several adjustments within two years, the data from the SHM system became stable and reliable in September of 2016. The receiver equipment can be remote controlled and monitored, and real-time updated data can be obtained directly from the server of the University of Nottingham anytime, which makes the monitoring process safer. It is unnecessary to arrange for technicians to collect the data at the site, especially in extreme weather conditions like typhoons. There are several procedures for transferring the data from the site to the Internet. The data from the sensor at the bridge is first transferred to the Ethernet, and then, through fiber optics, the signals are transmitted to the network of the Forth Road Bridge. Finally, the data is uploaded to the internet and received by the servers of the University of Nottingham. The dynamic displacement of the bridge is the key factor that may cause damage. Hence, more accurate displacement data extraction with developed processing techniques will be the focus of this article, as this influences the actual performance of the bridge under extreme wind conditions. The GPS displacement and wind speed data analyzed in this article were collected at SHM2 and ANE1, respectively, which were expected have the most significant dynamic response when a typhoon landed Edinburgh on 11^{th} Jan 2017.

2.3 Detail information of multimode sensors

The WindMaster Pro is constructed from stainless steel and installed on the pylon roof to measure the wind effect (Gillinstruments.com, 2017). It also has a maximum data output rate of 32 Hz as standard but, for the application on the Forth Road Bridge, the frequency of the anemometer was adjusted to 10 vHz. Besides these, other high-performance features, such as improved vertical resolution and less distortion due to wind loading, are also available on this device. Hence, it is extremely suitable for precision wind measurement requirements, particularly under extreme wind conditions. The Leica GR10 is designed for a wide variety of GNSS reference station applications, for which it provides better reliability and performance. Moreover, the GR10 also offers brilliant low-noise code and phase data, which, combined with powerful onboard RefWorx software, leads to logging and streaming rates of up to 50 Hz (Leica GR10 Brochure, 2017). It has a flexible configuration with up to 60 satellites, including the new satellite constellations. All of the GPS, GLONASS, Galileo, BeiDou, and QZSS could be tracked, which provides high reliability and accuracy. In order to synchronize the data from the anemometer more conveniently, the frequency of the Leica GR10 GNSS reference station was set to 10 Hz as well, while the frequency of PANDA PD318 was set to 1 Hz. Moreover, the displacement time series were collected by automatically transferring the GPS time to computer time, and the initial displacements were also converted to a bridge coordinate system (BCS) frame.

3. Data synchronization and results

3.1 Time period selection

The dynamic response monitoring data of the Forth Road Bridge was collected on January 11^{th}, 2017 (Theforthbridges.org, 2017), when a typhoon went through the region of Edinburgh. The SHM system recorded the deflection of the bridge and wind speed from 0:00 to 4:00 when strong winds came, which was believed to cause the main dynamic response of the bridge. According to **Figure 2**, it is clear that the maximum wind speed during this period was 98.78 km/h (27.56 m/s). The data collected from ANE1 and SHM2 were regarded as research objects using the proposed integration scheme. This section will present the results of the deflection of the bridge caused by wind in detail but, as shown in **Figure 3**, the analysis will focus on the time period between 00:30:00 and 00:50:00, where the strongest wind gust occurred.

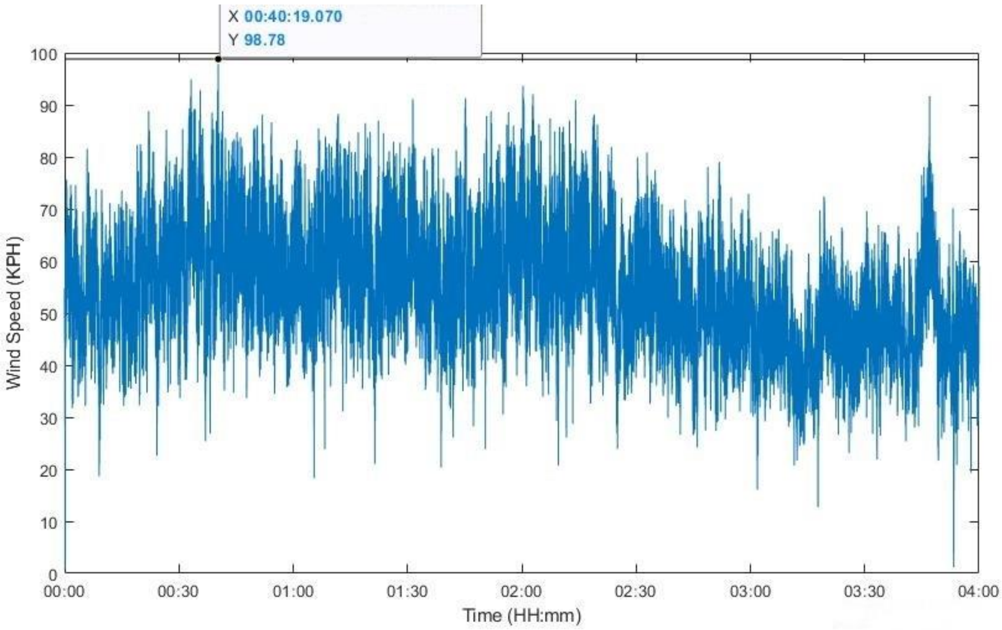


Figure 2 Wind speed records collected by ANE 1 (00:00:00 - 04:00:00).

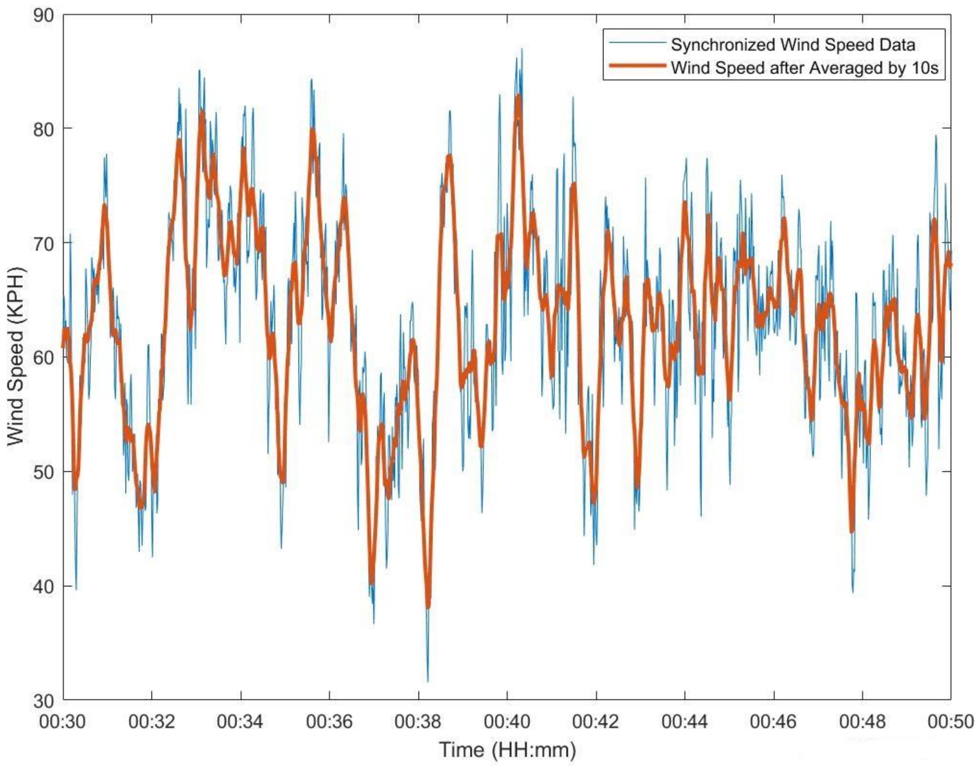


Figure 3 Wind speed in the time domain (00:30:00 - 00:50:00) when the strongest wind gust occurred. Blue line represents the collected data, and red line represents the time averaged value of 10 s.

It can be seen from **Figure 3** that the wind speed changed drastically during the data collection period. Through the moving average method, the author extracted the long-period component of the wind speed during this time period, as shown by the orange line. The window size of the moving average filter is 10 s.

3.2 Data synchronization

Before analyzing the SHM system, all the data collected by GPS and anemometer installed on the Forth Road Bridge needs to be synchronized. Although the embedded software has automatically transformed the time into uniform computer time and transformed the coordinate system into a bridge coordinate system (BCS), the accuracy of each device is different, which results in the time nodes of each record per second being slightly different. For example, both the frequency of anemometer and GPS reference station are set up to 10 Hz, but it is not exactly 10 data in one second through the 4-hour records, due to the signal being lost in the typhoon. In the first few rows of data, there are 10 rows of data in one second, but changes will happen in the following rows of data, such as 8, 9, or 11 rows of data in one second. Finally, 155,881 rows of wind speed data were collected by ANE1 in four hours, but for induced displacement of the bridge, only 143,999 rows of data were obtained by SHM2. This result leads to a problem in which it is impossible to align every wind speed and displacement data point for the purpose of analyzing the relationship between wind speed and displacement of the bridge. In order to solve this problem, data synchronizing techniques will be involved. The data processing method applied in this article is to first screen the amount of data per second, and then output the average results of the data per second. After running the code, the time, wind speed, and 3-axes displacement data were obtained. A sample of the first 10 rows is shown in **Table 1**.

Table 1 Processed data on time, wind speed, and displacement.

Time	Wind Speed	x-Axis / cm	y-Axis / cm	z-Axis / cm
2017-01-11 00:00:01	50.5690	0.0020	-0.7020	-0.0350
2017-01-11 00:00:02	48.4690	0.0170	-0.7280	-0.0480
2017-01-11 00:00:03	45.8260	0.0090	-0.7520	-0.0140
2017-01-11 00:00:04	44.7130	0.0030	-0.7770	0.0300
2017-01-11 00:00:05	44.0090	0.0050	-0.7940	0.0170
2017-01-11 00:00:06	48.3510	0.0130	-0.7930	-0.0310
2017-01-11 00:00:07	42.6970	0.0240	-0.7850	-0.0590
2017-01-11 00:00:08	42.6450	0.0330	-0.7760	-0.0490
2017-01-11 00:00:09	46.9440	0.0290	-0.7580	-0.0300
2017-01-11 00:00:10	49.7140	0.0180	-0.7410	-0.0420

3.3 Cross-correlation of wind speed and GPS displacement

Figure 4 shows the displacement data of the main span of the bridge along the three axes over time. It can be seen from the figure that, under extreme wind conditions, the dynamic response of the main span of the bridge vibrates at different frequencies and amplitudes. It shows different dynamic characteristics in three axial directions. The longitudinal and lateral displacement changes are around 0 cm, while the vertical displacement changes are at -1.3 cm. Meanwhile, the horizontal and vertical data have a larger amplitude than the vertical data. As shown in **Figure 5**, the intensity of the dynamic response of the Forth Road Bridge can be quantified by defining the rate of change of three axial deflections.

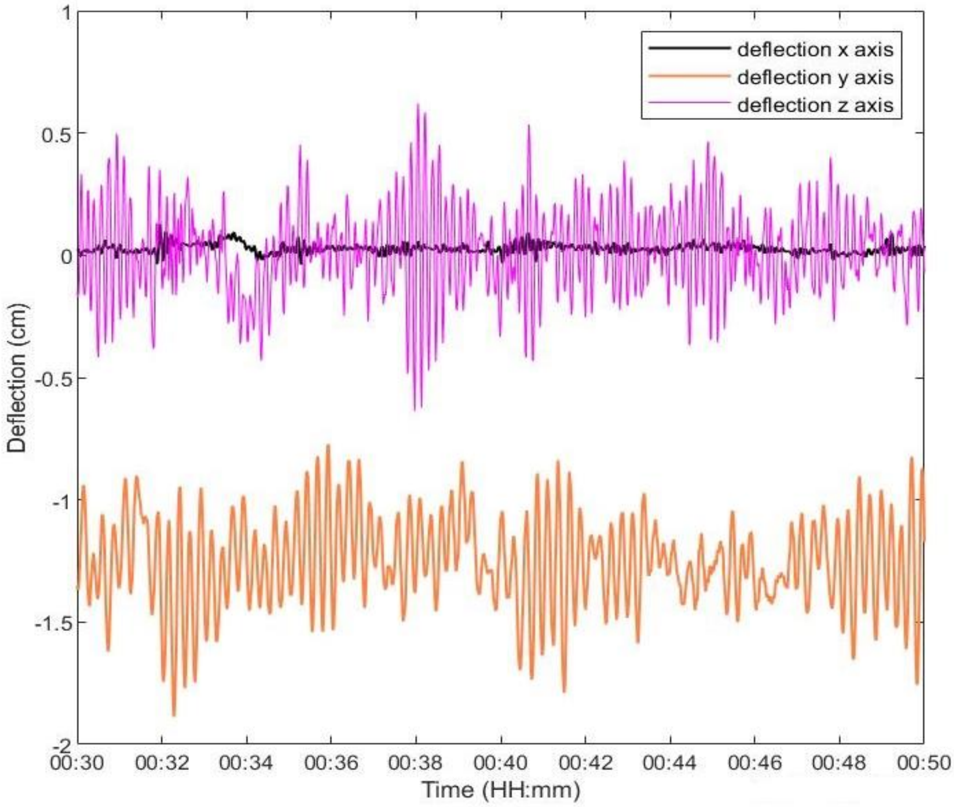


Figure 4 Displacements of the bridge in 3 axial directions (00:30:00 - 00:50:00).

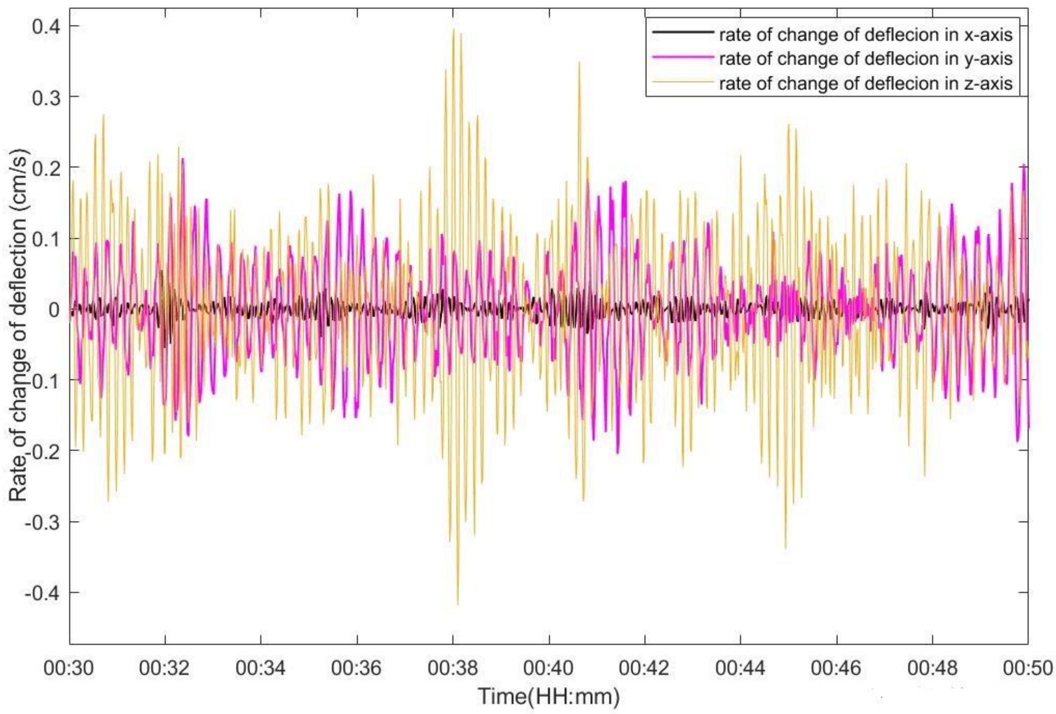


Figure 5 Rate of change of deflection in 3 axes.

When comparing the results of **Figure 4** with **Figure 5**, the rate of change of deflection in the y-axis and z-axis have the same order of magnitude, and are both bigger than the one in the x-axis. After calculating the variation of the rate of change of deflection, the dominant dynamic response of the bridge under strong wind loadings was found to occur in the vertical direction, which is along the z-axis.

Table 2 Variation of displacements in three axes.

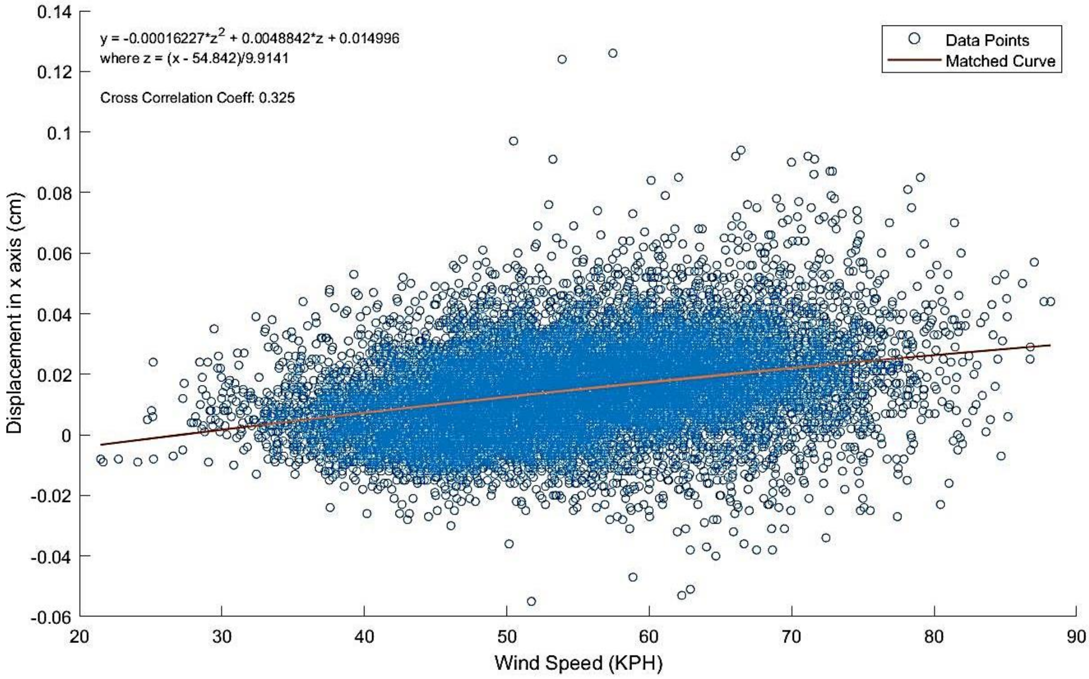
Displacement Direction	x-Axis / cm	y-Axis / cm	z-Axis / cm
Variation	1.2920e-04	0.0048	0.0119

Based on the synchronized data, cross-correlation analysis between wind speed and displacement was conducted to help find the best-fit curves passing through these data points by using the least-square method. As a result, a quadratic function was found to best match the data points. Details are shown in **Figure 6**, where the x-axis shows the wind speed and the y-axis represents the GPS displacement data. As shown in **Table 2**, the cross-correlation coefficients between wind speed and displacement of the bridge in 3 axes are 0.325, -0.440, and -0.032, respectively.

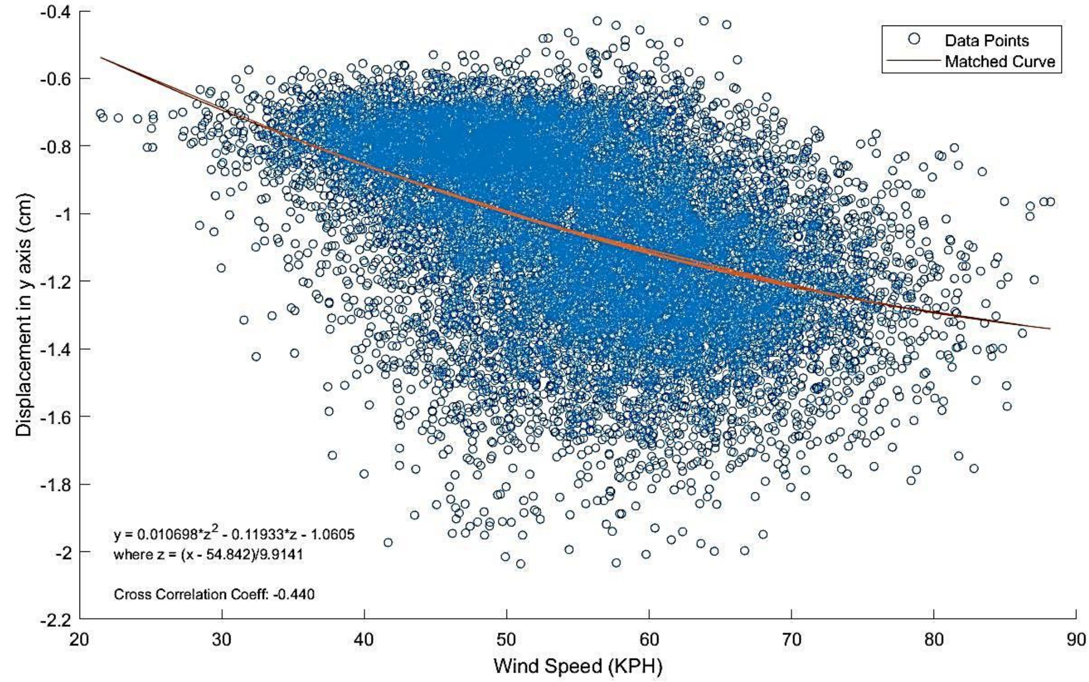
Table 3 Cross-correlation coefficient of wind speed and GPS displacement.

Displacement Directions	Cross-Correlation Coefficient
x-Axis	0.325
y-Axis	-0.440
Z-Axis	-0.032

From **Table 3**, it can be found that, within the range of collected data, the wind speed has a positive relationship with displacement in the x-axis, while it has a negative relationship with displacement in the y and z axes. Among the three best-match curves, the one for the y-axis has the largest absolute value of cross-correlation coefficient.

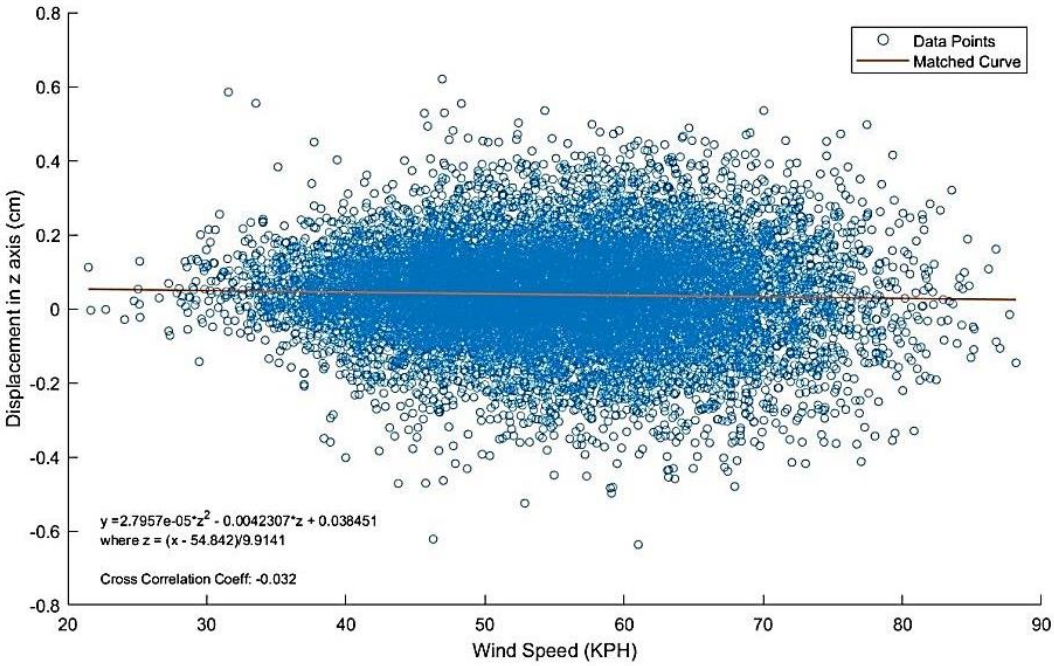


(a)



(b)

Figure 6 Cross-correlation analysis between wind speeds and displacement in (a) x-axis, (b) y-axis, (c) z-axis.



(c)

Figure 6 (continued) Cross-correlation analysis between wind speeds and displacement in (a) x-axis, (b) y-axis, (c) z-axis.

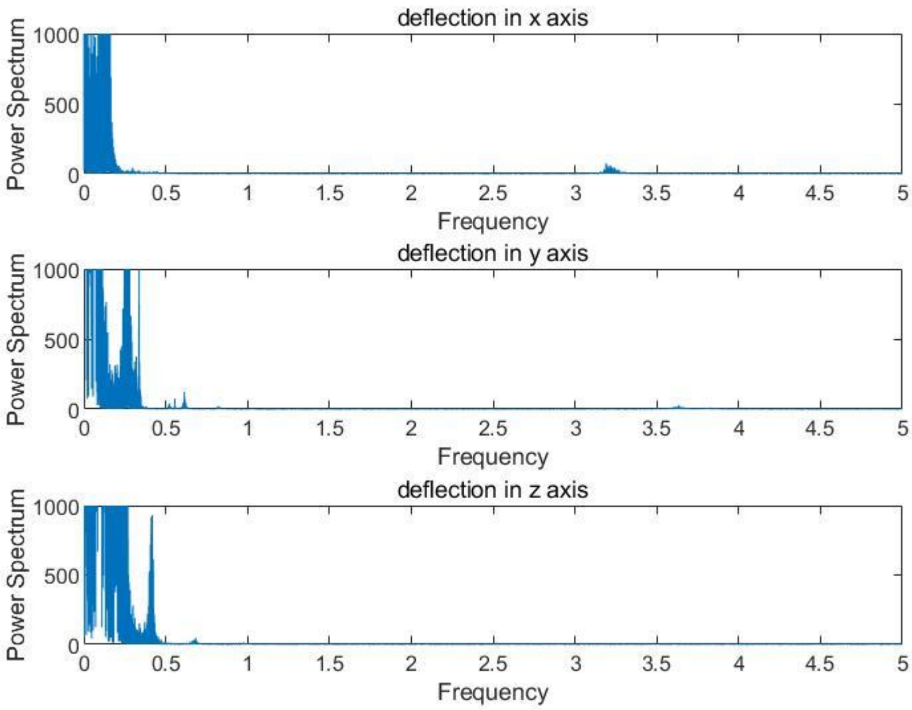


Figure 7 Power Spectrum of Deflection in three axes.

4. Error source extraction

4.1 Multipath effect

The raw data from the GPS/anemometer has already been processed by the embedded software in the instrument to get precise and stable data, such as by the RefWorx software installed in the Leica GR10 GPS reference station. Nevertheless, the GPS measurement will still suffer from multipath effects and noise caused by GPS signal disturbances. Both of these factors will influence the accuracy of GPS measurement for monitoring applications. Multipath effects are one of the primary errors in high-precision surveying applications (Encheng et al., 2013). Multipath effects are related to the observation environment and can be divided into three categories: 1) Diffuse multipath scattering from a widely distributed area with a repetition period of less than one minute to 2 - 3 min; 2) specular multipath from smooth reflective surfaces with a period ranging from 5 to 10 min; 3) low frequency multipath associated with reflection from the water surface, with long repetition period ranging from 26 to 60 min (Tranquilla et al., 1994). Compared with other systematic errors, multipath errors are not easily extracted or mitigated from the source of signals.

4.2 Application of low-pass filter

The main frequency of GPS displacement from anemometer could be obtained in the power spectrum by applying the Fast Fourier Transform (FFT) algorithm. As shown in **Figure 7**, the power spectrum of GPS displacement along three axial directions is obtained. Moreover, major frequencies of deflection in all axes are concentrated under 0.5 Hz, and around 0.3 Hz specifically. Hence, the expected frequency band used to mitigate the multipath effect is identified to be 0.3 Hz in all three axes. A frequency below this value is the actual displacement of the bridge (Wang et al., 2017). After isolating the background noises and the multipath effect, it could be observed in **Figure 8** that noises have occurred in all three axial directions, while the multipath effect was mainly along the x-axis. After applying the low-pass filter, most redundant vibrations along the x-axis are smoothed, and because the signal in lateral and vertical directions does not suffer much from the multipath effect, the curve without filtering almost coincides with the curve after filtering in those two directions.

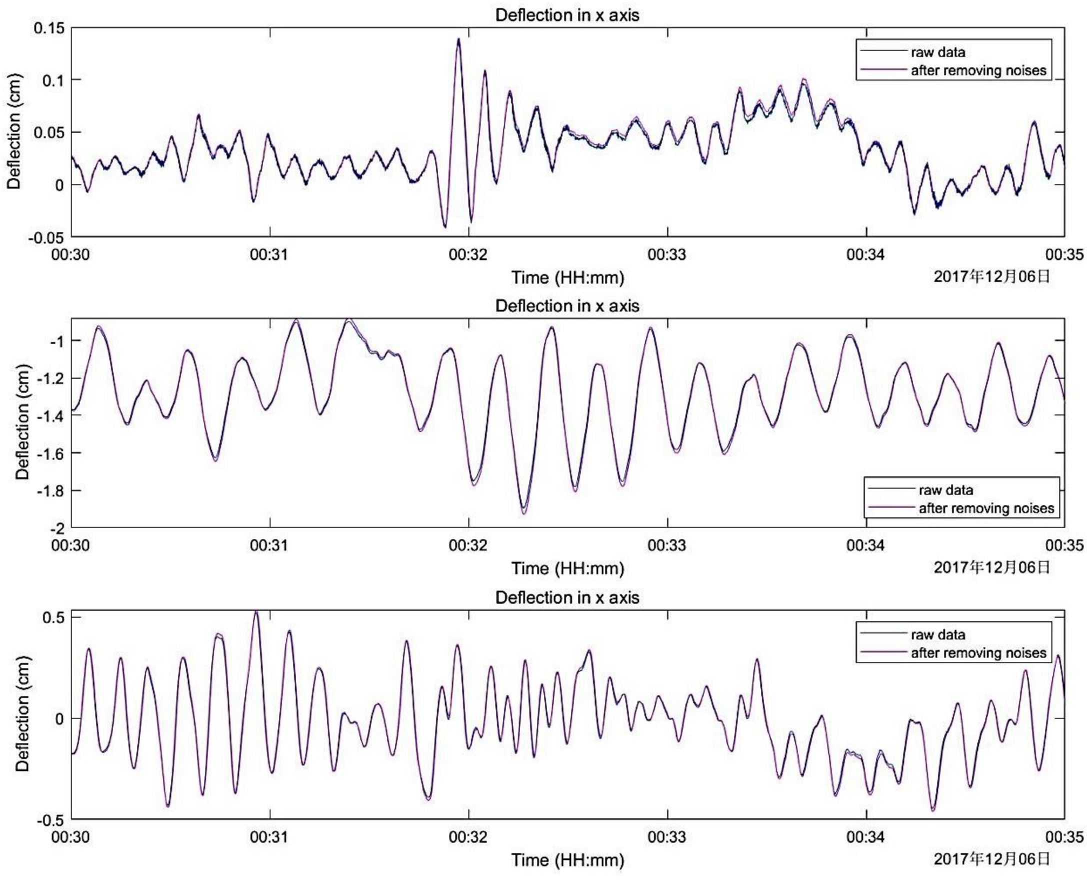


Figure 8 GPS displacement in three axes after removing noises.

5. Discussion and conclusions

Real-time bridge health monitoring has become more important with the development of bridge management systems and transportation safety. Nowadays, GNSS is commonly used for precise dynamic response detection of long-span bridges that are susceptible to huge wind loadings. This article investigates the dynamic response of the Forth Road Bridge under extreme wind conditions with GNSS. The data was collected on January 11th, 2017 by the structural health monitoring system of the bridge. In this article, four-hour data was collected, but only the period from the first 30 to 50 min was focused on, because that is when the strongest wind gust (98.78 kph) occurred.

After collecting the raw data, it was found that the data from different multimode sensors was inconsistent, due to signal loss under extreme weather conditions and inconsistency in the signal capture frequency for GPS station and anemometer. Hence, the raw data was first synchronized for cross-correlation analysis.

A time series analysis on GPS displacement in three axes was performed. By calculating the rate of change and variance of datasets, the results show that extreme wind loadings have a huge influence on the deflection of the bridge, especially in vertical and lateral directions. They have the same order of vibration amplitude, and displacement in the vertical direction has the greatest value among the three.

When the GPS displacement and wind speed data were synchronized, a quadratic function was found that best matched the data points by using the least-square method. Within the wind speed range of 20 to 90 kph, the wind speed has a positive relationship with displacement along the x-axis, but for displacements in lateral and vertical directions, they are negatively related to wind speed. Furthermore, after performing cross-correlation analysis, the y-axis deflection was found to have the highest cross-correlation coefficient of -0.440.

Background noise and multipath effects can be reduced by using software approaches. FFT algorithm was first applied to identify the dominant frequency band. After identifying the dominant frequency band, the background noise and multipath effects were effectively eliminated by using the low-pass filter. Additionally, the multipath effect was found to mainly occur in the displacement data along the x-axis.

However, some of the work still needs to be improved in this research. The first instance is that the research team does not have the GPS and anemometer data from the same position. From section two, it is known that the data used in the analysis was collected from SHM2 at the middle of the main span, and from ANE1 at the top of the left pylon. This will cause a systematic error between wind speed and displacement data. Second, accelerometers were not installed on the Forth Road Bridge. Thus, the natural frequency of the bridge and high-frequency components of displacement cannot be detected.

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