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Analysis of bridge displacement using GNSS time-series data

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Abstract. Analysis and identifying the displacement characteristics play a key role in timely monitoring and detecting the physical responses of the bridge to ensure the safety of the human and structure. Many previous kinds of research used GNSS data to identify displacement and oscillation modelling of the bridge with different algorithms. This study uses GNSS time-series data to determine linear displacement and model oscillation of the bridge using a procedure including filtering outliers, linear regression, and sin function to identify amplitude in three directions, the plane displacement velocity, spatial displacement velocity, and vibration model of the bridge. The data in the research in the GNSS time-series data from three P5 GNSS receivers of the CHC brand on the Dachongyong bridge in Nanning, China with 1646 observations, at one-hour sample intervals in 68 consecutive days. The plane and spatial velocity of the three points DCQ01, DCQ02, and DCQ03 is 0.0181 mm/h, 0.0185 mm/h; 0.0114 mm/h, 0.0173 mm/h; and 0.0071 mm/h, 0.0082 mm/h respectively. The study results are significant in analyzing and identifying the bridge's displacement characteristics.

1. Introduction

Bridges play an important role in the development of the economy and society of each country. This kind of work also has an asymmetrical design, subject to many external factors including wind, storm, self-load, and the load of vehicles on the surface as well as under the water [1,2]. Monitoring to timely monitor the response of the bridge over time is very significant and is the wish of the structural engineers. As a metaphor in civil engineering, based on the monitoring results, structural engineers understand more about the response of the bridges [3] and will devise reasonable operation and maintenance programs to ensure the safety of the people, vehicles, and structures. GNSS means Global Navigation Satellite System including GPS, GLONASS, Galileo, Beidou, and other existing constellations. The development of the global navigation satellite system increases the number of satellites in the sky and expanded the GNSS applications [4,5]. Therefore, a GNSS rover can get signals from 40-50 satellites for each epoch [6]. An increase in the number of satellites results in improvements in GNSS positioning accuracy which can match strict requirements in deformation monitoring.

Regarding the bridge monitoring field, GNSS is used in the structural health monitoring systems for long-span bridges [7,8] and to assess the safety status of the bridge [9,10]. Above all, GNSS plays a key role in structural health monitoring systems at all levels [11]. Meng et all [12] indicated that GNSS can be used to determine the dynamic character in the oscillation of the bridge and decisions of the maintenance procedure are supported by GNSS monitoring results. However, although GNSS had much progress in long-time monitoring, the sampling rate of the GNSS devices cannot meet the requirement, consist of a variety of noises [12], and can lead to some differences in the monitoring results [13]. Thus, a combination of GNSS and sensors is needed to interpret the bridge displacement better [14,15].

Some limitations of the GNSS were also mentioned in the studies [9,13] such as low sampling rate, and influences of the weather conditions, and both gave a conclusion that it is necessary to have a suitable solution to identify dynamic characteristics. Yu et all [16] used a multimode adaptive filter algorithm to identify the dynamic displacement and modal frequencies with data from GNSS and accelerometer. In this study, the accelerometer plays a key role to determine modal frequencies and dynamic displacement. An AFEC filtering was proposed in the study [17] and a CEEMDAN-KELM model to predict the displacement of the bridge via GNSS data was proposed in the study [18], or recently, a five-step approach was proposed to assess bridge oscillation with GNSS time-series data with two algorithms [19]. These studies focused on filtering outliers and predicting the displacement of bridges.

It can be seen that the above studies indicated the disadvantages of the GNSS technique and used different algorithms to improve the accuracy of forecasting or determining the displacement of the bridge. However, there was no detailed procedure for GNSS time series data. The paper proposes a procedure for the analysis of bridge displacement using GNSS time-series data. The procedure includes outliers filtering, statistic inspection and identifying data characteristics and separating characteristics.

2. Device, Data, and methodology

2.1. GNSS receiver

In this study, GNSS time series monitoring data will be used to analyze and identify the displacement of the bridge. Dachongyong is a concrete cable-stayed bridge in Nanning province, China with 888m in length in total, three main spans, designed with a high and a low tower. The Northern tower is 138m and the Southern tower is 103.5m (Figure 1,2). There are three GNSS monitoring points on the bridge, two on the northern and southern towers, and one on the bridge surface (Figure 3).

Figure 1. Dachongyong bridge.

Figure 2. A GNSS monitoring point.

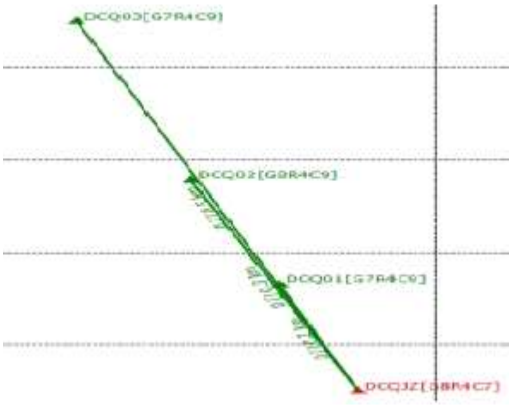


Figure 3. Monitoring points on the bridge.

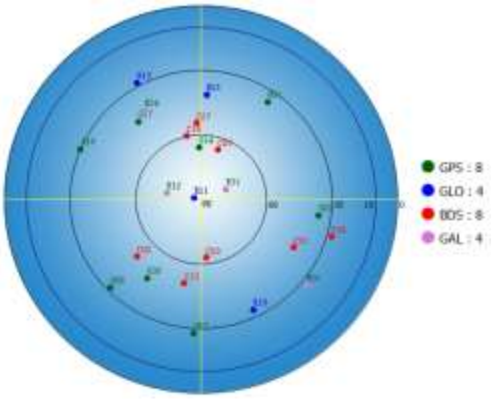


Figure 4. Constellations at an epoch at DCQ02.

In Figure 3, DCQ01, DCQ02, and DCQ03 are rover devices and play a role as the monitoring points while DCQJR is a single base. Monitoring points are the P5 GNSS receivers, multi-constellations, and 624 channels, designed for monitoring purposes with high accuracy. A sky plot at an epoch of the DCQ02 monitoring point is in Figure 4.

2.2. Monitoring data

In There are 1646 observations for each monitoring point extracted from March 2, 2022, with a one-hour sample interval. The displacement at the time i is calculated by the below equation.

$$\begin{cases} dx_i = x_{ti} - x_{t0} \\ dy_{ti} = y_{ti} - y_{t0} \\ dz_{ti} = z_{ti} - z_{t0} \end{cases}$$

where:

$dx_{ti}, dy_{ti}, dz_{ti}$: Displacement of x, y, z direction at time t_i
x_{ti}, y_{ti}, z_{ti}: Coordinates at time t_i
x_{t0}, y_{t0}, z_{t0}: Coordinates at time t_0

2.3. Data analysis

Monitoring data will be analyzed using three steps including outliers filtering, identifying characteristics, and characteristics separating (Fig.5). Outliers are the observations that differ from the rest of the data and depend on the assumptions regarding data structure and detecting methods [20–23]. For outliers filtering, LE et al made a comparison of five different algorithms for GNSS time-series data and concluded that the moving median is a robust statistic and is most sensitive to outliers [24]. In this study, data from three GNSS monitoring points will be filtered outliers using a moving median algorithm with sliding window size 24, interpolated using a modified Akima cubic algorithm, threshold 2.5.

Linear regression is a popular algorithm in the analysis of time-series data and can be used to predict [25,26] or analyze the relationship between two or more variables in which one of them is the dependent variable and the others are independent variables. There are some kinds of errors in geodetic time-series data including flicker noise, and random noise [27,28]. For this study, GNSS data from three monitoring points will be analyzed using statistical algorithms.

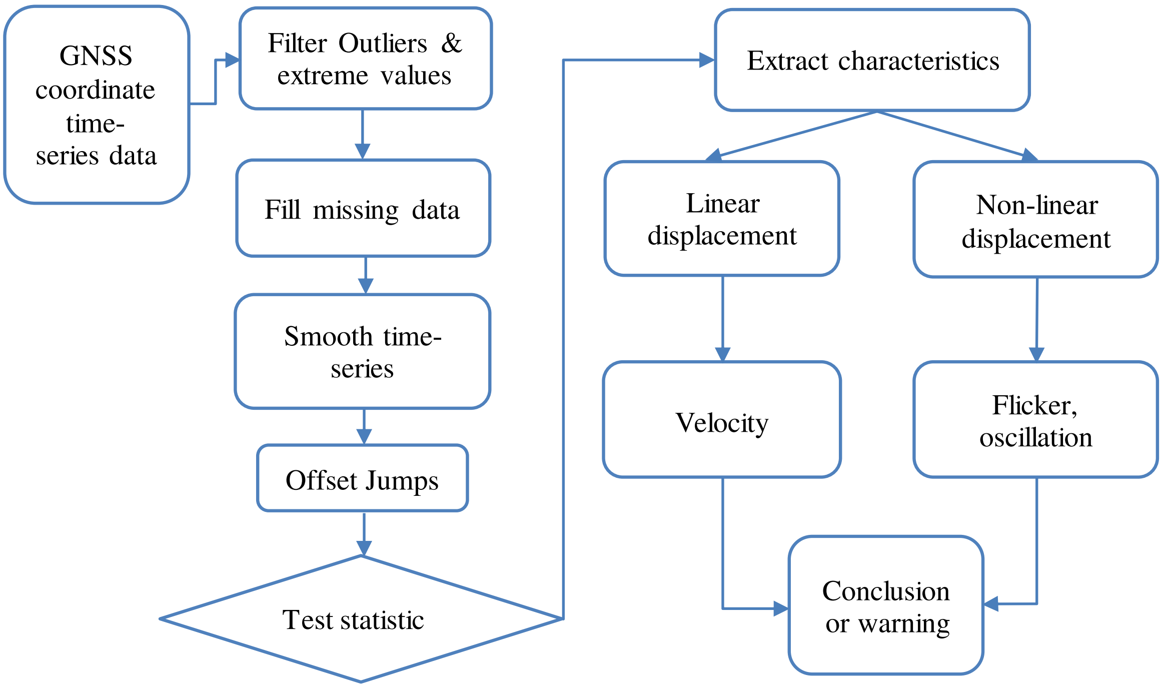


Figure 5. Analysis procedure.

Finally, linear displacement will be determined, and oscillation of the monitoring points will be modelled. Linear regression will be used to determine linear displacement and the sin function will be used for modeling the oscillation of the bridge.

3. Analysis results

3.1. Outliers filtering

Filtering outliers with moving median algorithm, sliding window size 24, threshold 2.5, and *Akima cubic* interpolation.

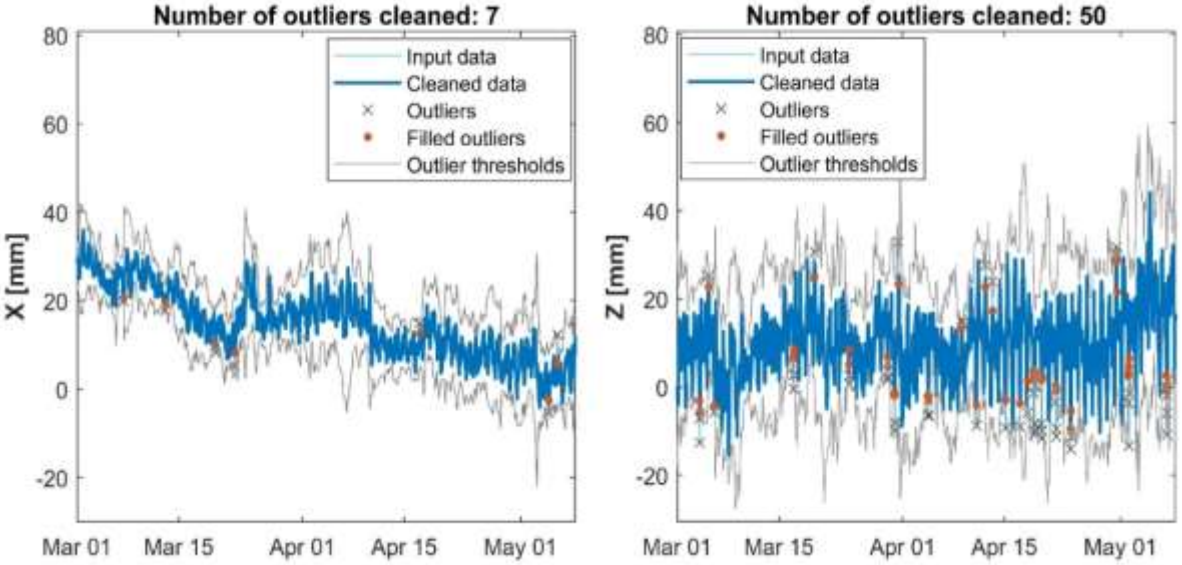


Figure 6. Filtering outliers for X and Z components of DCQ01.

Taking a look at Fig.6, the number of outliers with a 24-sliding window size is not high. However, the number of outliers in the Z direction is more than that in the X direction.

3.2. Linear displacement

The velocity and amplitude of the three monitoring points are in Table 1,2

Table 1. The velocity of three monitoring points.

Name	Vel_X (mm/h)	Vel_Y (mm/h)	Vel_Z (mm/h)	Vel_XY (mm/h)	Vel_XYZ (mm/h)
DCQ01	-0.01387	0.01167	0.00397	0.01812	0.01855
DCQ02	-0.00630	0.00960	0.01295	0.01148	0.01731
DCQ03	-0.00009	0.00709	0.00414	0.00709	0.00821

Table 2. Amplitude in three directions.

Name	Amplitude X (mm)	Amplitude Y (mm)	Amplitude_Z (mm)
DCQ01	2.619	2.140	3.257
DCQ02	2.173	1.550	13.133
DCQ03	6.232	27.777	13.471

The velocity of points DCQ01 and DCQ02 is higher than that of point DCQ03 although DCQ03 has the highest elevation compared to the two rest points. However, in Tab.2, the amplitude in all three directions of point DCQ03 has the highest values. There is one thing that needs to be taken note of is that the amplitude of the Z direction of the point DCQ03 is smaller than that of the Y direction.

Linear models of three monitoring points are in Figure 7,8,9

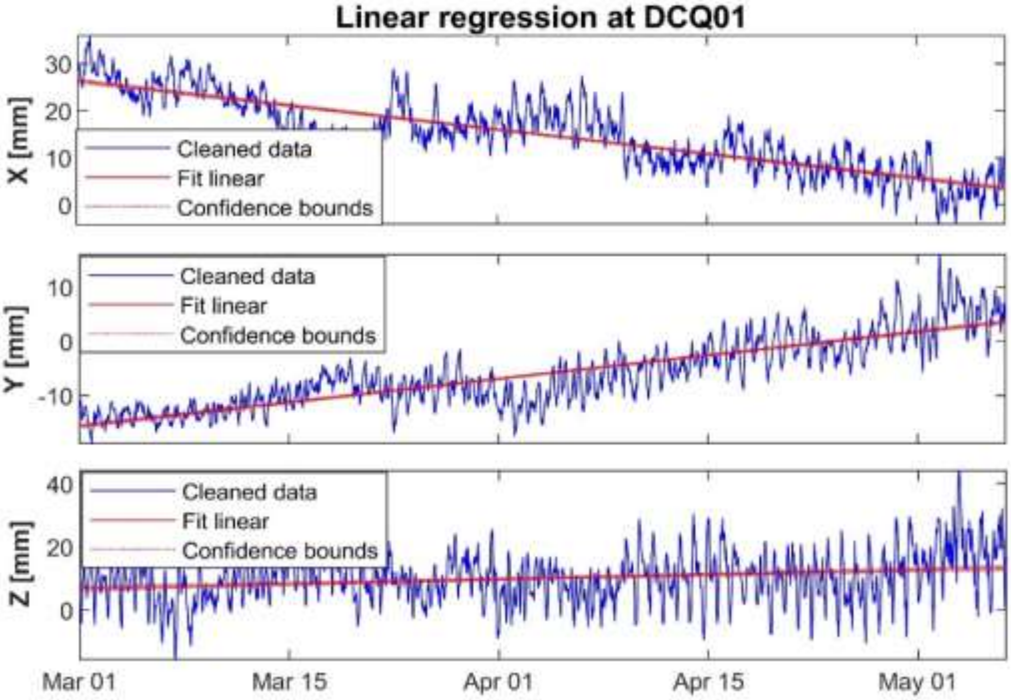


Figure 7. Linear regression of DCQ01.

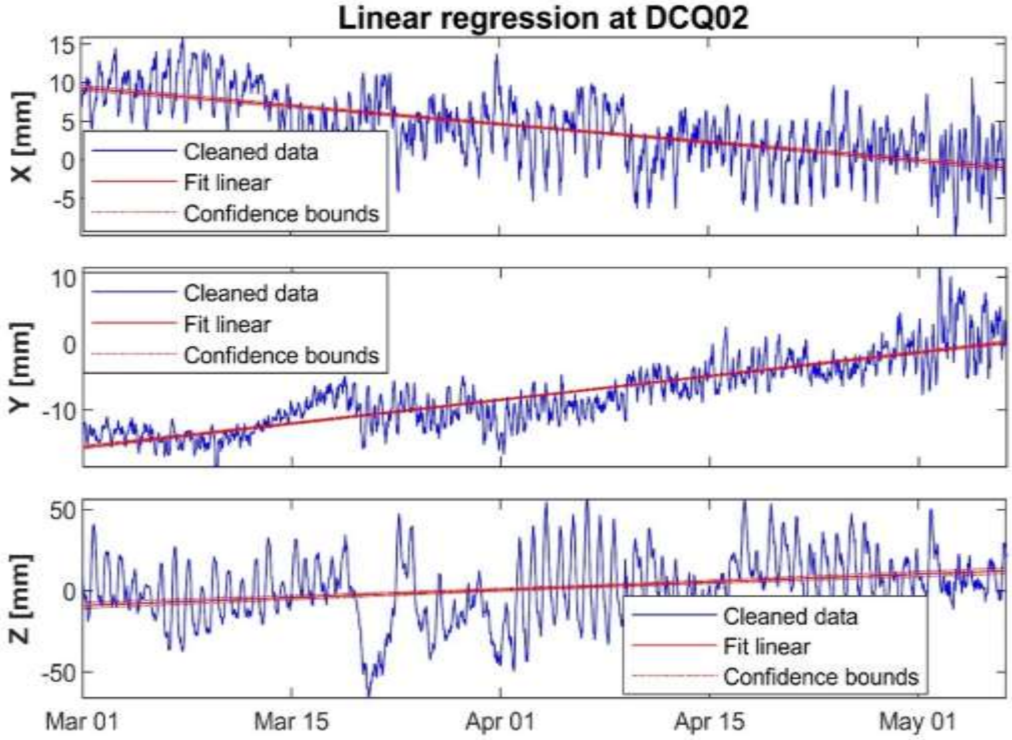


Figure 8. Linear regression of DCQ02.

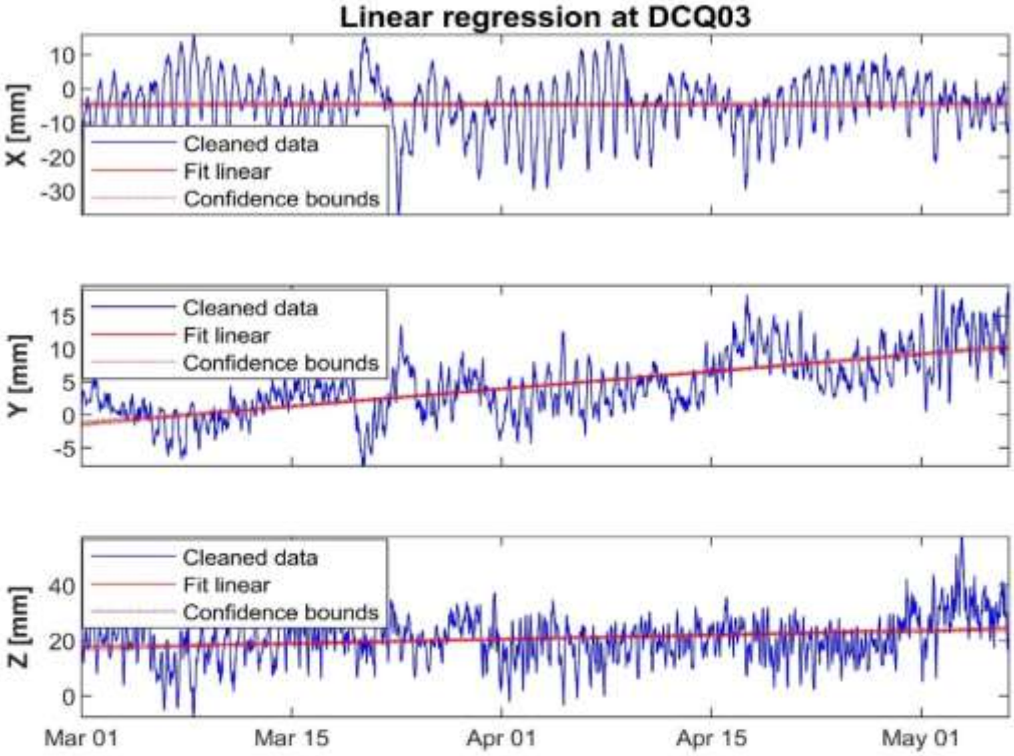


Figure 9. Linear regression of DCQ03.

3.3. Non-linear model

Separating characteristics, Q test white noise, and Q test flicker are in Figures 10 and 11.

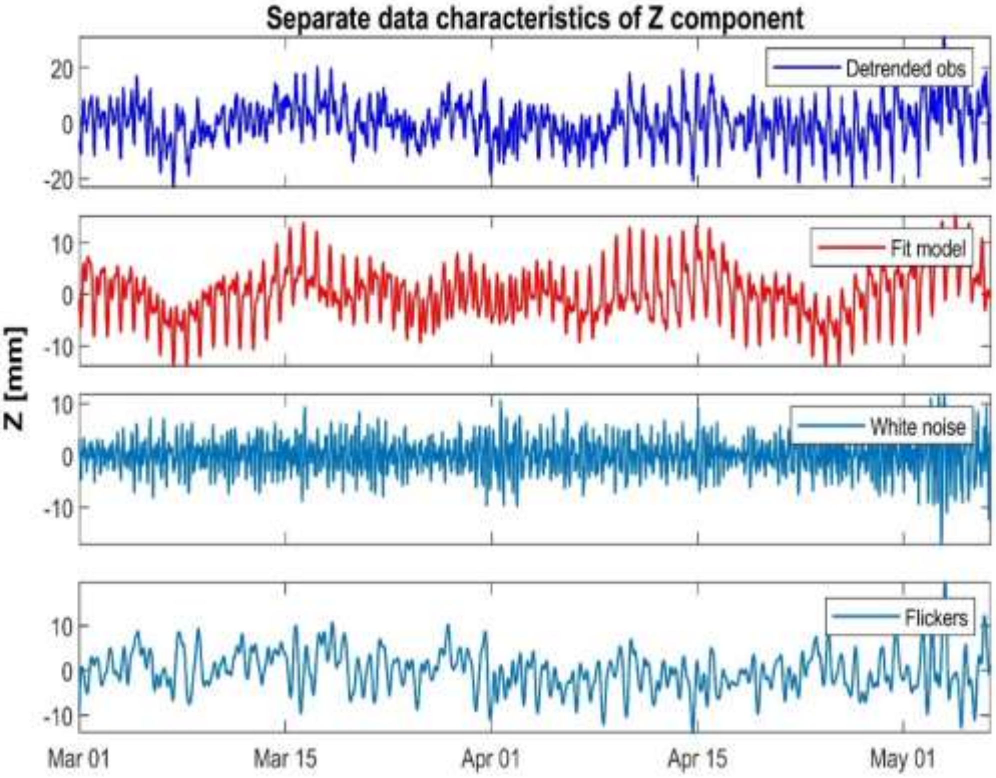


Figure 10. Separate characteristics for Z component at DCQ01.

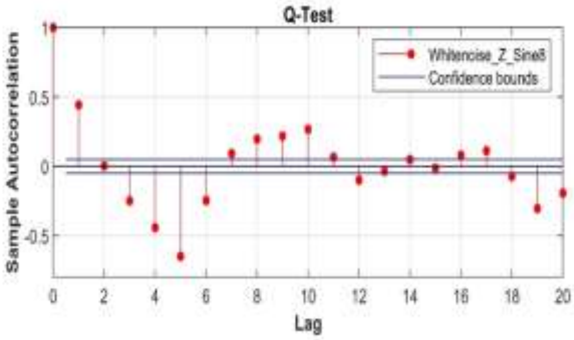


Figure 11. Q test white noise.

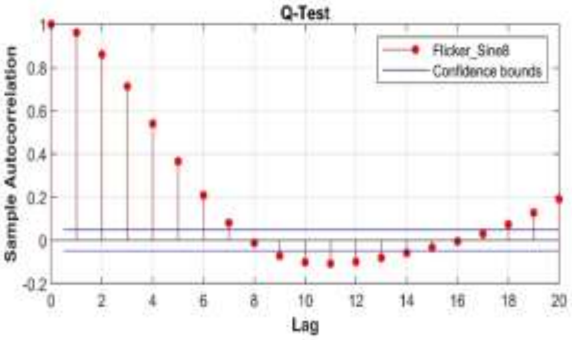


Figure 12. Q test flicker.

The oscillation of the bridge with sin 6 and sin 8 functions are in Figures 13, 14

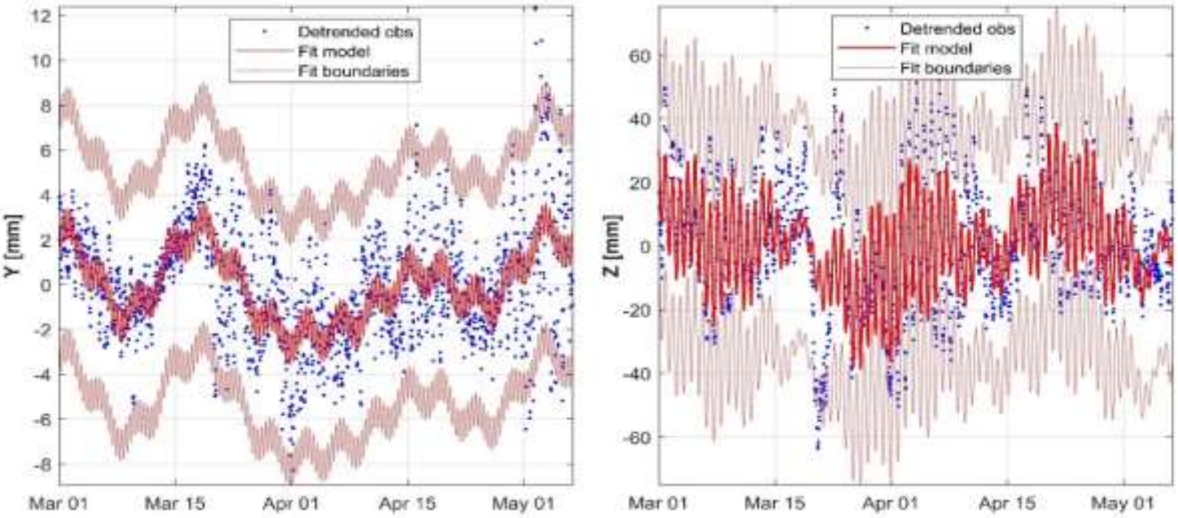


Figure 13. Fit model Sin 6 for Y and Z components (DCQ02).

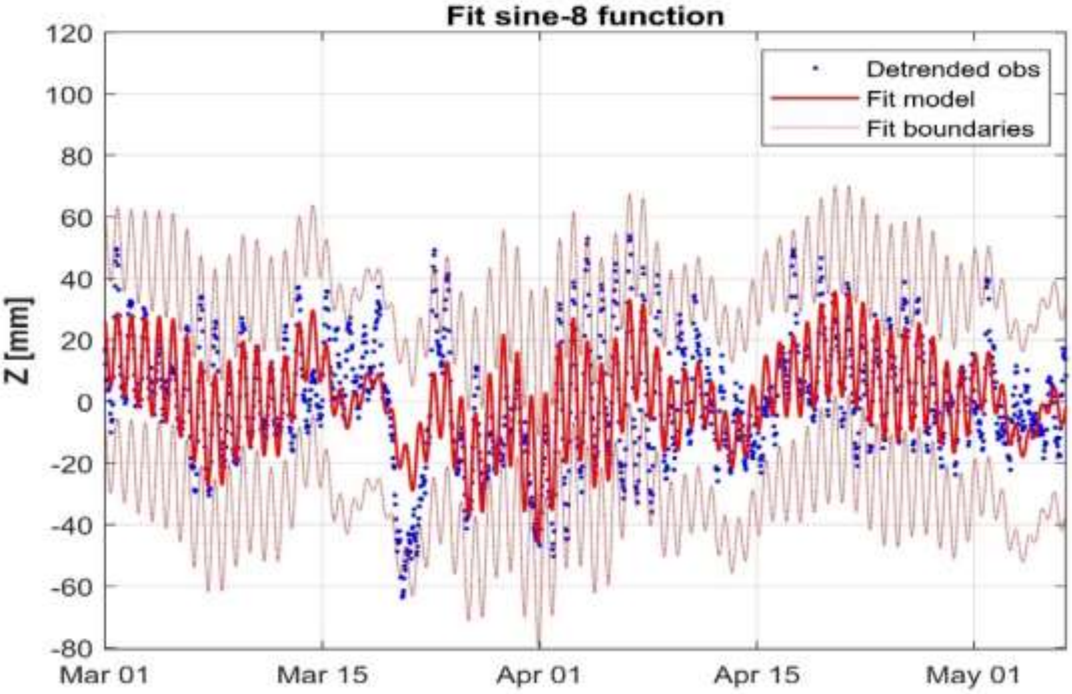
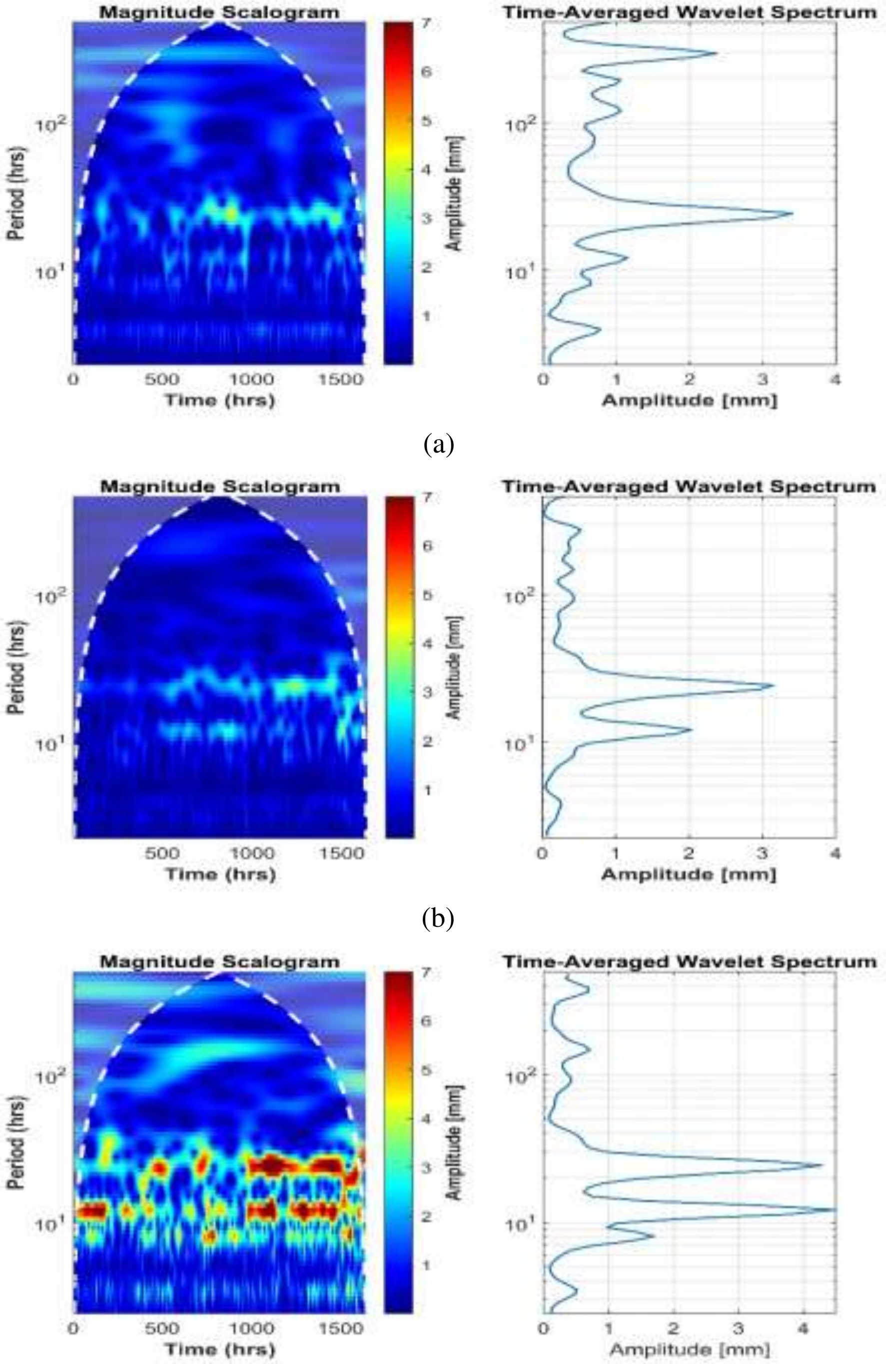


Figure 14. Fit model Sin 8 for Z component (DCQ02).

In this part, white noise and flicker noise in Fig.10 show a range of variation between -10mm and +10mm except in the last segment. This variation also is equivalent to the specifications of the monitoring devices. For the variation model, there is a similarity between the sin 6 and sin 8 functions.

3.4. Spectrum analysis

Spectrum analysis of GNSS time-series data is in the below figures

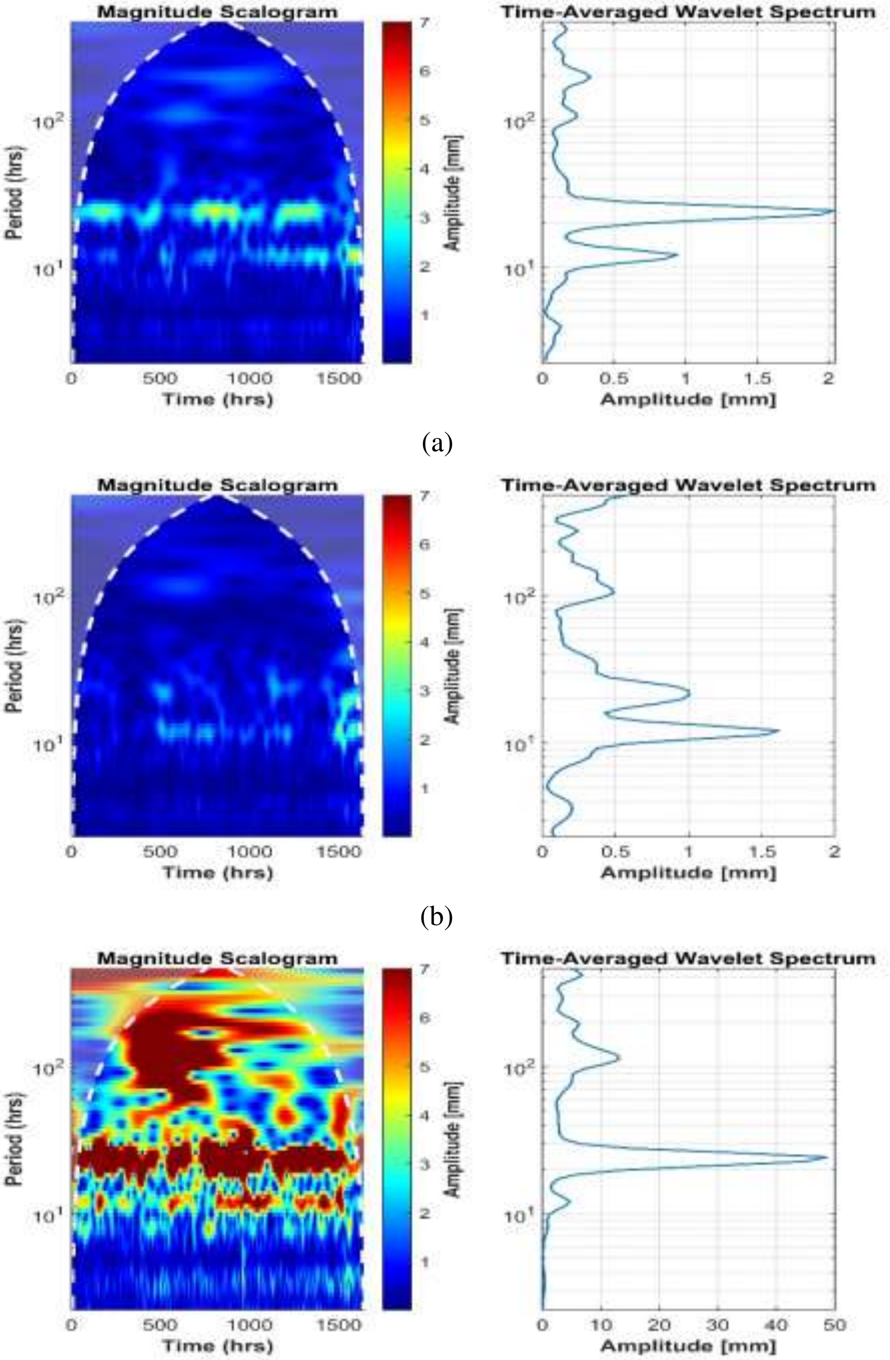


(a)

(b)

(c)

Figure 15. Spectrum analysis of point DCQ01: (a) X direction, (b) Y direction, (c) Z direction.

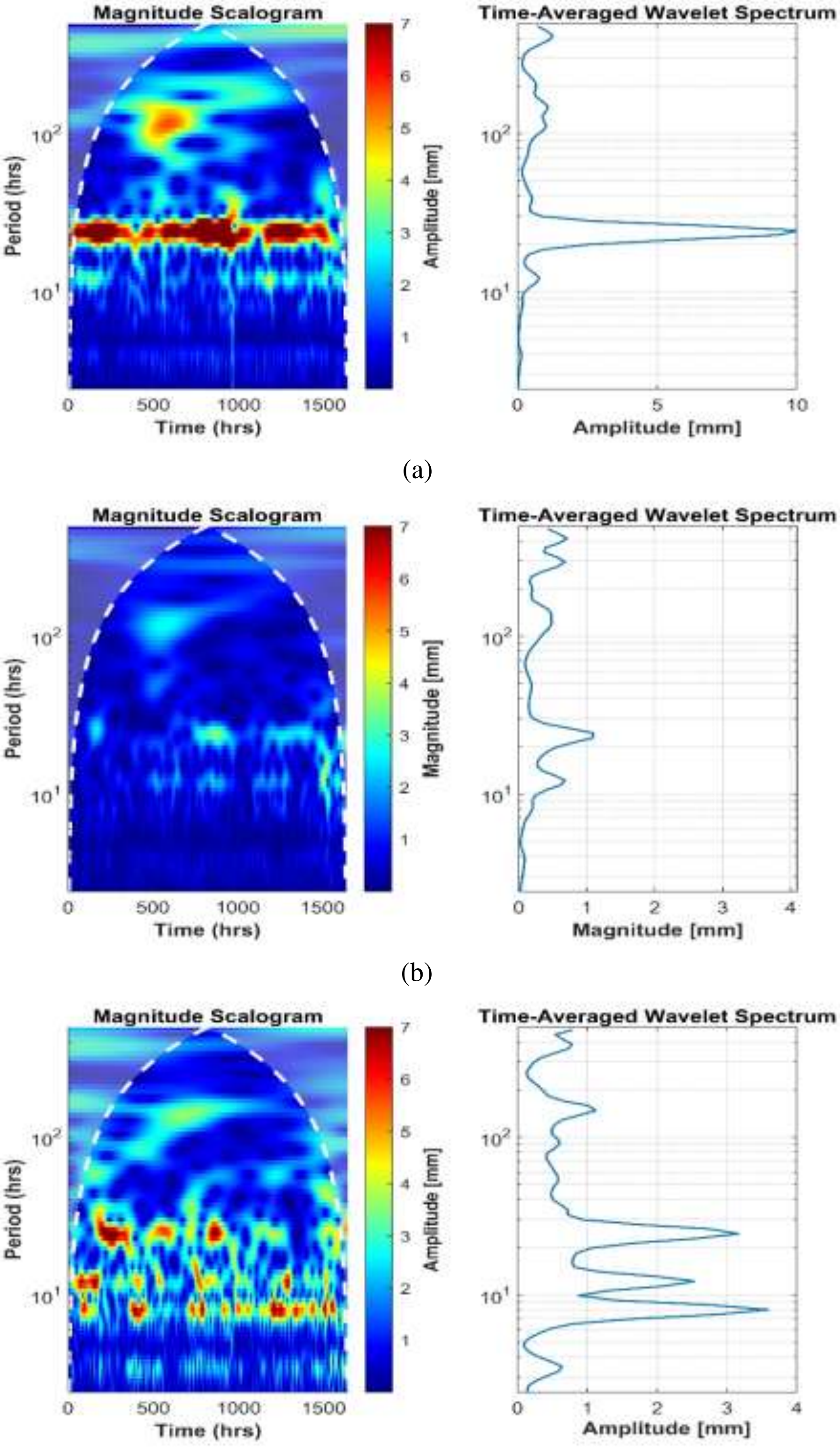


(a)

(b)

(c)

Figure 16. Spectrum analysis of point DCQ02: (a) X direction, (b) Y direction, (c) Z direction.



(a)

(b)

(c)

Figure 17. Spectrum analysis of point DCQ03: (a) X direction, (b) Y direction, (c) Z direction.

In Figures 16, 17, and 18, there is a similarity between the spectrum analysis of points DCQ01, DCQ02, and DCQ03 when the Z direction has the highest change. The most surprising display belongs to point DCQ02 when the amplitude is up to 50mm sometimes. This may be due to the influence of the vehicle when moving along the bridge and lead to some interruption of satellite tracking.

4. Discussions

The paper uses GNSS time series data with 1646 observations from three monitoring points on a bridge to identify bridge displacement using a procedure of filtering outliers, linear regression, and modelling variation of the bridge. Based on this procedure, the linear displacement of the bridge was calculated based on clean data after filtering outliers and the oscillation of the bridge was modelled.

The results of filtering outliers using the moving median algorithm show similar results to previous research when outliers in the Z time series data are much higher than that in X and Y time series data. These results are suitable with the reality of the GNSS technique for determining the Z component because of the affection of meteorological conditions in general and the variation of the bridge. This is also suitable with the specifications of the monitoring device in particular and the GNSS device in general. However, with a one-hour sampling rate, modal frequencies and cycles cannot be extracted accurately. To do that, a higher sampling rate should be applied to analyze.

5. Conclusions

The research proposed a procedure to analyze and identify displacement characteristics of the bridge using time-series GNSS data and quickly determine linear displacement with linear regression function, but a low rate of sample interval is one of the disadvantages of the research along with a limitation of bridge types (stayed cable bridge only).

The results study are a significant implementation in analyzing and identifying the bridge's displacement characteristics.

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