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Deformation Monitoring and Analysis of Super High-rise Building Based on GB-RAR

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ABSTRACT

Due to the characteristics of the height of the super high-rise building, the building body will produce yaw movement under the influence of sunlight, wind load, and other factors. When the deformation of a building exceeds a certain specification limit, the building structure will be destroyed. Therefore, monitoring and analyzing the deformation of buildings to master the deformation law, which is an important guarantee for building safety. Ground-based real aperture radar (GB-RAR) technique integrates SFCW and interferometry techniques, which can realize continuous deformation monitoring for monitoring targets. In this study, a GB-RAR was used to monitor the continuous deformation of a super high-rise building under construction in Wuhan, China. To investigate the deformation law of the building, we first extracted the deformation time series of the building during the monitoring period based on the time series InSAR technique. Furthermore, based on the wavelet analysis and time series analysis method, the accurate dynamic characteristics information of the building were extracted. Additionally, to further analyze the deformation change process of the building, four feature points in different heights were selected for deformation time series analysis. The results show that the deformation of the building body presented obvious nonlinear changes. The maximum deformation amplitude at the top of the building were 4.96 mm during the monitoring period, and the accuracy reached submillimeter level. Meanwhile, the natural frequency of the building was detected as 0.20 Hz. The GB-RAR technique can realize high accuracy continuous dynamic deformation monitoring and analysis of super high-rise buildings.

I. INTRODUCTION

Deformation monitoring and analysis of constructions (such as, high-rise buildings, dams, towers and bridges) are important in evaluating safety at an early stage and adopting the effective protection measures (Pieraccini et al., 2013; Atzeni et al., 2015). Mastering the deformation law of the buildings helps provide guidance in the construction and operation of the buildings (Chan et al., 2006; Marchisio et al., 2014).

In recent years, with the development of social economy and science and technology, the construction of super high-rise buildings in China has been developing continuously (Wang et al., 2017). By the end of 2017, China occupies 14 of the top 20 super-rise buildings in the world, all of which exceed 420 m. Deformation of the super high-rise buildings will occur under the influence of wind load, vibration, temperature and other factors, and when the deformation exceeds a certain threshold, it will destroy the structure of the super high-rise building (Li and Yi, 2016). Therefore, monitoring the deformation of super high-rise buildings and mastering the deformation law of the buildings have important scientific and practical significance for the construction and operation of super high-rise buildings.

For monitoring and analyzing super high-rise buildings deformation, traditional deformation monitoring methods, such as levelling, Global Navigation Satellite System (GNSS), total station, etc., are to collect deformation information from a single point with small monitoring range and low operation efficiency (Wang and Xu, 2017; Chen et al., 2018). As a result, effective monitoring and analysis of the overall deformation are difficult. Recently, the GB-RAR technique has been proposed and applied to deformation monitoring field. Luzi et al. (2012) used GB-RAR to monitor the health state of the Collserola

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tower of Barcelona, and the results showed that deformation ranging from µm up to several cm can be derived by GB-RAR with good monitoring conditions. Stabile et al. (2013) monitored the dynamic character of the Musmeci Bridge in Basilicata, Italy by using GB-RAR technique. The results were validated with data from accelerometers, and the results of both techniques showed high consistency. Huang et al. (2012) monitored the dynamic deflection of the Wuhan Yangluo Yangtze River Bridge through GB-RAR, the results showed that the GB-RAR can truly reflect the dynamic deformation characteristic of the structure. Diao et al. (2009) studied the ground-based aperture radar interferometer and used it to monitor the dynamic deformation of the main building of the new CCTV station in Beijing. Zhou et al. (2018) utilized the GB-RAR technique to monitor and analyze the subsidence of the ELH Bridge (Wuhan-Guangzhou high-speed railway bridge) during the crossing of the subway shield tunnel underneath the bridge, and the accurate deformation information of the bridge was retrieved through the joint application of ground-based interferometric radar and maximum likelihood estimation (MLE) in consideration of the effects of white and colored noises. However, at present few previous studies have investigated the deformation characteristics of super high-rise buildings based on GB-RAR technique.

In this study, a GB-RAR was used to monitor the continuous deformation of a super high-rise building (636 m design height) under construction in Wuhan, China. Meanwhile, the dynamic characteristics information of the super high-rise building, such as horizontal deformation, oscillation amplitude and significant frequenc, was achieved based on the wavelet analysis, time series analysis methods and Fast Fourier Transform Algorithm (FFT).

II. METHODOLOGY

A ground-based radar image contains amplitude and phase information, and the geometric distance between the radar and target is reflected in the phase information of the ground-based radar image. Therefore, the displacement between the radar and target can be computed with the interferometric technique by using the phase changes in ground-based radar images collected at different times (Pieraccini et al., 2013; Monserrat et al., 2014).

A. *The SFCW technique*

SFCW is a radar pulse signal with a stepwise change in frequency. The SFCW radar sensor generates N consecutive frequency sequences according to the step frequency Δf to form the SFCW radar signal (Pieraccini et al., 2004; Pieraccini et al., 2008). The time-frequency domain variation of the SFCW radar signal is shown in Figure 1. For pulse radar, the high resolution of the range direction is achieved by transmitting a narrow pulse width pulse signal. The range resolution ΔR can be expressed as follows (Carmelo and Giulia, 2010; Rödelsperger et al., 2010):

$$\Delta R = \frac{c}{2B} \tag{1}$$

As shown in Figure 1, $B = (N-1)\Delta f$ is the bandwidth of radar signal. According to equation (1), the resolution in the range direction is inversely proportional to the bandwidth. Therefore, the range resolution can be improved by increasing the bandwidth of the SFCW radar signal.

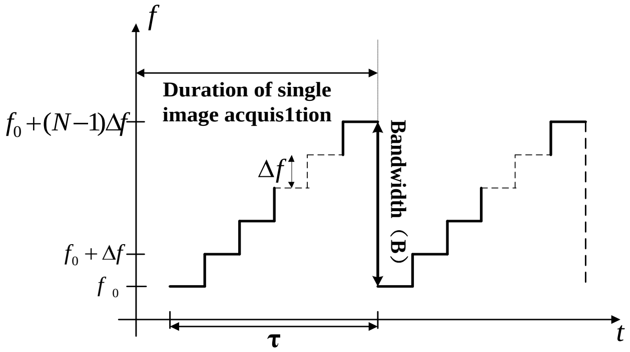

Figure 1. SFCW time-frequency domain change

B. *The interferometry technique*

The GB-RAR is a zero-baseline observation, so there is no influence of the flat terrain effect and the terrain effect in the interferometric phase of the monitored target at different times (Pieraccini et al., 2009; Luzi et al., 2012). The differential interferometric phase model by comparing the phase difference of the target point obtained at different times is expressed as follows (Takahashi et al., 2013; Iglesias et al., 2014):

$$\varphi_{diff} = \frac{4\pi d_{defo}}{\lambda} + \varphi_{atm} + \varphi_{noise} \tag{2}$$

Where φ_{diff} is the interferometric phase, d_{defo} is the deformation between the radar and target, φ_{atm} and φ_{noise} are the atmospheric disturbance phase and random noise phase, respectively. After removing the atmospheric disturbance phase and random noise phase, the interferometric phase is unwrapped in one-dimension, and then the deformation can be achieved based on equation (2). According to the time span of monitoring, the deformation time series of the monitored target can be obtained.

C. *Ground-based real aperture radar*

The ground-based real aperture radar used in this study is the IBIS-S (Image by Interferometric System-Structures) system developed by Italy IDS company, which is mainly composed of a tripod, an energy supply unit, a computer control unit, and a radar control unit, as shown in Figure 2.

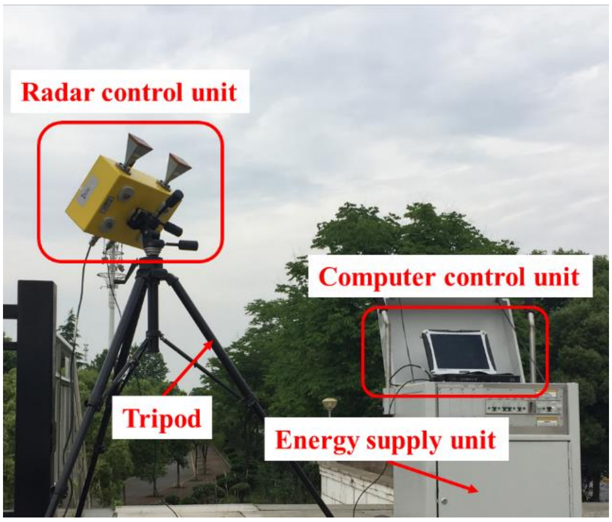

Figure 2. View of the IBIS-S system

The radar control unit is mounted on a tripod equipped with a 3-D rotating head to ensure that the radar monitoring direction can be arbitrarily adjusted, and the radar unit is equipped with two horn antennas for transmitting and receiving electromagnetic signals. The computer control unit is connected to the radar control unit via a standard USB interface, which is used to configure parameters, store data and display deformation information of monitored objects in real time. The energy supply unit is mainly responsible for providing power supply for system operation.

The ground-based real aperture radar simultaneously acquires deformation information of numerous monitored points placed at different distances in the radar monitored direction by combining the SFCW technique and the interferometry technique. The SFCW technique is employed to detect the positions of different monitored points, and the interferometry technique is used to compute the deformation of each monitored point by comparing the phase information acquired at different times.

III. EXPERIMENT AND RESULT ANALYSIS

A. *Data acquisition*

In this study, we adopted the IBIS-S system to collect deformation monitoring data. The monitored object is a super high-rise building (636 m design height) under construction. The super high-rise building is located in Wuhan, China. At the time of monitoring, the building was constructed to approximately 440 m. The IBIS-S system was rigidly fixed on a stable place in the northwest direction of the building, and the distance between the building and the IBIS-S system was approximately 300 m. During deformation monitoring period, we used the continuous dynamic measurement mode to collect data. Data acquisition adopted high-frequency data acquisition mode and the sampling frequency was 20 Hz. The main configuration parameters of the measurement campaign are listed in Table 1.

Table 1. Configuration of the IBIS-S system for the data acquisition

Parameter	Value
Maximum range	800 m
Resolution in range	0.5 m
Sampling frequency	20 Hz
Antenna type	Type3 (Azimuth 17° , Vertical 15°)
Total monitoring time	2h 36mins

Figure 3 illustrates the ground view of the monitored super high-rise building from the installation location of the IBIS-S system. P1, P2, P3 and P4 shown in Figure 3 represent the feature points of the building in different heights that were selected for deformation time series analysis.

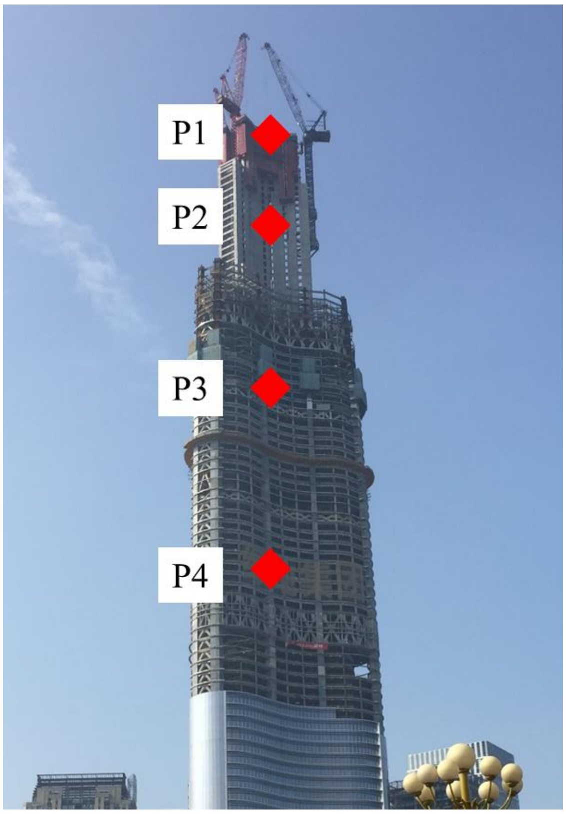

Figure 3. Ground view of the super high-rise building from the location of the IBIS-S radar, and the red diamond indicates the feature point to be analysed in this study.

B. *Deformation results and analysis*

In this study, we first processed the radar monitoring data of the super high-rise building acquired by the IBIS-S system based on the time series InSAR technique. Since the monitored building was under construction during the deformation monitoring, the building were simultaneously affected by vibration produced by the construction, wind load and other influence factors. Due to the above-mentioned reasons, the time series

InSAR-derived deformation time series was seriously affected by multi-aspect noises and contained some useless information. To achieved the accurate deformation time series and dynamic characteristics (e.g., horizontal deformation, oscillation amplitude, and significant frequency) of the building, we adopted the wavelet analysis to filter the deformation time series. Finally, in order to analyze the deformation of the super high-rise building during the monitoring period, four feature points (i.e., P1, P2, P3 and P4) were selected to discuss and analyze, and the deformation time series analysis of the feature points was carried out, the results are shown in Figures 4-7 and Table 2.

Figure 4 shows the deformation time series in the line of sight direction at the top of the building (i.e., P1), where the negative values indicate that the monitoring target point is close to the radar and the positive values indicate that the monitoring target point is moving away from the radar. It can be seen from the Figure 4 that the maximum negative deformation of the roof in the monitoring direction is 1.74 mm, and the maximum positive deformation is 3.22 mm. Therefore, the maximum deformation amplitude of the roof in the monitoring direction is 4.96 mm during the monitoring period, as shown in Table 2. In addition, the deformation monitoring accuracy of the radar at the top of the super high-rise building is 0.23 mm.

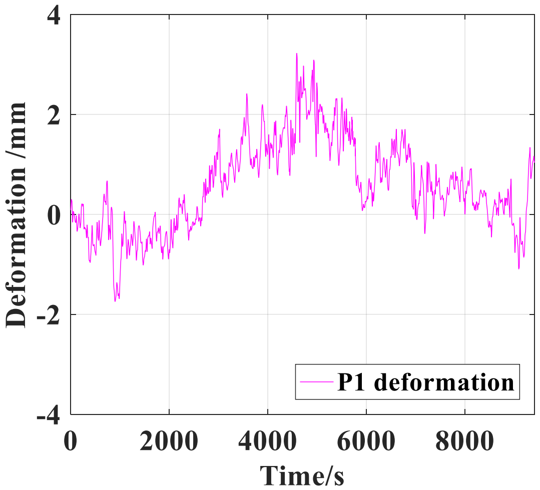

Figure 4. IBIS-S-derived deformation time series of P1

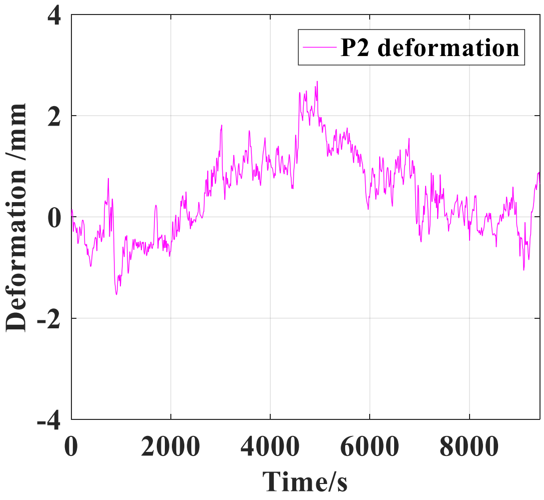

Figure 5. IBIS-S-derived deformation time series of P2

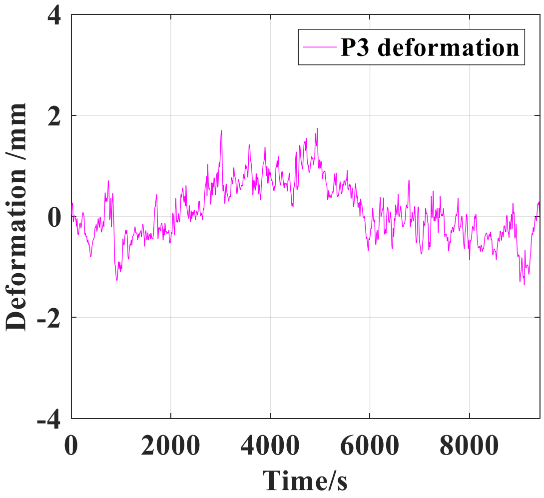

Figure 6. IBIS-S-derived deformation time series of P3

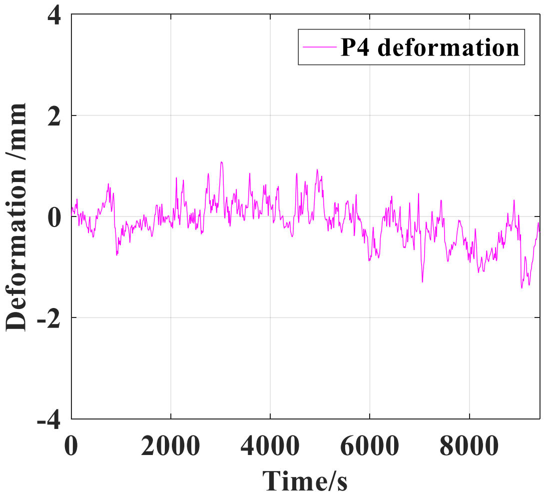

Figure 7. IBIS-S-derived deformation time series of P4

Figure 5 shows the deformation curves of P2. As shown in Figure 5, the maximum negative and positive deformation are 2.68 mm and 1.54 mm, respectively. Additionally, deformation monitoring accuracy at P2 is

0.21 mm. As listed in Table 2, the maximum deformation amplitude of the P2 is 4.22 mm. Compared to the roof (i.e., P1) of the super high-rise building, the amplitude at the P1 is 0.74 mm larger than that at P2.

Table 2. Analysis results of feature points deformation time series

Feature points	Max (mm)	Min (mm)	Amplitude(mm)
P1	3.22	-1.74	4.96
P2	2.68	-1.54	4.22
P3	1.75	-1.36	3.11
P4	1.08	-1.42	2.50

As shown in Figure 6 and Figure 7, the P3 and P4 show nonlinear deformation. The deformation of P3 is larger than that of P4, and the deformation fluctuation of P3 is more serious than that of P4. The deformation changes at P3 and P4 are basically within 2 mm. As shown in Table 2, the maximum amplitudes of P3 and P4 are 3.11 mm and 2.50 mm, respectively. In addition, the deformation monitoring accuracy of P3 and P4 are 0.19 mm and 0.18 mm, respectively.

Comparing the deformation curves at P1, P2, P3 and P4, it can be found that the deformation curves of the four feature points show a relatively high similarity. Among the four feature points, the deformation fluctuation of P1 is the most serious. Furthermore, the monitoring accuracy of P4 is the highest than other feature points.

To detect the significant frequency of the super high-rise building, we adopted FFT to identify the frequency. Based on the IBIS-S-derived deformation time series of P1, P2, P3, and P4, the natural frequency of the building was detected as 0.20 Hz.

Based on the above-mentioned analysis, the GB-RAR can realize the high-precision uninterrupted deformation monitoring and analysis of super high-rise building, and the deformation monitoring accuracy of the GB-RAR can reach sub-millimeter level. However, the deformation monitoring accuracy of the GB-RAR gradually decreased with increasing monitoring distance.

IV. CONCLUSION

In this study, the basic principles of the GB-RAR technique were studied. The GB-RAR technique integrates SFCW technique, interferometry technique and other key radar techniques, which can extract the micro-deformation information of the monitored targets that changes with time. The IBIS-S system was used to monitor the continuous deformation of a super high-rise building under construction located in Wuhan, China. The deformation time series of the super high-rise building was derived by time series InSAR technique. To investigate the deformation law of the building, the accurate dynamic characteristics information was derived by the joint application of the wavelet analysis, time series analysis method, and FFT based on the IBIS-S-derived deformation time series of the feature points on the building body. The main conclusions are as follows:

(1) The deformation of the building body presented obvious nonlinear changes, and the deformation curves at different heights of the super high-rise building show a relatively high similarity during the monitoring period.

(2) The maximum deformation amplitude at the top of the building were 4.96 mm during the monitoring period. Additionally, the natural frequency of the building was detected as 0.20 Hz. The deformation monitoring accuracy of P1, P2, P3 and P4 were 0.23 mm, 0.21 mm, 0.19 mm, and 0.18 mm, respectively, suggesting that the accuracy of GB-RAR is high. However, the monitoring accuracy gradually decreased with increasing monitoring distance.

In summary, The GB-RAR technique can realize high accuracy continuous dynamic deformation monitoring and analysis of super high-rise buildings.

V. ACKNOWLEDGEMENTS

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