Real-Time Bridge Dynamic Deflection Monitoring Using 5G-Integrated Sensing and Communication

Xianglei Liu [1], Tianyuge Yuan [1], Runjie Wang [1], Siyao Cai [1], Ming Huang [1], Liang Huo [1], Aychuah Nurbaht [1], Ruihan Liu [1]

[1] Key Laboratory for Urban Geomatics of National Administration of Surveying Mapping and Geoinformation, Engineering Research Centre of Representative Building and Architectural Database, Ministry of Education Beijing University of Civil Engineering and Architecture, Beijing 100044, China

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Abstract

This study investigates the potential of 5G-integrated sensing and communication (5G-ISC) for real-time monitoring of bridge dynamic deflection. This method is non-contact, high-precision, high-frequency, continuous, and real-time, and operates on principles similar to ground-based synthetic aperture radar (GBSAR), using differential interferometry to measure dynamic deflection. While 5G-ISC overcomes the limitations of traditional monitoring techniques, such as their inability to function in all weather conditions and their lack of continuous operation, it faces challenges due to interference from its vibrations, which can compromise measurement accuracy. To address this issue, the second-order blind identification (SOBI) algorithm was applied to filter out noise, significantly improving the precision of 5G-ISC measurements. Experimental results demonstrate that 5G-ISC and GBSAR achieve sub-millimeter accuracy in monitoring bridge deflection, meeting the required precision for bridge engineering. These findings suggest that with appropriate signal processing, 5G-ISC can be a reliable and effective method for monitoring dynamic bridge deflection.

1. Introduction

Bridges are vital components of transportation networks, but their bearing capacity gradually deteriorates due to aging, environmental factors, overload, and geological activity. In severe cases, this deterioration can lead to sudden collapse, resulting in significant loss of life and property. Therefore, effective damage detection is crucial. Recently, 5G Integrated Sensing and Communication (5G-ISC) has been employed to monitor bridge dynamic deflection due to its non-contact, high-precision, all-weather, and continuous measurement capabilities. 5G-ISC utilizes electromagnetic wave active detection and imaging, applying differential interferometry technology to measure small deformations of the target (Long, 2012). In this method, radar equipment transmits electromagnetic waves to the target twice, receives the reflected waves, and calculates the small displacement of the target in the line-of-sight direction based on the phase difference between the transmitted and reflected waves. However, the accuracy of 5G-ISC measurements can be compromised by vibrations from the system itself, which interfere with data analysis and reduce the reliability of damage detection. These vibrations are caused by factors such as wind and environmental conditions, which induce shaking of the radar equipment mounted on a tower. The shaking is characterized by randomness, irregularity, and high frequency and can overlap in both time and frequency with the micro-deformation signals of the monitored structure, leading to measurement errors. Correcting these vibration-induced errors is, therefore, critical when using 5G-ISC for bridge deflection monitoring (Catherwood et al., 2019; Salehin, 2022; Poole and Arbabian, 2024).

The vibration of 5G-ISC radar is often high-frequency and irregular, requiring the compensation algorithm to possess high real-time responsiveness and fast processing capabilities. Research on compensation for 5G-ISC radar vibration is limited in the literature, though its monitoring principles are similar to those of progressive radar interferometry. A common method is the use of auxiliary sensors for measurement and compensation. This approach employs inertial measurement units, such as accelerometers and gyroscopes, to capture the vibration information of the tower where the 5G-ISC radar is mounted in real-time. By processing this vibration data alongside radar measurement signals, a compensation algorithm can be applied to correct the measurement deviations caused by vibration (Mohanram et al., 2022; Wang et al., 2022). The advantage of this method lies in its ability to compensate for vibration effects accurately, regardless of amplitude or frequency. However, the accuracy of the sensors can be affected by environmental interference, leading to increased measurement errors. Furthermore, the addition of such contact sensors increases system complexity and maintenance costs, which may limit its practical application, particularly for real-time bridge dynamic deflection monitoring based on 5G-ISC base stations.

Current signal denoising methods include filtering (Makwana and Gupta, 2015), wavelet transform (Liu et al., 2018), singular value decomposition (SVD) (Zeng and Chen, 2020), and empirical mode decomposition (EMD) (Han et al., 2017). However, these methods not only remove noise but also attenuate the high-frequency components of non-stationary signals. Furthermore, they often require prior knowledge of the statistical characteristics of the signal and noise, which limits their effectiveness for non-stationary signals that contain sharp edges and short-duration pulses (Guo et al., 2017). As a result, without prior information about the dynamic time series displacement, these methods are unsuitable for denoising non-stationary bridge dynamic deflection data obtained using 5G-ISC. The blind source separation (BSS) technique allows for the separation of multiple source signals acquired simultaneously by different sensors, without any prior information, even when the signal mixing model is unknown (Taha and Abdel-Raheem, 2022). The second-order blind identification (SOBI) method is a robust BSS technique that utilizes second-order statistics of the sample data, such as the correlation matrix with different time delays, and the temporal structure of the source signal to achieve blind separation (Pan et al., 2022). In this study, we applied 5G-ISC technology to monitor bridge dynamic deflection, where multiple adjacent monitoring points in the same time domain have common noise information in the bridge dynamic phase signal. Generally, the bridge dynamic phase signal obtained using 5G-ISC is a complex non-stationary time series in which useful signals and noise are mixed. Therefore, the bridge dynamic phase data from three adjacent monitoring points can be regarded as a linear mixture of source signals (useful signals and noise). To mitigate the impact of vibration-induced noise, we applied the SOBI signal denoising method to reduce radar vibration noise in the 5G-ISC measurements of bridge dynamic deflection.

2. Methodology

2.1 5G-ISC Dynamic Deflection Measurement

In the context of bridge monitoring by a 5G base station, the measurements are primarily conducted from a downward or level perspective relative to the target bridge. The geometric relationship between the base station and the bridge is illustrated in Figure 1.

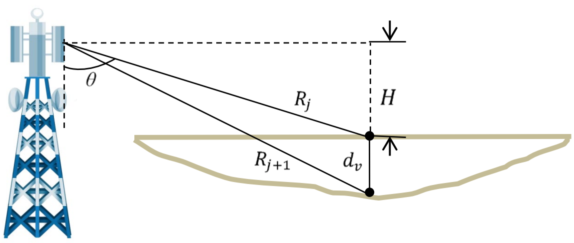

Figure 1. 5G-ISC measuring bridge dynamic deflection

(1) The dynamic deformation of the bridge is determined using the radial distance between the base station and the target point, the vertical height, and shape variables obtained through monitoring by the base station. The relationship governing these calculations is given by:

$$R_j^2 - H^2 = R_{j+1}^2 - (H + d_v)^2 \tag{1}$$

$$d_v = \left(\sqrt{H^2 + R_{j+1}^2 - R_j^2}\right) - H \tag{2}$$

Where R_j is the radial distance between the base station and the target point before deformation, R_{j+1} is the radial distance between the radar and the target point after deformation, h is the vertical height between the base station and the target point, and d_v is the deformation amount monitored by the base station.

(2) Alternatively, bridge dynamic deformation can be estimated based on the radial distance between target points, the phase variation measured by the 5G-base station, and the angle between the electromagnetic wave propagation direction and the vertical axis. This is expressed as:

$$d_v = R_{j+1} - R_j = \frac{\Delta\varphi \cdot \lambda}{2\pi \cdot \cos\theta} \tag{3}$$

Where, $\Delta\varphi$ is the phase difference between the base station monitoring time j and time $j + 1$, and θ is the angle between the electromagnetic wave propagation direction and the vertical direction.

2.2 The SOBI method

The SOBI method is a robust blind source separation (BSS) technique originally proposed by Adel Belouchrani et al. (1997). This method employs the joint approximate diagonalization of covariance matrices to estimate and recover source signals and mixing matrices from acquired mixed signals. It effectively separates source signals from noise without requiring a priori information. SOBI is based on the construction of a time-delay intercorrelation matrix and utilizes the second-order statistics of bridge dynamic deflection signal data to estimate the source signal components. This allows the method to separate multiple noisy source signals even when only a limited number of data points are available.

One of the most significant advantages of SOBI in the demising rotation stage is its ability to simultaneously diagonalize the correlation matrix using multiple non-zero-time delays. This approach mitigates the risk of unsatisfactory algorithmic results due to an inappropriate selection of individual time delays and avoids spectral aliasing. Consequently, SOBI is well-suited for extracting intrinsic mode functions (IMFs) dominated by useful information while effectively suppressing residual noise, making it particularly applicable to this study (Brewick and Smyth, 2017).

The blind source separation model is $x(t) = A * s(t)$, at this time, it is necessary to find the unknown mixing matrix A. Therefore, a separation matrix W is needed to transform the formula into $y(t) = W * x(t)$. That is, firstly, do the whitening of the mixed signal, calculate the sampling covariance array of the whitened data, and then seek the orthogonal gauge for a while by joint diagonalization of the sampling covariance array, and finally, seek the mixing matrix A and estimate the source signal $y(t)$. In summary, the algorithm flow for separating the source signal from the noise signal by the SOBI algorithm is as follows:

(1) Whitening the Mixed Signal and Computing the Whitening Matrix W:

The observed mixed signal $x(t)$is whitened so that the covariance matrix of y(t)y(t)y(t) becomes a unit matrix, thereby eliminating second-order correlations between components. The whitening matrix W, which is of dimension $m * n$ is then applied:

$$y(t) = W * x(t) \tag{4}$$

(2) Computing the Sample Covariance Matrix $R(\tau_j)$:

For a fixed time delay $\tau \in \{\tau_j | j = 1,2, .. k\}$, the sample covariance matrix of the whitened data is computed as:

$$R(\tau) = E[y(t)Y^T(t + \tau)] = AR_Y(\tau)A^T \tag{5}$$

(3) Computing the Orthogonal Normalized Matrix V:

The orthogonal normalized matrix V is determined by solving all $R(\tau_j)$ through a joint approximate diagonalization algorithm. The resulting diagonal matrices $\{D_j\}$ satisfy:

$$V^T R\{\tau_j\}\mathrm{V}{=}\mathrm{D}_j \tag{6}$$

(4) Estimating the Mixing Matrix A:

Using the results from the previous steps, the estimated source signals are given by:

$$Y(t) = V^T W x(t) \tag{7}$$

The mixing matrix is then computed as:

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$$A = W^{-1}V \tag{8}$$

Where W^{-1} is the pseudo-inverse matrix of the separation matrix W.

In this study, the SOBI algorithm is employed to perform BSS on independent source signals extracted from the dynamically mixed signals of the bridge, as collected by the 5G-ISC radar. The separation of each source signal is achieved through joint approximate diagonalization of the autocovariance matrix, effectively minimizing noise by setting each signal component’s noise to zero. The source signals are then reconstructed by computing the inverse of the mixing matrix.

2.3 Accuracy Assessment

To evaluate the signal de-noising quality of the improved SOBI signal method, the root mean square error (RMSE) index was used in this study. RMSE quantifies the deviation between the observed and true values (Cai et al., 2019). The RMSE is defined as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y(i) - s(i))^2} \tag{6}$$

Where $s(n)$ represents the original observation signal; $y(n)$ represents the signal after noise reduction; and n represents the number of sampling points. Generally, the smaller the RMSE value is, the more enhanced the signal de-noising is.

3. Experiment and Results Analysis

The monitoring target in this study was the side of the bridge, where corner reflectors were strategically deployed. The 5G-ISC radar was positioned approximately 70 meters from the target. To enhance the accuracy assessment of 5G-ISC, an IBIS device was placed nearby to simultaneously monitor the same bridge position. The field deployment location is illustrated in Figure 2.

Figure 2. Schematic diagram of instrumentation

Figure 3 shows the time-series phase data from three adjacent monitoring points. While the three data sets exhibit the same overall trend, minor differences are observed in local areas, attributed to the varying distances between the monitoring points.

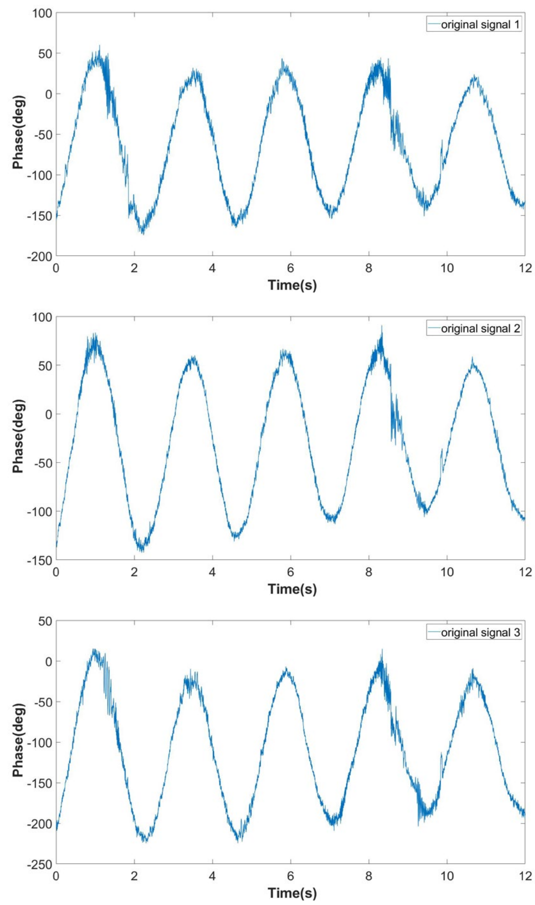
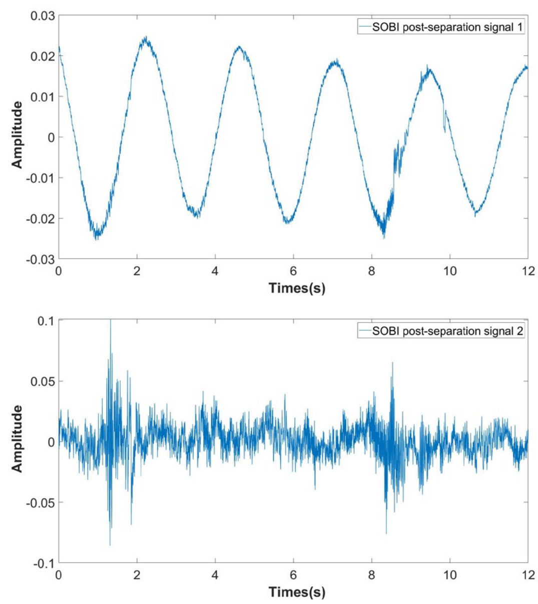


Figure 3. 5G-ISC original phase data

Figure 4 presents the results obtained after applying SOBI to separate and process the signal. The post-separated signal 1 exhibits a mirrored waveform with phase inversion relative to the original signal, indicating that it encapsulates shared vibration characteristics. Post-separated signals 2 and 3 exhibit only minor variations.



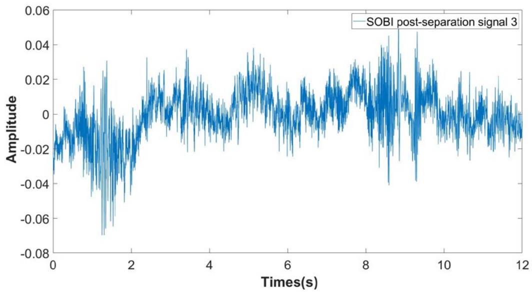


Figure 4. Results obtained by SOBI separation

Figure 5 illustrates a comparison of the results after SOBI processing. As shown, the noise caused by the 5G-ISC radar's vibration is significantly removed from the processed signal (red curve) when compared to the original signal (blue curve).

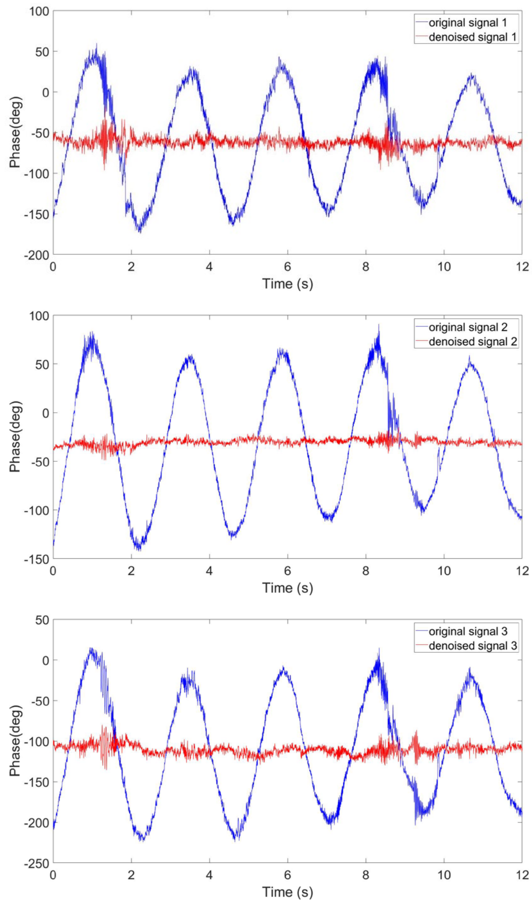


Figure 5. Comparison of results before and after SOBI of 5G-ISC vibration.

To further visualize the accuracy improvement before and after processing, the bridge's dynamic deflection data for this period is calculated, and the results before (blue curve) and after (red curve) processing are compared, as shown in Figure 6. The signal processing evaluation index, RMSE, is presented in Table 1.

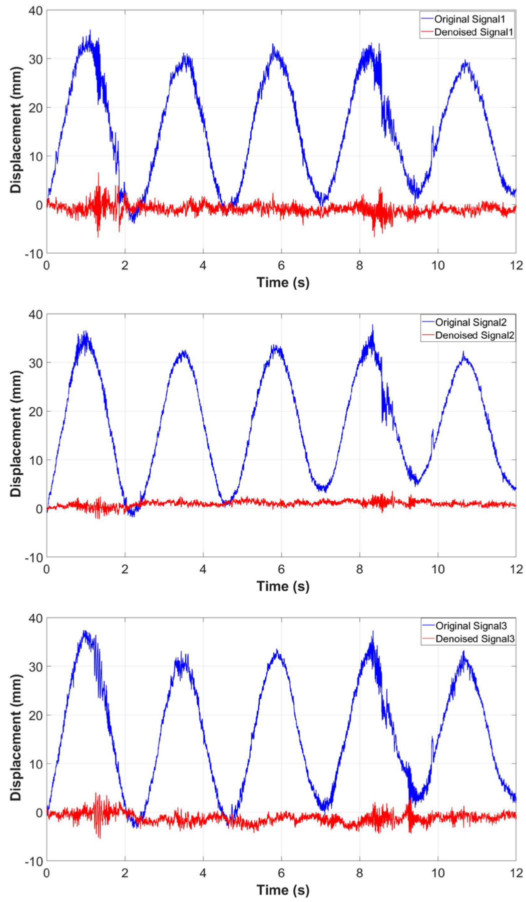


Figure 6. Comparison of 5G-ISC dynamic deflection results before and after SOBI

Index	Origin signal 1	After SOBI
RMSE	61.4744	6.2990
Index	Origin signal 2	After SOBI
RMSE	61.7732	3.5071
Index	Origin signal 3	After SOBI
RMSE	65.4748	6.0489

Table 1. Accuracy evaluation index

Table 1 presents the RMSE values of the 5G-ISC after SOBI processing. As shown, the RMSE of the processed signal is, on average, reduced by 90% compared to the original signal, demonstrating the effectiveness of the SOBI denoising method in mitigating errors caused by the radar's inherent vibration in this study. Since the true dynamic deflection values of the bridge cannot be directly obtained in this study, the mean of the pre-and post-processed signals is used as the reference value for RMSE calculation.

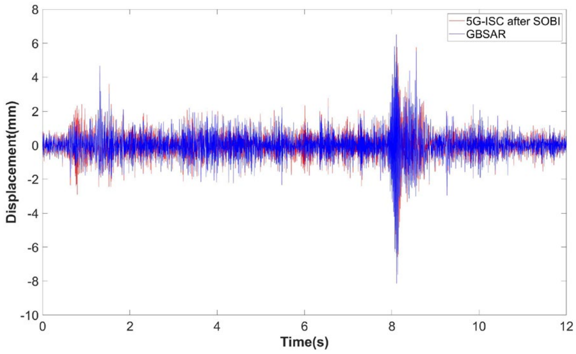


Figure 7. Comparison of GBSAR and 5G-ISC (after SOBI) joint monitoring of target dynamic deflection

As shown in Figure 7, a target point monitored jointly by GBSAR and 5G-ISC is selected. The dynamic deflection data from 5G-ISC after SOBI processing (red curve) is compared with that from GBSAR (blue curve). The comparison reveals that the significant errors caused by the radar's vibration are largely eliminated from the 5G-ISC signal after SOBI processing. When compared to the GBSAR results, the accuracy of the processed 5G-ISC measurements in monitoring bridge dynamic deflection reaches the sub-millimeter level. This confirms the effectiveness of the SOBI method in enhancing the monitoring accuracy of 5G-ISC.

4. Conclusions

This study investigates the application of 5G-ISC for real-time dynamic deflection monitoring of bridges. The 5G-ISC leveraging differential interferometry as its fundamental principle， enables high-precision, contactless, continuous, and all-weather monitoring, overcoming many limitations of traditional bridge monitoring techniques. However, self-induced vibrations caused by environmental factors, such as wind and structural movements, introduce significant noise, reducing measurement accuracy. To address this issue, this study applies the SOBI algorithm for vibration-induced noise suppression, refining the accuracy of 5G-ISC measurements. The proposed approach is validated through real-world bridge monitoring experiments, and a comparative analysis with GBSAR is conducted to assess the effectiveness of the method.

Experimental results demonstrate that 5G-ISC with SOBI processing achieves sub-millimeter accuracy, meeting the precision requirements for bridge deflection monitoring. The SOBI algorithm effectively eliminates vibration-induced noise, leading to an approximate 90% reduction in the RMSE, significantly improving measurement reliability. Furthermore, the comparison between 5G-ISC (after SOBI processing) and GBSAR measurements confirms that the processed 5G-ISC data closely aligns with GBSAR results, indicating the feasibility and reliability of 5G-ISC for real-time structural health monitoring. These findings highlight the potential of 5G-ISC as a viable and efficient alternative to traditional bridge deflection monitoring technologies.

Despite the promising results, several limitations and challenges remain. The study focuses on a single bridge under specific environmental conditions, which may limit the generalizability of the findings. Future research should extend the investigation to multiple bridge structures under varying environmental and operational conditions to further validate the effectiveness of the proposed approach.

The results suggest that 5G-ISC has great potential as a cost-effective, real-time, and scalable solution for infrastructure health monitoring, contributing to the advancement of intelligent transportation systems and smart city development. Future research should focus on further optimizing the algorithm, integrating complementary sensing technologies, and conducting long-term field tests to fully establish 5G-ISC as a standard tool for structural health monitoring in civil engineering applications.

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