Dynamic parameter identification of a super tall building based on field measurement

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Abstract. This work aims to identify the dynamic parameters (i.e., natural frequencies and damping ratios) of a super tall building under construction (i.e., Tianjin 117 Tower). Real time kinematic - global navigation satellite system (RTK-GNSS) receivers are applied to monitor the vibration of the structure. Considering the errors of receivers, a joint denoising method is proposed to weaken the influence of noise. Meanwhile, random decrement method (RDM) and fast Fourier transform (FFT) are adopted to derive the dynamic parameters of the structure. Moreover, the identified results from field measurement are compared with predicted values obtained from finite element model (FEM) of the structure. The outcomes of this study are that: (1) the proposed joint denoising method can be employed to weaken the RTK-GNSS observation errors; (2) the first natural frequency of the structure is derived successfully based on FFT analysis, and it agrees well with the finite element results; (3) the damping ratio of the structure is obtained by using RDM.

1. Introduction

The deformation information of super tall buildings is an important criterion for performance evaluation of super high-rise buildings. To ensure the safety of super high-rise buildings, deformation must be monitored. The most effective method to assess dynamic behavior of super tall buildings is usually undertaken by employing field measurement techniques.

Nowadays, accelerometers have been widely used to monitor the vibration of civil engineering structures. However, it is limited due to the trend term generated by quadratic integral cannot be eliminated. Subsequently, Global Positioning System (GPS) is developed to monitor the displacement information of large scale structures. Based on GPS measurement, Li and Wu [1] studied the displacement responses of a 79-storey tall building under the action of a typhoon. They demonstrated that GPS is a powerful tool for achieving the displacement information of super tall buildings. Kaloop et al. [2] investigated the deformation of a long-span bridge by using GPS technique. They indicated that the movement of the bridge can be determined via GPS measurement. The author of this paper has also done a lot of research on deformation monitoring of large-scale structures [3-5]. RTK is an accurate GPS technique for monitoring the dynamic deformation of structures, and it has been employed in the field of structural health monitoring [6].

In this article, RTK-GNSS receivers are used to monitor the horizontal displacement of a super tall building. Section 2 introduces the basic principles of the proposed denoising method and RDM in detail. Section 3 describes the experiment scheme. Meanwhile, the finite element model is established. In section 4, the dynamic parameters of the structure are identified by using FFT and RDM based on field measurement. Section 5 summarizes conclusions of this study.
2. Principles of the joint denoising method and RDM

The specific steps of complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) algorithm can be expressed by [7]:

(1) Define \( E_j(t) \) is an operator of the \( j \)-th Intrinsic Mode Function (IMF) decomposed by employing Empirical Mode Decomposition (EMD) method [8]. The first mode \( \text{imf}_1' \) of the signal \( y(t) + \varepsilon_0 \eta(t) \) can be obtained.

\[
\text{imf}_1'(t) = \frac{1}{N} \sum_{i=1}^{N} \text{imf}_{i1} (t)
\]  

(1)

where \( \varepsilon_0 \) is the amplitude of the added white noise, and \( \eta(t) \) is the white noise with unit variance.

(2) The corresponding first residual signal can be derived.

\[
r_1(t) = y(t) - \text{imf}_1'(t)
\]

(2)

(3) The second mode can be written as:

\[
\text{imf}_2'(t) = \frac{1}{N} \sum_{i=1}^{N} E_i \left( r_1(t) + \varepsilon_i E_i (\eta(t)) \right)
\]

(3)

(4) The \( j \)-th residual signal can be expressed as:

\[
r_j(t) = r_{j-1}(t) - \text{imf}_{j}'(t)
\]

(4)

(5) The \( (j+1) \)-th mode can be derived by using the following formula.

\[
\text{imf}_{j+1}'(t) = \frac{1}{N} \sum_{i=1}^{N} E_i \left( r_j(t) + \varepsilon_i E_i (\eta(t)) \right)
\]

(5)

(6) For next \( j \), go to step 4. The final residue has the following form:

\[
R(t) = y(t) - \sum_{j=1}^{J} \text{imf}_{j}'(t)
\]

(6)

where \( J \) is the total number of modes.

Then, the original signal \( y(t) \) can be written as:

\[
y(t) = \sum_{j=1}^{J} \text{imf}_{j}'(t) + R(t)
\]

(7)

Wavelet threshold (WT) technique has better ability to deal with non-linear signals. At present, the soft threshold function and the hard-threshold function are commonly used in signal processing field. In this paper, we use the soft threshold function [9]. It has the following form:

\[
w_{j,k} = \begin{cases} 
\text{sign}(w_{j,k}) \left| w_{j,k} \right| - \lambda & \left| w_{j,k} \right| \geq \lambda \\
0 & \left| w_{j,k} \right| < \lambda 
\end{cases}
\]

(8)

where \( w_{j,k} \) is the modified coefficient via threshold processing, \( w_{j,k} \) is the wavelet decomposition coefficient.

This article put forward a joint denoising method, i.e., CEEMDAN-WT. The steps are as follows:

(1) A series of IMFs are obtained via using CEEMDAN method;

(2) For each of the IMF components, we can derive the corresponding Power Spectral Density (PSD) function via employing FFT approach. After that the IMF components without dominate frequency information are removed, and the remaining components are retained and reconstructed. With this, we can derive the first-time reconstructed signal.
(3) The three-level WT approach is further used to decompose the first-time reconstructed signal. We select the Symlet as the mother wavelet, and the second-time reconstructed signal was obtained.

(4) Output the final results.

The RDM is proposed by Cole [10]. We can adopt this method to derive free attenuation signals from random response signal. Then the natural frequencies and the corresponding damping ratios are derive based on free attenuation signals. In this paper, the vibration signal \( y(t) \) is divided into a series of time sample functions \( y(t_i + \tau) (i = 1, 2, 3, \ldots, n) \). In this paper, the vibration signal \( y(t) \) is divided into a series of time sample functions \( y(t_i + \tau) (i = 1, 2, 3, \ldots, n) \). \( n \) is the number of samples and \( \tau = t - t_i \). Subsequently, we can derived the random decrement signature (RDS) \( R(\tau) \) via the average of the time segments \( y(t_i + \tau) \).

\[
R(\tau) = \frac{1}{n} \sum_{i=1}^{n} \{ y(t_i + \tau) | y(t_i) = C \}
\]

where \( C \) represent the initial condition.

Finally, the natural frequencies and damping ratios can be obtained by using the following form:

\[
f = \frac{1}{T} \quad \xi = \sqrt{\frac{\beta^2}{4\pi^2 + \beta^2}}
\]

where \( T \) is the time interval of one cycle on the RDS, \( \beta \) is logarithmic decrement ratio.

3. Field measurement and FEM of the structure

Fig. 1(a) shows the current status of Tianjin 117 tower. This building is a frame-core tube structure. Its height-to-breadth ratio is 9.7 and the total height is 597 m. Fig. 1(b) depicts the GNSS reference station, and it is nearly 150m away from the building. Fig. 1(c) shows one of the four GNSS rover stations, and they were mounted at the corner of the top floor, respectively. Fig. 1(d) shows the three-dimensional FEM of the structure, and the first order mode shape was shown in Fig. 1(e). We can obtain the first natural frequency of the structure via FEM analysis, i.e. 0.2017Hz. This experiment lasted 34 hours. The sampling rate is set to 1 Hz.

![Image](image.png)

Figure 1. (a) Tianjin 117 tower; (b) The GNSS reference station; (c) The GNSS rover station; (d) FEM of the building; (e) The first order mode shape.

4. Results and Discussion

Fig. 2 shows the horizontal displacements of one of the measured points and its PSD functions. It is easy seen that there is a peak in the PSD graph, which is the first natural frequency of the building (i.e., North-South direction: 0.1893 Hz, East-West direction: 0.1907 Hz). These values are close to the FEM result. Fig. 3 depicts all the IMFs and their PSD functions of the north-south component obtained via using CEEMDAN approach, i.e. IMF1 ~ IMF14. It can be seen that IMF5-IMF14 do not contain dominate frequency information, hence they were removed. Then we can obtain the first-time
constructed signal (i.e. signal $X_{11}$), as shown in Fig. 4. It is easy found that the background noise has been weakened. Fig. 5 depicts the second-time constructed signal (i.e. signal $X_{22}$) derived by employing three-level WT technique. It is seen that the amplitude of the signal is further reduced, which indicate that the background noise is further diminished. Moreover, we can derive the denoising signal of the east-west component via using the same approach (see Fig. 6).

![Figure 2](image2.png)

**Figure 2.** The horizontal displacements and their PSD functions of the monitoring point.

![Figure 3](image3.png)

**Figure 3.** The IMFs of original signal and their PSD functions.
Damping ratio is an important criterion for evaluating structural safety. This paper adopts field measurement technique to monitor the vibration of a super tall building, and the damping ratio is obtained via employing RDM. Figs 7(a) and 7(b) show the free attenuation signals of the building. Based on the equation (11), we can further obtain the damping ratio of the building (i.e. North-South direction: $\xi = 0.90\%$; East-West direction: $\xi = 1.16\%$). Thus far, the dynamic parameters of Tianjin 117 Tower are successfully derived by using CEEMDAN-WT, FFT and RDM.

![Figure 4](image1.png)  
Figure 4. The first-time reconstructed signal of North-South direction and its PSD function.

![Figure 5](image2.png)  
Figure 5. The second-time reconstructed signal of North-South direction and its PSD function.

![Figure 6](image3.png)  
Figure 6. The second-time reconstructed signal of East-West direction and its PSD function.

5. Conclusion  
Based on the field measurement, the dynamic deformation of a super tall building is investigated in this paper. The following conclusions are derived: (1) The measurement accuracy of GNSS receivers can be improved via using a joint denoising method, i.e. CEEMDAN-WT; (2) The dynamic parameters of the building are successfully derived by employing FFT and RDM; (3) The result identified by using field measurement technique agrees well with the FEM.

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