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RECONSTRUCTION METHOD OF HORIZONTAL TWO-DIRECTIONAL DYNAMIC DISPLACEMENT OF TRANSMISSION TOWER BASED ON LIMITED STRAIN DATA

Qing Zhang [1, 2, *] and Wen-Qiang Jiang [1]

[1] *Hebei Key Laboratory of Electric Machinery Health Maintenance & Failure Prevention, North China Electric Power University, Baoding 071003, China*
[2] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China*
* *(Corresponding author: E-mail: zhangqing@ncepu.edu.cn)*

ABSTRACT

Transmission towers serve as critical carriers for electric energy transmission, making health monitoring research highly significant. Horizontal dynamic displacement is a key indicator in health monitoring; however, estimating the horizontal displacement of transmission towers using conventional equipment or methods remains challenging. Therefore, this paper proposes a reconstruction method for horizontal two-directional dynamic displacement based on measured strain data. Firstly, the simplified mechanical model of the transmission tower and the strain decoupling formula for main members are established. Then, the two-directional modal superposition method is developed by integrating the stochastic subspace identification (SSI) theory to realize the transformation from strain to displacement. Subsequently, the two-directional vibration simulations of the transmission tower show that the reconstruction error at the 27 m high measuring point is only 2.07%, and the method maintains high precision even under high noise conditions. Finally, a scaled model test of the transmission tower confirms that the reconstructed horizontal two-directional dynamic displacement matches the measured values closely in both time and frequency domains.

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1. Introduction

The transmission tower is a vital component of the power grid, playing a significant role in clean energy utilization and national energy security[1, 2]. Therefore, monitoring its health to obtain dynamic responses is crucial for ensuring grid safety [3-5]. Among various monitoring indices, the dynamic displacement field, especially the horizontal dynamic displacement, accurately characterizes the overall structural performance[6, 7], is necessary to estimate the safety and dependability of the structure [8-10]. Thus, precise measurement of horizontal two-directional dynamic displacement is critical for health monitoring and performance assessment of transmission tower structures[11].

Displacement can be attained using a variety of measuring equipment[12, 13], such as Total Station, Static Level Meter, Global Navigation and Positioning System (GNSS), Vision-based Measurement System, etc. [14-16]. Nevertheless, the above equipment has the following shortcomings: (1) They require fixed reference points on the structure, which may shift under extreme weather (e.g., typhoons, earthquakes) or long-term use; (2) Their high requirements for sight, light, and expensive cost render them unsuitable for long-term health monitoring of transmission towers.

In order to overcome the above problems, displacement reconstruction technology has become a research hotspot [17-21], namely, the structural displacement can be calculated indirectly using easily measured data, such as acceleration and strain. Acceleration-based methods primarily involve time and frequency domain integration [22, 23]. For overcoming the problem that the sensor is difficult to attain the deflection of the bridge directly, Park et al.[24] developed a method to derive the dynamic displacement of the bridge using measured acceleration, a high-pass filter and an initial velocity estimation algorithm were introduced in view of the non-negligible initial conditions in the integration process, and the field measurement shows that the reconstructed displacement accuracy is well, but the acceleration needs to be segmented and integrated for pseudo-static displacement, and the segmentation principle has not yet been determined. Zhu et al.[25] proposed a frequency domain integration algorithm based on low-frequency attenuation method, then compared with the conventional integration method by simulation, and the superiority of the method was proved, a shaking table test was also conducted to study the effect of precision control factor on the performance of the above method simultaneously. The frequency domain integration algorithm utilizes the filter to reduce the effect of low frequency measurement noise on the acceleration integration process to a certain extent, but it also causes the loss of effective low frequency components in displacement, hence, the selection of the cutoff frequency of the filter has strong experience and autonomy. Additionally, it is difficult to estimate the initial position and velocity accurately without GNSS technology, which leads to many challenges in the reconstruction of non-zero mean dynamic displacement and pseudo-static displacement.

Reconstruction methods based on limited strain data include inverse finite element method (iFEM) [26] and modal superposition technique [27]. You et al.[28] proposed an enhanced inverse beam element iEBT2, numerical analysis and experiments suggest that the inverse element can estimate the deformation accurately in the absence of strain data, but the inverse element type for transmission tower structure has not been studied. The modal superposition method only needs the measured strain and mode shapes of the structure to realize the displacement reconstruction. Therefore, this method is widely used in the shape perception and displacement reconstruction of beam-slab structures. Lu et al.[29] developed a continuous dynamic response analysis algorithm based on decoupled vibration differential equation, and the correctness was confirmed by jacket platform simulation and cantilever beam model test. Skafte et al.[30] proposed a method that can predict the displacement mode shape and response only by measured strain data, and reconstructed the displacement response of a civil structure under random load. However, this technology has not been applied to the horizontal two-directional displacement reconstruction of transmission tower. In addition, some scholars have carried out preliminary research on the displacement reconstruction of lattice tower [31, 32], which can provide reference for the two-dimensional displacement reconstruction of transmission tower.

It can be seen from the above review that there is still no method suitable for horizontal two-directional displacement reconstruction of transmission tower structure. Hence, the two- directional modal superposition method based on limited strain data was proposed in Section II, which can calculate the two-directional displacement of the transmission tower directly from the measured strain data. In Section III, the ANSYS model of transmission tower is built, then the effectiveness and noise immunity of the proposed method are validated by two-dimensional random vibration simulation. In Section IV, a scaled model of a transmission tower is fabricated and the dynamic loading test is conducted to further confirm the practicability of the proposed reconstruction method. Finally, the research is summarized in Section V.

2. Horizontal two-directional displacement reconstruction theory

2.1. Strain decoupling technology of main member

The transmission tower is a complex spatial structure composed of main and brace members, and it is very difficult to carry out displacement reconstruction analysis directly. It is assumed that the transmission tower is always in the range of linear elastic deformation. Note that the transmission tower belongs to the large cantilever structure, which can be considered as a variable cross-section cantilever beam, as shown in Fig. 1. The neutral layer refers to the existence of a transition layer that is neither tension nor compression when the beam is bent, usually located in the geometric center, which is the dotted line in Fig. 1 The transmission tower structure is easy to vibrate along two orthogonal horizontal directions, which is called the main vibration direction. When there is an angle between the load and the main vibration direction, the response of the transmission tower has components along both main vibration directions, which is called two-dimensional response. The existing method should be improved to make it suitable for the vibration of the transmission tower along any horizontal direction.

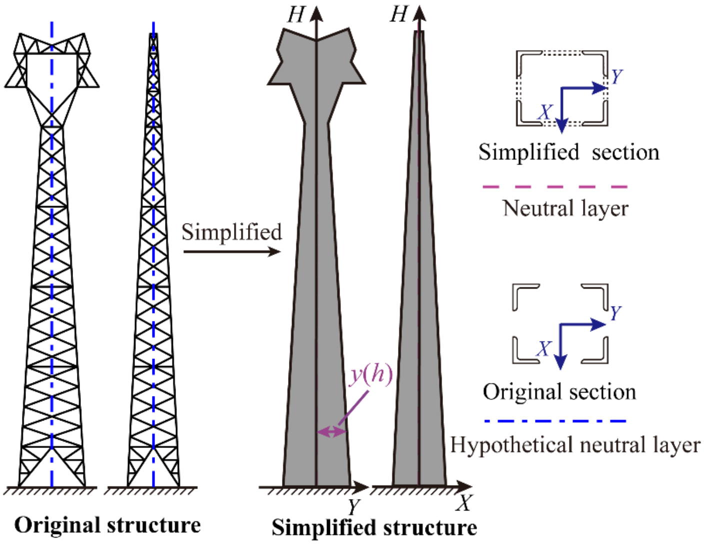


Fig. 1 Transmission tower structure simplification process

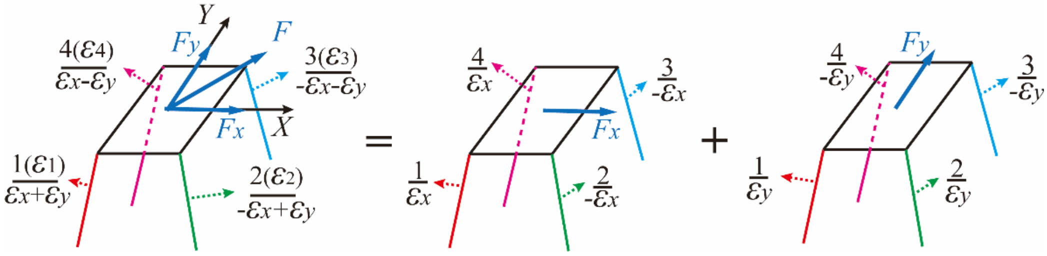


Fig. 2 Strain decoupling process of main member

Fig. 2 suggests the stress state of the main member when the transmission tower generates two-directional displacement. Due to the different synthesis rules of strain and displacement, it is impossible to calculate the strain mode shape along the main vibration direction directly using the main member strain, and the strain decoupling of the main member is needed. The four main members are numbered from 1 to 4, then the effect caused by F is the same as the effect caused by two components Fx and Fy according to the principle of force synthesis.

The strain of the transmission tower under the load of two separate forces can be acquired by the formula:

$$\varepsilon_x=\frac{\varepsilon_1-\varepsilon_2}{2},\varepsilon_y=\frac{\varepsilon_1+\varepsilon_2}{2} \tag{1}$$

where ε_1 and ε_2 are the two-dimensional strains generated by the No.1 main member and the No.2 main member, respectively. The above formula decomposes the synthetic strain generated by the main member under any horizontal load into the strain generated by the component force acting alone along the main vibration direction, which is called the main member strain decoupling formula. Since the strain and displacement mode shapes of the transmission tower in the main vibration direction can be converted to each other, the displacement reconstruction problem in any direction can be solved by decomposing it into the main vibration direction.

2.2. Two-directional modal superposition method

Due to the displacement reconstruction processes in the two main vibration directions are similar, the X direction displacement reconstruction is taken as an example to illustrate the process of the proposed method. It is assumed that the transmission tower is subjected to the action of force F, and a total of $2m$ strain measuring points are arranged on two adjacent main members, the strain $\{\varepsilon_x\}_{m\times 1}$ of the transmission tower under the load of Fx can be calculated by (1) Then the SSI algorithm is used to acquire strain mode shapes $\{\mathbf{\Psi}_x\}_{m\times n}$ in the X direction, the flow chart of SSI method is shown in Fig. 3.

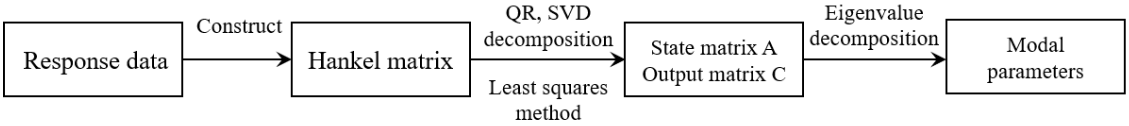


Fig. 3 SSI method process

The modal coordinates are calculated according to the least square method:

$$\{q_x^s\}_{n\times 1}=(\{\mathbf{\Psi}_x\}_{m\times n}^T\{\mathbf{\Psi}_x\}_{m\times n})^{-1}\{\mathbf{\Psi}_x\}_{m\times n}^T\{\varepsilon_x\}_{m\times 1} \tag{2}$$

where n denotes the obtained modal order; the s stands for strain. Then the strain and displacement mode shape function in the X direction $\Psi_x^i(h)$ and $\Phi_x^i(h)$ are acquired by the integral method:

$$\Phi_x^i(h)=\iint\frac{\Psi_x^i(h)}{x(h)}dhdh+Eh+F=\iint f_i(h)dhdh \tag{3}$$

where $x(h)$ is the function between the distance from the response extraction point to the assumed neutral axis and the height, and the integral constants E and F are both 0. Taking Fig. 1 as an example, this distance is the distance between the point on the main member and the H axis; E and F are integral constants related to boundary conditions. $\Psi_x^i(h)$ is obtained by fitting the strain mode shape value and the corresponding height. Then $f_i(h)$ is expanded by using the Taylor formula to solve the problem of complex integral function:

$$\frac{\Psi_x^i(h)}{x(h)} = f_i(h) = \frac{f_i(h_0)}{0!} + \frac{f_i'(h_0)}{1!}(h-h_0) + \cdots + \frac{f_i^z(h_0)}{z!}(h-h_0)^z + R_z(h) \tag{4}$$

Moreover, the specific mode shape value of the target point can be determined according to its corresponding height coordinates, then the X direction displacement at the corresponding position can be acquired by using the modal superposition principle:

$$\{\mathbf{D}_x^s\} = \{\mathbf{\Phi}_x\}\{q_x^s\}_{n\times1} \tag{5}$$

where $\{\mathbf{D}_x^s\}$ is the X direction displacement vector of the reconstructed target point; $\{\mathbf{\Phi}_x\}$ represents displacement mode shape matrix. The process of modal superposition is shown in Fig. 4.

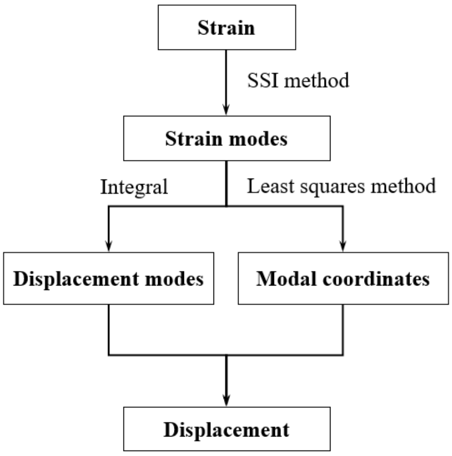


Fig. 4 Modal superposition process

Thus far, the reconstruction of dynamic displacement field in the X direction of transmission tower structure under load F is finished. It is noted that the strain decoupling process is carried out before this, namely, the strain of the transmission tower under load Fy is also known, and the reconstruction procedure of the Y direction dynamic displacement is basically the same as that in X direction, only the strain data used is different. Therefore, the horizontal two-directional displacement reconstruction of the transmission tower can be completed simultaneously. Fig. 5 is the flowchart of the horizontal two-directional displacement reconstruction approach of transmission tower.

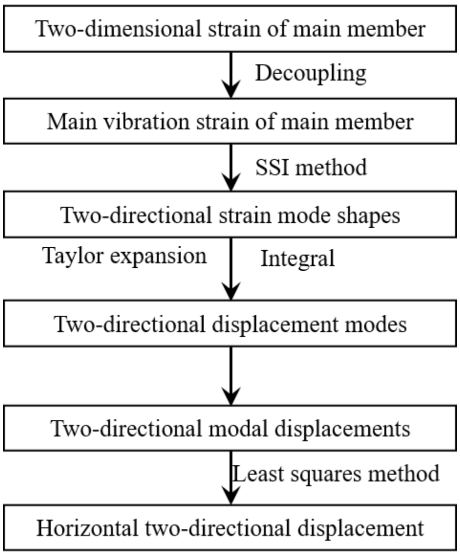
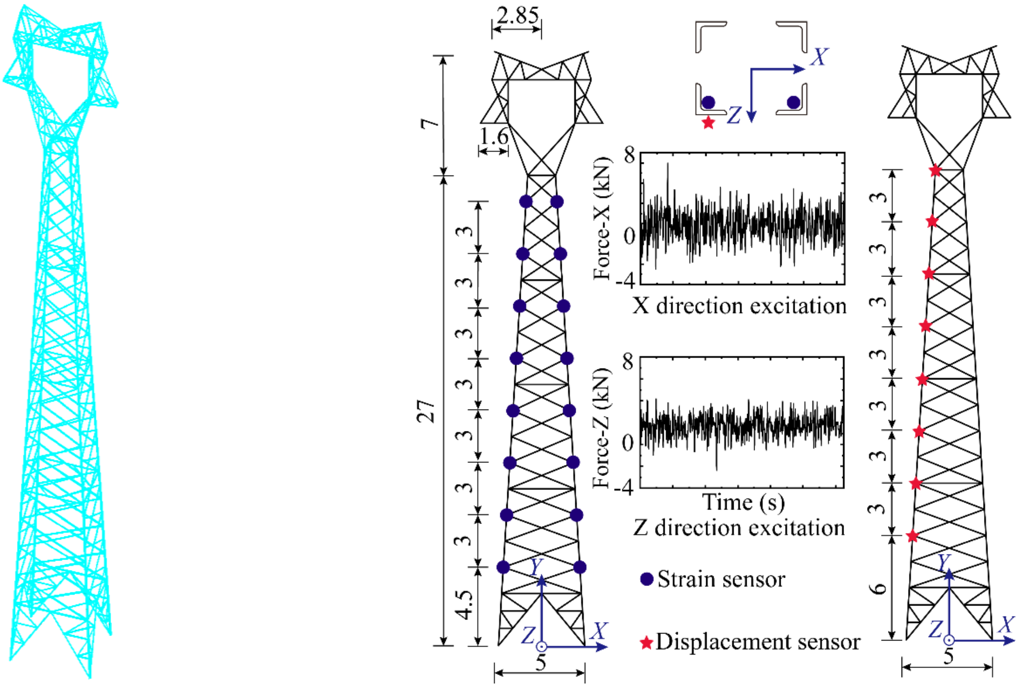


Fig. 5 Horizontal two-directional displacement reconstruction method flowchart

3. Numerical validation via two different beam structures

3.1. Finite element model

Taking a transmission tower of Jiangmen-Gewen line in Guangdong province as the prototype, the finite element model (FEM) is established by using ANSYS software, the beam188 element is used to simulate the members, and the rigid connection is adopted between the members. The material elastic modulus is 206 GPa, the density is 7800 kg/m3, the Poisson's ratio is 0.3, and the damping ratio is 0.04. The tower is a lattice angle steel transmission tower, whose 7 m high head is cat-shaped, the whole height of the tower body and legs is 27 m. The length of cross arm is 1.8 m and the main angle steel specifications including L90 × 8, L80 × 7 and so on. The specific geometric size and built FEM are shown in Fig. 6.



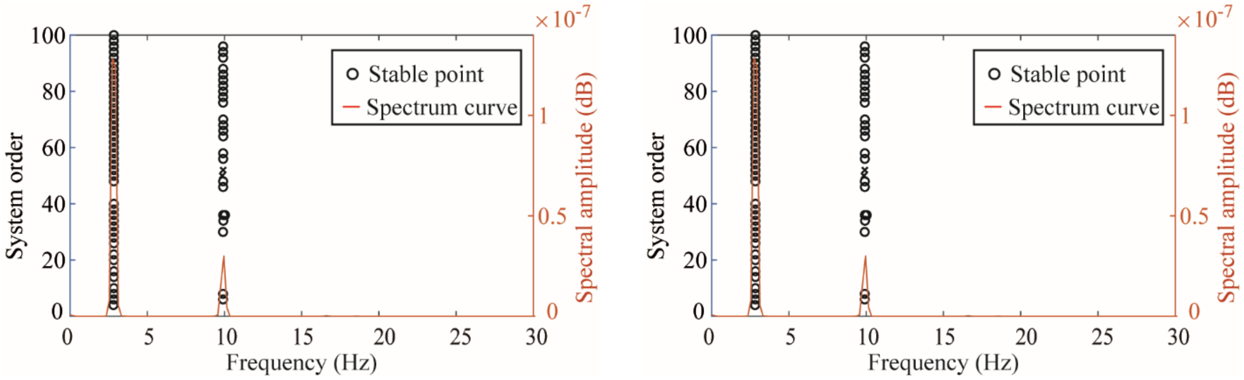
(a) FEM (b) Dynamic response extraction points position (m)

Fig. 6 FEM and extraction point position

Fig. 6(b) shows the specific location of the dynamic response extraction point. 16 dynamic strain extraction points are evenly set along the height direction on the No.1 and No.2 main members of the transmission tower, eight displacement response measuring points are settled to confirm the reconstruction accuracy of proposed method simultaneously, and the dynamic response sampling interval is 0.0025 s. To reflect the ability to reconstruct the displacement field, the placements of the strain and displacement measuring points do not coincide. Random excitations are applied along the horizontal directions (*X* and *Z*) in the figure to cause two-dimensional dynamic deformation of the transmission tower. The excitation time history can also be referred to Fig. 6, and the excitation frequency range is 0-20 Hz.

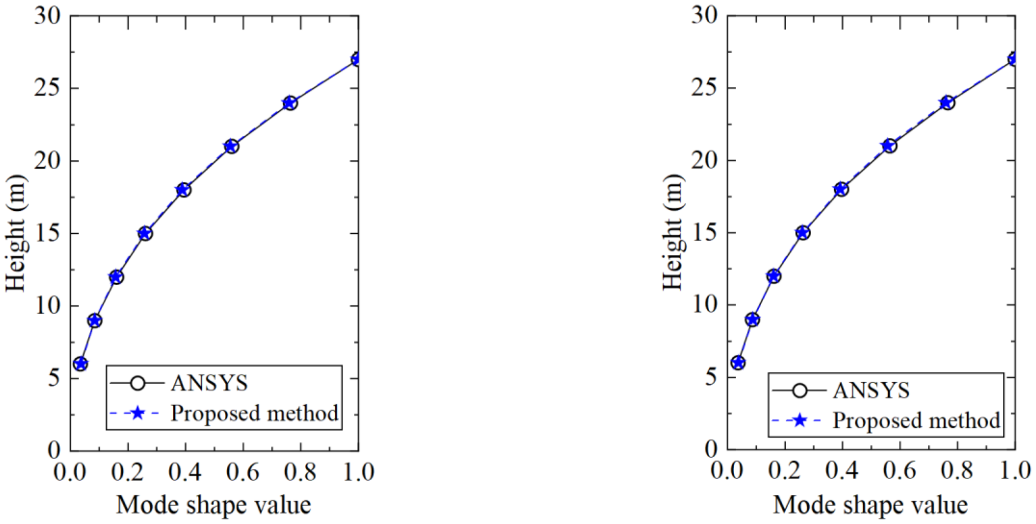
3.2. Reconstruction results analysis

The extracted strain data are processed by strain decoupling formula, and the strain modal parameters are calculated by the SSI algorithm. Fig. 7 shows the obtained stability diagram, the stable point in the diagram represents the stable solution of the modal parameters. The proposed method accurately calculates the first four-order modal parameters in both horizontal directions of the transmission tower without aliasing phenomenon.



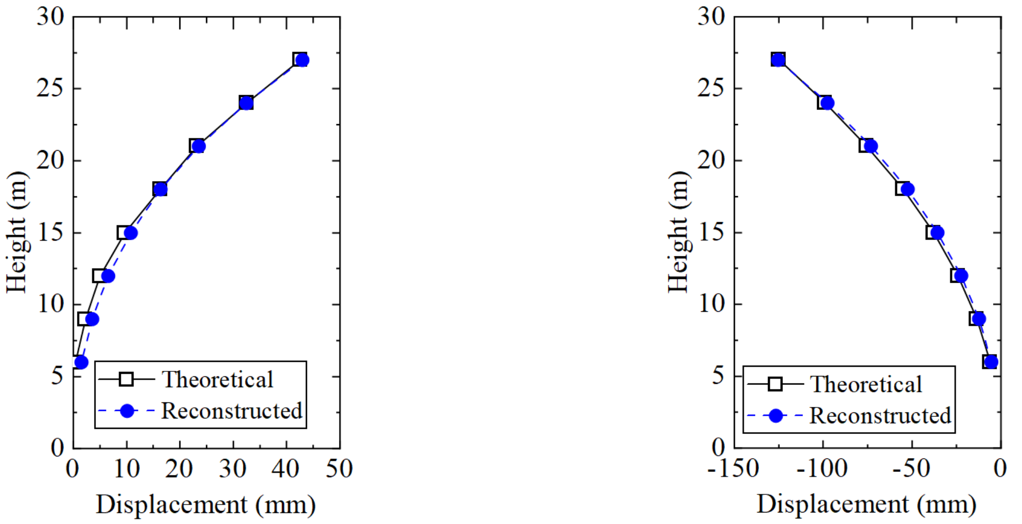
(a) *Z* direction (b) *X* direction

Fig. 7 Strain stability diagram



(a) *Z* direction (b) *X* direction

Fig. 8 Comparison of different first-order displacement mode shapes



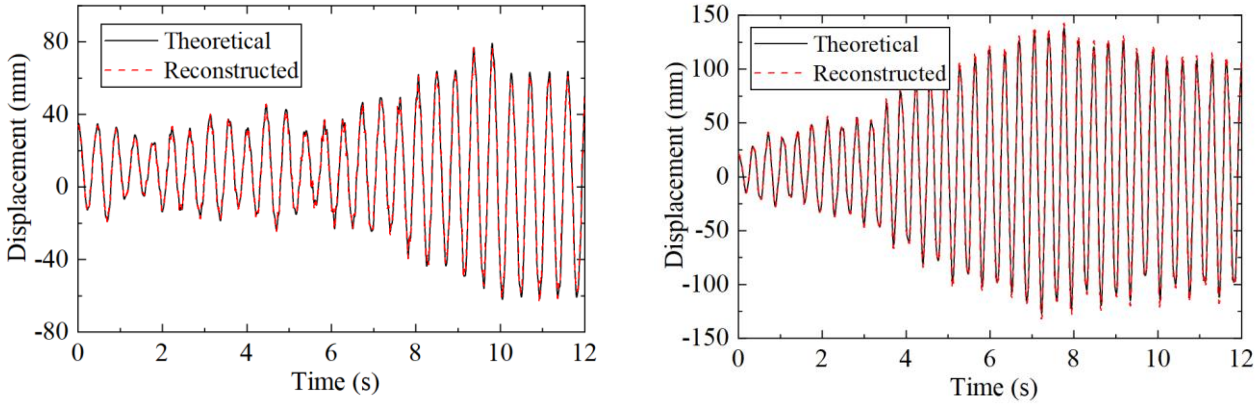
(a) *Z* direction (b) *X* direction

Fig. 9 The comparison of the displacement field of the transmission tower at 7 s

We extract the strain mode shapes in the stability diagram to acquire the displacement mode shapes using the developed method, and then contrasted with the ANSYS modal analysis results. The first-order mode is taken as a case, as displayed in Fig. 8. The reconstructed displacement mode shape curve closely coincides with the theoretical curve, indicating that the developed method can calculate the displacement modal parameters of transmission tower accurately based on the limited strain data.

Then we calculate the two-directional displacements of all the target points on the transmission tower structure. Fig. 9 compares the reconstructed two-directional displacement field at 7 s with the theoretical value calculated by ANSYS. It can be seen that the two are very close, indicating that the proposed two-directional modal superposition method can obtain the two-directional displacement field of transmission tower accurately.

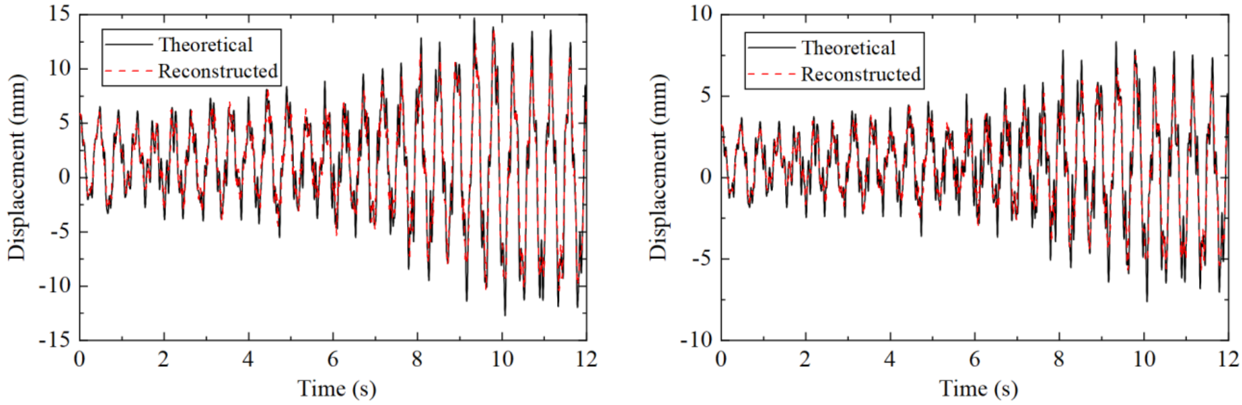
For convenience, the following adopts the 27 m high displacement measuring point as an example to compare the reconstructed two-directional displacement and the theoretical value time history calculated by ANSYS. Fig. 10 demonstrates the two-directional dynamic displacement comparison time history diagram, the reconstructed value is very close to the theoretical value at most of the time. which suggests that the proposed method can achieve the accurate reconstruction of two-directional dynamic displacement of the transmission tower only utilizing the strain data.



(a) *Z* direction (b) *X* direction

Fig. 10 Dynamic displacement comparison (27 m high)

In order to prove the ability of the proposed method to calculate the displacement of the middle and lower part of the tower, the theoretical displacement and reconstruction displacement of the 12 m and 9 m heights are compared, as shown in Fig. 11. It can be seen that although the reconstruction accuracy is slightly reduced, the reconstruction value and the theoretical value are still in good agreement on the whole.



(a) 12 m (b) 9 m

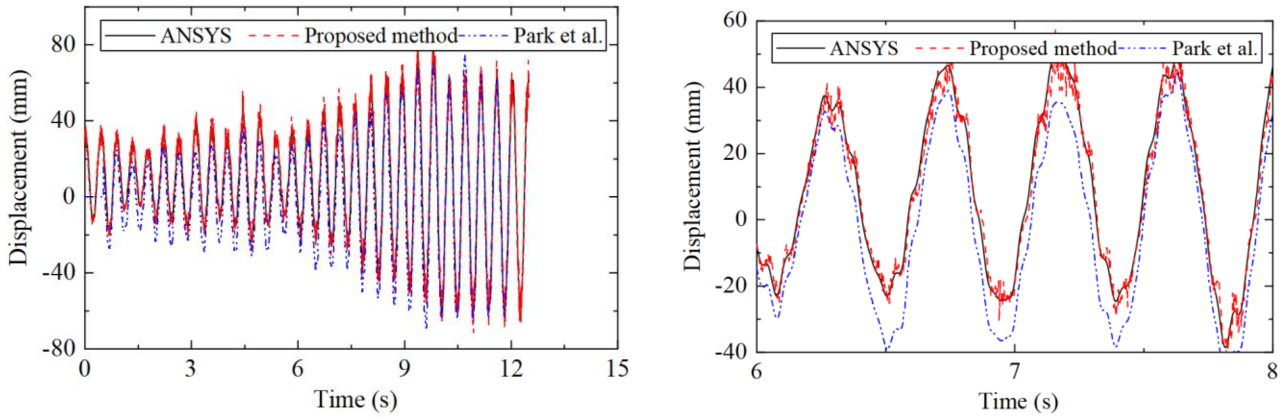
Fig. 11 Dynamic displacement at different heights in the *Z* direction

For investigating the ability of the proposed two-directional displacement reconstruction method to resist noise, different levels for Gaussian white noise were added to dynamic strain collected by ANSYS to simulate measurement noise case. The signal-to-noise ratio (SNR) is commonly used to measure the noise intensity, the calculation formula is:

$$\mathrm{SNR} = 20\log_{10}\left(\frac{f_{\text{signal}}}{f_{\text{noise}}}\right) \tag{6}$$

where f_{signal} is the amplitude of the original signal, and f_{noise} is the amplitude of the noise. It is found that the noise amplitude accounts for less than 10 % through the analysis of the actual strain signal, and the corresponding SNR ratio is 20 dB, so the SNR of noise are set to 20 dB, 40 dB and 60 dB, respectively.

The above has already verified the ability of the developed method to calculate the horizontal two-directional displacement field accurately, so just the reconstruction of the displacement of 27 m high measuring point in the *Z* direction is discussed. Fig. 12 presents the displacement time history at the highest point, with noise at 20 dB, calculated by different methods. The figure suggests that the reconstructed curve is basically consistent with the theoretical displacement curve even in the case of high noise, which demonstrates that the developed reconstruction method has strong robustness. On the other hand, the displacement reconstructed by Park et al.[20] is roughly consistent with the theoretical displacement, but as shown in the enlarged diagram, the reconstruction accuracy is lower than that of the proposed method.



(a) 0-15 s (b) 6-8 s

Fig. 12 The displacement comparison of the 27 m high measuring point (20 dB)

To achieve the quantitative analysis of the reconstruction precision, the error index K is determined to evaluate the reconstruction error degree of each working condition:

$$K = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_t - x_r)^2}}{\max(x_t) - \min(x_r)} \times 100\% \tag{7}$$

where N is the number of extracted data, x_t stands for the theoretical displacement, x_r is the reconstructed displacement. Table 1 shows the error index K under different working conditions. K is only 1.71 % when SNR is 20 dB, showing that the proposed method has a strong ability to resist noise interference for reconstructing two-directional displacement.

Table 1
Error index corresponding to different working conditions

SNR (dB)	K (%)	Standard deviation (%)
20	2.08	3.11
40	1.84	3.07
60	1.71	3.05

4. Test verification

4.1. Scaled model and experimental design

Taking the transmission tower in Section III as the prototype, the scaled model is made according to the similarity theory. The production process can refer to the existing reference [33], the geometric scale ratio of the scale model is 1:15 considering the limitation of laboratory space. On the other hand, the thin aluminum sheet is processed into an equal angle steel section to simulate the structural members to ensure the similarity of the aerodynamic shape, and the scaled model is displayed in Fig. 13.

Fig. 13 Scaled model of transmission tower

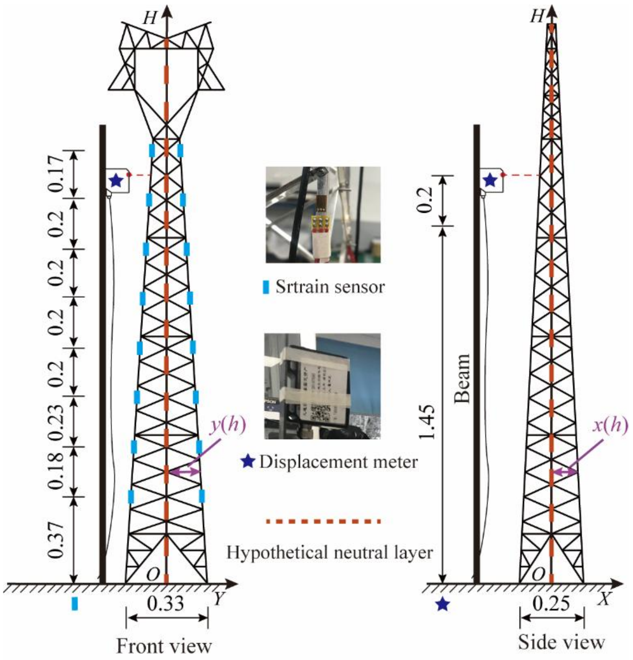
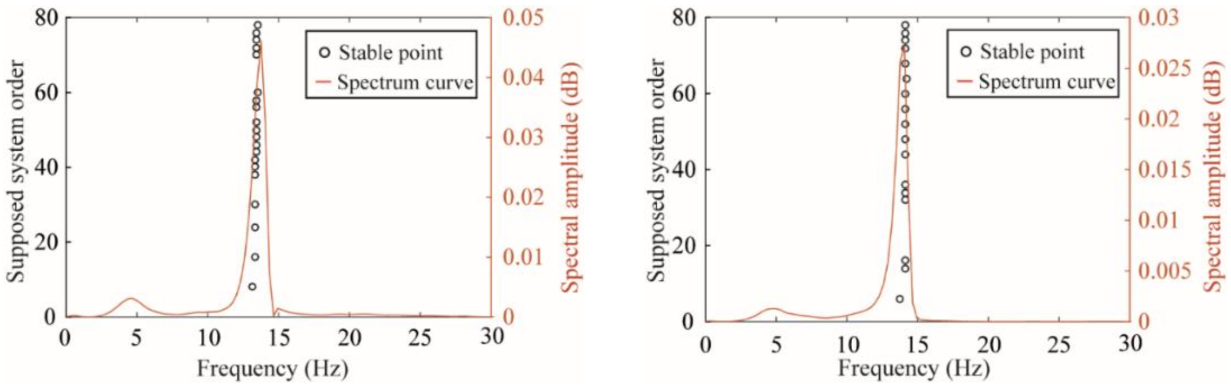


Fig. 14 Sensors photograph and measuring points layout (Unit: m)

Eight pairs (16) of strain gauges were settled along the height on the two main members of the scaled model. In order to facilitate the measurement of displacement response and demonstrate the ability of the developed reconstruction method to calculate the horizontal two-directional displacement field, two displacement sensors were arranged at a height that did not coincide with the strain gauge position, the specific sensor layout is demonstrated in Fig. 14. The sampling rate of the strain response is determined to be 200 Hz, and that of the displacement sensor is determined to 10 kHz, which is then reduced to 600 Hz by re-sampling method. The knocking method is used to make the structure produce a two-directional dynamic displacement with free attenuation. The function $x(h)$ and $y(h)$ of the distance from the sensor on the main member to the assumed neutral layer can be calculated by the geometric size given in the figure.

4.2. Test results and analysis

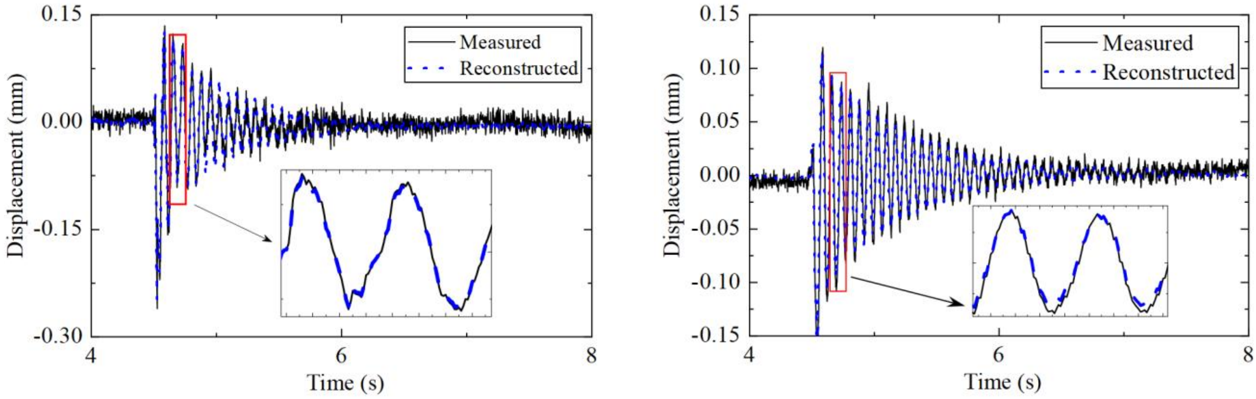
The proposed main member strain decoupling technique is utilized to handle the collected strain data to calculate that caused by the structure vibration along the main vibration direction. Then the FFT method and SSI method are applied to process the strain time history along the main vibration direction, and the spectrum curves and strain stability diagrams are demonstrated in Fig. 15.



(a) *X* direction (b) *Y* direction

Fig. 15 Strain stability diagrams and spectrum curves in different directions

The dynamic displacement curve of target point is calculated by the proposed method, and the reconstructed results are displayed in Fig. 16. Fig. 16 compares the time history curves measured by two laser displacement meters and the displacement curves calculated by the developed method, the reconstructed two-directional displacement time history is basically the same as the measured displacement time history, and there are only differences at individual times. Considering that the displacement response amplitude is only 0.3 mm, this difference is acceptable, and the larger variation of the initial measured value is caused by the higher measurement accuracy of the strain gauge.



(a) *X* direction (b) *Y* direction

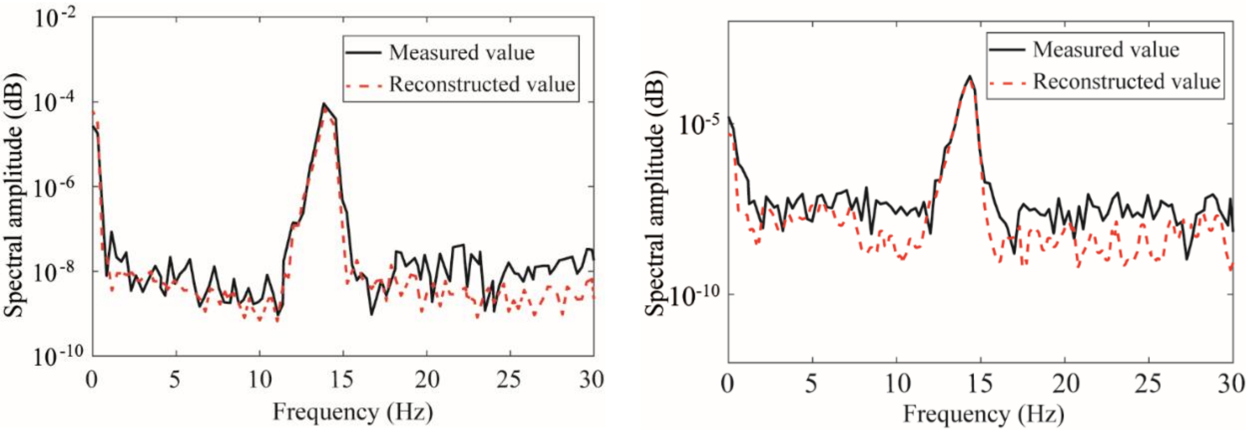
Fig. 16 Two-directional displacement time histories calculated by different methods

The relative error between the reconstructed displacement and the measured displacement in the model test is shown in Table 2, which can be seen that the error is within 10 %, indicating that the proposed method has high accuracy.

Table 2
Model test reconstruction error

Error index	X direction	Y direction
K	7.45%	6.37%

Fig. 17 compares the divergence between the reconstructed two-directional displacement and measured value in the frequency domain. It can be seen from the figure that the spectrum curves of the reconstructed value and the measured value are relatively close, and both of them have peaks at the first-order frequency of the tower, which is consistent with the calculation results of the stability diagram, and the amplitude is basically the same. The two spectrum curves are negligibly different in the frequency bands above and below the first-order frequency, which is related to the different measurement levels of the laser displacement sensor and the strain gauge besides the reconstruction error. Generally, the reconstructed displacement curve can reflect the spectral characteristics of the real displacement of the structure well. The time and frequency domains analysis suggest that reconstructed horizontal two-directional displacement and the measured value are not only very close in the time domain, but also highly consistent in the frequency domain, which proves the precision of the proposed horizontal two-directional displacement reconstruction method.



(a) *X* direction (b) *Y* direction

Fig. 17 Comparison of different displacements in frequency domain

5. Summary and conclusion

This paper proposes a horizontal two-directional displacement reconstruction method for transmission towers based on a two-directional modal superposition technique. Firstly, the strain decoupling formula is established to decompose the two-directional displacement reconstruction problem into independent main vibration direction problems. Then, the SSI algorithm is employed to extract strain modes in two orthogonal directions and derive the corresponding displacement mode functions. Finally, the transformation from limited strain measurement data to horizontal two-directional displacements is achieved.

The feasibility of the proposed method is validated through numerical simulations and scaled model tests, with noise immunity analysis showing that the error index remains within 2%. In the model test, even when the displacement amplitude is as low as 0.3 mm, the reconstructed displacements in both orthogonal horizontal directions exhibit high consistency with measured values in both time and frequency domains.

Notably, the proposed reconstruction method enables estimation of horizontal two-directional displacements of transmission tower structures using only limited strain measurements, eliminating the need for initial position information. This feature is of significant importance for operational maintenance and performance evaluation of transmission towers, providing a reliable reference for structural assessment and reducing maintenance costs of power infrastructure. On the other hand, when combined with online modal parameter identification technology, the proposed method can also mitigate the impact of environmental factors on displacement reconstruction.

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