Research on Dynamic Characteristics Detection Method of Tall Power Transmission Tower

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Abstract. In addition to the gravity of the structure itself and the supported object, the open-air high-rise supported steel structure tower mainly bears dynamic loads. Take the transmission line tower as an example, such as wind load, conductor galloping, tower vibration and sudden unbalanced tension caused by line breaking. It is necessary to study the dynamic characteristic parameters to know the structural resistance to dynamic load. Therefore, from the perspective of dynamic safety evaluation, this paper designed the acquisition method of dynamic characteristic parameters and established a reliable finite element modal analysis model of transmission tower. Finally, the dynamic characteristic parameters such as natural frequency, vibration mode and amplitude of transmission line steel tower were obtained. It was found that the inclined material of the transmission tower might be unstable when the high-order natural frequency resonance occurred, which had important practical significance for structure design optimization and safety evaluation.

Keywords: high-rise steel structure; transmission line tower; dynamic characteristic; modal testing.

1. Introduction

Transmission line towers, communication base station towers, billboard supports, various landscape towers and other high-rise steel structure support towers will be subjected to various dynamic loads in the open air, resulting in uneven stress and vibration. Under long-term alternating loads, tower materials or fasteners are prone to fatigue failure. Transmission line tower is a typical open-air steel structure tower, and transmission line project is an important part of power system construction [1]. In China, tower collapse accidents caused by strong wind, downburst and other extreme weather occur frequently, which is the main reason for the damage of transmission lines in inland areas. At the same time, wind load is also the main control load for the design of overhead transmission lines [2-4]. In addition, the sudden unbalanced tension caused by lightning, ice coating and wire fatigue will also lead to tower collapse [5]. The above loads are dynamic loads, and the impact of dynamic loads will produce greater internal force and displacement response. For high-rise flexible structures such as transmission towers, the damage caused by dynamic load impact is more obvious [6,7].

When studying the performance of steel structure tower under dynamic load, you must first understand the dynamic characteristics of the structure system itself, mainly including the natural frequency (period), damping and vibration mode [8,9] of the structure. These three parameters are called the modal parameters of the structure, which are the inherent properties of the structure. The process of obtaining modal parameters is called modal analysis [10]. If this process is carried out by the finite element method, it is called computational modal analysis; If modal parameters are identified through field tests, it is called experimental modal analysis [11]. Modal analysis is used to determine the inherent vibration characteristics of the structure itself, and determine the weak links of the structure through the distribution of frequency and vibration mode, so as to avoid resonance of the system [12].

In this paper, taking the transmission line tower as an example, the dynamic characteristics testing method of high-rise steel tower is studied. Through the field modal test of angle steel tower on the actual transmission line, the dynamic characteristics detection technology of the transmission tower is studied, and the dynamic parameters of the transmission tower are obtained. At the same time, the finite element calculation model is established, and the modal calculation is carried out. The comparison with the field test and testing is made to improve the accuracy of the finite element calculation. At the same time, the reliable finite element calculation model is used to continue to carry out higher order dynamic characteristics analysis of the transmission tower.

2. Modal test method based on environmental excitation

For high-order modal analysis of large high towers, in addition to field tests, finite element modal analysis can also be used. However, due to different structural forms of tower members, different connection methods between members and other factors, it is difficult to determine the coincidence between the finite element calculation model and the actual situation [13]. The calculation results should be verified by comparing the modal parameters identified in the field tests. The identification of modal parameters is an important part of the field of structural dynamics, and is also the basis and prerequisite for structural state assessment, finite element model correction, damage identification and vibration control [14].

The transfer function is a mathematical tool to study the mapping relationship between the input excitation and output signals of the system. In order to obtain the transfer function of the dynamic characteristics of the transmission tower, it is necessary to excite the structure and measure the input (force) and output (response) signals. The excitation methods mainly include sine sweep frequency and steady random force pulse hammering excitation. Sine sweep sweeps the frequency step by step in the analysis frequency band, which takes a lot of time and is difficult to install the exciter. The method of single point excitation and multi-point synchronous measurement is often used. The measurement system must have many channels for synchronous measurement. The test cost is high and the test cycle is long. Due to the continuous energy supplement, more stable results can be obtained; The frequency characteristics of steady state random signal generator are difficult to control, the choice of goods is small, and the price is expensive, so it is not often used in general modal tests; The pulse hammering method is the most common modal test method because of its simple equipment, convenient operation, time saving and cost saving; For complex structures, especially when multiple components and the connection between components are not rigid, it is difficult to excite the overall mode by knocking, so it is better to sweep the frequency with an exciter or place the test piece on a sinusoidal vibration table for testing [15-17].

Under the excitation of environment such as wind, water impact, earth pulsation, vibration caused by moving vehicles and so on, the structure will generate vibration of varying degrees. Although we cannot accurately quantify these excitation characteristics, we can still reasonably assume that these excitations are approximate stationary random signals, whose spectrum is a continuous spectrum with a certain bandwidth, basically covering the frequency band we are interested in the structure [18], Based on this assumption, a test method based on environmental excitation is designed to carry out field test modal analysis of transmission towers.

The main idea of the test method designed in this paper is to use the vibration response of all measuring points under environmental excitation and the vibration response of a fixed reference point as dual channel FFT respectively. First, identify the resonance frequency f_i on the self power spectrum, then take the ratio $\Phi(f_i)$ of the amplitude spectrum of each measuring point and the reference point on the resonance frequency as the relative value of the vibration mode of the point, and take the positive and negative of the real part of their cross power spectrum on this frequency as the phase of the vibration mode of the point [19].

$$|\Phi(f_i)| = \left|\frac{B(f_i)}{A(f_i)}\right| = \left|\frac{B(f_i)\overline{B}(f_i)}{A(f_i)\overline{A}(f_i)}\right|^{\frac{1}{2}} = \left|\frac{G_{bb}(f_i)}{G_{aa}(f_i)}\right|^{\frac{1}{2}} \tag{1}$$

$$\mathrm{sgn}(\Phi(f_i)) = \mathrm{sgn}(\mathrm{Real}(\mathrm{G_{ba}}(f_i)) \tag{2}$$

$A(f_i)$: Fourier Transform of Reference Point Signal

$B(f_i)$: Fourier Transform of Measuring Point Signa

$G_{aa}(f_i)$: Reference point signa

$G_{bb}(f_i)$: Self power spectrum of measuring point signal

$\mathrm{G}_{\mathrm{ba}}(f_i)$: Cross power spectrum of reference point signal of measuring point signa

This modal test method has obvious advantages:

• The test adopts natural excitation, which does not require manual operation of equipment to stimulate the transmission tower structure, saving a lot of manpower, material resources and time costs, and avoiding the damage to the structure caused by excessive impact during the excitation process.

• The modal test method proposed in this paper is carried out under the actual operation of the transmission tower. The excitation environment is reasonable, the data reliability is high, and it is convenient to compare with the theoretical calculation.

• The method of fixed reference point and moving measuring point is used to collect vibration data. Only a few channels of sensors, acquisition instruments and other equipment are needed to better achieve the collection of vibration data from a large number of measuring points.

In this paper, the field test modal analysis of 100 # corner tower of a line is carried out using the above methods, and the reliable first six order modal parameters are obtained.

3. Modal analysis of field test

3.1 Layout of measuring points

The main bearing parts of the transmission tower are four main tower leg materials and tower body inclined materials. According to the characteristics of the transmission tower structure, measuring points are arranged to adequately describe the vibration form of the transmission tower. Figure 1 shows the layout of measuring points of the transmission tower. Among the 44 measuring points, 1, 11, 21 and 31 are not measured as constraint nodes. Therefore, a total of 40 measuring points are collected, and each measuring point is measured for vibration in X and Y vertical directions. The fixed reference point is measuring point No. 6.

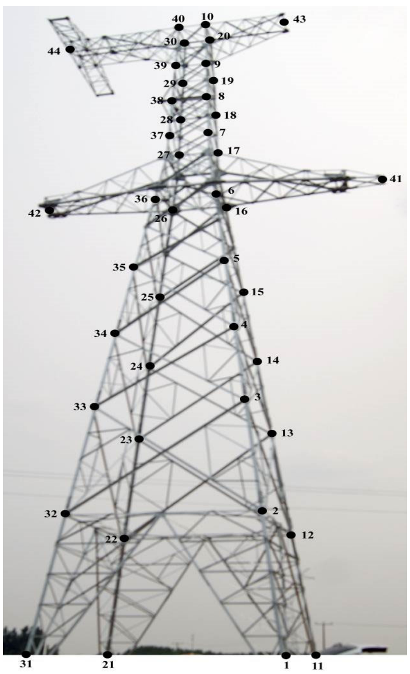

Figure 1. Layout of Measuring Points for Modal Analysis of Field Test

According to the actual structure and testing requirements of the transmission tower, first determine the physical coordinate system describing the transmission tower structure, extract a total of 56 key nodes that constitute the main bearing part of the transmission tower structure, make the coordinates describing the key nodes of the transmission tower into a node coordinate table, connect the nodes of the transmission tower, and make a connection table. According to the node coordinate table and the connection table, the test model can be obtained, as shown in Figure 2.

The vibration signals of 40 measuring points collected in the field are input to the nodes in the corresponding positions in the physical model, and the vibration parameters and mode shapes of the transmission tower can be obtained through the stochastic subspace algorithm (SSI).

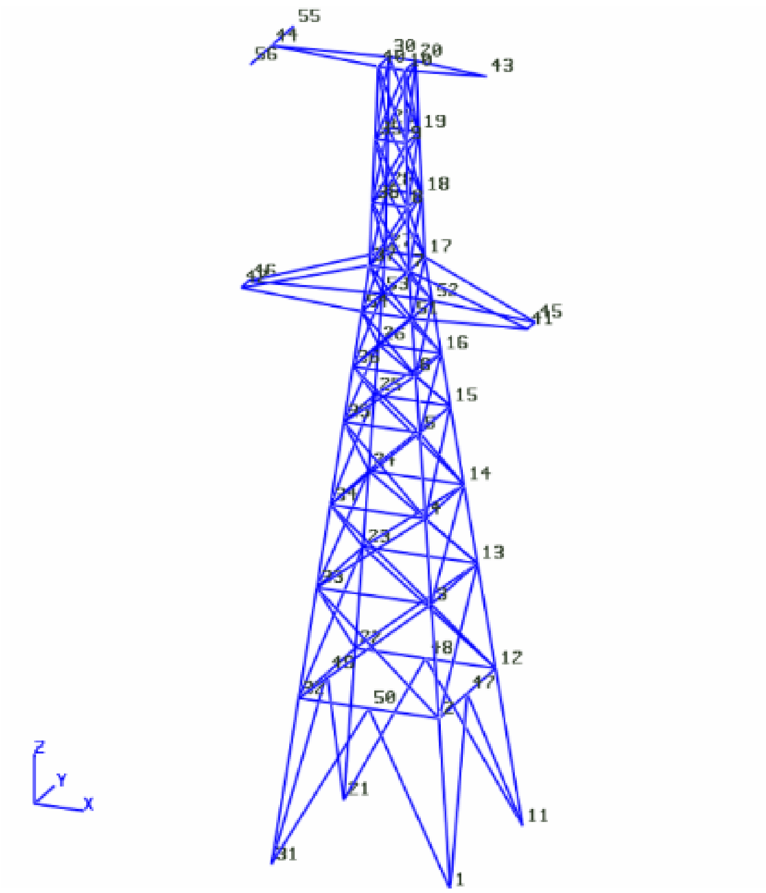

Figure 2. Experimental modal analysis of tower structure model

3.2 Modal parameter acquisition and processing

The modal test of the whole tower is carried out by means of environmental excitation. Considering the structural characteristics of the transmission tower, the on-site test sensor adopts 941B type vibration pickup suitable for high flexible structure, low frequency and large amplitude parameter acquisition. After several tests and comparisons, point 6 was selected as the reference point. Four channels are used for measurement. Each time, the x and y directions of the sixth reference point and the x and y directions of a measuring point are measured. In this way, a total of 40 groups were measured to obtain the vibration response data of all measuring points. The measured natural frequency of the transmission tower is within the range of 5Hz, and a total of 6 modes are identified. Figure 3 shows the first 6 modes of the transmission tower acquired and processed. Table 1 lists the sixth order modal parameters.

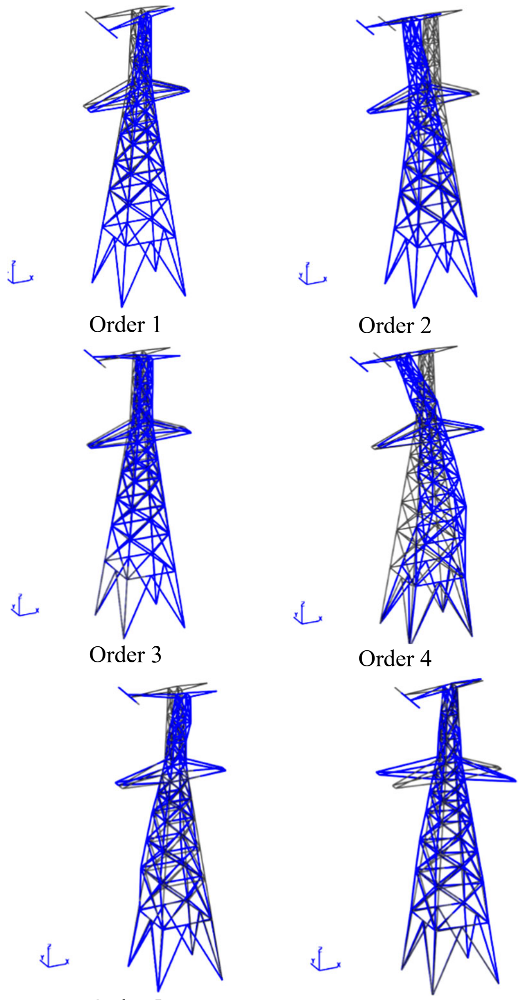

Figure 3. Sixth order vibration mode of transmission tower before field test

Table 1. Sixth order modal parameters of transmission tower before field test

Order	***Modal Shape***	***Frequency***
1	First order bending in y direction	2.20
2	First order bending in x direction	2.55
3	First-order torsion	3.10
4	X-direction second-order bending	4.00
5	Y-direction second-order bending	4.10
6	Second-order torsion	4.65

4. Finite element modal analysis of transmission tower

4.1 Model establishment

The transmission tower is a spatial high-rise steel structure connected by angle steel. Each member in the structure mainly bears the combined action of axial force and bending moment, and should be modeled as a tension (compression) bending member. Therefore, the assumption of rigid frame model is adopted, that is, the geometric model of the iron tower is established according to the actual structure size. Considering the joint rigidity and the secondary internal force of the members, beam element Beam188 is used to disperse all members, and the members are connected by rigid nodes. During finite element modeling, each member is represented by its centroid, ignoring the specific structure at the connection, and only considering the connection quality [20,21].

Finite element modal analysis model is established for 100 # tower of the line, as shown in Figure 4. The tower is 30m in height, 45m in total height and 12.876m in root opening. The main limb of the tower is connected by Q420 and Q345 angle steel of different specifications, and the inclined material is connected by Q235 angle steel of different specifications.

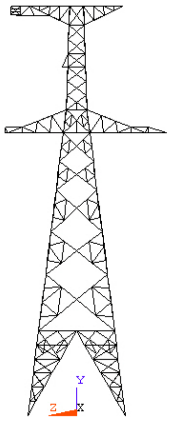

Figure 4. Finite element calculation model of transmission tower

4.2 Modal Analysis

Using the established finite element model of the transmission tower, the first 8 frequencies and vibration modes of the corner tower are calculated, and the results are listed in Table 2. From the first six order results, it can be seen that the measured vibration mode is consistent with the simulated vibration mode, and the measured frequency is also very close to the simulated frequency. According to the parameter values obtained from the field modal test and the comparison of the calculated modal results, the modal analysis results of the finite element dynamic model of the transmission tower show that the frequency simulation value of the finite element analysis is too large, but it is close to the measured frequency, and the vibration modes of each order are basically consistent. This model can be used as the reference model for finite element dynamic characteristic analysis.

The first three order calculated vibration modes are shown in Figure 5-Figure 7. Using this model, continue to calculate the modal parameters of the seventh and eighth order. The vibration modes are shown in Figure 8 - Figure 9. It can be seen that the local vibration modes of the tower body inclined members appear from the seventh order mode of the structure.

Table 2. Comparison between measured mode and calculated mode

Order	*Test mode*	*Test frequency*	*Calculated mode*	*Calculated frequency*
1	First order bending in z direction	2.20	First order bending in z direction	2.20
2	First order bending in x direction	2.55	First order bending in x direction	2.58
3	First-order torsion	3.10	First-order torsion	3.34
4	X-direction second-order bending	4.00	X-direction second-order bending	4.19
5	Z-direction second-order bending	4.10	Z-direction second-order bending	4.14
6	Second-order torsion	4.65	Second-order torsion	4.73
7				5.17
8				5.99

The first order vibration mode of the tower shows the first order bending dominated by the overall Z direction, accompanied by the X direction bending, and the maximum offset point occurs at the end point of the bottom line support inside the corner tower.

The second order vibration mode shows the first order bending dominated by the overall X direction, accompanied by the Z direction bending, and the maximum offset point occurs at the end point of the bottom line support inside the corner tower.

The third order vibration mode shows the overall first order torsion, the rotation axis is approximate to the Y direction, and the maximum offset point occurs at the top of the bottom line support inside the corner tower.

The fourth order vibration mode is the second order bending dominated by the overall X direction, accompanied by the Z direction bending, and the maximum offset point occurs at the end point of the bottom line support inside the corner tower.

The fifth order vibration mode is the second order bending dominated by the overall X direction, accompanied by the Z direction bending, and the maximum offset point occurs at the end point of the bottom line support inside the corner tower.

The sixth order vibration mode is the overall second order torsion, the rotation axis is approximate to the Y direction, and the maximum offset point occurs at the top of the bottom line support inside the corner tower.

The 7th mode shows that the overall first order X direction bending is coupled with the local mode in the middle of the tower body. There is a bulge at the bottom of the tower body, and the maximum displacement occurs at the bottom of the tower body.

The 8th order vibration mode is shown as the local vibration mode in the middle of the tower body. The middle of the tower body has a bulge deviating from the XY neutral plane and a depression deviating from the XZ neutral plane. The bottom of the tower body has a bulge deviating from the ZY neutral plane and a depression deviating from the XY neutral plane. The maximum displacement occurs in the middle of the tower body.

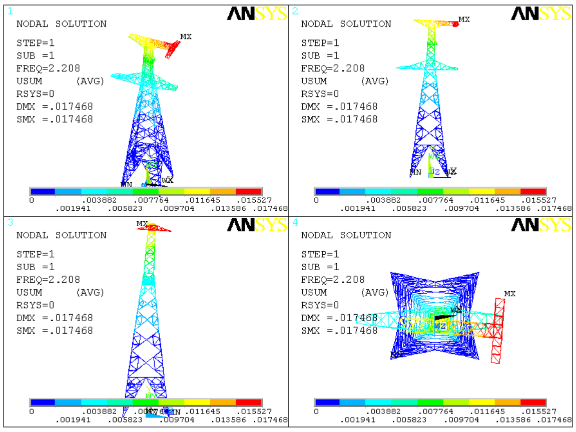

Figure 5. 1st order calculated modal shape

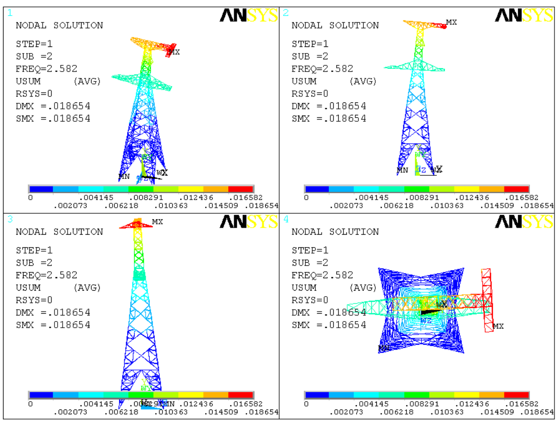

Figure 6. 2ed order calculated modal shape

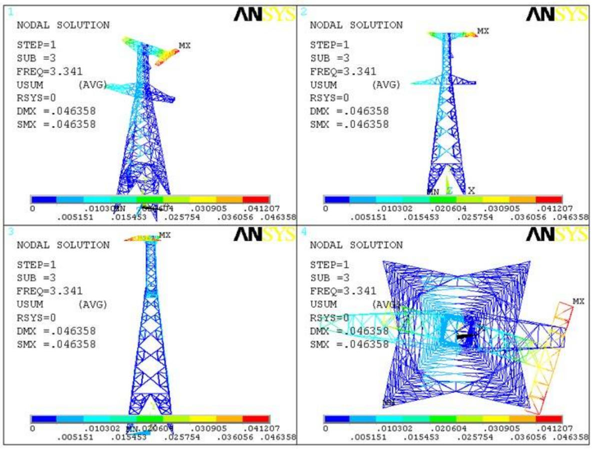

Figure 7. 3rd order calculated modal shape

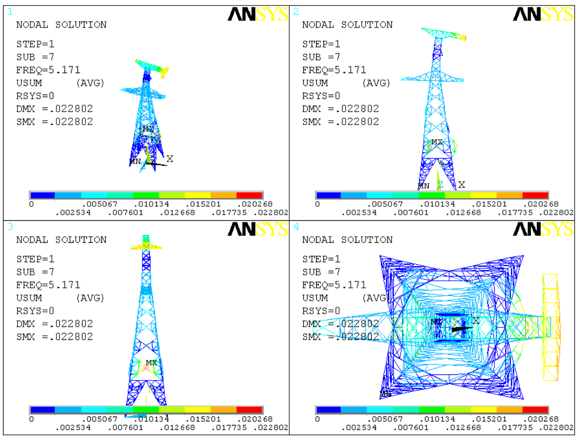

Figure 8. 7th order calculated modal shape

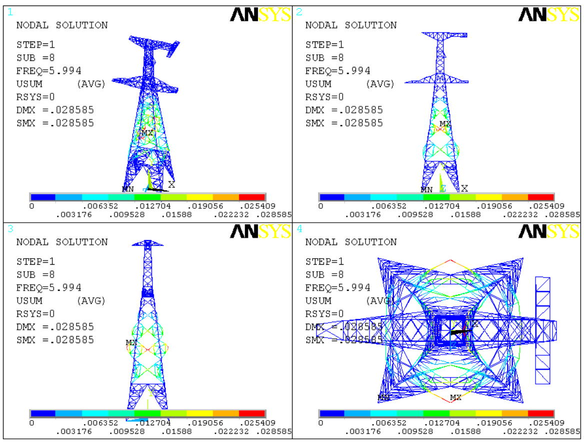

Figure 9. 8st order calculated modal shape

5. Result analysis

(1) The environmental excitation method was used to carry out the field test modal analysis of the actual line operating tower. According to its main bearing structure, a total of 40 measuring points were designed to collect the vibration parameters of the transmission tower, and the corresponding physical structure input model was established. Finally, the first six natural frequencies of the tower were obtained, which were 2.20Hz, 2.55Hz, 3.10Hz, 4.00Hz, 4.10Hz, 4.65Hz in turn. At the same

time, the corresponding vibration mode of each frequency was obtained, The third and sixth order are torsional vibration modes. Considering the bearing characteristics of the corner tower during operation, the vibration source of this frequency in the working environment should be avoided as far as possible to avoid resonance;

(2) A finite element modal analysis model has been established for the above transmission tower. By comparing the measured and calculated results, it can be found that the frequency in the calculated modal analysis results is very close to the field measured frequency, with the maximum error of 7.74%, less than 10%. Among them, the calculated modal analysis value is too large, and the vibration mode is basically the same. This result is completely acceptable for studying the structural performance of large high-rise structures such as transmission towers, The established finite element modal analysis model of the tower can be used to calculate the dynamic characteristic parameters of the tower.

(3) A higher order modal calculation of the tower is carried out by using the finite element modal analysis model. It is found that when the tower has a high order natural frequency resonance, local vibration modes appear in the middle and bottom of the transmission tower. The weak link lies in the intersection of the longest webs. The node has the largest deformation displacement, which may lead to instability. In order to avoid local vibration hazards, the method of increasing local stiffness can be used to change its dynamic characteristics, such as attaching angle steel inside for welding and reinforcement, Add auxiliary rods, etc.

(4) For this particular structure, the natural frequency of the tower is required to deviate from the frequency of the vibration source in the working environment as much as possible during design to avoid resonance. Similarly, the previous vibration modes of the structural modal analysis results should also deviate from the frequency of the vibration source in the working environment as much as possible.

6. Epilogue

According to the characteristics of transmission line angle steel tower, which is a kind of large and high-rise structure, it is determined to use the modal test method based on environmental excitation to carry out field test modal analysis on a typical transmission line angle tower. The analysis principle, measurement point layout, acquisition method, equipment selection, etc. of the field test are introduced, and the dynamic characteristic parameters of the transmission tower are obtained.

The finite element calculation model of the transmission line angle steel tower is established, and the reliability of the finite element calculation results is verified by using the results of the field test modal analysis. Compared with the field measurement, the dynamic characteristics of the transmission tower can be calculated by using the finite element method, which can greatly reduce the cost of manpower, material resources and time. Therefore, it is important to obtain a reliable finite element model for studying the mechanical properties of this kind of high-rise large structures.

All kinds of open-air high-rise steel structure towers are under the action of dynamic load for a long time during operation, so it is very necessary to study and obtain their dynamic characteristics. The method of modal measurement of steel structure towers proposed in this paper and the finite element model established have important practical significance for the design optimization and safety evaluation of steel structure towers from the aspect of dynamic characteristics.

Acknowledgements

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