Influence of Transmission Lines on Dynamic Characteristics of Transmission Tower

Qilong Hu, Heng Zhang and Xudong Chen
Xi’an Thermal Power Research Institute Co., Ltd., 99 Yanxiang Road, Xi’an, 710054, China
Correspondence should be addressed to Qilong Hu; huqilong@tpri.com.cn

Abstract: The influence of transmission lines on dynamic characteristics of transmission tower should not be ignored due to the heavy quality of transmission lines. The finite element models of independent tower and transmission tower-line system are established by ANSYS. The modal analysis is carried out to study the influence of transmission lines on dynamic characteristics of transmission tower. Meanwhile, it is verified by experimental modal analysis. Results show that, the tower-line coupling effect has a great influence on dynamic characteristics of transmission tower. The coupling effect strengthens the vibration intensity. In terms of frequencies, it mainly affects longitudinal bending mode and torsional mode frequencies of transmission tower, but has little effect on transverse bending mode frequency. Therefore, the influence of tower-line coupling effect must be considered in vibration reduction design of transmission tower-line system.

1. Introduction
Transmission tower is a typical lattice space structure with characteristics of high structure, large span, small damping and strong flexibility. It is susceptible to wind-induced dynamic excitation. Transmission tower collapse caused by wind-induced vibration has been widely reported, which has caused huge economic losses [1]. The influence of transmission lines on dynamic characteristics of transmission tower should not be ignored due to the heavy quality of transmission lines. At present, the vibration control of transmission towers mainly uses tuned mass damper (TMD). The effectiveness of vibration control using TMD mainly depends on accurate estimation of the dynamic characteristics of controlled structure. The tower-line coupling effect must be considered in design of TMD, otherwise the vibration control effect will be seriously reduced [2].

Many studies have been carried out by domestic and abroad researchers to investigate the transmission tower-line coupling effect. Considering the difference of transmission tower dynamic response under different frequencies and the interaction between tower and line, Ozono et al [3] established different transmission tower-line system models in high and low frequency bands for different needs. Li et al [4-5] established a lumped mass model of transmission tower-line system, which was used to study the influence of tower-line coupling effect on dynamic characteristics of transmission tower. Liang et al [6] proposed a multi-degree-of-freedom system calculation method for dynamic characteristics analysis of long span transmission tower-line system, and an engineering example was analyzed. They pointed out that, in the longitudinal direction, the low order natural frequencies of transmission tower decrease due to tower-line coupling effect; however, in the transverse direction, the coupling effect has little effect on the natural frequencies. Yuan et al [7] and
Zhang et al [8] established the finite element (FE) model of transmission tower-line system, and the influence of transmission lines on dynamic characteristics of transmission tower was analyzed.

In this paper, based on a transmission tower model, the FE models of independent tower and tower-line system are established. The influence of transmission lines on dynamic characteristics of transmission tower is analyzed, and is verified by experimental modal method. The study results can provide guidance for design of transmission tower-line system vibration reduction.

2. FE model

Figure 1 shows the transmission tower model. The tower is cup-type with a height of 1.80 m, a head width of 0.80 m, and a root opening width of 0.40 m. It is composed of angle steel and flat steel. The cross section of main body is square. The bottom of the tower is fixed to ground with glass glue. Its total weight is 18.2 kg. Meanwhile, the transmission line is ZR-BVR multi-core copper wire cable with single layer plastic insulation. Its cross-sectional area is 16 mm², and the mass of unit length is 0.175 kg/m.

![Figure 1. Transmission tower model.](image)

In this paper, the FE models of transmission tower and transmission tower-line system are established by ANSYS. The entire body of towers adopts beam-link mixed model. Beam188 elements are used to simulate the main materials and main auxiliary materials, and link8 elements are used to simulate the other auxiliary materials and insulators. The transmission lines are simulated by link180 elements. Figures 2 and 3 show FE models of independent tower and transmission tower-line system, respectively.

![Figure 2. FE model of independent tower.](image)

![Figure 3. FE model of tower-line system.](image)

3. Dynamic characteristic analysis

3.1 Computational modal analysis

The vibration differential equation under external excitation is
\[ M \ddot{x} + C \dot{x} + Kx = F(t) \]  \hspace{1cm} (1)

where \( M, C \) and \( K \) are mass, damping and stiffness matrices of the system, respectively. \( \dddot{x}, \dot{x} \) and \( x \) are acceleration, velocity and displacement vectors, respectively. \( F(t) \) is the external excitation vector.

For undamped free vibration, the free vibration equation of the system is

\[ M \dddot{x} + Kx = 0 \]  \hspace{1cm} (2)

The characteristic equation is

\[ (K - \omega^2 M)A = 0 \]  \hspace{1cm} (3)

where \( \omega \) is natural frequency. \( A=(A_j) \) is \( n \)-order array composed of every coordinate amplitudes.

The condition that equation (3) has a nonzero solution is

\[ \det(K - \omega^2 M) = 0 \]  \hspace{1cm} (4)

All the natural frequencies of the system can be obtained by solving equation (4). Each natural frequency \( \omega_i \) corresponds to its own eigenvector \( A^{(i)} \), which is satisfied

\[ (K - \omega^2 M)A^{(i)} = 0 \quad (i = 1,2,...,n) \]  \hspace{1cm} (5)

The \( n \)th mode of the system can be obtained by normalizing \( A^{(i)} \).

### 3.2. Dynamic characteristic analysis of independent tower

Modal analysis of independent tower is carried out by ANSYS. The first three modes of independent tower are extracted by Block Lanczos method. The natural frequencies are listed in Table 1, and the corresponding mode shapes are shown in Figure 4.

| Order | Frequency/Hz | Mode shape          |
|-------|--------------|---------------------|
| 1     | 12.31        | Longitudinal bending|
| 2     | 22.05        | Torsional           |
| 3     | 27.20        | Transverse bending  |

![Table 1. Natural frequencies of independent tower.](image1.jpg)

3.3. Dynamic characteristic analysis of transmission tower-line system

The same method is used to modal analysis of transmission tower-line system. Considering only the influence of transmission lines on transmission tower, the first three modes of tower in tower-line system are extracted. The mode shapes are shown in Figure 5. The natural frequencies of independent
tower and tower-line system are listed in Table 2.

| Order                  | Frequency/Hz | Variation/% |
|------------------------|--------------|-------------|
| 1 (Longitudinal bending)| 12.31        | -10.89      |
| 2 (Torsional)          | 22.05        | -49.98      |
| 3 (Transverse bending) | 27.20        | -3.01       |

Table 2. Frequency comparison of tower-line system and independent tower.

It can be observed from Figures 4 and 5 that the coupling effect strengthens the free vibration intensity of the tower, so the vibration control for tower-line system is more important.

Table 2 indicates that the coupling effect mainly affects longitudinal bending mode and torsional mode frequencies of transmission tower, but has little effect on transverse bending mode frequency. The transmission lines have great influence on longitudinal bending mode and torsional mode frequencies of transmission tower, reaching -10.89% and -49.98% respectively. Therefore, the influence of tower-line coupling effect on transmission tower frequencies must be considered in the design of TMD.

4. Experimental verification
To verify the results of the finite element analysis, modal experiments are carried out on the transmission tower model mentioned above.

4.1. Experimental modal analysis
Laplace transform is used for both sides of Equation (1). The equation is obtained

\[
(Ms^2 + Cs + K)X(s) = F(s)
\]

It can be rewrite as

\[
Z(s)X(s) = F(s)
\]

\[
X(s) = H(s)F(s)
\]

where \(Z(s)=Ms^2+Cs+K\), \(H(s)=[Z(s)]^{-1}\).

Let \(s=j\omega\), then the frequency response function \(H(\omega)\) in frequency domain can be expressed as

\[
H(\omega) = X(\omega) / F(\omega)
\]

\(H(\omega)\) contains information of modal shapes and frequencies. Once the frequency response functions are obtained by experiment, all modal information of the system can be obtained by modal
parameter identification technology.

4.2. Test rig and test method

In this paper, a test rig for dynamic characteristics of transmission tower-line system is built (see Figure 6). The transmission line is 1.55 m away from the ground, and its single span is 5 m. The test system is composed of force hammer (including force sensor), acceleration sensors, charge amplifier and 652U dynamic signal analyzer of IOTECH Company Limited.

![Figure 6. Transmission tower-line system dynamic characteristics test rig.](image)

The multiple input single output (MISO) method is used in the test. With different nodes excited by pulse which is output by a force hammer, the frequency response functions in two directions of 7th node (see Figure 7) are obtained by eZ-Analyst dynamic signal analyzer. Then modal parameters were identified by modal identification software ME'scope.

![Figure 7. Nodes in modal experiment.](image)

4.3. Experiment results

In order to reduce the random error and improve the accuracy of tests, each group of tests is carried out for 5 times, and the average values are taken as the frequency response function. Figure 8 shows the frequency response function of a measuring point.

![Figure 8. Frequency response function of a measure point.](image)

After the tests and modal identification, the first three modal shapes of independent tower (shown in Figure 9) are obtained, which are demonstrated as longitudinal bending, torsional and transverse bending, respectively.
Considering only the influence of transmission lines on transmission tower in modal identification of transmission tower-line system, the first three modal shapes can be obtained. The modal shapes are the same as those of independent tower.

The natural frequencies of independent tower and tower-line system obtained by modal experiments are listed in Table 3. It can be observed from Table 3 that the coupling effect mainly affects longitudinal bending mode and torsional mode frequencies of transmission tower, but has no effect on transverse bending mode frequency. The experiment results are consistent with the finite element analysis results.

![Figure 9. First three mode shapes of independent tower obtained by modal experiments.](image)

Table 3. Frequency comparison of tower-line system and independent tower obtained by modal experiments.

| Order                          | Frequency/Hz | Variation/% |
|-------------------------------|--------------|-------------|
| Independent tower             | Tower-line system |          |
| 1 (Longitudinal bending)      | 12.25        | 10.63       | -13.22 |
| 2 (Torsional)                 | 25.25        | 13.63       | -46.02 |
| 3 (Transverse bending)        | 26.88        | 26.88       | 0      |

5. Conclusion

In this study, the finite element analysis and experimental modal analysis of independent tower and transmission tower-line system are carried out. The influence of transmission lines on dynamic characteristics of transmission tower is studied. The main conclusions involved are as follows:

1. The tower-line coupling effect can strengthen the free vibration intensity of transmission tower.
2. The coupling effect mainly affects longitudinal bending mode and torsional mode frequencies of transmission tower, but has little effect on transverse bending mode frequency.

The results indicate that the tower-line coupling effect has a significant impact on dynamic characteristics of transmission tower. The influence of tower-line coupling effect on transmission tower frequencies must be considered in the study of dynamic characteristics of long-span transmission tower-line system and design of TMD.

Acknowledgments

The authors would like to extend their sincere thanks to staffs at Xi’an Thermal Power Research Institute Co., Ltd., China, for the support and experimental tests.

References

[1] Wang J, Fu X and Li H N 2020 Dynamic Analysis of a Transmission Tower-Line System under Wind Loading with Multiple Factors Journal of Shenyang Jianzhu University (Natural Science) 36 1-10.
[2] Zhai C H, Wu G, Li S and Xie L L 2012 Tower-Lines In-Plane Coupling and TMD Seismic
Control of Large Crossing Transmission Tower Lines System *Journal of Vibration Engineering* **25** 431-438.

[3] Ozono S, Maeda J and Makino M 1988 Characteristics of In Plane Free Vibration of Transmission Line Systems *Engineering Structures* **10** 272-280.

[4] Li H N, Shi W L and Jia L G 2004 Simplified Aseismic Calculation Method Considering Effects of Lines on Transmission Tower *Journal of Vibration Engineering* **23** 1-8.

[5] Li H N and Wang Q X 1997 Dynamic Characteristics of Long-Span Transmission Lines and Their Supporting Towers *China Civil Engineering Journal* **30** 28-36.

[6] Liang S G, Zhu J H and Wang L Z 2003 Analysis of Dynamic Characters of Electrical Transmission Tower-Line System with a Big Span *Earthquake Engineering and Engineering Vibration* **23** 64-69.

[7] Yuan Z F and Cheng H 2017 Influence of Conductors on Dynamic Characters of Transmission Tower *The World of Building Materials* **38** 73-77.

[8] Zhang Q, Fu X, Ren L and Jia Z 2020 Modal Parameters of a Transmission Tower Considering the Coupling Effects between the Tower and Lines *Engineering Structures* **220** 110947.