# Design of Transmission Line System's Full Aero-elastic Model and Analysis of its Dynamic Behavior

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**ABSTRACT:**

The model's aerodynamic shape, mass and stiffness distribution have been controlled strictly when the full aero-elastic model of transmission line system is manufactured and tested in wind tunnel. Insulator Strings and spacers have been designed and made according to the comparison principle of aerodynamic shape and mass. The boundary constraint of the system has simulated actually its dynamics character. The dimensionless mode and frequency of the model also consist with the performance of prototype system. So it's a full aero-elastic model of transmission line system, and its tested result is more dependable and is a true copy of prototype according to the dynamic characteristics's comparison. The proposed model and the design method are successful in the simulation of static and dynamic action when studying the coupling action of the transmission line system.

**KEYWORDS:** transmission line system, full aero-elastic model, dynamic characteristics, coupling action

## 1. INTRODUCTION

The tower-line coupling system, as an important composition of the electric system constantly working in the open country, is affected by various natural factors, especially for the most frequent wind-induced. Because of the nonlinear line, the high-rise tower structure, the tower-line coupling effect, and also the gas-solid coupling interaction, they form a very complicated dynamic coupling system (Liang Shuoguo et al, 1999; Xun Bing-nan et al, 2005; Li Hongnan and Wang Qianxin, 1997; Liu Qun et al, 1997; Han Yinquan, 2008).

It's the key technical problem in the full aero-elastic model's design of the tower-line system, how to simulate correctly its wind-induced static and dynamic responses. The model's aerodynamic shape should be similar to that of the antetype, and its some dimensionless parameters, Strouhal number, Froude number, Cauchy number, Scruton number, damping ratio, etc should be similar to also, which are crucial to ensure the dynamical similarity. Therefore, the full aero-elastic model of the transmission tower-line system needs a high accuracy, and its manufacturing process is difficult and complicated greatly. The design idea and technique referred is practicable and has some reference for the aero-elastic model design of the similar structures.

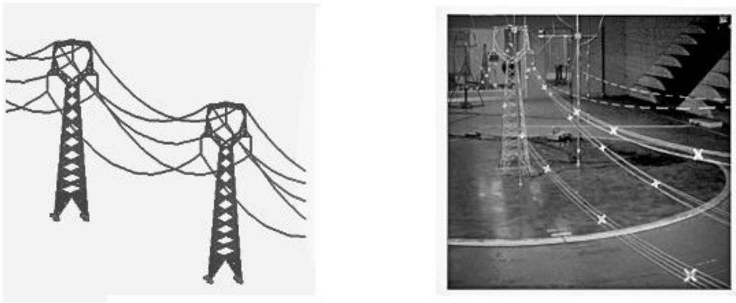
In order to explore the objective law, some existing research results, both forreign and domestic, have been analyzed about their common ideas and disparities firstly, and then two kinds of model towers, transmission line sets XA and XB are designed. The two line sets are hung up separately on each model tower to make modal analysis of tower-line coupling systems.

## 2. MODEL DESIGN

### *2.1 Engineering Situation*

Chosen the Qianxi-Nanchang 500kV transmission tower-line system as the prototype, the latticed cathead tower's main members are angle steels, and its height is 48.50m, its sapn 400m, its practical height 39m. The long rod suspension composite insulator and three-phase conductors are using in the system. The horizontal interval between two side phases is 15m, and the interval of the side-middle phases 11.336m, which composes of 4-bundle conductors with the bundle spacing 45cm (4×LHGJT-440), and the cruciform damp spacers' interval 20+45+60+45+60+45+60+45+20m, and the ground wires are alvanized steel strands (2×GJ-196). The tower-line system's circuit diagram is shown in Figure 1, in which (a) is the calculation model, (b) is the real model in the wind tunnel.

The transmission line is more in exposure category B of the rural open areas with the gradient level 350m, and its mean wind profile has the index distribution of the roughness α=1.6. The return periods of the basic wind pressure 0.30, 0.45 and 0.55kN/m2 are 10, 50 and 100 years respectively, and the biggest mean wind velocity in which period are 21.9, 26.8 and 29.7m/s, while that of tower top are 28.2, 34.5 and 38.2m/s.



(a) calculation model (b) real model in the wind tunnel

Figure 1 Transmission tower-line system

### *2.2 Model design of transmission tower*

The special lattice tower' frame's integral stiffness, mass and damping depend mainly on the material and the constraint form of the spatial members, the joint plates and the tower's bearings. To reflect and simulate really the influence of each component on the whole tower's dynamic characteristics, the spatial distributions of stiffness, mass and members of the full aero-elastic model are similar to that of the prototype, that is the key technique in the model's design and its making process. Considered the size limit of the wind tunnel test section (2×15×14m), the geometry scale ($\lambda_L$) of the model is chosen $\lambda_L$=1:30, then the model's height is 1.617m, and the blockage ratio is less than 5% expected.

To satisfy the dynamic similarity criteria and the making feasibility, the model's Strouhal number and Froude number are similar to that of the prototype, but the Reynolds criterion is not strictly performing, that is, the wind speed scale ($\lambda_U$) is $\lambda_L^{0.5}$, and the frequency's scale ($\lambda_n$) is 1:$\lambda_L^{0.5}$. So all the design wind speed of the prototype are simulated among the wind speed scope of the wind tunnel.

The tower's members are regarded as two force members to simplify the mechanical analysis, and the tension stiffness scale of every member ($\lambda_{EA}$) is $\lambda_L^3$, which obeys the Cauchy number similarity condition. The light-weight ABS plastic board is used to enwrap the member to satisfy the aerodynamic configuration's similarity, and appropriate lead wire is fixed in the right angle to satisfy the mass scale $\lambda_m = \lambda_L^3$.

Stainless needle tubes are chosen to simulate the tower's corner columns, which satisfy the tension stiffness's similarity and the invariability of main members' material. Considering that some slant rods and transverse layer's members have only a few influence on the tower's dynamic characteristics, and it is very difficult to choose the appropriate material satisfied the tension stiffness's similarity, their material use the stainless piano string with the diameter of 0.21mm to provide the tension stiffness, so the stiffness is more than the expectation. Based on the analysis above, all the model's scale are collected as shown in Table 1.

Table 1 Some scales of the full aero-elastic model (*n*=1:30)

| Similarity ratio | length | Wind speed | frequency | tension stiffness | mass | Damping |
|---|---|---|---|---|---|---|
| Formula | $n$ | $n^{0.5}$ | $n^{-0.5}$ | $n^3$ | $n^3$ | 1 |

*2.3 Model design of the line*

According to the the geometry scale $\lambda_L$ of 1:30, it is very difficult to fit the two-span model in TJ-3 boundary layer wind tunnel that does not have such a wide section. Therefore, applied the distorted modelling technique of transmission lines (Davenport and Loredo-Souza, 2001), the line's new geometry scale $\lambda_{Ll}$ is then

$$\lambda_{Ll}=\gamma\lambda_L \quad (1)$$

where $\gamma$ is the correction coefficient of the new length scale in the distorted model ($\gamma$=0.5).

The largest Reynolds numbers ($R_e$) of lines in the wind tunnel and in the real entironment are all in the subcritical range, so the drag coefficient $C_D$ and $Re$ are independent and constant. When the line's outer diameter scale $\lambda_{Dl}$ is adjusted to be 1:15, that is, $\lambda_{Dl}=\lambda_L/\gamma$, the windward area scale is calculated to be the square of $\lambda_L$. So the wind drag scale is deduced to be the cube of $\lambda_L$, just as other load scale.

In order to study the tower-line dynamic coupling effect, the line model's frequency scale ($\lambda_{nl}$) must be equal to the tower model's, that is, $\lambda_{nl}$ is equal to $\lambda_n$ through adjusting the line's sag, so the sag scale ($\lambda_{sl}$) is calculated to be 1:30. To satisfy that the line's mass scale ($\lambda_{Ml}$) is the cube of $\lambda_L$, the model's linear density scale ($\lambda_{ml}$) should be

$$\lambda_{ml}=\lambda_L^2/\gamma \quad (2)$$

Considered the similarity condition of Cauchy number, the tension stiffness scale of the model's mandrel is ensured to be the cube of $\lambda_L$, so the mandrel's diameter ($d_m$) is solved as follows

$$d_m=\sqrt{4\gamma\lambda_L^3[EA]_P/(\pi E_m)} \quad (3)$$

where $[EA]_p$ is the tension stiffness of the real line and $E_m$ is the elastic modulus of the model's mandrel.

According to Eqn 3, the stainless steel wire is used to simulate the line, and its diameter is calculated by the tension stiffness scale. But its external diameter and linear density are less than that calculated by the scales of the aerodynamic configuration and the mass, so it must use a package of plastic tube inserted the adequate lead bar.

*2.4 Design of the insulator string and the phase spacers*

Compared with the tower and line, the insulator string with the less size and larger stiffness relatively is simplified as the rigid rod with two hinged ends. So the mass of the copper tube with the size Φ4x1 mm choosed is simulated mainly that of the real insulator, and the umbrella ABS plastic board with diameter 8mm and equally spaced 10mm is used to simulated the insulator's wavy contour.

The phase spacer plays an important role in fixing the line, controlling the aeolian vibration and the subspan oscillation, so its close leaf spacing and spacers' laid space are designd respectively on the scale $\lambda_{Dl}$ and $\lambda_{Ll}$, meanwhile, the its mass scale is the same as the scale $\lambda_{Ml}$.

*2.5 Design of the system's boundary condition*

In order to simulate the real boundary condition, two equivalent towers are designed, which are used as the boundary towers in the four-span system shown in Figure 2. The scales of their overall dimension and mass are respectively the same as the scale $\lambda_L$ and $\lambda_m$, and their former two-class nature frequencies are very similar to that of the forenamed model tower by adjusting the connecting height of the diagonal studdles and the axostyle.

Through the insulator string, the line is hung in the proper spatial position of the equivalent tower, and its end is connected in series with the spring fixed in the wind tunnel's wall, which has an appropriate length in order to let the insulator hang downward in no wind case.

## 3. KEY MANUFCTURE CRAFT

The actual manufacture technic of the full aero-elastic model is very complex, especially in some detail steps. But it is the basic guarantee of the vibration mode and frequency calculated and expected that the model's aerodynamic configuration, the spatial distribution of the mass and stiffness are designed on the dynamic similarity theory strictly.

### *3.1. Similarity design of the mass's spatial distribution*

Along the vertical axis of the transmission tower, the mass's distribution has certain irregularity, the cat head is more heavy relatively the other part, and its meass has a spatial continuity, so it is very difficult to simulate completely the distribution. Regarding the semi-rigid model, the fundamental mode of the model with additional mass is usually satisfied the similarity rule, but the other order modes is difficult to obey the rule. The additional mass located usually on the tower head, which is used to obtain the tower's fundamental mode as soon as possible, can easily cause the whiplash effect and lead to other modes distorting.

Therefore, the additional mass of the full aero-elastic model should be calculated by the mass scale and spatial distribution strictly, and it is fixed in the model as piecewise and dispersedly as possible.

Considering the marked local modes of the reduced scale model's slant rods, the adding mass will easily cause the local modes aggravating, so the mass matched in the tower body is located on the model's corner columns to reduce the influence of local modes as small as possible.

### *3.2. Similarity design of the stiffness spatial distribution*

Whether the model's dimensionless vibration mode and frequency are satisfied the the similarity depends greatly on the spatial distribution of model's stiffness which completely conforms to that of the antetype. Therefore, the similarity design of the stiffness spatial distribution is one of the most important steps in the full aero-elastic model's process.

Usually, the global stiffness distribution of the cantilever structure along its vertical axis has certain regularity, and mostly present the multi-step inverted trapezium. So the stiffness of every segment intersected is regarded as a constant, and the core material with different section is selected to simulate the equivalent stiffness of different segment, then the gossamery ABS plastic board is used to simulate the member's aerodynamic configuration.

For the transmission tower's head with broaden size and short members comparatively, its stiffness is bigger than that of other tower segment. The tower in engineering practice is usually designed to be asymmetric structure, namely the tower has two different axial stiffness in the cross section. At the same time, the line hung on the tower has an appreciable restriction effect on the tower. Therefore, this model gives up use the traditional method, that the steel plate is adopted to simulate the trapezium distribution of the stiffness. The main members are designed according to the stiffness scale strictly, but some local linking members are relaxed the stiffness requirement.

In the model processing, each member's coat is gapped 1mm regularly to avoid the stiffness increase, but the coat on the joint plate is one-piece simulated the joint's active mechanical action, and this technique could guarantee the force transmission route between the members only along the core material (stainless needle tube and steel wire). Similarly, the line's coat and lead wire matched are parted with the regularly spacing.

## 4. DYNAMIC CHARACTERISTIC CALCULATION AND CALIBRATING EXPERIMENT

### *4.1. Vibration modes and frequencies*

The modal analysis of the tower and line is made by Ansys software separately. Some partial members' vibration mode has an interferential effect on the tower's integral mode, therefore the calculation model of the cantilever bar with lumped mass is established, and the corresponding flexibility matrix and the mass matrix are extracted to simplify the computation of modes. Before and after the lines be hung on the tower models, one fixed on the wind tunnel turntable and the other two equivalent towers on both sides, the dynamic characteristic of the single tower model, the line and the tower-line coupling system are respectively calibrated by the hammering test. The results obtained are shown in Tables 2, 3, and 4.

Table 2 Contrasting line's frequencies

| Comparing terms | conductor | | ground wire | |
|---|---|---|---|---|
| Mode description | Out plane | In-plane | Out plane | In-plane |
| Antetype (Hz) | 0.15 | 0.31 | 0.16 | 0.32 |
| calculated by ANSYS (Hz) | 0.84 | 1.68 | 0.89 | 1.77 |
| ratio | 5.56 | 5.49 | 5.56 | 5.48 |
| hammering test (Hz) | 0.83 | 1.65 | 0.85 | 1.72 |
| ratio | 5.50 | 5.37 | 5.31 | 5.31 |

Table 3 Contrasting transmission tower frequencies

| Antetype (Hz) | Calculated (Hz) | ratio | calculated by ANSYS (Hz) | ratio | hammering test (Hz) | ratio | Mode description |
|---|---|---|---|---|---|---|---|
| 1.64 | 9.15 | 5.6 | 9.68 | 5.9 | 8.40 | 5.12 | In-plane |
| 2.22 | 12.39 | 5.6 | 13.1 | 5.9 | 11.33 | 5.10 | Out plane |
| 3.95 | | | 25.4 | 6.5 | 23.33 | 5.90 | Torsional |

Table 4 Contrasting tower-line system's coupling frequencies

| Antetype (Hz) | 1.53 | 2.45 | 3.76 | 3.99 | 4.32 |
|---|---|---|---|---|---|
| hammering test (Hz) | 8.15 | 14.1 | 20.3 | 21.7 | 23.1 |
| ratio | 5.33 | 5.76 | 5.75 | 5.44 | 5.35 |
| Mode description | In-plane | Out plane | Torsional | In-plane | In-plane |

### *3.2 Contrastive analyse*

The first several natural frequencies of the line are lower than that of the transmission tower obviously, and the ratio of the model's frequency to the prototype's satisfies the comparability. The maximal ratio in the torsional direction of single tower is reached 5.9:1, and the elative errors between the experimental value and the design value 5.48:1 is about 7.6%. The reason may be that, the member's tension stiffness was only taken into account when the equivalent stiffness was calculated according to the comparability, but the bend and shear stiffness is neglected.

Comparing the natural frequency of the tower-line coupling system and that of the single tower, the first three modes present the different change rule, that is, the first natural frequency in plane of the system is lower than that of the single tower, the system's second frequency out plane is bigger, and the system's third frequency in the torsional direction is lower again. But the first three mode shapes of the coupling system are the same as that of the single tower.

In the Ansys modal analysis process and the data results from the hammering test, the fundamental modes in arbitrary direction of the single tower and the tower-line coupling system are judged out because of the line's low serried frequency vibration and the influence from some slender members' vibration. Once the line's some order frequency is equal to that of tower's local member, the local vibration would be aggravated by the resonant effect. So the slender members and the line are easily caused the fatigue failure.

## 5. CONCLUSION

Based on the actual project of some transmission tower-line system, the design idea and manufacture technique of the full aero-elastic model are discussed, then the contrastive analyse of the model's dynamic characteristic and the antetype's is developed. Some useful conclusions are obtained as follows.

1. The light ABS plastic board and soft plastic tube are used to be the coat simulated the model's aerodynamic configuration, and the matching mass provided by the lead wire calculated is collocated in segments to avoid the stiffness increasing as same as the plastic coat. It is depended mainly on the stainless needle tube, piano string and wire to satisfy the stiffness scale. All these technologies are key to manufacture the full aero-elastic model.

2. The insulator strings and damping spacers are designed according strictly to the similarity theory of the aerodynamic configuration and the mass, and the boundary equivalent towers and the terminal constraints are fully simulated the mechanical characteristic of the real system.

3. The tower-line coupling effect should be taken into account, and the stiffness in or out plane of the tower is adequate to avoid its large variety when the lines are hung on.

4. This models are satisfied the similarity of aerodynamic configuration, the spatial distribution of mass and stiffness, and the models' dynamic characteristic is very similar to the expectation by the dynamic similitude theory. So its tested result is more dependable and is a full aero-elastic model, that is, the proposed model and the design method are successful in the simulation of static and dynamic action when studying the coupling action of the transmission line system.

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