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Rigid Model Design and Wind Tunnel Tests of Large Span Tower-Cable Network System

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Abstract

The structural system of an antenna station, comprising an ultra-high tower and a large span cable network with a tower height reaching 340m and a cable network span exceeding 1km, poses unique challenges in understanding wind-induced loads. The wind load distribution especially under strong wind action is relatively complex and may even control the design. Under the conditions of simulating the atmospheric boundary layer wind field and the terrain and features near the site, wind tunnel tests for rigid model were conducted using scale models (1:200 and 1:300 ratios) and the bottom reaction force response of the tower structure under different wind load conditions was obtained. Moreover, due to limitations in materials and testing sites, cable diameters were scaled up by 50 times during the wind tunnel test. Consequently, an investigation into the influence of different cable diameters on the drag coefficient of arc cables was also conducted.

Keywords: tower-cable network, wind tunnel text, rigid model, reaction force of the tower bottom

1. Introduction

The large span tower-cable network system is a flexible and towering structure due to the large span and light weight and the wind load is its main dynamic load[1]. The basal response caused by wind loads acting on the tower-cable system is very important for the design of foundations. The correctness and accuracy of the wind load response will directly affect the safety and design of the structure[2]. It is not possible to directly and perfectly solve these problems due to the scale of the actual structure and the limitations of the existing theory, so it is more economical and effective to design a rigid model wind tunnel force measurement test to determine the reaction force at the bottom of the tower-cable system for engineering design applications[3].

In Ref. [4], the towering transmission tower model was designed with 3D printing technology to carry out the high-frequency force balance test, and the vibration response of the transmission tower structure under wind loads was analyzed, but the overall model of the tower-cable system model was not designed for experimentally study. In Ref.[5], the aeroelastic model of the tower-cable system is designed and the wind tunnel test is carried out to study the wind vibration coefficient of the tower-cable system and the influence of the transmission line on the system under different wind directions. For the design of the wind tunnel model of long-span transmission lines, A.M. Loredo-Souza et al. proposed the polycondensation theory, introducing the polycondensation coefficient and increasing the cross-sectional size of the conductor wind tunnel model to facilitate experimental measurement, but it could not strictly meet the similarity principle[6]. The cable tower of the test object is composed of an edge tower, two middle towers and a central tower, with a tower height of up to 340m, whose body is a lattice steel tower with a triangular cross-section, and a tripartite fiber rope is arranged; The antenna network is composed of a diamond-shaped wire network including a top capacity line, a sling and a lower lead, and the maximum span is more than 1km.

2. Model and overview of the test

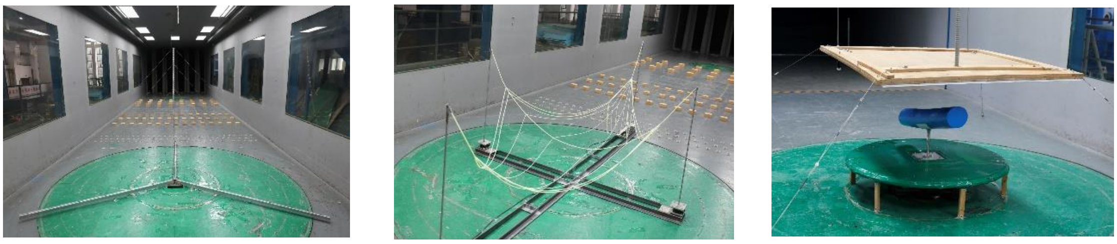
2.1 Model design

According to the requirements of rigid force test, the test model must meet the condition of geometric similarity ratio, sufficient stiffness and lighter weight. The test model is divided into two parts: tower model and cable network model, the tower model is one of each of the three types, using stainless steel pipe material; Four cable network models are made according to different length increased status which are the normal length status, the 1/3 length increased status, the 2/3 length increased status and the length increased to the ground status, and photosensitive resin materials are used by 3D printing. All models have sufficient strength and stiffness. The diameter of the original middle tower to be tested is 1244m, the height is 303m, combined with the cross-sectional size of the wind tunnel of Zhejiang University, the wind speed of the wind field and the feasibility of model making, the geometric similarity ratio of the tower structure is finally determined to be 1:200, and the geometric similarity ratio of the cable network structure is 1:300. However, after scaling according to the 1:300 similar ratio, the diameter of the cable model is too small(as is shown in the table 1), which is difficult to make and cannot meet the requirements of sufficient stiffness of the rigid model, so the diameter of the model is enlarged by 50 times, and a test on exploring the influence of different diameters on the drag coefficient of the arc cable is designed, and the conclusions are used for test data processing.

Table 1: Diameter of cable sections

cable section	diameter(mm)		
	original	model	enlarged model
drxf1b	32.7	0.109	5.45
drxf2b	21.4	0.071	3.56
ds	35.1	0.117	5.85
xyx	25.1	0.084	4.18

The ground beam is designed for the tower structure to be used as the foundation of the cable-stayed fiber rope, and the connecting plate is arranged in the center of the bottom beam to connect with the bottom force measuring balance, and the support column structure is designed for the cable network structure to support the structure, and the force is transmitted to the bottom force measurement balance at the same time. Stainless steel is used for the ground beam and support column structure.



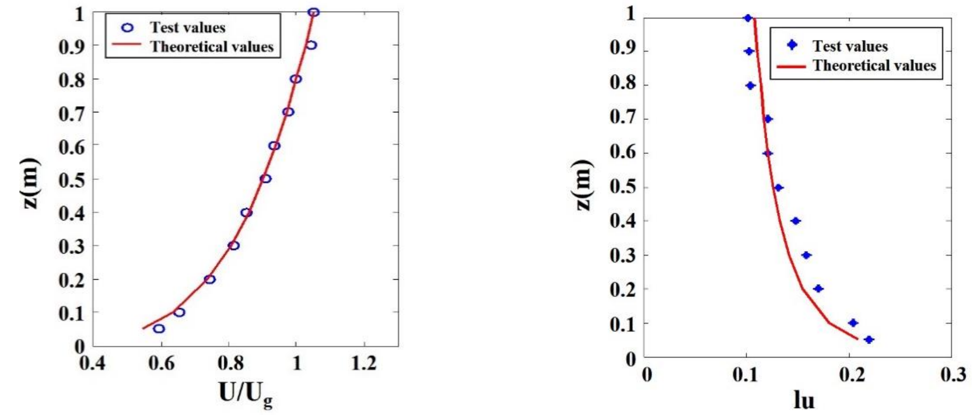
(a) Tower model (b) Cable networks model (c) Cable section model

Figure 1: Tower and cable models

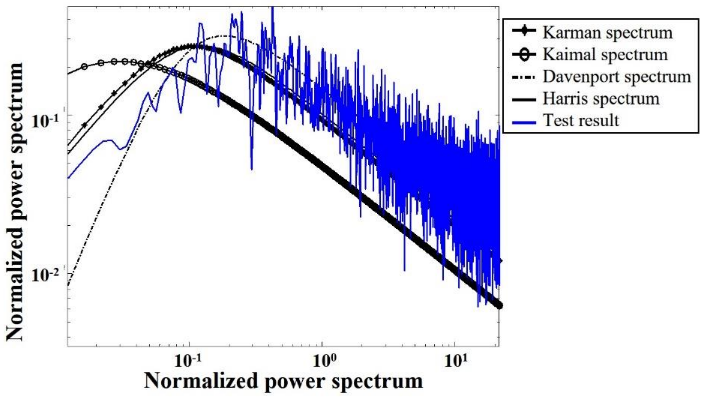
2.2 Simulation of the wind field in the atmospheric boundary layer

The test was completed in the ZD-1 boundary layer wind tunnel of Zhejiang University. The ZD-1 boundary layer wind tunnel is a hybrid structure type combining a single-return closed-mouth vertical steel structure and a concrete structure. The test section is closed-mouth, 18 meters long, with a cross-sectional size of 4 meters wide and 3 meters high, and the maximum wind speed in the wind tunnel is 55 m/s.

The test simulates the roughness of Class A floor, and the scale ratio is 1:300. The test section is equipped with an atmospheric boundary layer simulation device composed of minarets, rough elements and baffles. The measured wind field simulation results are shown in Figure 3. In the figure: Mourning coordinates f = nz/U where z is the height and U is the average wind speed at z. The test results show that the atmospheric boundary layer of the simulated test section is reasonable, and Figure 2-(c) shows the comparison results of the normalized power spectrum at a height of 0.6 m (the height of the original structure is 180 m), and the simulated power spectrum is the closest to the Davenport spectrum.



(a) Wind speed profile test results (b) Turbulence profile test results



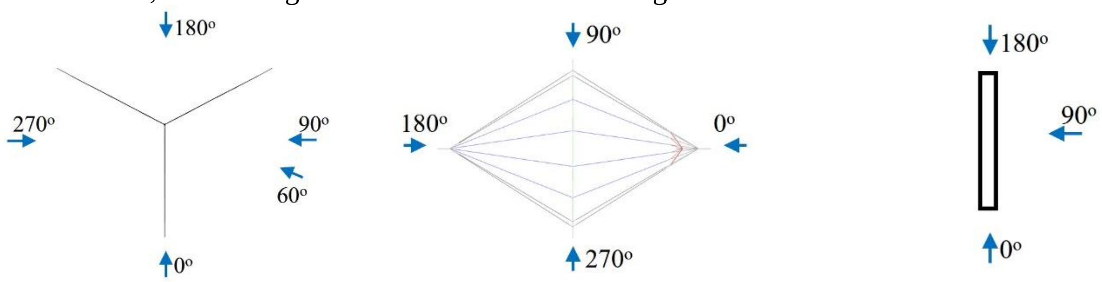
(c) Turbulent power spectrum

Figure 2: The stimulant results of atmosphere boundary layer

3. Test conditions and results

3.1 Test conditions

According to the symmetry of the tower, the wind direction angle of the tower model changes from 0°~60° at an interval of 5°, the wind speed is 10m/s, each wind direction angle is a working condition, a total of 13 working conditions; The wind speed of the cable network model test is 10m/s, each wind direction angle is a working condition, the wind direction angle changes from 0°~180° at an interval of 10°, a total of 19 working conditions; The arc cable section model test wind speed range from 5m/s to 25m/s at an interval of 5m/s, and the wind direction angle is 0~180° at an interval of 15°, a total of 65 working cases for each model. The arc cable section model is mounted on a turntable in the center of the cable section, and the angle of the turntable can be changed to simulate each wind direction.



(a) Tower model (b) Cable network model (c) Cable section model

Figure 3: Schematic diagram of wind direction

3.2 Drag coefficient of arc cable section under the maximum windward area

The drag coefficient Cd_X and Cd_Y of the arc cable section in the *X* direction (the direction of the vertical cable axis) and the *Y* direction (along the cable axis) are calculated as follows:

$$\mathrm{Cd}_X = \frac{W_X}{0.5\rho v^2 L d} \tag{1}$$

$$\mathrm{Cd}_Y = \frac{W_Y}{0.5\rho v^2 L_c d} \tag{2}$$

Where W_X is the wind load in the direction of the vertical cable axis, W_Y is the wind load in the direction of the cable axis, v is the wind speed, L is the arc length of the arc cable section, ρ is the air density, and d is the cable diameter.

In order to obtain a more conservative reference value of the drag coefficient, the drag coefficient is calculated when the windward area is the largest and the drag force is maximum. When the wind speed is 5m/s, the drag coefficient increases with the increase of diameter, the drag coefficient of the 0.25m diameter model is 1.496 times that of the 0.005m diameter model; When the wind speed is 10m/s, the drag coefficient decreases with the increase of the diameter, and the drag coefficient of the 0.25m diameter model is 0.697 times that of the 0.005m diameter model; When the wind speed is 15m/s, the drag coefficient of the 0.25m diameter model is 0.675 times that of the 0.005m diameter model; When the wind speed is 20m/s, the drag coefficient of the 0.25m diameter model is 0.628 times that of the 0.005m diameter model.

When the wind speed is 5 m/s, the drag coefficient increases with the increase of diameter due to the influence of the Reynolds number range. The simulation results show that when the Reynolds number is greater than 40000 and the drag coefficient is less than 1.0, the drag coefficient decreases with the increase of diameter. Therefore, in the test, the average value of the drag coefficient change multiples of wind speed of 10m/s, 15m/s, and 20m/s is 0.667 as the correction coefficient of diameter amplification.

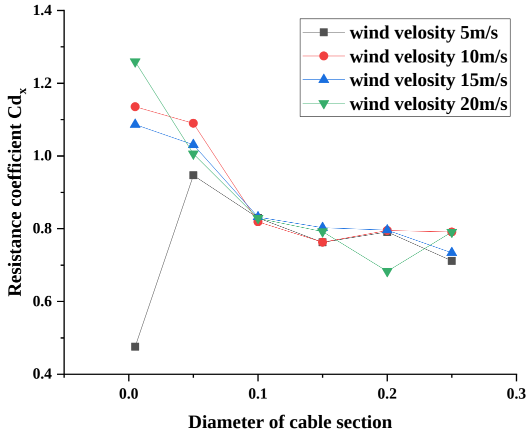


Figure 4: The drag coefficient of the arc cable section *Cd_x*

3.3 Base reaction response of tower-cable network system

The wind force F produced by the wind pressure acting on the surface of the structure is

$$\mathrm{F} = \frac{1}{2} v^2 S \tag{3}$$

Where ρ is the air density, v is the wind speed, and S is the windward area of the structure.

From the above equation, it can be deduced that the wind force similarity ratio in the air (assuming that the air density is constant) is

$$S_F = S_v^2 S_A \tag{4}$$

Where S_v is the similarity ratio of the wind speed, and S_A is the similarity ratio of the windward area.

The geometric similarity ratio of the tower structure is S_{lT}=1:200, and the geometric similarity ratio of the cable network structure is S_{lC}=1:300, which corresponds to the windward area ratio of the tower structure $S_{AT}=S_{lT}^2$=1:40000, and the cable network structure $S_{AC}=S_{lC}^2$=1:90000.

Due to the limitations of manufacturing process, material selection, measurement means, etc., the cable network structure model introduces the amplification factor λ to the cable diameter, that is, on the basis of the cable network structure model obtained under the geometric similarity ratio S_{lC}, the model diameter is amplified by λ times, and the modified windward area ratio of the cable network structure is $S_{AC\lambda}=\lambda S_{AC}$, and the comprehensive consideration is λ=50, then $S_{AC\lambda}=\lambda S_{AC}$=1:1800.

After exploring the influence of different diameters on the drag coefficient of the arc cable section, it is concluded that when the diameter is amplified by 50 times, the drag coefficient will decrease by 0.667 times, that is, the corrected drag coefficient ε=0.667

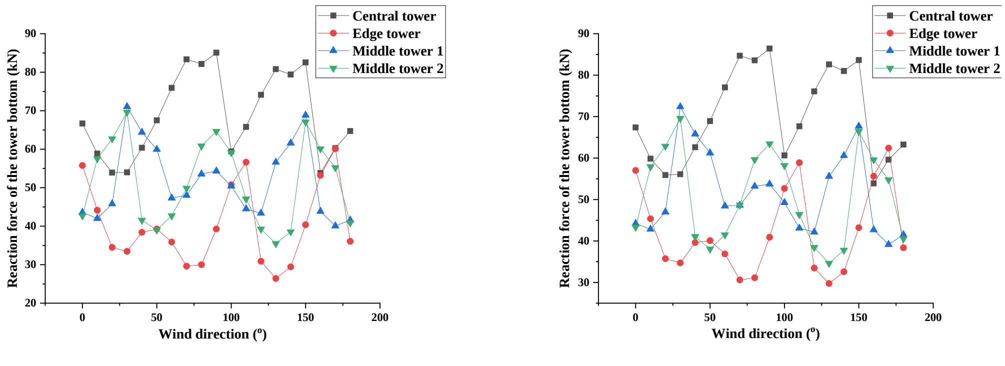
From the above analysis, the relationship between the actual structural wind force and the model test results is as follows:

Tower structure: $$F_T = \frac{F_{MT}}{S_v^2 S_{AT}} = 4000 F_{MT}/S_v^2 \quad (5)$$

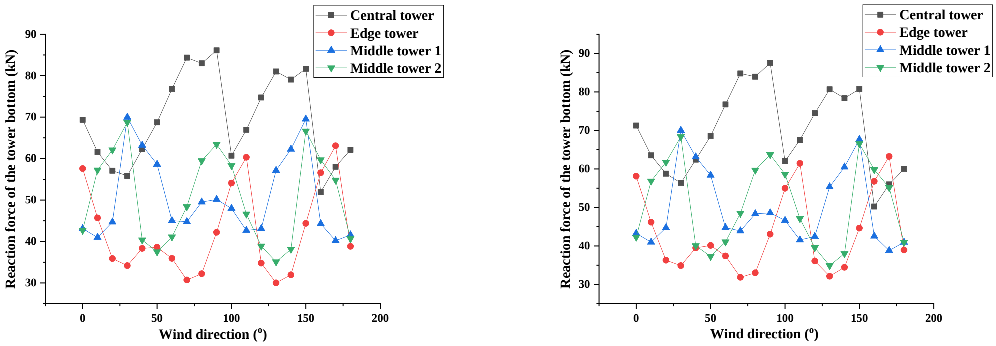
Cable network structure: $$F_C = \frac{F_{MC}}{\varepsilon S_v^2 S_{AC\lambda}} = 2700 F_{MC}/S_v^2 \quad (6)$$

F_{MT}, F_{MC} are test results of the tower structure and the cable network structure.

From the above formula, the direct test results can be transformed into the reaction force response of the tower bottom under the actual structural wind load. Fig. 5 shows the reaction force at the bottom of the tower-cable network system with different length increased status at a wind speed of 10 m/s. In the process of wind direction change, the reaction force trend of each tower bottom is not affected by the change of increased length; But the reaction force at the bottom of a single tower is obviously affected by the wind direction, and there are multiple inflection points. Fig. 6 shows the change of the reaction force of a single tower bottom in different length increased statuses under the same wind speed and wind direction. It can be seen that with the increase of cable length, the reaction force at the bottom of the central tower and the edge tower shows an upward trend, while the reaction force at the bottom of the middle tower decreases, indicating that with the increase of the cable length, the wind load shared by the central tower and the edge tower gradually increases, while the share of the middle tower decreases.



(a) normal length (b) 1/3 length increased



(c) 2/3 length increased (d) length increased to the ground

Figure 5: Reaction force of the tower bottom in the tower-cable networks system

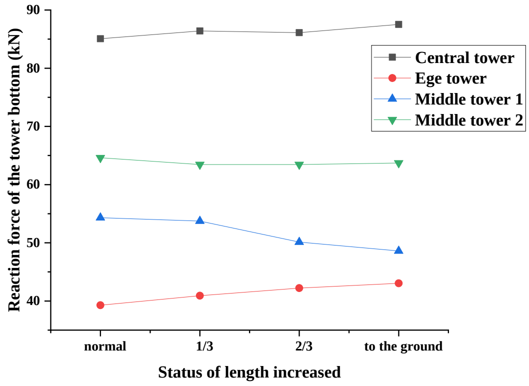


Figure 6: Reaction force of the tower bottom under the condition of 90° wind direction

4. Conclusion

By carrying out the high-frequency force balance test of the tower and the cable network respectively, the reaction force of the tower bottom is measured. Combined with the test on exploring the influence of different diameters on the drag coefficient of the arc cable section, the reaction force of the bottom of each tower of the tower-cable network system under wind load is obtained, and the following conclusions are drawn:

1. In a certain range of Reynolds number, the drag coefficient of the arc cable gradually decreases with the increase of its diameter.

2. Under different wind directions, the reaction force trend at the bottom of the tower is not related to the increased length, but it is obviously affected by the change of wind direction, and the influence of wind direction should be fully considered in the engineering design.

3. The test results show that the wind load sharing of each tower changes in the process of increasing cable length, and should be further explored in combination with the subsequent simulation results.

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