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Wind-induced vibration of UHV transmission tower line system: Wind tunnel test on aero-elastic model

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ABSTRACT

A wind tunnel test on the aero-elastic model of UHV transmission tower line system was carried out for researching tower line system's dynamic behavior under different wind speeds. The effect of wires' vibration on tower was particularly addressed in the paper. For comparison, the single tower model and tower line system model were involved. Both alongwind and crosswind responses of tower were investigated. The wire's dynamic strain was traced synchronously for exploring the coupling vibration effect of tower line system. Comparing the responses of the single tower model and the tower line model, it is found that 70–90% displacement and strain are induced by wires. This action is more prominent in the alongwind direction. However, the peak response values of the tower line model are smaller than those of the single tower model. Test results in frequency domain indicate that the dynamic behavior of the tower becomes more susceptible to wind speed when it connects with wires. As to the tower line system, the response power spectra of the tower and the conductors show the tendency of moving to lower and higher frequency region respectively with the crests weakened and vibration energy dispersed when wind speed increases.

1. Introduction

Power transmission tower line system consists of three basic components, the tower, the wires (including conductor and ground wire) and insulators. With the increasing demand for electricity and its long-range transmission, UHV transmission lines arouse wide concern of engineers. UHV transmission tower line system means higher tower, larger span and longer insulation distance. Accordingly, the steel tube lattice tower is adopted, conductors have more bundles and the size of insulators needs to be increased.

Because tower line system is wind-sensitive, its wind-induced response is the main concern. Wind-induced interaction between tower and wires is a tricky issue: the tower response is amplified remarkably due to the existence of wires while the wire constraints vary along with the tower vibration. Researchers attempt to reveal and conclude the dynamic rule of tower line system by field monitoring, wind tunnel test and numerical analysis.

Mehta Kishor and Kadaba (1990) presented results on a 500 kV transmission line by field monitoring. In addition to the response spectrum analysis, they also took aerodynamic damping into consideration and compared the test results with the values calculated by gust loading factor method. Paluch et al. (2007) carried out a one-year monitoring of a river-crossing transmission line and evaluated the wind load effect on conductors. As to transmission tower, the field monitoring was implemented mainly for investigating its dynamic properties, wind-resistant performance and wind load (Ballio et al., 1992; Savory et al., 1998). A 3-year field monitoring in the mountainous area found that tower's vibration was strongly influenced by conductor as well as wind direction (Momomura et al., 1997). Okamura et al. (2003) took a similar full-scale measurement in mountainous area and conducted a wind tunnel test for exploring the vibration characteristics of tower. According to the field monitoring, the aerodynamic damping of tower line system was also identified and corresponding theoretical model was established (Takeuchi et al., 2010).

Field monitoring means high expenditure and long period, so wind tunnel test is favored by most researchers. In early time, Cooper and Wardlaw (1970) implemented a wind tunnel test to a two-bundle conductor model and found the reduced scale model could not reflect the real vibration. Loredo-Souza and Davenport (2001, 2002) proposed a novel approach for wind tunnel modelling of transmission lines and carried out a wind tunnel test on two parallel conductors for investigating their dynamic behavior under strong wind. Then, more wind tunnel tests to cables and transmission conductors were carried out in order to explore drag coefficients and aerodynamic characteristics (Eguchi et al.,

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2002; Kikuchi et al., 2003; Bartoli et al., 2006). When coupling vibration in tower line system is concerned, the aero-elastic model of tower line system is frequently used. Huang et al. (2012) investigated the aero-elastic model of a long-span tower line system whose real height reached 370 m. This experimental study concentrated on the gust loading and response factor of the transmission tower. Liang et al. (2015) designed a test for a 500 kV transmission tower line system in which dynamic properties of tower with and without lines were discussed.

The analytical-numerical study on the wind-induced responses of tower line system was also addressed by researchers. Dynamic models of tower line system were built and further used to analyze the stability of transmission tower under ultimate wind (Yasui et al., 1999; Battista et al., 2003).

Wind-induced vibration of tower line system is complex and the issues that may occur are diverse, so researchers pay their attention to different aspects. Recent literature concerns the dynamic behavior of conductors such as galloping, aeolian vibration and buffeting (Yan et al., 2012; Barry et al., 2013). Other studies focus on the mechanical behavior and safety of the tower under wind action (Klinger et al., 2011; Rao et al., 2010). As a system, the tower and the conductor influence each other, so the coupling vibration effect is always a hot topic.

The paper studies the dynamic behavior of the tower as well as the coupling effect between tower and conductor performance. Here, the tower line system is subjected to normal wind and the dynamic behavior of conductor is just due to buffeting. In Section 2, the wind tunnel test on the aero-elastic model of an UHV suspension tower line system is addressed: two models are considered, i.e. the single tower model and tower line model. In Section 3, the dynamic properties of the single tower and the tower with wires are investigated with experimental and numerical means. In Section 4, according to the test data, the dynamic responses of the tower in two directions (alongwind and crosswind directions) and the dynamic strain of conductors under five levels of wind speed are expressed in time domain for comparison analysis. In Section 5, the concern turns to the frequency domain: the changes in the response power spectrums of tower and conductor are quantified for revealing the dynamic rule of tower line system when wind speed increases continuously. At last, the wind-induced coupling vibration effect within tower line system is described and concluded.

2. Wind tunnel test on aero-elastic model

2.1. Aero-elastic model design

The UHV double-circuit power transmission line from Huainan City, Anhui Province to Shanghai City in China is the prototype of the wind tunnel test. The transmission tower is a lattice-type steel tube tower. The geometrical and material information of the tower and wires (conductors and ground wires) are listed in Table 1. The wind tunnel test was implemented in TJ-3 wind tunnel of Tongji University.

In order to obtain the reliable aerodynamic responses, the tower model and line model should be designed exactly based on the similarity theory. In the test, the primary geometric, kinematic and mechanical similarity conditions were satisfied, and the secondary similitude demands were simplified.

(1) Similarity Design for Tower Model

The geometric and wind velocity similarity scales were prescribed depending on the wind tunnel size and power. As shown in Eq. (1a) and Eq. (1b), λ_i is the similarity scale with i representing the specific physical quantity. The subscripts of m and p mean the test model and prototype respectively. As the basic similarity scales, the values of λ_L and λ_V are presented with α and β.

$$\lambda_L = \frac{L_m}{L_p} = \frac{1}{60} = \alpha \tag{1a}$$

$$\lambda_V = \frac{V_m}{V_p} = \frac{1}{3} = \beta \tag{1b}$$

Accordingly, the area similarity scale is $\lambda_A = \lambda_L^2 = \alpha^2$.

Because the dimensionless parameters for test model and prototype should be equal (Eq. (2a) and Eq. (3a)), the frequency (Eq. (2b)) and mass (Eq. (3b)) similarity scales can be calculated as follows:

$$\left(\frac{f \cdot L}{V}\right)_m = \left(\frac{f \cdot L}{V}\right)_p \tag{2a}$$

$$\lambda_f = \frac{f_m}{f_p} = \frac{\lambda_V}{\lambda_L} = \frac{\beta}{\alpha} \tag{2b}$$

$$\left(\frac{M}{\rho_a L^3}\right)_m = \left(\frac{M}{\rho_a L^3}\right)_p \tag{3a}$$

$$\lambda_M = \frac{M_m}{M_p} = \lambda_L^3 = \alpha^3 \tag{3b}$$

The Cauchy number for test model and prototype should be the same (Eq. (4a)), so the similarity scale of elastic modulus was deduced (Eq. (4b)). However, it is difficult to meet the elastic modulus scale in actual material selection, so the axial stiffness scale is adopted here (Eq. (5)). Therefore, the modulus scale and area scale do not need to be met strictly when manufacturing the inner rod of tower members.

$$\left(\frac{E}{\rho V^2}\right)_m = \left(\frac{E}{\rho V^2}\right)_p \tag{4a}$$

$$\lambda_E = \frac{E_m}{E_p} = \lambda_V^2 = \beta^2 \tag{4b}$$

$$\lambda_{EA} = \frac{(EA)_m}{(EA)_p} = \lambda_V^2 \cdot \lambda_L^2 = (\alpha\beta)^2 \tag{5}$$

In order to ensure the similarity of drag force (Strouhal number), the shape scale of tower member should be determined. For the steel tube member, the drag coefficients of model and prototype are regarded as the same, then the drag force scale is just related to geometry scale (Eq. (6)). C_D is the drag coefficient and D was the outer diameter of members.

$$\lambda_D = \frac{(C_D D)_m}{(C_D D)_p} = \lambda_L = \alpha \tag{6}$$

(2) Similarity Design for Wire Model

The test model of tower line system contained four spans and five towers. Limited by the tunnel size, the span similarity scale as well as the

Table 1
Information of the prototype.

Tower			Conductors			Ground wires	
Total height	Nominal height	Span	Type	Material	Sag	Material	Sag
103.6 m	57 m	510 m	eight-bundled	ACSR-630/40	24 m	LBGJ-240-20AC	18 m