

## **Design wind loads for transmission towers with cantilever cross-arms based on the inertial load method**

\*Shuang Zhao<sup>1)</sup> and Zhitao Yan<sup>2)</sup>

*1), 2) School of Civil Engineering and Architecture, Chongqing University of Science and Technology, Chongqing 401331, China*

*<sup>1)</sup> [644621771@qq.com](mailto:644621771@qq.com)*

### **ABSTRACT**

Appropriate design wind loads can effectively avoid damage to transmission towers under strong wind. Therefore, it is necessary to accurately model the design wind loads for transmission towers. The wind-induced vibration coefficient  $\beta(z)$  is a critical parameter for the design wind loads. Based on the inertial load approach, a calculation method for the design wind loads of transmission towers considering the effects of cross-arms and diaphragms was proposed step by step. In order to be consistent with actual transmission towers, the correction coefficient expressions of  $\beta(z)$ , such as  $\theta_b$ ,  $\theta_l$  and  $\theta_\eta$ , considering the influence of local shape, mass and windshield area and spatial correlation of the fluctuating wind respectively, were derived and investigated. Through introducing these three coefficients, the design wind loads for transmission towers with cross-arms and diaphragms can be determined. For transmission towers with cantilever cross-arms, based on the analyses of 6 tower samples, design wind load formulae were derived. The parameter analyses of the design wind loads showed that cross-arms have a great influence on  $\beta(z)$  and the wind-induced vibration response of transmission towers, but diaphragms have a marginal influence on them. Thus, as an approximate calculation, the influence of diaphragms on the design wind loads are negligible. The research results provide a calculation method for the wind-resistant design of transmission towers.

### **1. INTRODUCTION**

Transmission towers are wind-sensitive structures and their wind-induced vibration responses are a prime concern for structural designers and researchers. Generally, dynamic time-history analyses can be used to solve the wind-induced vibration responses of transmission towers. However, this method involves many parameters, is complicated in procedure and time consuming, such that it is not convenient for transmission tower design. By comparison, the design wind loads in

---

<sup>1)</sup> Ph.D.

<sup>2)</sup> Prof.

standards or codes are both simple and effective. At present, the code approach is still widely used by structural designers.

Many researchers have investigated design wind loads for transmission towers. According to the calculation parameters of design wind loads, these research results can be divided into two categories. One includes the aerodynamic parameters with regards to those used to determine 3D aerodynamic forces. The other is the dynamic parameter, also termed as the wind-induced vibration coefficient  $\beta(z)$  or the gust load factor (GLF) (Davenport, 1967).

For the aerodynamic parameters of design wind loads, through wind tunnel tests on two cross-arm models of a tubular-angle steel transmission tower under 19 yaw angles (Yang et al, 2015), the skewed wind load factors, the wind load distribution factors and the drag coefficients were calculated and suggestions on these factors and coefficients were proposed for determining the design wind loads of cross-arms under skewed wind. However, since cross-arms and the tower body are artificially separated, this method over-simplifies the interference of the flow field between cross-arms and the tower body. For providing an accurate evaluation on the exact wind forces, a direct force measurement method was proposed (Zhou et al, 2019a) to identify the drag coefficients and cross-wind force coefficients for cross-arms. In fact, 3D wind loads often attack transmission towers, especially for those constructed on the top or slope of mountains, with both yaw and tilt angles. By performing wind tunnel tests (Zhou et al, 2019b), the drag coefficients under 19 yaw angles and 13 tilt angles were obtained. Then, a more accurate modified formula for the skewed wind load factor was provided and concepts of tilted and combined wind load factors were proposed with recommended formulae.

For the dynamic parameter of design wind loads, the addition of diaphragm bracings enhances the strength and stiffness of transmission towers without too much increase in mass (Albermani et al, 2004). Therefore, they may also improve the tower's dynamic response and further affect  $\beta(z)$ , which need to be assessed. By means of a scaled rigid model, the tests of high frequency force balance were performed (Xiao and Li, 2011) to research the ESWLs for transmission towers. The research showed that the distributions of  $\beta(z)$  are not only related to the mode shape, but also closely related to the mass. On account of the tower mass used in the calculation has an abrupt change at the cross-arms position, this always affect the overall design wind loads. The use of the classical influence functions of cantilever beams neglects the crossing of diagonal members, so this will lead to inconsistencies with the final design state of transmission towers. Within the framework of the GLF technique, specific influence functions for displacements, shear forces, overturning moments and axial forces in leg elements were derived (Calotescu and Solari, 2016). Then, these influence functions were used to investigate dynamic wind loads and alongwind load effects on free-standing lattice towers, which contribute to the improvement of design wind loads. In addition, both the material of components and the wind field characteristics can also affect the dynamic behavior of transmission towers. Through wind tunnel tests on an aeroelastic model, the ESWLs of a super high-rise (455m) transmission tower were investigated (Zhao et al, 2019). Meanwhile, the influences of the concrete-filled steel tube and the gradient wind height on  $\beta(z)$  were analyzed and some suggestions regarding the applicability of design wind load formulae in the Chinese code was

proposed.

The above researches allow the development of effective calculation methods for the design wind loads on transmission towers. However, most of the existing researches rely on specific test models, and the results of these research may not be generalized to other transmission towers beyond the scope of these test transmission towers. Moreover, due to the complex shape and huge mass of the cross-arms, the dynamic parameter of design wind loads for transmission towers have not been studied in a sufficient depth. Thus, much research should be succeeded for the developing of the calculation methods of design wind loads for transmission towers.

In this paper, a new method for determining design wind loads for transmission towers, which accurately considers the influence of diaphragms and cross-arms on wind-induced dynamic behavior, is proposed. At first, the calculation model for design wind loads on uniformly-shaped transmission towers (those whose mass and windshielding area are constant along their height) is established. Then, the factors of varying shape and the influences of diaphragms and cross-arms are introduced into the model. Thus, conforming to the actual structure, a new calculation model of design wind loads for transmission towers is ultimately proposed. By means of fitting formulae, a parameter list, distribution assumptions for the structural parameters and other simplifications, design wind load formulae for transmission towers with cantilever cross-arms (as shown in Fig. 1) are derived herein. Finally, the parameter analyses of the design wind loads is conducted. It is expected that the study results from this paper will contribute to the design practice of transmission towers.



(a) "干" type



(b) horn shape

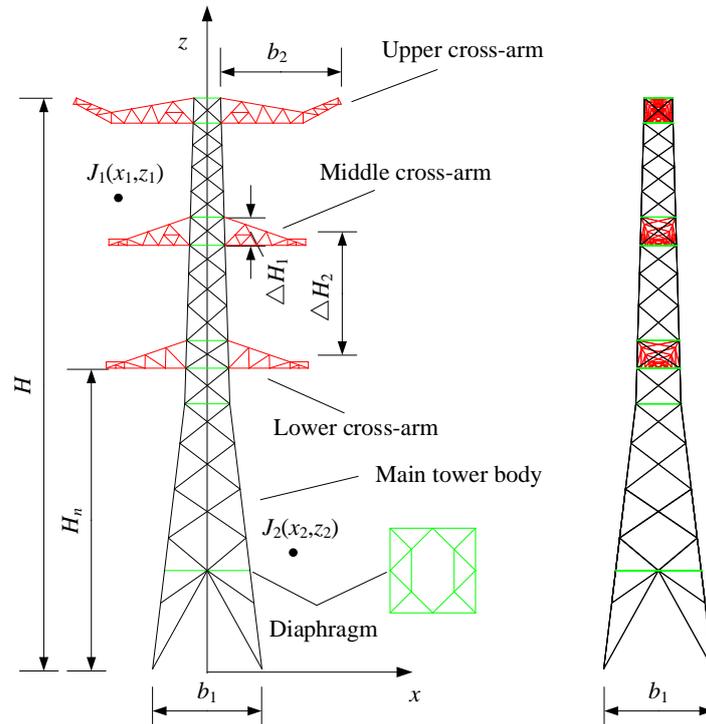


(c) drum type

**Fig. 1** Transmission towers with cantilever cross-arms

## 2. General formulae for equivalent static wind loads

Transmission towers consist of three parts: cross-arms, diaphragms and the main tower body, as shown in **Fig. 2**. Here,  $b_1$  is the width at the tower bottom;  $b_2$  is the single lateral width of a cross-arm;  $H$  is the total height;  $H_n$  is the nominal height, that is the height of the lower brim of the lower cross-arm;  $\Delta H_1$  is the vertical thickness of a cross-arm near the tower body;  $\Delta H_2$  is the vertical center distance between two adjacent cross-arms;  $J_1(x_1, z_1)$  and  $J_2(x_2, z_2)$  are any two points in space. Due to different mass distributions and windshielding area distributions, the cross-arms, diaphragms and main tower body should be treated separately in the calculation process for wind loads.



**Fig. 2** Calculation diagram for the design wind loads on transmission towers

Before the formula derivation, four important assumptions need to be elaborated. First, the method of tower-line separation is adopted in the design wind loads of transmission towers which ignores the tower-line coupling effect. A transmission tower designed by this method is deemed more conservative according to **Xie and Yang (2013)**. Second, if the design wind loads for the tower body in the  $x$  and  $y$  directions and for the cross-arms in the  $y$  direction can be determined, the loads of a transmission tower in the many critical directions, including  $x$  direction, can be calculated by the known wind load distribution factor. Third, aerodynamic damping is considered by decreasing the value of the peak factor  $g_s$ , such as  $g_s=2.5$  rather than  $=3.6$  (**ASCE, 2010**). Fourthly, design wind loads in the alongwind direction can only excite the wind-induced vibration in that direction and are considered herein. These four assumptions are consistent with Chinese codes (**GB 50009-2012, 2012; DL/T5154-2012, 2012**) and the study in this paper is within the framework of the Chinese code. To summarize, the present analysis focuses on free-standing normal-height lattice towers without lines and can consider the influence of wind direction.

For high-rise tower structures, the first flexural mode is dominant in wind-induced buffeting and higher order modes are assumed to be negligible (**Lou et al, 2015**). Hence, the wind-induced vibration inertial load can be expressed as:

$$\hat{f}'_{D_1}(z) = \omega_1^2 m(z) \phi_1(z) g_s \sigma_{q_1}, \quad (1)$$

where  $\omega_1$  is the undamped natural circular frequency for the first mode;  $m(z)$  is the mass per unit height;  $\phi_1(z)$  is the mode shape for the first mode;  $\sigma_{q_1}$  is the standard deviation of  $q_1(t)$ ;  $q_1(t)$  is a time-varying generalized coordinate for the first mode.

The ESWLs are the sum of the mean wind load and the wind-induced vibration

inertial load. In the Chinese load code (GB 50009-2012, 2012), the ESWLs may be easily obtained by amplifying the mean wind load by the height-dependent  $\beta(z)$ :

$$f_{ESWL}(z) = \bar{f}(z) + \hat{f}'_{D_1}(z) = \beta(z) \bar{f}(z), \quad (2)$$

where  $\bar{f}(z)$  is the mean components of  $f(z,t)$ ;  $f(z,t)$  is the time-varying alongwind direction drag per unit height.

Obviously,  $\beta(z)$  plays an important role in the solution of ESWLs and represents the dynamic effect of wind-induced vibration. In other words,  $\beta(z)$  is an alternative variable for studying ESWLs, and it can be written as:

$$\beta(z) = 1 + \frac{\omega_1^2 m(z) \phi(z) g_s \sigma_{q_1}}{\omega_{10} \mu_z(z) C_d(z) b_s(z)} = 1 + \xi_1 u_1 r_1(z), \quad (3)$$

where  $\omega_{10}$  is the mean wind pressure at  $z=10$  m;  $\mu_z(z)$  is the wind pressure height variation coefficient;  $C_d(z)$  is the local drag coefficient;  $b_s(z)$  is the local effective windshielding width;  $\xi_1$  is determined by the mechanical admittance function and it can be termed the dynamic coefficient caused by wind-induced vibration;  $u_1$  is related to the wind fluctuation characteristics and it is termed the comprehensive influence coefficient;  $r_1(z)$  is related to the position of the calculation point and it can be termed the position coefficient. Eq. (1) to (3) are general formulae for ESWLs, suitable for any transmission tower. However, on account of involving many parameters and multiple integrals, these equations are difficult to apply in transmission tower design practice. Thereby, it is a challenge to propose concise and accurate formulae for calculating wind loads on transmission towers.

### 3. Derivation of design wind load formulae

Section 2 illustrated the general calculation model for transmission towers of any type and the inconvenience of this model in design practice. The aim of this section is to provide the design wind loads for transmission towers with cantilever cross-arms based on the inertial load method. First of all, the calculation model for the design wind loads is established for a uniformly-shaped transmission tower. Then, the model is improved gradually to make it conform to an actual transmission tower. Afterwards, the design wind load formulae for a transmission tower with cantilever cross-arms is derived.

#### 3.1 Uniformly-shaped transmission towers

For uniformly-shaped transmission towers, the mass and windshielding area are constant along the height. Thus,  $m(z)$ ,  $b(z)$ ,  $C_d(z)$  and  $\delta(z)$  are constants, and equal to the values at  $z=0$ . Thus,  $\beta(z)$  in Eq. (3) can be rewritten as:

$$\beta(z) = 1 + 2g_s I_{10} B_z(z) \sqrt{1 + R^2}, \quad (4)$$

$$B_z(z) = k_\gamma H^{a_\gamma} \rho_z \rho_x \frac{\phi_1(z)}{\mu_z(z)}, \quad (5)$$

$$\left\{ \begin{array}{l} \rho_z = \frac{10\sqrt{H + 60e^{\frac{H}{60}} - 60}}{H} \\ \rho_x = \frac{10\sqrt{b(0) + 50e^{\frac{b(0)}{50}} - 50}}{b(0)} \end{array} \right. , \quad (6)$$

$$R = \frac{\pi}{\sqrt{6\zeta_1}} \frac{x_1'^2}{(1 + x_1'^2)^{4/3}} , \quad (7)$$

$$x_1' = 30n_1 / \sqrt{\omega_{10}} , \quad (8)$$

where  $I_{10}$  is the turbulence intensity at  $z=10\text{m}$ ;  $B_z(z)$  is the background component factor;  $R$  is the resonance component factor; both  $k_y$  and  $a_y$  are coefficients of a fitting formula through a nonlinear least squares method, which related to roughness categories and the values of them are listed in the Chinese load code (GB 50009-2012, 2012);  $\rho_z$  and  $\rho_x$  are the vertical direction and horizontal direction correlation coefficient of fluctuating wind loads, respectively;  $b(z)$  is the local outline width;  $\zeta_1$  is the damping ratio for the first mode;  $n_1$  is the first flexural frequency value.

Eq. (4) is also the expression for  $\beta(z)$  in the Chinese load code (GB 50009-2012, 2012), which is suitable for a high-rise structure having a fixed shape. It illustrates that  $\beta(z)$  of the Chinese load code (GB 50009-2012, 2012) can be used for uniformly-shaped transmission towers.

### 3.2 Uniformly tapered transmission towers

In Section 3.2, an ideal uniformly-shaped transmission tower was analyzed. However, such towers are rare in practice. Generally speaking, the shape of the tower body tapers with increasing height. Diaphragms are horizontally spaced apart on the main tower body and the spacings are not exactly the same. The size of a transmission tower is abruptly increased at the cross-arms position. These three-part distributions of a transmission tower are shown in Fig. 2. At the same time, as a supporting structure, the transmission tower should be designed to minimize its self-weight and, thus, to be able to withstand greater external loads. Hence, the outer diameter and (or) the side length of the material of the transmission tower members are both large at the bottom and small at the upper part, gradually decreasing as the height increases.

For the main tower body,  $m(z)$  and  $b_s(z)$  vary along the height and can be approximated by a taper change. This section analyzes the calculation model for the design wind loads of more realistic, uniformly tapered transmission towers, without considering the effects of cross-arms and diaphragms. In order to avoid confusion, the subscript "a" is added to  $\phi_1(z)$ ,  $\eta_{xz1}$  and so on, denoting that the shape of the structure varies along the height, such as  $\phi_{a1}(z)$ ,  $\eta_{axz1}$  and so on. The following is a derivation for  $\beta(z)$  of uniformly tapered transmission towers.

$$B_z(z) = k_y H^{a_y} \rho_z \rho_x \frac{\phi_1(z)}{\mu_z(z)} \theta_v \theta_b(z) , \quad (9)$$

$$\theta_v = \frac{\int_0^H \mu_z(z) \phi_{a1}(z) I_z(z) b_s(z) dz}{\int_0^H \mu_z(z) \phi_1(z) I_z(z) dz} \frac{\int_0^H \phi_1^2(z) dz}{\int_0^H m(z) \phi_{a1}^2(z) dz}, \quad (10)$$

$$\theta_b(z) = \frac{m(z)/m(0)}{b_s(z)/b_s(0)}, \quad (11)$$

where  $I_z(z)$  is a local turbulence intensity;  $\theta_v$  is the correction coefficient of  $\beta(z)$  considering the overall shape change, which was tabulated to Table 8.4.5-2 in the Chinese load code (GB 50009-2012, 2012);  $\theta_b(z)$  is the correction coefficient of  $\beta(z)$  considering the local shape change.

When  $\rho_x$  is calculated by Eq. (6),  $b(0)=b_1$ . By substituting Eq. (9) into Eq. (4), the  $\beta(z)$  for uniformly tapered transmission towers can be obtained. This  $\beta(z)$  is consistent with that of a high-rise structure with uniformly varying shape in the Chinese load code (GB 50009-2012, 2012). It illustrates that the  $\beta(z)$  of the Chinese load code (GB 50009-2012, 2012) can be used for uniformly tapered transmission towers.

### 3.3 Transmission towers with cantilever cross-arms

In order to resist shear and torsion forces, diaphragms are arranged at intervals along the height of transmission towers. Cross-arms capable of suspending conductors and ground wires are arranged on the upper part of the towers. Different from the main tower body, the mass and the windshielding area of cross-arms and diaphragms abruptly change with height locally. In this section, the change laws of the mass and the windshielding area of cross-arms and diaphragms are discussed. Thus, a realistic calculation model for the design wind loads for transmission towers is established. The following is a discussion of transmission towers with cantilever cross-arms and the design formulae for  $\beta(z)$  are derived.

As shown in Fig. 2, the width of the cross-arms is larger than the width of the main tower body, a correction coefficient  $\theta_\eta$  of  $\beta(z)$  is introduced.  $\theta_\eta$  consider the spatial correlation of the fluctuating wind and can be expressed as:

$$\theta_\eta = \frac{\sqrt{\int_0^{b(z_1)} \int_0^{b(z_2)} coh_x(x_1, x_2) dx_1 dx_2}}{\sqrt{\int_0^{b(0)} \int_0^{b(0)} coh_x(x_1, x_2) dx_1 dx_2}} \times \frac{\left[ \int_0^H \int_0^H \mu_z(z_1) \phi_{a1}(z_1) I_z(z_1) \delta(z_1) \mu_z(z_2) \phi_{a1}(z_2) I_z(z_2) \delta(z_2) \times coh_z(z_1, z_2) dz_1 dz_2 \right]^{0.5}}{\sqrt{\int_0^H \int_0^H \mu_z(z_1) \phi_1(z_1) I_z(z_1) \mu_z(z_2) \phi_1(z_2) I_z(z_2) coh_z(z_1, z_2) dz_1 dz_2}} \times \frac{b(0) \int_0^H \mu_z(z) \phi_1(z) I_z(z) dz}{\int_0^H \mu_z(z) \phi_{a1}(z) I_z(z) b_s(z) dz} \quad (12)$$

where  $\delta(z)$  is the local solidity for the  $b(z)$ ;  $coh_x(x_1, x_2)$  and  $coh_z(z_1, z_2)$  are the

horizontal correlation function and the vertical correlation function, respectively.

$\theta_\eta$  is mainly affected by the outline shape of a transmission tower and can be calculated by a simplified model, as shown in Fig. 3. In Fig. 3, the outline width of the main tower body is assumed to be constant and equal to  $b_1$ ; The single lateral widths of every cross-arm are assumed to be the same and equal to the average value  $\bar{b}_2$ ; The thicknesses of every cross-arm near the tower body are assumed to be the same and equal to the average value  $\Delta H_1$ ; The center distances between two adjacent cross-arms are assumed to be the same and equal to the average value  $\Delta H_2$ . Through analyses,  $\theta_\eta$  is mainly affected by the width and numbers of the cross-arms. Besides, the differences of the width of every cross-arm are not significant for a tower and the relative error of  $\theta_\eta$  from the actual model and simplified model (such as Fig. 3) is less than 5%. Hence, these assumptions are reasonable for the calculation of  $\theta_\eta$ .

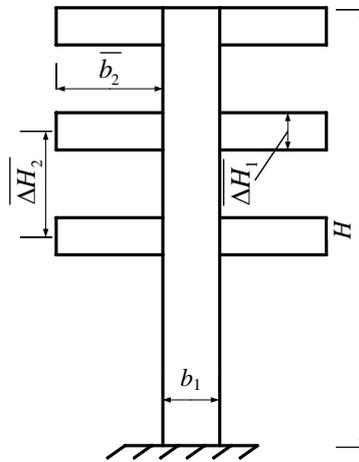


Fig. 3 Simplified calculation model of  $\theta_\eta$

According to the above analyses, the influence parameters of  $\theta_\eta$  are  $b_1$ ,  $\bar{b}_2$ ,  $\Delta H_1$ ,  $\Delta H_2$ ,  $H$  and  $n_c$ , where  $n_c$  is the number of cross-arms. Nevertheless, these influence parameters are not independent. According to the control relationship of the tower structure,  $H$  is correlated with  $b_1$ , such that  $b_1$  increases with  $H$ ;  $\bar{b}_2$  is correlated with  $\Delta H_1$ , with  $\Delta H_1$  increasing with  $\bar{b}_2$ .  $\bar{b}_2$  and  $\Delta H_2$  are controlled by electrical requirements, related to voltage levels, and are independent of structural requirements. In the same way,  $n_c$  is also controlled by electrical requirements. The shape distributions of diaphragms are limited by the main tower body. With increasing  $H$ , the windshielding area and mass of the diaphragms increase, but  $\bar{b}_2$  will remain unchanged. By means of these analyses, the independent influence parameters are reduced to  $\bar{b}_2$ ,  $H$  and  $n_c$ .

Through the analyses of 6 transmission towers with cantilevered cross-arms (as shown in Fig. 4), the expressions obtained are  $\bar{b}_2=3.491\Delta H_1$ ,  $\Delta H_2=1.377\bar{b}_2$  and  $H=5.272b_1$ . Based on the limited number of towers analysed here, the standard deviation in the average numerical values given here are 0.045 for 3.491, 0.037 for 1.377 and 0.232 for 5.272, respectively. By specifying that the nominal height  $H_n$  must

not be less than 15m, the range of  $n_c$  values can be limited. Obviously, it is cumbersome to calculate  $\theta_\eta$  through Eq. (12). For the sake of convenient design,  $\theta_\eta$  can be calculated by tabular search. Within the range of engineering design parameters, the values of  $\theta_\eta$  are listed in **Table 1** via calculation.

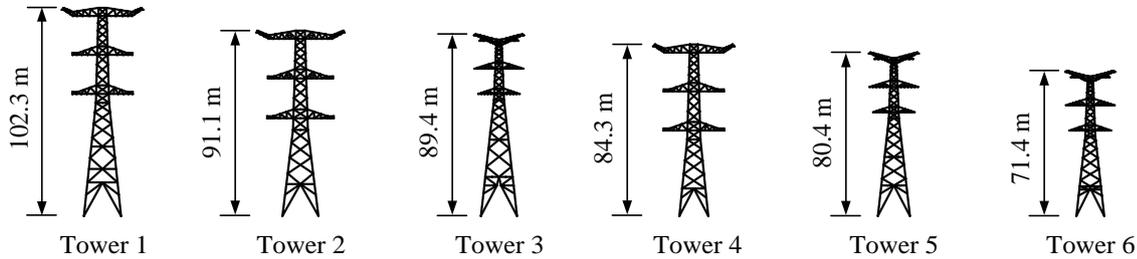


Fig. 4 Transmission towers with cantilevered cross-arms used in the statistical analysis

Table 1  
 $\theta_\eta$  values for transmission towers with cantilever cross-arms

$b_2/H$	$n_c=1$	$n_c=2$	$n_c=3$	$n_c=4$	$n_c=5$	$n_c=6$	$n_c=7$
0.05	1	1	0.99	0.99	0.99	0.99	0.99
0.10	0.99	0.98	0.98	0.98	0.97	0.97	0.97
0.15	0.97	0.97	0.96	0.95	0.94	0.94	-
0.20	0.95	0.94	0.93	0.91	-	-	-
0.25	0.93	0.91	0.89	0.88	-	-	-
0.30	0.91	0.88	0.86	-	-	-	-

The influence of the mass and windshield area of cross-arms and diaphragms on  $\beta(z)$  need to be considered. Therefore, two correction coefficients are introduced and can be expressed as:

$$\theta_a = \left[ \int_0^H \mu_z(z) \phi_{a1}(z) I_z(z) b_s(z) dz + \sum_I \mu_z(z_I) \phi_{a1}(z_I) I_z(z_I) A_s(z_I) + \sum_J \mu_z(z_J) \phi_{a1}(z_J) I_z(z_J) A_s(z_J) \right] / \int_0^H \mu_z(z) \phi_{a1}(z) I_z(z) b_s(z) dz, \quad (13)$$

$$\theta_m = \frac{\int_0^H m(z) \phi_{a1}^2(z) dz}{\int_0^H m(z) \phi_{a1}^2(z) dz + \sum_I M(z_I) \phi_{a1}^2(z_I) + \sum_J M(z_J) \phi_{a1}^2(z_J)}. \quad (14)$$

where  $\theta_m$  is the additional mass correction coefficient for  $\beta(z)$ ;  $\theta_a$  is the additional windshield area correction coefficient for  $\beta(z)$ ;  $\Sigma_I$  and  $\Sigma_J$  are the summation symbols for all cross-arms and all diaphragms, respectively.

Generally, for transmission towers with cantilever cross-arms, the diaphragms are arranged in two ways; above the nominal height and below the nominal height. Above the nominal height, there is a diaphragm at the upper and lower edges of the fixed end of every cross-arm. Below the nominal height, there is a diaphragm at the slope change position on the tower body and the distance between this diaphragm and the adjacent upper diaphragm is assumed to be  $\Delta H_1$ . There is a diaphragm next to the position of the tower legs and the distance between this diaphragm and the ground can be assumed to be  $b_1$ . There are  $n_d$  diaphragms between the bottom diaphragm and the

diaphragm at the slope change position and  $n_d = \text{round}\left(\frac{H}{b_2} - 5\right)$ , where the round symbol represents integer rounding. These  $n_d$  diaphragms are arranged at equal intervals. The distributions of diaphragms in the tower body have been determined. Next, the distributions of the windshielding area and the mass of the diaphragms and cross-arms need to be determined. Similarly, statistical analyses from 6 transmission towers with cantilever cross-arms (as shown in Fig. 4) were carried out to obtain the relationships:  $A_s(z_I) = 3.796b_s(0)\left(\frac{b_2}{H}\right)$ ,  $A_s(z_J) = 1.015b_s(0)\mu_{b_s}^{1.5}(z_J)$ ,  $M(z_I) = 2.147m(0)\left(\frac{b_2}{H}\right)$  and  $M(z_J) = 1.334m(z_J)$ . The standard deviation in the average numerical values given here are 0.091 for 3.796, 0.044 for 1.015, 0.029 for 2.147 and 0.065 for 1.334, respectively.

The simplified distributions of  $M$  and  $A_s$  for the diaphragms and cross-arms determined herein not only establish the relationship with the main tower body, but also adopt the calculation model in Fig. 3. These distributions achieve the purpose of simplifying the calculations. Because the independent influence parameters of  $\theta_a$  and  $\theta_m$  are  $\frac{b_2}{H}$ ,  $H$ ,  $n_c$  and  $b_s(H)/b_s(0)$ , for the convenience of tabulating, let  $\theta_l = \theta_a \theta_m$ .

$A_s(z_I)$ ,  $A_s(z_J)$ ,  $M(z_I)$  and  $M(z_J)$  may be substituted into Eq. (13) and (14) to calculate  $\theta_l$ . In the same way, within the range of engineering design parameters,  $\theta_l$  is tabulated for convenient calculation, as shown in Table 2. In Table 2, after letting  $T = b_s(H)/b_s(0)$ ,  $\theta_\eta$  values corresponding to  $T=0.3$  and  $T=0.5$  are listed and  $\theta_\eta$  values can be determined by linear internal interpolation for other  $T$  values.

Table 2  
 $\theta_l$  value for transmission towers with cantilever cross-arms

$\frac{b_2}{H}$	$n_c=1$		$n_c=2$		$n_c=3$		$n_c=4$		$n_c=5$		$n_c=6$		$n_c=7$	
	$T=0.3$	$T=0.6$												
0.05	0.88	0.91	0.85	0.88	0.82	0.86	0.80	0.85	0.78	0.84	0.78	0.84	0.78	0.84
0.10	0.86	0.92	0.81	0.90	0.79	0.90	0.78	0.90	0.79	0.91	0.79	0.91	0.79	0.91
0.15	0.80	0.92	0.76	0.91	0.76	0.93	0.78	0.95	0.79	0.97	0.79	0.97	-	-
0.20	0.75	0.91	0.73	0.92	0.75	0.96	0.78	0.98	-	-	-	-	-	-
0.25	0.70	0.90	0.71	0.94	0.75	0.98	0.76	1.00	-	-	-	-	-	-

$\theta_b(z)$  for the main tower body,  $\theta_b(z_I)$  for cross-arms and  $\theta_b(z_J)$  for diaphragms can be calculated using the following formulae:

$$\theta_b(z) = \mu_{b_s}(z), \quad (15)$$

$$\theta_b(z_I) = \frac{M(z_I)/m(0)}{A_s(z_I)/b_s(0)} = 0.565, \quad (16)$$

$$\theta_b(z_J) = \frac{M(z_J)/m(0)}{A_s(z_J)/b_s(0)} = 1.314\sqrt{\mu_{b_s}}, \quad (17)$$

$$\mu_{b_s}(z) = 1 + \frac{z}{H} \left[ \left( \frac{b_s(H)}{b_s(0)} \right) - 1 \right]. \quad (18)$$

When calculating  $\beta(z)$  of transmission towers with cantilever cross-arms,  $B_z(z)$  adds the correction coefficients  $\theta_\eta$  and  $\theta_l$  to Eq. (9). In order to ensure the simplicity

of the expression and consistency with the  $\beta(z)$  expression in the Chinese load code (GB 50009-2012, 2012),  $B_z(z)$  for the main tower body, the diaphragms and the cross-arms were combined into a single equation for  $B_z(z)$  (Eq. (19)). The diaphragms and the cross-arms are discretely distributed and so can be calculated in segments, with the calculated height of each segment taken as the height of their geometric center. Correction coefficients  $\theta_b(z)$  caused by local shape changes are calculated according to Eq.(15) to (17), respectively.

$$B_z(z) = k_\gamma H^{a_\gamma} \rho_z \rho_x \frac{\phi_1(z)}{\mu_z(z)} \theta_v \theta_\eta \theta_l \theta_b(z) \quad (19)$$

By substituting Eq. (19) into Eq. (4), the  $\beta(z)$  values for transmission towers with cantilever cross-arms can be obtained. So far, based on the inertial load method, the derivation of design wind loads for the transmission towers with cantilever cross-arms has been completed herein.

#### 4. Analyses of influence parameters

The main tower body is a steel space frame system, which acts as the skeleton to transfer the wind load and the self-weight load to the foundation. The diaphragms are local strengthened members, which improve the shear and torsion force resistance of the skeleton and enhance the stability of the main tower body. The cross-arms are mainly used for hanging conductors and ground wires to meet the power transmission needs of the line. The diaphragms and cross-arms are considered as influencing parameters, and the influences of the two parameters on  $\beta(z)$  and  $\hat{u}(z)$  of the transmission tower with cantilever cross-arms are discussed. In this section, these influencing parameters are calculated and analyzed.

In order to analyze the influences of diaphragms and cross-arms, three cases were set up. Tower 2 as shown in Fig. 2 was used to analyses these three cases. Case 1 considers only the main tower body; Case 2 adds the diaphragms on the basis of case 1; Case 3 adds the cross-arms on the basis of case 2. The values of  $\beta(z)$  and  $\hat{u}(z)$  for the transmission tower under the three cases are calculated, as shown in Fig. 5. As shown in Fig. 5(a), the R.M.S. differences of case 1 and case 2 for the main tower body in Fig. 5(a) and of case 2 and case 3 for the main tower body in Fig. 5(a) are 0.018 and 0.108, respectively. Thus,  $\beta(z)$  for the main tower body decreases slightly with the addition of diaphragms, while  $\beta(z)$  for the main tower body and diaphragms decreases significantly with the addition of cross-arms. In conclusion, the influence of diaphragms on  $\beta(z)$  for a transmission tower is small, while the influence of cross-arms on  $\beta(z)$  for a transmission tower is large. As shown in Fig. 5(b),  $\hat{u}(z)$  of the main tower body increases slightly with the addition of diaphragms, while  $\hat{u}(z)$  of the main tower body and diaphragms increases significantly with the addition of cross-arms. In short, the influences of cross-arms and diaphragms on  $\beta(z)$  and  $\hat{u}(z)$  are opposite. Due to the large windshielding area and mass of the cross-arms and its location at the upper part of a transmission tower, the influence of the cross-arms on  $\beta(z)$  and  $\hat{u}(z)$  of a transmission tower is obvious.

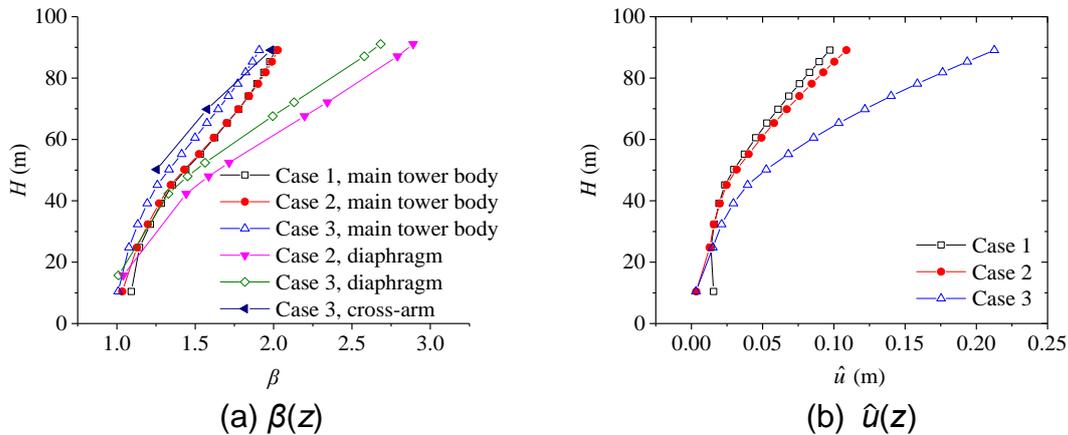


Fig. 5  $\beta(z)$  and  $\hat{u}(z)$  for a transmission tower with cantilever cross-arms based on the inertial load method

## 5. Conclusions

- The Chinese load code (GB 50009-2012, 2012) can be used to calculate the design wind loads for uniformly-shaped transmission towers and uniformly tapered transmission towers. In this paper, simplified distribution models of the mass and the windshielding area for cross-arms and diaphragms were proposed. Although the simplified distributions are different from the actual distributions, the analyses and calculations show that the standard deviation are acceptable for 6 tower samples and have only a small influence on the calculation of the correction coefficients  $\theta_b$ ,  $\theta_l$  and  $\theta_\eta$ . For transmission towers with cantilever cross-arms, based on the analyses of the 6 tower samples, the design wind loads can be determined by using the correction coefficients  $\theta_b$ ,  $\theta_l$  and  $\theta_\eta$  proposed in this paper.

- $\beta(z)$  for the three parts of a transmission tower with cantilever cross-arms increases with increasing height. For a given height,  $\beta(z)$  for the diaphragm is the largest and that for the cross-arm is the smallest.  $\hat{u}(z)$  of a transmission tower obtained by time domain analyses coincide well with those calculated by the design wind loads, indicating that the design wind load formulae proposed in this paper meet the engineering requirements. The influence of diaphragms on  $\beta(z)$  for the main tower body is small, while the  $\beta(z)$  of the main tower body and diaphragms decrease significantly with the addition of cross-arms. The  $\hat{u}(z)$  values for a transmission tower increase slightly with the additions of diaphragms, and increase significantly with the addition of cross-arms. Therefore, as an approximate calculation, the influence of diaphragms on the design wind loads are negligible.

- Based on the inertial load approach, a design wind load method for transmission towers was proposed in this paper. Because there are many types of transmission towers, this paper only determines the design wind load expression for transmission towers with cantilever cross-arms, which is not applicable to other types of transmission tower. For other types of tower, this proposed method can be used to determine the design wind load expression for the selected tower based on the inertial load approach.

● In this paper, extensive references have been made to the Chinese code. In order to apply the present work in other countries and regions that use different tower design codes, the methodology proposed in this paper should be used in relationship to those national codes. In this paper, only 6 transmission towers with cantilever cross-arms were used in the statistical analyses. For application in tower design, more samples should ideally be considered.

### **Acknowledgments**

This study was supported by Scientific Research Foundation of Chongqing University of Science and Technology via Grant No. ckr2019036.

### **REFERENCES**

- Albermani F., Mahendran M., Kitipornchai S., (2004), "Upgrading of transmission towers using a diaphragm bracing system", *Eng. Struct.* **26**, 735-744.
- American Society of Civil Engineers (ASCE), (2010), *ASCE Manuals and Reports on Engineering Practice No.74*. Reston, USA.
- Calotescu, I., Solari, G., (2016), Alongwind load effects on free-standing lattice towers. *J. Wind Eng. Ind. Aerod.* **155**, 182-196.
- Davenport, A.G., (1967), Gust load factors. *J. Struct. Div.* **93**, 11-34, ASCE.
- DL/T 5154-2012, (2012), *Technical Code for the Design of Tower and Pole Structures of Overhead Transmission Lines*. China Planning Press, Beijing, China (in Chinese).
- GB 50009-2012, (2012), *Load Code for the Design of Building Structures*. China Architecture and Building Press, Beijing, China (in Chinese).
- Xiao, Z.Z., Li, Z.L., (2011), Research on equivalent wind loads of UHV transmission tower based on high frequency force balance tests. *Power Sys. Techno.* **35**(5), 32-37 (in Chinese).
- Xie, Q., Yang, J., (2013), Wind tunnel test and numerical simulation on transmission tower-line coupling system. *Power Sys. Techno.* **37**(5), 1237-1243 (in Chinese).
- Yang, F.L., Yang, J.B., Niu, H.W., et al., (2015), Design wind loads for tubular-angle steel cross-arms of transmission towers under skewed wind loading. *J. Wind Eng. Ind. Aerod.* **140**, 10-18.
- Zhao, S., Yan, Z.T., Li, Z.L., et al., (2019), Investigation on wind-induced vibration coefficients of Sutong long span transmission tower based on wind tunnel tests. *J. Build. Struct.* **40**(11), 35-44 (in Chinese).
- Zhou, Q., Ma, B., Zhu, Q., et al., (2019a), Investigation on wind loads on angle-steel cross-arms of lattice transmission towers via direct force measurement. *J. Wind Eng. Ind. Aerod.* **191**, 117-126.
- Zhou, Q., Zhang, H.J., Ma, B., et al., (2019b), Wind loads on transmission tower bodies under skew winds with both yaw and tilt angles. *J. Wind Eng. Ind. Aerod.* **187**, 48-60.