(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; $\triangle H_1$ is the vertical thickness of a cross-arm near the tower body; $\triangle H_2$ 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.

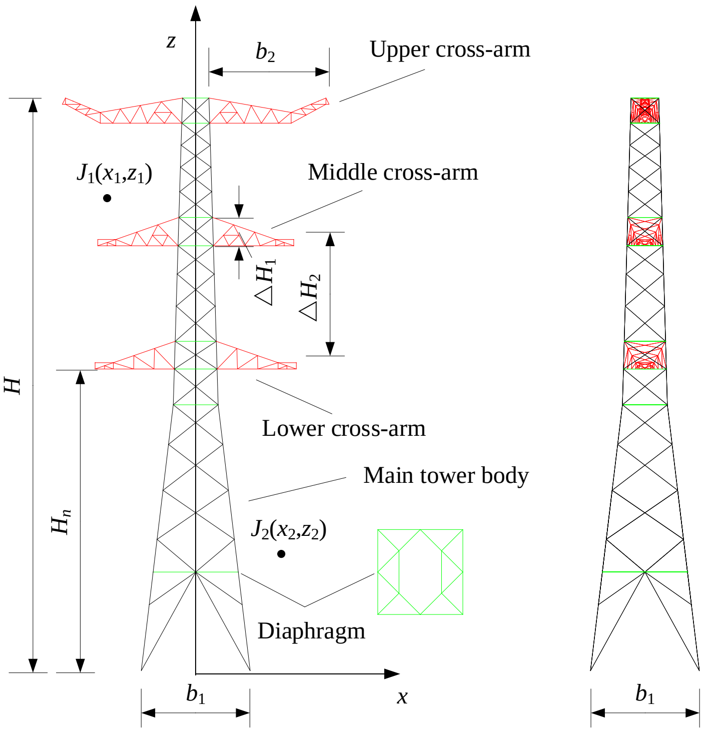


Fig. 2 Calculation diagram for the design wind loads on transmission towers

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 ω_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; σ_{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 $\beta(z)$:

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

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:

$$\beta(z)=1+\frac{\omega_1^2 m(z)\phi_1(z)g_s\sigma_{q_1}}{\omega_{10}\mu_z(z)C_d(z)b_s(z)}=1+\xi_1 u_1 r_1(z), \tag{3}$$

where ω_{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; ξ_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:

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

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

$$\begin{cases} \rho_z = \dfrac{10\sqrt{H+60e^{-\frac{H}{60}}-60}}{H} \\ \rho_x = \dfrac{10\sqrt{b(0)+50e^{-\frac{b(0)}{50}}-50}}{b(0)} \end{cases}, \tag{6}$$

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

$$x_1' = 30n_1 \Big/ \sqrt{\omega_{10}}, \tag{8}$$

where I_{10} is the turbulence intensity at z=10m; $B_z(z)$ is the background component factor; R is the resonance component factor; both k_γ and a_γ 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); ρ_z and ρ_x are the vertical direction and horizontal direction correlation coefficient of fluctuating wind loads, respectively; $b(z)$ is the local outline width; ζ_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 $\phi_1(z)$, η_{xz1} and so on, denoting that the shape of the structure varies along the height, such as $\phi_{a1}(z)$, η_{axz1} and so on. The following is a derivation for $\beta(z)$ of uniformly tapered transmission towers.

$$B_z(z) = k_\gamma H^{a_\gamma} \rho_z \rho_x \frac{\phi_1(z)}{\mu_z(z)} \theta_v \theta_b(z), \tag{9}$$

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

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

where $I_z(z)$ is a local turbulence intensity; θ_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 ρ_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 θ_η of $\beta(z)$ is introduced. θ_η consider the spatial correlation of the fluctuating wind and can be expressed as:

$$\theta_\eta = \frac{\sqrt{\int_0^{b(z_1)}\int_0^{b(z_2)} coh_x(x_1,x_2)\mathrm{d}x_1\mathrm{d}x_2}}{\sqrt{\int_0^{b(0)}\int_0^{b(0)} coh_x(x_1,x_2)\mathrm{d}x_1\mathrm{d}x_2}} \times \left[\int_0^H\int_0^H \mu_z(z_1)\phi_{a1}(z_1)I_z(z_1)\delta(z_1)\mu_z(z_2)\phi_{a1}(z_2)I_z(z_2)\delta(z_2)\times coh_z(z_1,z_2)\mathrm{d}z_1\mathrm{d}z_2\right]^{0.5} / \sqrt{\int_0^H\int_0^H \mu_z(z_1)\phi_1(z_1)I_z(z_1)\mu_z(z_2)\phi_1(z_2)I_z(z_2)coh_z(z_1,z_2)\mathrm{d}z_1\mathrm{d}z_2} \times \frac{b(0)\int_0^H \mu_z(z)\phi_1(z)I_z(z)\mathrm{d}z}{\int_0^H \mu_z(z)\phi_{a1}(z)I_z(z)b_s(z)\mathrm{d}z} \tag{12}$$

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.

θ_η 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 $\overline{b_2}$; The thicknesses of every cross-arm near the tower body are assumed to be the same and equal to the average value $\overline{\triangle H_1}$; The center distances between two adjacent cross-arms are assumed to be the same and equal to the average value $\overline{\triangle H_2}$. Through analyses, θ_η 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 θ_η from the actual model and simplified model (such as Fig. 3) is less than 5%. Hence, these assumptions are reasonable for the calculation of θ_η.

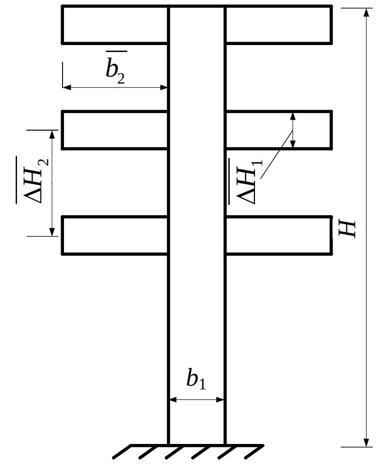


Fig. 3 Simplified calculation model of θ_η

According to the above analyses, the influence parameters of θ_η are b_1, $\overline{b_2}$, $\overline{\triangle H_1}$, $\overline{\triangle H_2}$, 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; $\overline{b_2}$ is correlated with $\overline{\triangle H_1}$, with $\overline{\triangle H_1}$ increasing with $\overline{b_2}$. $\overline{b_2}$ and $\overline{\triangle H_2}$ 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 $\overline{b_2}$ will remain unchanged. By means of these analyses, the independent influence parameters are reduced to $\overline{b_2}$, H and n_c.

Through the analyses of 6 transmission towers with cantilevered cross-arms (as shown in Fig. 4), the expressions obtained are $\overline{b_2}$=3.491$\overline{\triangle H_1}$, $\overline{\triangle H_2}$=1.377$\overline{b_2}$ 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 θ_η through Eq. (12). For the sake of convenient design, θ_η can be calculated by tabular search. Within the range of engineering design parameters, the values of θ_η are listed in Table 1 via calculation.

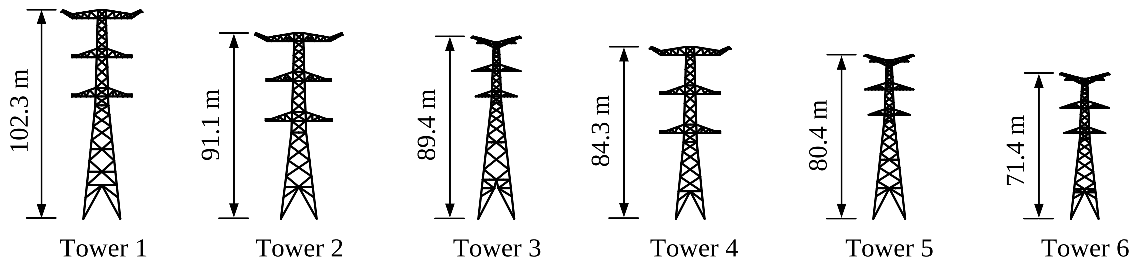


Fig. 4 Transmission towers with cantilevered cross-arms used in the statistical analysis

Table 1
θ_η values for transmission towers with cantilever cross-arms

$\overline{b_2}/H$	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 aera of cross-arms and diaphragms on $\beta(z)$ need to be considered. Therefore, two correction coefficients are introduced and can be expressed as:

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

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

where θ_m is the additional mass correction coefficient for $\beta(z)$; θ_a is the additional windshield area correction coefficient for $\beta(z)$; Σ_I and Σ_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 $\overline{\triangle H_1}$. 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=round$\left(\frac{H}{\overline{b_2}}\text{-}5\right)$, 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: $A_s(z_I)$=3.796$b_s(0)(\frac{\overline{b_2}^2}{H})$, $A_s(z_J)$=1.015$b_s(0)\mu_{b_s}^{1.5}(z_J)$, $M(z_I)$=2.147$m(0)(\frac{\overline{b_2}^2}{H})$ and $M(z_J)$=1.334$m(z_J)$. 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 θ_a and θ_m are $\overline{b_2}$, 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 θ_l. In the same way, within the range of engineering design parameters, θ_l is tabulated for convenient calculation, as shown in Table 2. In Table 2, after letting T= $b_s(H)/b_s(0)$, θ_η values corresponding to T=0.3 and T=0.5 are listed and θ_η values can be determined by linear internal interpolation for other T values.

Table 2
θ_l value for transmission towers with cantilever cross-arms

$\overline{b_2}/H$	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	T=0.3	T=0.6	T=0.3	T=0.6	T=0.3	T=0.6	T=0.3	T=0.6	T=0.3	T=0.6	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:

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

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

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

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

When calculating $\beta(z)$ of transmission towers with cantilever cross-arms, $B_z(z)$ adds the correction coefficients θ_η and θ_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.

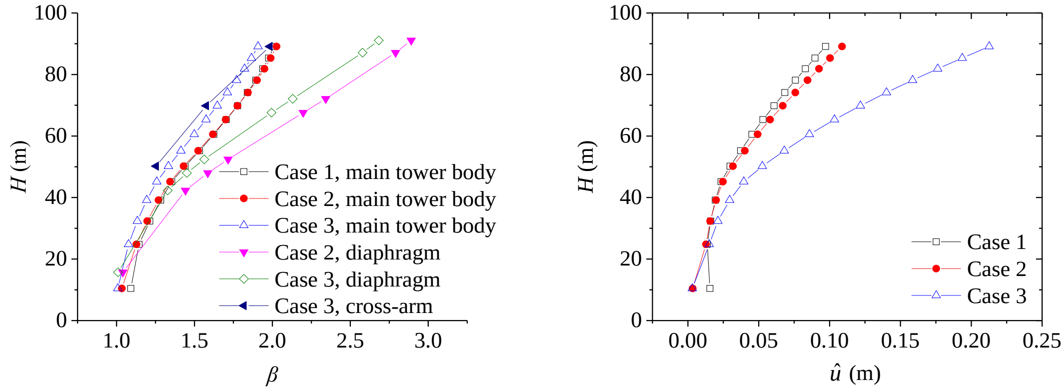
$$B_z(z) = k_\gamma H^{a_\gamma} \rho_z \rho_x \frac{\phi_1(z)}{\mu_z(z)} \theta_v \theta_\eta \theta_l \theta_b(z) \tag{19}$$

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.



(a) $\beta(z)$ (b) $\hat{u}(z)$

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 θ_b, θ_l and θ_η. 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 θ_b, θ_l and θ_η 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.

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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 onhigh 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.