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Stability of suspension bridge catwalks under a wind load

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Abstract. A nonlinear numerical method was developed to assess the stability of suspension bridge catwalks under a wind load. A section model wind tunnel test was used to obtain a catwalk's aerostatic coefficients, from which the displacement-dependent wind loads were subsequently derived. The stability of a suspension bridge catwalk was analyzed on the basis of the geometric nonlinear behavior of the structure. In addition, a full model test was conducted on the catwalk, which spanned 960 m. A comparison of the displacement values between the test and the numerical simulation shows that a numerical method based on a section model test can be used to effectively and accurately evaluate the stability of a catwalk. A case study features the stability of the catwalk of the Runyang Yangtze suspension bridge, the main span of which is 1490 m. Wind can generally attack the structure from any direction. Whenever the wind comes at a yaw angle, there are six wind load components that act on the catwalk. If the yaw angle is equal to zero, the wind is normal to the catwalk (called normal wind) and the six load components are reduced to three components. Three aerostatic coefficients of the catwalk can be obtained through a section model test with traditional test equipment. However, six aerostatic coefficients of the catwalk must be acquired with the aid of special section model test equipment. A nonlinear numerical method was used study the stability of a catwalk under a yaw wind, while taking into account the six components of the displacement-dependent wind load and the geometric nonlinearity of the catwalk. The results show that when wind attacks with a slight yaw angle, the critical velocity that induces static instability of the catwalk may be lower than the critical velocity of normal wind. However, as the yaw angle of the wind becomes larger, the critical velocity increases. In the atmospheric boundary layer, the wind is turbulent and the velocity history is a random time history. The effects of turbulent wind on the stability of a catwalk are also assessed. The wind velocity fields are regarded as stationary Gaussian stochastic processes, which can be simulated by a spectral representation method. A nonlinear finite-element model set forepart and the Newmark integration method was used to calculate the wind-induced buffeting responses. The results confirm that the turbulent character of wind has little influence on the stability of the catwalk.

Keywords: catwalk; stability; nonlinear numerical method; aerostatic coefficients; wind tunnel test; turbulent wind.

1. Introduction

The stability of a catwalk under a wind load is critical in the construction of long-span suspension

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bridges (Zheng & Liao 2002). In former times, the stability of the catwalk in strong wind was reinforced with wind cables. However, for a catwalk on a super long-span suspension bridge, wind cables have many drawbacks, such a protracted construction period, inconvenient navigation, and anchorage problems (Larsen 1993). Nowadays wind cables are seldom used. Thus, the stability of a catwalk on a super long-span suspension bridge must be emphasized more than ever before. In particular, there is a great need for a good method of investigating the stability of a catwalk under a wind load.

Under wind action, the catwalk is subjected to wind forces that are functions of the wind attack angle, the wind yaw angle, and the wind velocity (Simiu & Scanlan 1986). At a critical wind velocity, where the overturning pitching moment exceeds the torsional resistance of the catwalk or its effective stiffness is reduced to zero, the catwalk experiences static instability (Boonyapinyo, *et al.* 1994). Note also that the instability of the catwalk is generally preceded by a nonlinear load-displacement process due to the following: the nonlinear behavior of cables; nonlinear wind loads; and nonlinear geometric positions due to large displacement.

There are currently two methods of assessing the stability of a catwalk under a wind load. The first method is based on full model wind tunnel tests. A wind tunnel test with a full elastic model seems to be a good solution for studying the stability of catwalks. However, as the span of the suspension bridge is extended, the span of the catwalk becomes much longer; thus, it is impossible to simulate the prototype precisely in a wind tunnel with a full model based on a very small geometric scale (Jones, *et al*. 1995, Diana, *et al*. 1995). Moreover, wind tunnel tests are time-consuming and expensive. The second method is a nonlinear numerical method based on the data obtained from section model tests. This method requires measurement of the aerostatic coefficients of the catwalk through section model wind tunnel tests. A section model has a much larger geometric scale, and achieves greater precision, than a full model with a small geometric scale. When consideration is given to the displacement-dependent wind loads and the geometric nonlinearity of the catwalk, the nonlinear numerical method can give a satisfactory assessment of the stability of a catwalk.

The task of assessing the stability of a catwalk has until now been based on an assumption that wind comes in a direction that is normal to the catwalk. However, given that the wind may attack the catwalk from any direction, we need to consider the effects of the yaw angle of the wind.

In this paper, we present a nonlinear numerical method based on the data obtained from a section model test. The static aerodynamic coefficients of the catwalk were obtained from section model wind tunnel tests. Because the wind load that acts on the catwalk is displacement-dependent and the catwalk behavior is geometrically nonlinear, we used a linear increment method to study catwalk stability. After using a full model test on a catwalk with the mid-span of 960 m to check its stability as the wind velocity increased, we then compared the full model test results with the results obtained from the numerical method. The comparison confirms that the numerical method can efficiently assess catwalk stability with less time and cost than a full model test. We also studied the stability of another catwalk with a mid-span of 1490 m, under a wind load with a yaw angle, and calculated the wind-induced buffeting responses of the catwalk. The results show that the turbulent character of the wind has little influence on the stability of the catwalk.

2. Nonlinear numerical method for static stability

To evaluate the static stability behavior of a catwalk under displacement-dependent wind loads, we used an approach based on a nonlinear finite-element method (FEM). The catwalk structure was modeled with the FEM. The bearing cables and the handrail ropes were idealized by cable elements, and the U-shape frames were idealized by beam elements. The formulating equations of the catwalk are based on the following assumptions: the stiffness of the steel wire-mesh is negligible; 2) the wind-induced deflections of the pylon can cause catwalk displacement but have no obvious effect on catwalk stability; and the middle span and the side spans of the catwalk can be evaluated independently. We focused our discussion on the behavior of the middle span of the catwalk.

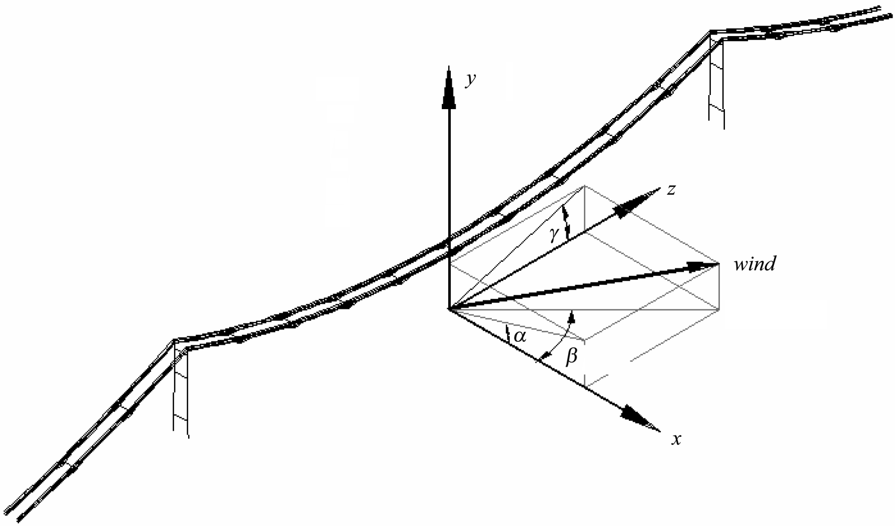


Fig. 1 The coordinate system of catwalk and wind direction definition

We defined our coordinate system as follows: the x-axis is the same as the transverse direction of the catwalk, the y-axis is vertical upward, and the z-axis is longitudinal along the bridge. According to the coordinate system, the wind forces have six components: F_x, F_y, F_z, M_x, M_y, and M_z. These components are functions of wind velocity, U; dislacement, u; the angle of attack, a; the posture angle, γ; and the yaw angle, β. The six components can be represented as follows:

$$\begin{aligned} &F_x = \frac{1}{2}\rho U^2 LHC_x;\ F_y = \frac{1}{2}\rho U^2 LBC_y;\ F_z = \frac{1}{2}\rho U^2 BHC_z; \\ &M_x = \frac{1}{2}\rho U^2 L^2 BC_{mx};\ M_y = \frac{1}{2}\rho U^2 L^2 HC_{my};\ \text{and}\ M_z = \frac{1}{2}\rho U^2 B^2 LC_{mz} \end{aligned} \tag{1}$$

where C_x, C_y, C_z, C_{mx}, C_{my}, and C_{mz} are the six component coefficients of the wind forces. They can be obtained from a section model tunnel test with special equipment, and they are also functions of wind velocity, displacement, the angle of attack, the posture angle, and the yaw angle. If the posture angle and the yaw angle both equal zero, the coefficients C_z, C_{mx}, and C_{my} reduce to zero, and the coefficients C_x, C_y, and C_{mz} are the component coefficients of the drag force, the lift force, and the pitching moment, respectively. These coefficients are called the three coefficients of the components. The parameter ρ is the air density; U is the wind velocity; H and B are the height and width of the step channel, respectively; and L is the length of the influence of the wind forces.

The nonlinear equations are written in the following form:

$$[K]u = F(U, u, \alpha, \gamma, \beta) \tag{2}$$

where $[K]$ is the structural stiffness matrix, which is comprised of a linear elastic stiffness matrix $[K]_e$ and a geometric stiffness matrix $[K]_g$; $F(U, u, \alpha, \gamma, \beta)$ is the generalized force vector, which is composed of the wind force; and $\boldsymbol{u}$ is the generalized displacement vector.

For each nonlinear analysis step, we used the wind forces obtained from Eq. (1) to form the generalized force vector $F(U, u, \alpha, \gamma, \beta)$, and we solved Eq. (2) by a linear increment method.

The convergence for a given wind velocity can be attained when the Euclidean norm of the static aerodynamic coefficients is less than the prescribed tolerance, that is,

$$\left\{ \frac{\sum_N [C_k(\alpha_j) - C_k(\alpha_{j-1})]^2}{\sum_N [C_k(\alpha_{j-1})]^2} \right\} \le \varepsilon \qquad (k = x, y, z) \quad (3)$$

where ε is the prescribed tolerance and N is the number of nodes subjected to the wind forces.

The catwalk is a cable structure with a small amount of stiffness. Hence, a large amount of displacement occurs in a strong wind. The displacement causes a change in the angle of attack. Furthermore, the static wind forces acting on the catwalk also change as a result of changes in the angle of attack, the posture angle and the yaw angle. That is, the behavior of the catwalk in a strong wind is geometrically nonlinear due to the large displacement, and the wind load is displacement-dependent.

3. Wind tunnel model test and the feasibility of the numerical method

To verify the feasibility of using the nonlinear numerical method to determine static stability, we performed a test with a wind tunnel model and then compared the results of the test with the results of our calculation. For our sample, we used a catwalk with a middle span of 960 m. The step channel of the catwalk was 3.8 m wide and 1.5 m high and its mass per unit of length was 182 kg/m; in addition, the elastic modulus of the cables was 1.3×10^5 MPa, and the mass of the lateral gallery was 7800 kg. The sag of the catwalk, which was the same as that of the main cable, was 88 m. The porosity of the wire-mesh was 70% at the bottom and 90% at the side.

3.1. Section model test of the step channel

Under normal wind action, the step channel is subjected to three components of the wind forces: the drag force, the lift force and the pitching moment. We used a section model test to obtain the coefficients of the three forces, termed static aerodynamic coefficients. A 2.1 m long section model of the step channel was constructed with a steel bar and a steel sieve in a scale of 1:6.

Because the wind forces that act on the catwalk mainly depend on the porosity of the steel wire-mesh, the porosity of the steel sieve of the section model must be the same as that of the prototype. To ensure that the Reynolds number achieves a reasonable effect, we chose the diameter of the wire of steel sieve in accordance with the experimental relation of the drag coefficient (C_D) of the cylinders versus Reynolds number, without meeting geometric similarity principles.

The section model test was performed in the second work section of the XNJD-1 wind tunnel of the Southwest Jiaotong University. The static aerodynamic coefficients of the step channel were measured by a force balance in a smooth flow with a yaw angle that varied from –12° to +12° in steps of 2°. The test was conducted for incoming wind velocities of 10 m/s, 20 m/s and 30 m/s. Fig.

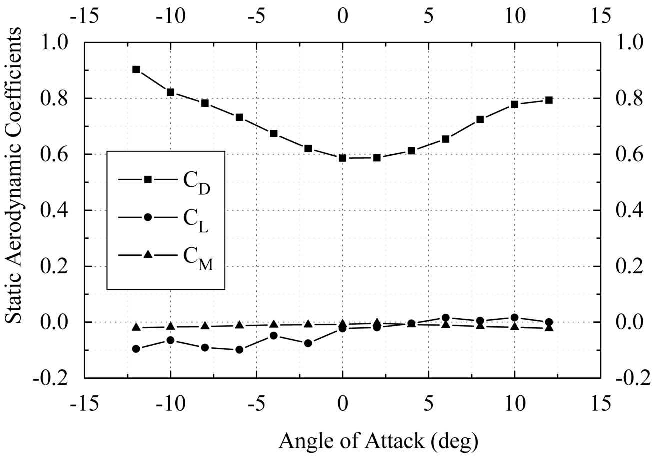


Fig. 2 Static aerodynamic coefficients versus angle of attack

2 shows the average static aerodynamic coefficients.

3.2. Wind tunnel test of the full catwalk model

The full catwalk model was made of nylon ropes, a sieve, steel U-shape frames and wooden lateral galleries. The geometric scale was 1:100, and the full catwalk model was 9.6 m long for the middle span.

The load-displacement behavior of cable structures such as a catwalk is known to depend mainly on gravity stiffness and geometric stiffness. The geometric stiffness is relative to the wind load and the gravity of the catwalk. The elastic parameter is insignificant in this situation. Thus, in designing the full catwalk model we need to match three parameters: the mass parameter, the gravity parameter (Froude number), and the porosity of the wire-mesh. In the same gravitational field, the mass similarity guarantees that the gravity stiffness of the model is similar to that of the prototype.

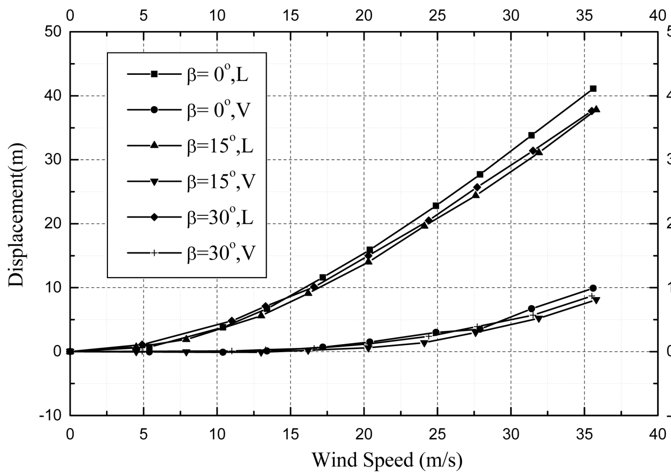


Fig. 3 Displacements of middle span versus wind speed

Because the static aerodynamic coefficients depend strongly on the Reynolds number, particularly in the lower wind velocity range, we had to ensure that the scaled forces acting on the small details of the model were not significantly different from those of the prototype.

The full model test, which was carried out in wind tunnel FL-13 of CARDC, had the following dimensions: 12 m (width) × 16 m (height) × 25 m (length). The incoming flow was smooth, and its velocity was measured with an anemometer. The test was performed with different yaw angles and a varying number of lateral galleries.

The displacements in the full model test of the catwalk were recorded. Fig. 3 illustrates the displacements at the middle of the catwalk with five lateral galleries at different wind speeds and different yaw angles. In Fig. 3, L is the lateral displacement, V is the vertical displacement, and β is the yaw angle. Fig. 3 shows that the yaw angle has little effect on the displacement of the catwalk. When the yaw angle, β, is 0°, the catwalk suffers the largest displacement.

The results of the full model test indicate that no instability occurs when the wind velocity is less than 35 m/s, which is larger than the design wind velocity (27 m/s). When the wind velocity is up to 60 m/s, the catwalk oscillates with a large lateral asymmetrical swing.

3.3. Comparison of the test and calculation results

Fig. 4 shows the displacement results at the middle of the span, as obtained from the test (after conversion to the prototype) and from the numerical calculation.

As shown in Fig. 4, the results of the full model test and the numerical calculation differ slightly for two main reasons. First, the geometric scale of the full model is smaller than that used in the section model. Furthermore, the components in the full model are smaller than those in the section model, and the Reynolds number for the full model test is smaller than that of the section model test. Because the drag coefficient of the circular member increases as the Reynolds number decreases, the wind forces that act on the full model are larger than the forces used in the nonlinear calculation, the static coefficients of which were acquired from the section model test. As a result, the displacement values in the full model test are larger than those in the calculated results. A second reason for the slight discrepancy between the results of the full model test and the prototype

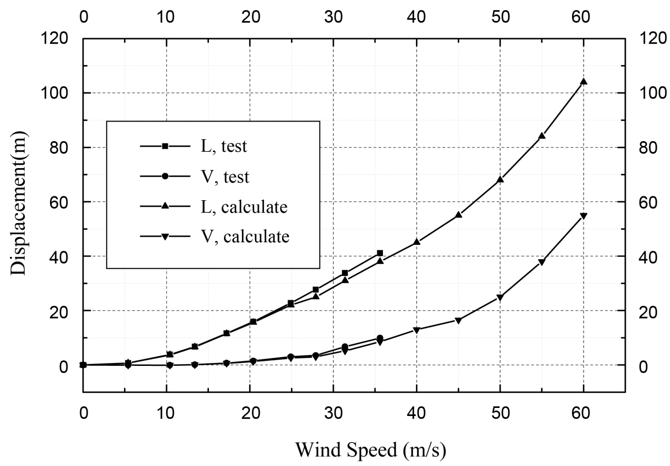


Fig. 4 Comparing between the results from test and from calculation

is the geometric scale of 1:100; at this scale, some model components of the full catwalk were too small to be manufactured.

The nonlinear numerical method (based on the section model test) can be used to assess the stability of a catwalk with a comparable degree of accuracy as the full model wind tunnel test but at lower cost and in a shorter time.

4. Catwalk stability under a wind load at a yaw angle

To analyze catwalk stability under a wind load at a yaw angle, we undertook a case study of the catwalk of the Runyang Yangtze suspension bridge, which is currently the longest catwalk in China.

4.1. Catwalk layout and parameters

The span of the catwalk of the Runyang Yangtze suspension bridge is 470 m + 1490 m + 470 m. The sag of the main cable or the catwalk is 135.362 m. Each step channel of the catwalk consists of 10ϕ54 bearing ropes, 2ϕ20 hand ropes (upper), 4ϕ16 hand ropes (middle and lower), wire meshes, wooden steps, gallows frames, vertical stays, horizontal stays, and so on. The step channel is 4.0 m wide and 1.5 m high. The elastic modulus of the bearing ropes is 1.3×10^5 MPa. The bottom meshes are stacked by ϕ5 (50 × 70) wire mesh and ϕ2 (25 × 25) wire mesh. The side mesh is ϕ5 (50 × 100) wire mesh. The porosity of the wire mesh is 83.6% at the top, 84.6% at the bottom, and 85.5% at the side. There are nine cross bridges in the middle span and two cross bridges on each side span.

The roughness of the terrain at the site of the Runyang Yangtze suspension bridge is between category A and B (Chinese code). The design wind velocity is 29.0 m/s at the construction stage. The allowable velocity for the aerostatic stability is 40.0 m/s. The aerostatic stability of the catwalk is guaranteed when the critical velocity of the stability is larger than the allowable velocity.

4.2. Catwalk stability in normal wind

In normal wind, the step channel is subjected to three components of the wind forces: the drag

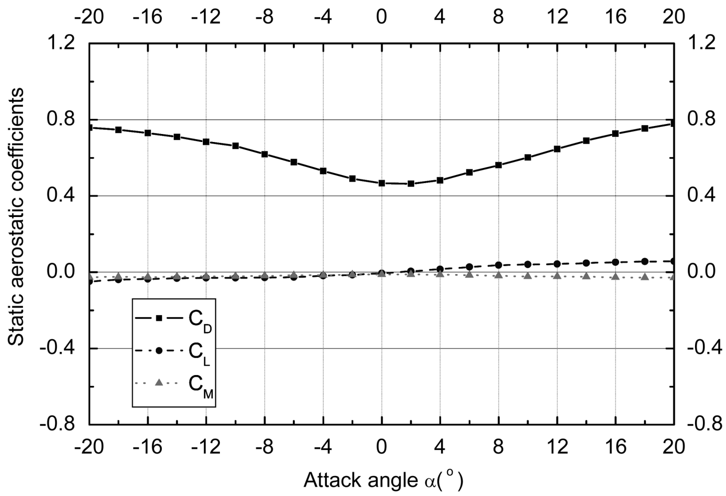


Fig. 5 Static aerostatic coefficients versus angle of attack

force, the lift force, and the pitching moment. We obtained the coefficients of the three forces, termed aerostatic coefficients, from the section model tests. A 2.1 m long section model of the step channel was constructed with a steel bar and a steel sieve at a geometric scale of 1:6.

Because the wind forces that act on the catwalk depend mainly on the porosity of the steel wire-mesh, the porosity of the steel sieve in the section model must be the same as that of the prototype. To ensure that the Reynolds number achieves a reasonable effect, we chose the diameter of the wire in the steel sieve in accordance with the experimental relation between the drag coefficient (C_D) of

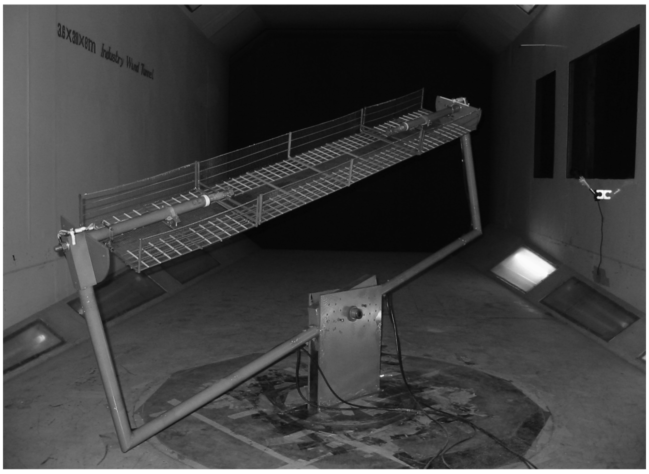


Fig. 6 Special experiment apparatus used to measure 6 aerostatic coefficients

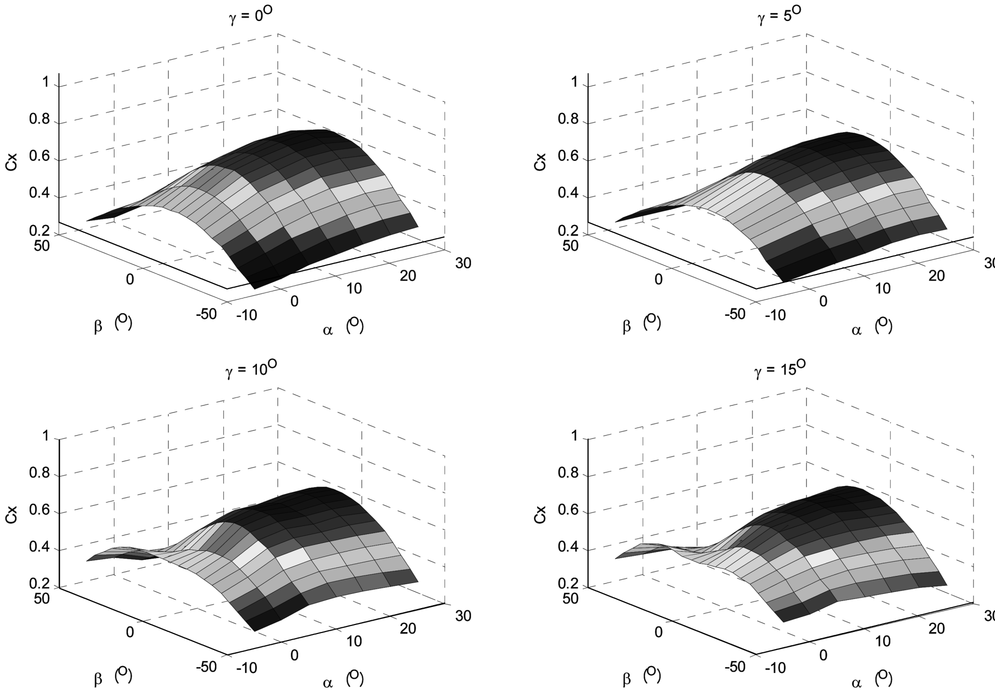


Fig. 7 Aerostatic coefficients C_X

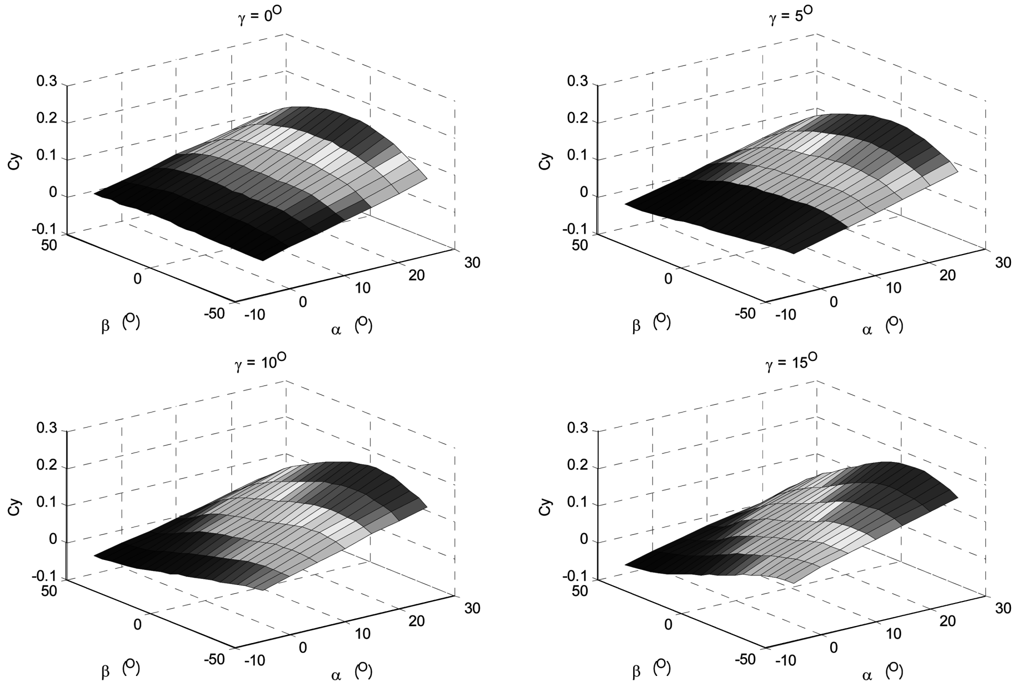


Fig. 8 Aerostatic coefficients C_Y

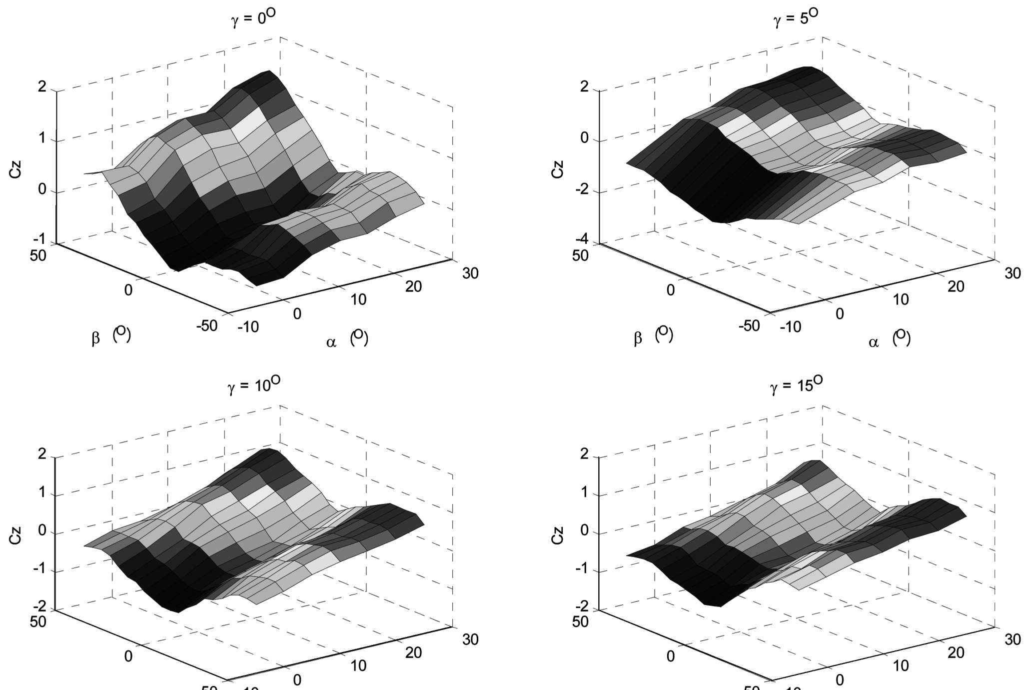


Fig. 9 Aerostatic coefficients C_Z

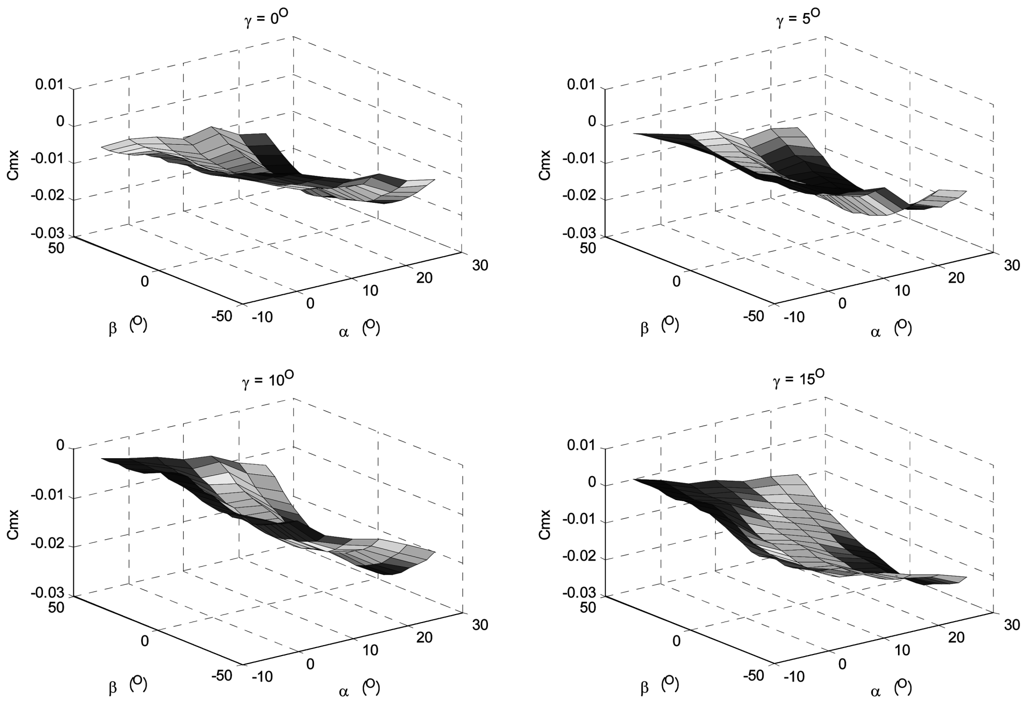


Fig. 10 Aerostatic coefficients C_{mx}

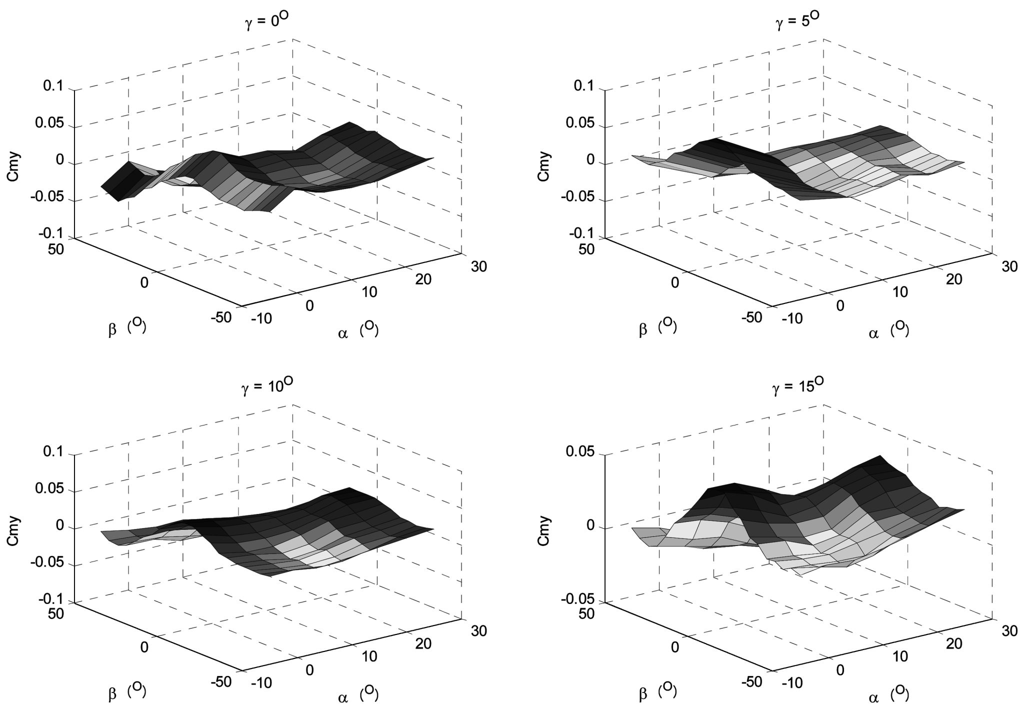


Fig. 11 Aerostatic coefficients C_{my}

the cylinders versus Reynolds number, without meeting geometric similarity principles.

The test was conducted at incoming wind velocities of 10 m/s, 20 m/s, and 30 m/s. Fig. 5 shows the average aerostatic coefficients.

The initial state in the nonlinear numerical simulation was set to a state in which the incoming wind was normal to the bridge axis in a horizontal plane; that is, where the yaw angle and the posture angle are both zero.

In building a finite-element model of the catwalk, we simulated the bearing ropes and handrail ropes with bar elements and we modeled the cross bridges, gallows frames, and pylons with beam elements. We then used a nonlinear numerical method based on a section model test to analyze the critical velocity of the catwalk. This analysis was based on the supposition that the stiffness of the net was zero. The critical velocity of the aerostatic instability was 71 m/s, which is larger than the allowable velocity.

4.3. Catwalk stability under a wind load with a yaw angle

Natural wind is always not perpendicular to the axis of the catwalk. Under a wind load with a yaw angle, the step channel is subjected to six components of wind forces according to the global coordinate. As a result, six aerostatic coefficients are needed. We measured the coefficients by using a special experimental apparatus that could be rotated in three directions. The section model of the catwalk was in a scale of 1:12 and the model length was 1.0 m. At each end of the model, a 0.5 m long pseudo-model was preset to eliminate the end effect (see Fig. 6).

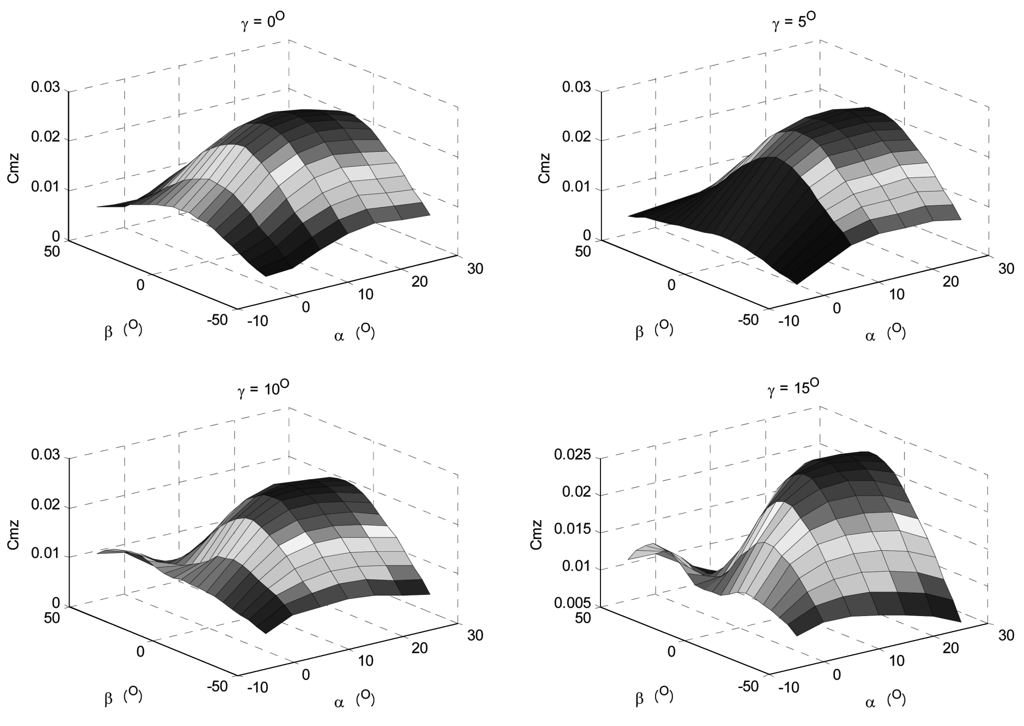


Fig. 12 Aerostatic coefficients C_{mz}

The test was carried out at an incoming wind velocity of 10 m/s and 15 m/s; the attack angle, α, was varied between -5° and +25° at $\Delta\alpha = 5°$; the posture angle, γ, was varied between 0° and +20° at $\Delta\gamma = 5°$; and the yaw angle, β, was varied between -50° and +50° at $\Delta\beta = 5°$. Obviously, as shown in Fig. 5, when $\gamma = 0°$ and $\beta = 0°$, C_x, C_y, and C_{mz} are the same as the three aerostatic coefficients: namely the coefficients of the drag force, the lift force, and the pitching moment.

Averaging the aerostatic coefficients under the two test wind velocities, we obtained the six aerostatic coefficients, which change with the attack angle, α, the posture angle, γ, and the yaw angle, β. Although we obtained a great amount of test data, our descriptions are limited to C_x, C_y, C_z, C_{mx}, C_{my}, C_{mz} in Figs. 7, 8, 9, 10, 11 and 12, respectively. Figs. 7 to 12 confirm that C_x, C_y and C_{mz} reach a maximum value when the yaw angle, β, equals 10°.

We used the finite-element model to analyze the stability of the catwalk under a normal wind load. The catwalk is a three-dimensional space structure. Under a wind load with a yaw angle, the posture angles of every position along the catwalk differ from one another other. Thus, the wind forces under a wind load with a yaw angle differ from the wind forces under a normal wind load.

At the same time, under strong wind the catwalk is deformed with large displacement and the attack angle and the posture angle change with the displacement. The geometrical nonlinearity and the load nonlinearity must be considered. Furthermore, the wind load is a critical issue in any assessment of catwalk stability under a wind load with a yaw angle. For each moment and different location of the catwalk, the posture angle and the attack angle differ; thus, for each nonlinear step, we need to calculate the angles and, accordingly, the wind load.

We studied catwalk stability in terms of eight yaw angles: namely 0°, 5°, 10°, 15°, 20°, 30°, 45° and 60°. The study is based on the assumption that the velocity along the longitudinal axis of the bridge at any one moment is the same at the same height; we also ignored the effects of wind turbulence.

The analytical results show that the maximum lateral displacement and the maximum vertical displacement both appear at the middle of the main span. The maximum twist angle occurs at the middle of the two cross bridges near the middle of the main span. When the wind velocity rises, the catwalk's maximum lateral displacement, maximum vertical displacement, and maximum twist

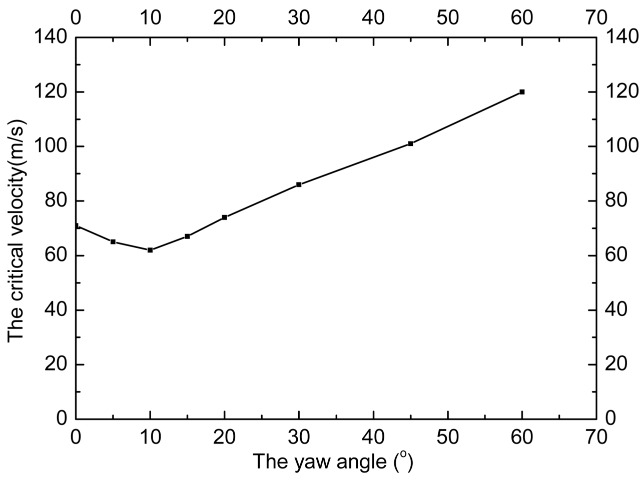


Fig. 13 The critical velocity versus the yaw angle

angle increase nonlinearly. When the wind velocity reaches the critical velocity, the catwalk suffers instability, the maximum twist angle rises sharply, and the step channel of the catwalk between the two adjacent cross bridges near the middle of the main span overturns.

Fig. 13 shows the critical velocity versus the yaw angle. When $\beta = 10^{\circ}$, the aerostatic coefficients C_x, C_y and C_{mz} have maximum values. As a result, the wind load that acts on the catwalk is at its most harmful level and the critical velocity, which is equal to 62 m/s, is at its smallest level, though this velocity is still larger than the allowable velocity. The static catwalk stability of the Runyang Yangtze suspension bridge is satisfactory even when the wind attacks the catwalk with a yaw angle.

Table 1 shows the displacements at the middle of the catwalk span at the design wind velocity. The table shows that when $\beta = 10^{\circ}$, the displacements at the middle of the catwalk span are at a maximum value because the aerostatic coefficients are at a maximum value at the yaw angle.

Table 1 Displacements at middle of span of catwalk at design wind velocity

β	0°	5°	10°	15°	20°	30°	45°	60°
Lateral displacement (m)	16	14	16.9	13.1	11.5	4.7	3.3	1.9
Vertical displacement (m)	3	2.6	3.2	2.5	2.2	1.5	1.1	0.8

5. Effect of turbulent wind

In the atmospheric boundary layer, the wind is turbulent and the wind velocity is a random time history. Thus, there is a need to assess how the turbulent wind affects catwalk stability.

5.1. Simulation of the stochastic wind velocity fields

Random wind velocity fields are usually regarded as stationary Gaussian stochastic processes, and can therefore be simulated by a spectral representation method. For engineering application, a three-dimensional correlated stochastic wind field of a long span catwalk can be simplified into many one-dimensional independent wind fields along the pylons and step channel of the catwalk. These one-dimensional stochastic wind fields, which can be treated as an independent one-dimensional multivariate stochastic process, can be efficiently and computationally simulated by a spectral representation method.

The samples of a one-dimensional multivariate Gaussian process with a zero mean can be simulated with the following equation (Li, *et al.* 2005):

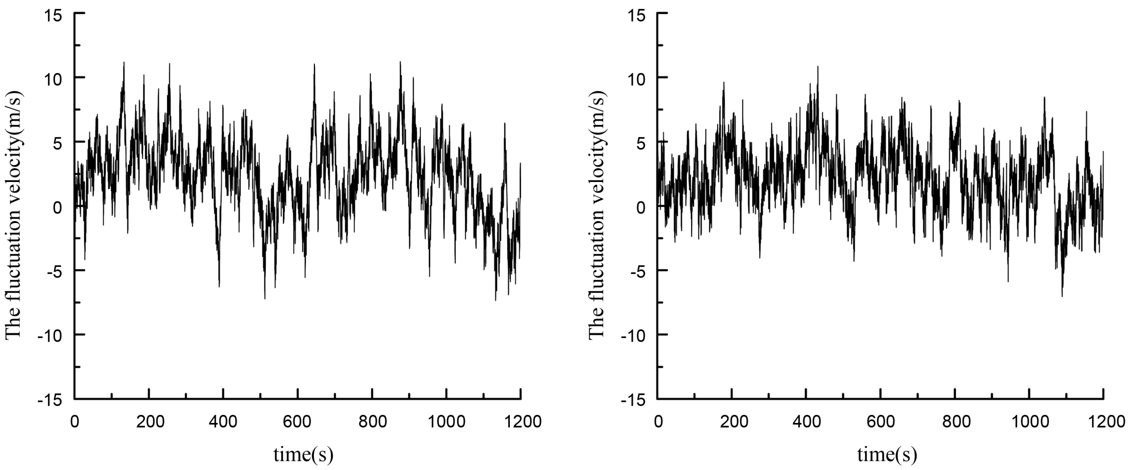
$$f_j(t) = 2\sqrt{\Delta\omega}\sum_{m=1}^{j}\sum_{l=1}^{N}|H_{jm}(\omega_{ml})|\cos(\omega_{ml}t - \theta_{jm}(\omega_{ml}) + \phi_{ml}),$$

where $j = 1, 2, \ldots, n$; n is the number of the simulation points on the catwalk; N is the number of frequency interval, often being a sufficiently large positive integer; $\Delta\omega$ is the frequency interval, and $\Delta\omega = w_u/N$; ϕ_{ml} is a set of independent random phase angles uniformly distributed between 0 and 2π with density of $1/2\pi$; ω_{ml} is the double-indexing of the frequency, and $\omega_{ml} = (l-1)\Delta\omega + m\Delta\omega/N$; ω_u the upper cutoff frequency; H_{jm} is an element of the lower triangular matrix which is obtained by the Cholesky's decomposition of the cross-spectral density matrix of one dimension multivariate

Gaussian process; and $f_i(t)$ is a sample of the stochastic wind speed history which will be used to determine wind loads on the catwalk at each time step.

The application of FFT technique can dramatically improve the computational efficiency. The wind spectrum and the mean velocity are homogeneous along the catwalk. Under such conditions, by applying the explicit expression of the Cholesky's decomposition to the cross-spectral density matrix, we can quickly simulate the wind velocity fields along the catwalk.

We present the horizontal wind spectrum in Kaimal's form and the vertical spectrum in the form presented by Lumley and Panofsky. The coherence function is in Davenport's form, and the coefficient relating to the wind correlation is 7. The time interval is 0.125 s and the total time is 1200 s. We used 60 simulation points, uniformly distributed along the catwalk at intervals of 25 m. Fig. 14 shows the simulated wind velocity history for the mean velocity of 29 m/s, which is the design wind velocity of the catwalk.



(a) At middle span (b) At 1/4 span

Fig. 14 The simulated wind velocity history for the mean velocity of 29 m/s

5.2. Wind loads on the catwalk

The static wind loads on the catwalk can be determined by means of a sectional model wind tunnel test. We can then express the buffeting loads induced by stochastic wind fluctuations as follows:

$$L_b(x, t) = -\rho U^2 B\left[C_L(\alpha_0)\frac{u(x, t)}{U} + \left[\frac{1}{2}\frac{dC_L}{d\alpha}\bigg|_{\alpha=\alpha_0} + \frac{A}{B}D_D(\alpha_0)\right]\frac{w(x, t)}{U}\right]$$

$$D_b(x, t) = \rho U^2 B\left[\frac{A}{B}C_D(\alpha_0)\frac{u(x, t)}{U}\right]$$

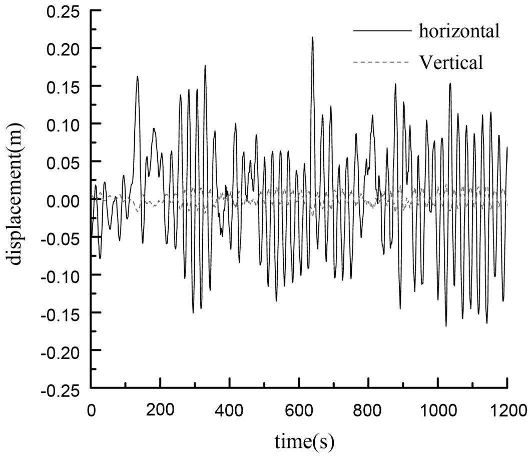
$$M_b(x, t) = \rho U^2 B^2\left[C_M(\alpha_0)\frac{u(x, t)}{U} + \frac{1}{2}\frac{dC_L}{d\alpha}\bigg|_{\alpha=\alpha_0}\frac{w(x, t)}{U}\right],$$

where C'_L and C'_M are the slopes of C_L and C_M, respectively; $u(x, t)$ is the wind velocity fluctuation in the mean wind flow direction; $w(x, t)$ is the wind velocity fluctuation in the vertical direction, with $u(x, t)$ and $w(x, t)$ capable of being simulated by means of a simplified spectral representation method; A is the height of the catwalk; U is the mean velocity; and B is the width of the catwalk. The aerodynamic admittance functions are assumed to be 1.0.

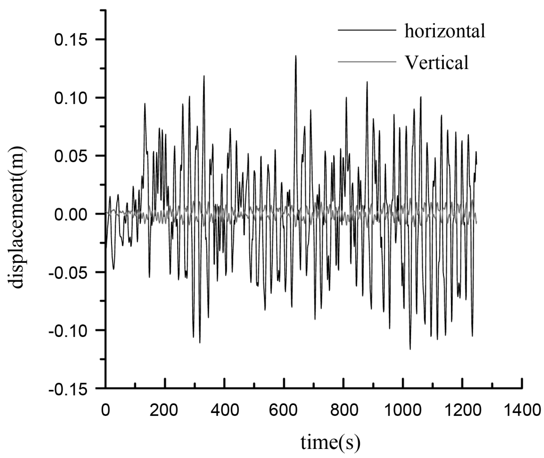
5.3. Results

To calculate the wind-induced buffeting responses, we used our nonlinear finite-element model which was set at forepart, and the Newmark integration method. The mean velocity was 29 m/s and the yaw angle, β, was 0º. The static wind responses by the stationary wind loads are shown in Table 1, and the wind-induced buffeting displacement responses for two special sections of the catwalk are shown in Fig. 15.

Fig. 15 confirms that the buffeting displacements are very small. At the middle of the span, the maximum buffeting displacement in the horizontal direction is 0.215 m, and the maximum buffeting displacement in the vertical direction is 0.024 m. Accordingly, the displacement at the middle of the catwalk span at the design wind velocity (as shown in Table 1) is 16 m in the horizontal direction and 3 m in the vertical direction. At the 1/4 span, the maximum buffeting displacement in the horizontal direction is 0.136 m and the maximum buffeting displacement in the vertical direction is 0.013 m. We can deduce therefore that the buffeting displacements are much smaller than the static wind responses and that turbulent wind has little influence on the stability of the catwalk.



(a) At middle span



(b) At 1/4 span

Fig. 15 The wind-induced buffeting displacement responses

6. Conclusions

The nonlinear numerical method (based on the section model test) can be used to assess the stability of a catwalk with a comparable degree of accuracy as the full model wind tunnel test but at lower cost and in a shorter time.

Natural wind is not always normal to the catwalk. Under a wind load with a yaw angle, the wind forces on the step channel of the catwalk are the functions of the wind attack angle, the wind yaw angle, and the wind velocity. According to the global coordinate, there are six aerostatic load components on the catwalk. At the critical wind velocity, static instability of the catwalk occurs whenever the overturning pitching moment exceeds the torsional resistance of the catwalk or the catwalk's effective stiffness is reduced to zero. The behavior of the catwalk in strong wind is geometrically nonlinear due to large displacement, and the wind load is displacement-dependent. Using data obtained from the section model test, we can analyze the aerostatic stability of the catwalk by means of the nonlinear finite-element approach. We measured six aerostatic coefficients with a special experimental apparatus. Our results verify that the static stability of the catwalk of the Runyang Yangtze suspension bridge is satisfactory even when the wind attacks the catwalk with a yaw angle.

On the basis of the wind-induced buffeting responses, which we calculated with the finite-element model and the nonlinear numerical method, we deduce that the turbulent character of wind has little influence on the stability of the catwalk.

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