Research Article

Analysis of Span-Directional Coherence Function and Buffeting Response of a Long-Span Natural Gas Pipeline Suspension Bridge under a Turbulent Wind Field

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A long-span natural gas pipeline suspension bridge is prone to buffeting under the action of a turbulent wind field. In order to accurately calculate the buffeting response of the structure under a turbulent wind field, the 1:15 segment model wind tunnel test is used to obtain the aerodynamic coefficient and flutter derivative of the bridge deck structure. According to the test results, the buffeting force coherence functions under five different span-directional spacing are fitted. The results show that the buffeting force coherence function corresponding to different wind attack angles has a peak at the corresponding wing grid vibration frequency in the low-frequency region; when the spacing increases to $r = 0.51$ m or above, the amplitude of coherence function decreases significantly; for the spacing of $r = 0.17$ m, the buffeting force coherence functions in different directions are obviously different but the corresponding coherence functions of resistance, lift, and torque show a similar curve trend between different wind attack angles. Based on the Scanlan buffeting force correction model, the buffeting response under the reference wind speed of 30.1 m/s is analyzed in the frequency domain and compared with the wind tunnel test results of the whole bridge. The results show that the buffeting response calculated in this paper is in good agreement with the wind tunnel test results of the whole bridge and the buffeting response law is consistent. The maximum value of vertical buffeting response is located near the 1/4 span, and the maximum values of lateral and torsional response are located in the middle of the span. The lateral buffeting displacement response is significantly greater than the vertical buffeting displacement response. Under different wind attack angles, the vertical, lateral, and torsional buffeting displacement responses of the bridge deck structure increase nonlinearly with the increase of wind speed.

1. Introduction

Buffeting phenomenon is the random-forced vibration of the structure caused by turbulent wind in nature. It is a limited amplitude vibration. When the buffeting effect is severe, it may cause structural fatigue [1]. The buffeting aerodynamic theory appeared in the 1930s [2, 3]. The buffeting force models in the classical buffeting theory include the Davenport quasi-steady buffeting force model, modified quasi-steady buffeting force model, and Scanlan buffeting force-modified model [4]. The Davenport quasi-steady buffeting force model is based on quasi-steady assumption and rigid model assumption, without considering the influence of fluctuating wind on buffeting force and the incomplete correlation of buffeting force in the span direction. The modified quasi-steady buffeting force model considers the unsteady characteristics of buffeting force by introducing the aerodynamic admittance function which depends on the frequency characteristics of fluctuating wind [5–8]. The Scanlan buffeting force correction model is based on the assumption of the elastic model, and the coupling relationship between structural vibration and wind field is considered by introducing aerodynamic stiffness and aerodynamic resistance through self-excited force expression.
This paper analyzes the buffeting response under a turbulent wind field based on the Scanlan buffeting force correction model.

The long-span pipeline suspension bridge has small stiffness and low damping. The wind-resistant cable system is usually used to improve the wind-resistant stability of the structure [4]. It is a three-dimensional spatial structure. The buffeting force model of the classical Sears aerodynamic admittance function can only describe its two-dimensional effect, and the spatial correlation of aerodynamic force along the span direction needs to be further considered. In the early research, the spatial correlation of fluctuating wind load along the bridge span direction was not fully considered and the incoming fluctuating wind correlation was used to replace the correlation of fluctuating wind load. In recent years, scholars have found [16–18] that the span-directional correlation of buffeting force acting on the structure is stronger than that of wind speed in this direction. The span-directional correlation of buffeting force is characterized by coherence function in the frequency domain. Taking a suspension pipe bridge project as the research background, Li established a finite element model and carried out static and dynamic analysis and buffeting response analysis based on the virtual excitation method [19]. Huang et al. carried out finite element numerical simulation analysis on buffeting response of the suspension pipeline bridge with the main span of 376 m by using the virtual excitation method [20]. Taking the Lancang River Suspension pipeline bridge of China-Myanmar Oil and Gas Pipeline as an object, Chen studied the influence of different structural parameters on its natural vibration characteristics, conducted buffeting time-domain response analysis, and conducted variable-universe fuzzy-adaptive control research on the structure [21]. Li analyzed the buffeting force correlation of the suspension pipeline bridge through the section model wind tunnel test and obtained the aerodynamic admittance function [22]. In this paper, wind tunnel tests are carried out to investigate the influence of the wind attack angle on span-directional coherence function under different span distances. According to the measured aerodynamic coefficient, coherence function, aerodynamic admittance function, and flutter derivative in the wind tunnel, the buffeting response of the pipeline suspension bridge under the design reference wind speed of 30.1 m/s is analyzed in the frequency domain and compared with the results of the full bridge wind tunnel test.

2. Section Model Wind Tunnel Test

2.1. Design of the Test Model. In order to obtain the aerodynamic coefficient, aerodynamic admittance function, and flutter derivative required for the calculation of buffeting response of the pipeline suspension bridge, fit the span-directional coherence function and investigate the influence of the wind angle of attack on the span-directional coherence function under different span distances; a 1:15 segment model wind tunnel test is designed for a natural gas pipeline suspension bridge. The diameter of the natural gas pipeline is 610 mm and the width of the bridge deck is 2.76 m. The bridge deck structure is shown in Figures 1 and 2.
The wind tunnel test adopts the high-frequency balance force measurement method of the rigid segment model. The lower support structure is the steel structure, and the model is separated. The overall model includes 12 intersegment models, the design length of each intersegment model is 167 mm, the distance between each model is 2 mm, and the spring connection is adopted between the models. In order to ensure that the test device and test instrument will not affect the aerodynamic shape of the structure, the dynamometer balance and support are placed inside the pipe model, as shown in Figures 3 and 4.

2.2. Test Equipment and Test Conditions. The test was carried out in a XNJD-1 wind tunnel laboratory. The width, height, and length of the wind tunnel test section are 2.4 m, 2.0 m, and 16.0 m, respectively. The turbulent wind field can be simulated in the laboratory, which can be realized by the passive turbulence generation method or active turbulence generation method. In this paper, the latter is used to simulate the turbulent wind field. The test device is a self-developed vibrating wing grid structure, which can provide the rotation frequency of the 1 Hz turbulent wind field with average wind speeds of 7.0 m/s and 10.0 m/s under an amplitude of 30°.

The measurement test of the span-directional correlation of buffeting force takes the vertical centerline of the wind tunnel as the symmetrical center. The buffeting force of five pairs of internode models (1~5) is measured successively.

Table 1: Buffeting force measurement condition.

<table>
<thead>
<tr>
<th>Number</th>
<th>Wind speed (m/s)</th>
<th>Wind angle of attack (°)</th>
<th>Wing grid vibration frequency (Hz)</th>
<th>Integral scale (m)</th>
<th>Turbulence intensity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>-3</td>
<td>1.0</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>0</td>
<td>1.0</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>+3</td>
<td>1.0</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>-3</td>
<td>1.0</td>
<td>10</td>
<td>5.6</td>
</tr>
<tr>
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<td>0</td>
<td>1.0</td>
<td>10</td>
<td>5.6</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>+3</td>
<td>1.0</td>
<td>10</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Figure 5: Schematic diagram of buffeting force measurement condition.

Figure 6: Coherence function of working condition 1 (wind speed 7 m/s, wing grid vibration frequency 1.0 Hz, and wind angle of attack −3°).
Figure 7: Coherence function of working condition 4 (wind speed 7 m/s, wing grid vibration frequency 1.0 Hz, and wind angle of attack 0°).

Figure 8: Coherence function of working condition 7 (wind speed 7 m/s, wing grid vibration frequency 1.0 Hz, and wind angle of attack +3°).

Figure 9: Coherence function of working condition 10 (wind speed 10 m/s, wing grid vibration frequency 1.0 Hz, and wind angle of attack −3°).
The buffeting force is symmetrical on both sides of the measurement center line. The working conditions of buffeting force correlation measurement include two wind speeds of 7 m/s and 10 m/s and three wind attack angles of \(-3^\circ\), 0°, and +3°. The layout of five pairs of measurement points is shown in Figure 5, which corresponds to five span distances (\(r = 0.17\) m, 0.51 m, 0.85 m, 1.18 m, and 1.52 m). The buffeting force measurement condition is shown in Table 1.

### 2.3. Span-Directional Correlation Function

At present, there are many empirical models for the study of the coherence function of buffeting force [23]. Some of the main coherence function models include the Davenport model, Kimura model, Dryden model, and Jakobsen model. In this paper, the test results are fitted by using the buffeting force coherence function formula considering the influence of the model scale ratio proposed by Ma [23] and the expression is as follows:

\[
\text{Coh}_L(r, f) = \alpha \left( \eta^{2/7} K_{300}(\eta) - \frac{\eta^{8/8} K_{100}(\eta)}{\theta} \right),
\]

where

\[
\eta = \left( \frac{L_w^x}{B^{2x+b}} \right)^{\frac{1}{2}} \beta \sqrt{1 + \frac{\lambda(fB/U)^y(L_w^x)^d}{B^{2x}}},
\]

\[
\theta = 1 + \frac{\mu(fB/U)^y(L_w^x)^d}{B^{2x}}.
\]

In formulas (1)–(3), \(a, b, c, d, e, c, \alpha, \beta, \lambda, \) and \(\mu\) are the parameters to be fitted.

Through the wind tunnel test, the span-directional coherent functions of buffeting force under the 3°, 0°, and
+3° wind attack angles are obtained. The wind tunnel test wind speed is 7 m/s and 10 m/s, and the wing grid vibration frequency is 1.0 Hz, as shown in Figures 6–11.

The abscissa is dimensionless frequency. It can be seen in Figure 6 that there is a peak value of about 1 in the low-frequency region of the buffeting force coherence function in all directions under 3° wind angle of attack. The peak value corresponds to the vibration frequency of the wind tunnel vibrating wing grid. Comparing the coherence functions of different r values, it can be seen that the coherence of buffeting force is significant for small spacing r (r = 0.17 m); when the spacing increases to r = 0.51 m and above, the value of the coherence function in the frequency domain outside the peak decreases significantly and fluctuates close to the value 0. For the coherence function of r = 0.17 m with obvious coherence, it can be seen that the buffeting force coherence function in different directions is obviously different. Comparing Figures 6–8, it can be seen that the characteristics of buffeting force coherence function corresponding to different wind attack angles are very similar: a peak appears at the corresponding wing grid vibration frequency in the low-frequency region; when the spacing increases to r = 0.51 m or above, the amplitude of coherence function decreases significantly; for the spacing of r = 0.17 m, the buffeting force coherence functions in different directions are obviously different but the corresponding coherence functions of resistance, lift, and torque show a similar curve trend between different wind attack angles.

3. Frequency Domain Analysis of Buffeting in the Turbulent Wind Field

3.1. Frequency Domain Analysis Method of Buffeting Response. In this paper, the buffeting response analysis under the turbulent wind field is carried out based on the Scanlan buffeting force correction model. The aerodynamic load acting on the pipeline suspension bridge deck mainly considers the aerodynamic self-excited force and buffeting force [24]. In the calculation, the Davenport buffeting force model and Scanlan self-excited force model are used to
analyze the buffeting response [1, 9, 14, 15]. According to the characteristics of the pipeline suspension bridge, the coupling between vibration modes in different directions and the correlation between fluctuating wind and horizontal components and vertical components of the suspension pipeline bridge are ignored in the analysis. The generalized coordinate power spectrum is as follows:

\[
S_{\xi\omega} = \frac{1}{I_i} (\rho U)^2 |J_{h,i}(\omega)|^2 |H_{h,i}(\omega)|^2 S_{\xi}(\omega),
\]

\[
S_{\xi\rho} = \frac{1}{I_i} (\rho U)^2 |J_{p,i}(\omega)|^2 |H_{p,i}(\omega)|^2 S_{\rho}(\omega),
\]

\[
S_{\xi\alpha} = \frac{1}{I_i} (\rho U)^2 |J_{\alpha,i}(\omega)|^2 |H_{\alpha,i}(\omega)|^2 S_{\alpha}(\omega),
\]

where

\[
|J_{h,i}(\omega)|^2 = \left| \int_{a_i}^{b_i} r_i(x_1) r_i(x_2) \text{Coh}(K, |x_1 - x_2|) dx_1 dx_2 (r_i = h, p, \alpha) \right|^2.
\]

\[
|H_{r,i}(\omega)|^2 = \frac{1}{(\Omega_{r,i} - \omega^2)^2 + \left( 2\xi_{r,i}\Omega_{r,i}\omega \right)^2} (r_i = h, p, \alpha).
\]

\[
|J_{h,i}(\omega)|^2 \text{ and } |H_{r,i}(\omega)|^2 \text{ are the joint acceptance function and frequency response function of the } i\text{th mode in three motion directions, respectively, and } \text{Coh}(K, |x_1 - x_2|) \text{ is the aerodynamic span-directional coherence function. In equation (6),}
\]

\[
\Omega_{h,i} = \omega_{h,i},
\]

\[
\Omega_{p,i} = \omega_{p,i},
\]

\[
\Omega_{\alpha} = \sqrt{\frac{\rho B^3 w^3 A_s^2 G_{\alpha}}{I_i}},
\]

\[
|J_{\alpha,i}(\omega)| = \left( \int_{a_i}^{b_i} r_i(x_1) r_i(x_2) \text{Coh}(K, |x_1 - x_2|) dx_1 dx_2 (r_i = h, p, \alpha) \right). \]

Figure 13: Aerodynamic admittance function of a single-layer pipeline with a 0° wind attack angle.
ζ′ = \frac{1}{2\Omega_h} \left( 2\xi_h \omega_h - \frac{\rho B^2 \omega H^2 G_h}{I_h} \right),
ζ′ = \frac{1}{2\Omega_p} \left( 2\xi_p \omega_p - \frac{\rho B^2 \omega P^2 G_p}{I_p} \right),
ζ′ = \frac{1}{2\Omega_\alpha} \left( 2\xi_\alpha \omega_\alpha - \frac{\rho B^2 \omega A^2 G_\alpha}{I_\alpha} \right),

where \( \omega \) and \( \xi \) correspond to the natural frequency and damping ratio of each moving direction of the structure, respectively.

The power spectrum of displacement response of any point on the bridge girder in three motion directions is as follows:

\[
S_h(x, K) = \sum_i \sum_j B^2 h_i(x) h_j(x) S_{\xi_i}(K),
\]

\[
S_p(x, K) = \sum_i \sum_j B^2 p_i(x) p_j(x) S_{\xi_p}(K),
\]

\[
S_\alpha(x, K) = \sum_i \sum_j B^2 \alpha_i(x) \alpha_j(x) S_{\xi_\alpha}(K).
\]

3.2. Wind Spectrum. At present, the commonly used empirical formulas of wind spectrum applicable to the fluctuating wind in the atmospheric boundary layer include the Davenport spectrum, Kailmal spectrum [25], Karman spectrum, and Hino spectrum [26, 27]. Take the Karman spectrum empirical formula as the wind spectrum used for buffeting
response calculation, and the wind spectrum expression of pulsating wind in three directions is as follows:

\[
\begin{align*}
\frac{nS_u(n)}{\sigma_u^2} &= \frac{4X_u}{(1 + 70.8X_u^2)^{5/6}}, \\
\frac{nS_v(n)}{\sigma_v^2} &= \frac{4X_v(1 + 755.2X_v^2)}{(1 + 283.2X_v^2)^{11/6}}, \\
\frac{nS_w(n)}{\sigma_w^2} &= \frac{4X_w(1 + 755.2X_w^2)}{(1 + 283.2X_w^2)^{11/6}},
\end{align*}
\]

(10)

where

\[
X_r = \frac{nL_r}{U} (r = u, v, w),
\]

(11)

where \(n\) is the wind speed frequency, \(\sigma_r^2 (r = u, v, w)\) is the variance of pulsating components in each direction, \(L_r^x\) is the turbulence integral scale of pulsating wind in the corresponding direction, and \(C\) is the average wind speed.

3.3. Aerodynamic Admittance Function. Based on the wind speed of 7 m/s and the wing grid vibration frequency of 1.0 Hz, the measured aerodynamic admittance functions of the single-layer suspension pipeline bridge corresponding to the \(-3^\circ\) wind attack angle, \(0^\circ\) wind attack angle, and \(+3^\circ\) wind attack angle are shown in Figures 12–14.

<table>
<thead>
<tr>
<th>Wind angle of attack (°)</th>
<th>(C_D)</th>
<th>(C_L)</th>
<th>(C_M)</th>
<th>(C_V)</th>
<th>(C_M)</th>
</tr>
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<tbody>
<tr>
<td>-12</td>
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<td>-0.038</td>
<td>0.543</td>
<td>-0.154</td>
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<tr>
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<td>0.544</td>
<td>-0.154</td>
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<tr>
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<td>-0.052</td>
<td>0.537</td>
<td>-0.148</td>
<td>0.1</td>
</tr>
<tr>
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<td>-0.063</td>
<td>0.537</td>
<td>-0.149</td>
<td>0.1</td>
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<tr>
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<tr>
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</table>

Table 2: Aerodynamic coefficient of the main beam section (wind shaft system and body shaft system).
Table 3: Flutter derivatives of the main girder of the suspension pipeline bridge.

<table>
<thead>
<tr>
<th>$V^*$</th>
<th>$A_1^*$</th>
<th>$A_3^*$</th>
<th>$H_1^*$</th>
<th>$H_4^*$</th>
<th>$V^*$</th>
<th>$A_2^*$</th>
<th>$A_3^*$</th>
<th>$H_2^*$</th>
<th>$H_3^*$</th>
</tr>
</thead>
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<tr>
<td>4.188</td>
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<td>0.755</td>
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<td>-0.052</td>
<td>-0.043</td>
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</tr>
<tr>
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<td>-0.31</td>
<td>0.861</td>
<td>4.008</td>
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<td>-0.077</td>
<td>0.998</td>
<td>0.516</td>
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<td>-0.068</td>
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<td>-0.162</td>
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<td>0.091</td>
<td>-0.187</td>
<td>-2.276</td>
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</tr>
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</table>

Figure 16: Vertical buffeting response at the 0° wind angle of attack.

Figure 17: Vertical buffeting response at the 3° wind angle of attack.
3.4. Aerodynamic Coefficient and Flutter Derivative. The aerodynamic coefficient is measured by the wind tunnel test of the suspension pipeline bridge segment model, as shown in Table 2 and Figure 15. $C_D$ and $C_L$ represent the drag coefficient and lift coefficient of the wind axis system, respectively. $C_L$ and $C_V$ represent the drag coefficient and lift coefficient of the body axis system, respectively. $C_M$ represents the lifting moment coefficient. The Scanlan self-excited force model is adopted, as shown in formula (1). Its flutter derivative is determined by the wind tunnel test of the segment model, as shown in Table 3.

$$L_{se} = \frac{1}{2} \rho U^2 B \left[ KH_1 \frac{h}{U} + KH_2 \frac{B_0}{U} + K^2 H_1^2 \alpha + K^2 H_4^2 \frac{h}{B} \right],$$

$$M_{se} = \frac{1}{2} \rho U^2 B^2 \left[ KA_1^2 \frac{h}{U} + KA_2^2 \frac{B_0}{U} + K^2 A_1^2 \alpha + K^2 A_4^2 \frac{h}{B} \right].$$ (12)

3.5. Analysis of Buffeting Response in the Frequency Domain. Based on the Scanlan buffeting force correction model, the fishbone beam finite element model, the measured aerodynamic coefficient, flutter derivative, aerodynamic admittance, and the fitted span coherence function in the wind tunnel are used to calculate the root mean square value of the buffeting response of the suspension pipeline bridge under the design reference wind speed of 30.1 m/s. The calculation results are shown in Figures 16–21.

4. Buffeting Response of the Full Bridge Wind Tunnel Test

4.1. Full Bridge Wind Tunnel Test Model. In order to test the buffeting of the suspension bridge in the turbulent wind field, the full bridge aeroelastic model wind tunnel test was carried out in the XNJD-3 wind tunnel laboratory and the size of the wind tunnel test section is 22.5 m (width) × 4.5 m (height) × 3.5 m (height).
m (high) × 36 m (length), with a wind speed range of 1.0 m/s~16.5 m/s. Among them, the wind speed field is measured by the stream line four channel hot wire anemometer of the Denmark DANTEC company and the displacement response of the model is measured by the laser displacement meter.

The test object is a completed single-span simply supported steel truss-stiffened suspension pipeline bridge in China, and its main geometric parameters are shown in Table 4. The cable towers are steel towers, and the cable towers on both sides are designed symmetrically. The main beam consists of 35 internode models, of which 33 standard sections are 397 mm long and two special sections are 498.5 mm and 698.5 mm long. The pneumatic shape of the internode model is carved from the PVC plastic plate. The stiffness of the internode model is provided by a 6 mm × 6 mm solid iron bar. The simulation of the stiffness of the main beam is realized by the special “U” spring connection between the internode models, with a 3 mm gap between the internode models. The mass and mass moment of inertia of the main beam are simulated by the weight of the lead bar and copper block. Tables 5 and 6 display the
model geometry and quality parameters and modal test parameters, respectively. The wind tunnel test model is shown in Figure 22.

4.2. Turbulent Wind Field Simulation. In order to meet the similar conditions between the wind field of the wind tunnel test and the wind field at the bridge site, the wind field simulation of the wind tunnel test is carried out in the form of a spire and rough element, as shown in Figure 23.

Figure 24 shows the comparison between the simulated wind spectrum and the measured value of the atmospheric boundary layer where the model is located. The simulated wind spectrum is in good agreement with the target spectrum within the converted frequency range \((f > 10^{-1})\), which meets the requirements of the buffeting test. Field measurement in the bridge site and model measurement in the wind tunnel are shown in Table 7.

4.3. Test Conditions. The full bridge aeroelastic model wind tunnel test is carried out under a turbulent flow field, focusing on the buffeting response of the suspension pipeline bridge in the corresponding atmospheric boundary layer. The case setups are shown in Table 8.

5. Comparative Analysis of Test Results and Frequency Domain-Calculated Values

Through the full bridge wind tunnel test, the root mean square value of buffeting response of the pipeline suspension bridge under a 0° wind angle of attack and +3° wind angle of attack is obtained. Through the comparative analysis between the measured value and the calculated value, it is found that they are in good agreement and show a consistent buffeting response law, which shows that the calculation method proposed in this paper can accurately calculate the structural buffeting response under the turbulent wind field.

The buffeting response law under a 0° wind angle of attack is analyzed. It can be seen in Figures 25–30 that the measured vertical, lateral, and torsional displacement
responses of the wind tunnel increase nonlinearly with the increase of wind speed. The comparison between the test results and the calculation results shows that they are highly consistent in the overall trend and very close in amplitude. The location of the maximum displacement response of the test is as follows: the vertical buffeting response is located at 1/4 of the span, and the lateral and torsional responses are located at the middle of the span, which is consistent with the calculation results. Among them, the lateral buffeting displacement response is significantly greater than the vertical buffeting displacement response.

Table 7: Field measurement in the bridge site and model measurement in the wind tunnel.

<table>
<thead>
<tr>
<th>Height (m/s)</th>
<th>Rough length (m)</th>
<th>Design wind speed (m/s)</th>
<th>( I_u ) (%)</th>
<th>( I_w ) (%)</th>
<th>( L_u ) (m)</th>
<th>( L_w ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 (1)</td>
<td>1</td>
<td>30.1 (6.02)</td>
<td>29 (29)</td>
<td>14.5 (14.5)</td>
<td>90 (3.6)</td>
<td>40 (1.6)</td>
</tr>
</tbody>
</table>

The values in brackets indicate model measurement in the wind tunnel.

Table 8: Case setups of the turbulent flow field.

<table>
<thead>
<tr>
<th>Number</th>
<th>Wind deflection angle (°)</th>
<th>Wind angle of attack (°)</th>
<th>Test wind speed range (m/s)</th>
<th>Wind speed range of real bridge (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0–6.0</td>
<td>0–30.1</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>0–6.0</td>
<td>0–30.1</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0</td>
<td>0–6.0</td>
<td>0–30.1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>3</td>
<td>0–6.0</td>
<td>0–30.1</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>3</td>
<td>0–6.0</td>
<td>0–30.1</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>3</td>
<td>0–6.0</td>
<td>0–30.1</td>
</tr>
</tbody>
</table>

Figure 25: Comparison of vertical buffeting response in the mid span under a 0° wind attack angle.

Figure 26: Comparison of vertical buffeting response at a 1/4 span under the 0° wind attack angle.

Figure 27: Comparison of lateral buffeting response in the mid span under the 0° wind attack angle.

Figure 28: Comparison of lateral buffeting response at the 1/4 span under the 0° wind attack angle.
Figure 29: Comparison of torsional buffeting response in the mid span under the 0° wind attack angle.

Figure 30: Comparison of torsional buffeting response at the 1/4 span under the 0° wind attack angle.

Figure 31: Comparison of vertical buffeting response in the mid span under the +3° wind attack angle.

Figure 32: Comparison of vertical buffeting response at the 1/4 span under the +3° wind attack angle.

Figure 33: Comparison of lateral buffeting response in the mid span under the +3° wind attack angle.

Figure 34: Comparison of lateral buffeting response at the 1/4 span under the +3° wind attack angle.
measured vertical, lateral, and torsional displacement responses of the wind tunnel increase nonlinearly with the increase of wind speed. The comparison between the test results and the calculation results shows that they are highly consistent in the overall trend and very close in amplitude. The location of the maximum displacement response of the test is as follows: the vertical buffeting response is located at 1/4 of the span, and the lateral and torsional responses are located at the middle of the span, which is consistent with the calculation results. Among them, the lateral buffeting displacement response is still significantly greater than the vertical buffeting displacement response. The response law of buffeting angle +3° is consistent with that of the wind buffeting angle test. However, the torsional displacement response of the 0° wind angle of attack is significantly greater than that of the +3° wind angle of attack.

6. Conclusion

The aerodynamic coefficient, flutter derivative, and aerodynamic admittance are obtained by the wind tunnel test, and the span-directional coherence function is fitted. The buffeting response analysis under the turbulent wind field is carried out based on the Scanlan buffeting force correction model. The results are in good agreement with the results of the full bridge wind tunnel test, and the two show consistent regularity.

Through the test of the span-directional coherence function, it is found that the corresponding coherence functions of drag, lift, and moment show a similar curve trend between different wind attack angles. There is a peak in the low-frequency region of the buffeting force coherence function, which corresponds to the vibration frequency of the vibrating wing grid of the wind tunnel; when the span distance increases to $r = 0.51$ m or above, the value of coherence function in the frequency domain outside the peak decreases significantly and fluctuates near 0; for the spacing of $r = 0.17$ m, the buffeting force coherence function in different directions is obviously different.

According to the analysis of the test and calculation results of buffeting response, the lateral and torsional peak responses of suspension bridge structure are located in the middle of the span, while the vertical buffeting peak response is located in 1/4 of the span.

Comparing the lateral buffeting displacement response and vertical buffeting displacement response of suspension bridge, it is found that the former is significantly greater than the latter.

Comparing the buffeting displacement response test results of the 0° wind angle of attack and the +3° wind angle of attack, they maintain a high degree of consistency in the law but the torsional displacement response of the 0° wind angle of attack is significantly greater than that of the +3° wind angle of attack.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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