Correlation Analysis of Bridge Flutter Critical Wind Speed and Three-Component Force Coefficient Based on Grey Correlation Method

Gao Hui, Li Xing*

School of Civil Engineering, Erdos Institute of Technology, Ordos, Inner Mongolia, China

*Corresponding author: 20090040@oit.edu.cn

Abstract. Based on the grey correlation theory, analyze the correlation between the three typical main girder section flutter critical wind speed and three-component force coefficient of long-span bridge truss section, closed steel box girder section, and slotted steel box girder section. Provide a reference for establishing the prediction model of the flutter critical wind speed estimated from the static wind load. It is convenient to quickly and accurately judge the stability of bridge flutter. The analysis results show that the lift coefficient, the lift moment coefficient and their derivatives have a good correlation.

Keywords: Bridge engineering, grey correlation method, critical flutter wind speed, three-component force coefficient.

1. Introduction

Since the Tacoma Bridge in Washington State, USA, was destroyed by the wind in 1940, bridge experts around the world began to explore the wind resistance of bridges. In the design of long-span bridges, especially the flutter stability is an important part of the bridge wind resistance design. Generally, wind tunnel tests are used to test the flutter stability of long-span bridges, but the wind tunnel vibration test takes a long time and is expensive. Therefore, domestic and foreign scholars have begun to study the work of quickly judging the stability of bridge flutter. In particular, predict the flutter critical wind speed of the main beam section with different wind resistance measures. Bai Hua, Gao Hui etc. [1-2] used the flutter derivative to analyze the relationship between aerodynamic damping, aerodynamic stiffness and the three-component force coefficient and gave the bridge flutter stability evaluation parameter F, which was used to quickly select the bridge section aerodynamics. Zhu Zhiwen etc. [3-4] used numerical simulation to predict the flutter critical wind speed of long-span bridges, but this method is only suitable for simple streamlined sections, and the calculation accuracy of the cross section needs to be improved considering various wind resistance measures. In order to quickly and accurately determine the flutter stability, a direct relationship between the flutter critical wind speed and the three-component force coefficient should be established. Based on the grey correlation theory, this paper analyzes the correlation between the critical flutter wind speed and the three-component force coefficient by applying the wind resistance test data of the built bridges. It provides reference for establishing the prediction model of flutter critical wind speed estimated by static wind load. which is convenient for faster and accurate judgment of bridge flutter Stable performance.
2. Grey relational analysis

Grey Relational Analysis (GRA) [5] is a multi-factor statistical analysis method, which is based on the sample data of various factors and uses the degree of gray relevance to describe the strength, size and order of the relationship between factors. In grey relational analysis, firstly, determine the reference series \(X_0=(x_0(1), x_0(2), \cdots, x_0(m))\), \(m\) is the number of indicators. Secondly, determine the comparison sequence \(X_i=(x_i(1), x_i(2), \cdots, x_i(k))^T\); \(i=1, 2, \cdots, n\), \(k=1, 2, \cdots, m\). Calculate the correlation coefficient:

\[
\zeta_i(k) = \min_{k} \frac{\min_i |x_0(k)-x_i(k)| + \rho \cdot \max_i |x_0(k)-x_i(k)|}{|x_0(k)-x_i(k)| + \rho \cdot \max_i |x_0(k)-x_i(k)|}
\]

(1)

Where: \(|x_0(k)-x_i(k)|\) is the difference sequence, \(i=1, 2, \cdots, n\), \(k=1, 2, \cdots, m\). \(\rho\) is the resolution coefficient, 0.5 is usually taken. Calculate the degree of relevance:

\[
r_i = \frac{1}{m} \sum_{k=1}^{m} \zeta_i(k)
\]

(2)

3. Correlation analysis of flutter critical wind speed and three-component force coefficient

In this paper, the flutter critical wind speed of three typical main girder sections of truss, closed steel box girder and slotted steel box girder is used as the reference sequence, and the corresponding three-component force coefficient is used as the comparison sequence to analyze the correlation of long-span bridge under wind load between the two.

3.1. Steel truss section

The Liujiaxia Suspension Bridge has a main span of 536m and a steel truss cross section. The original plan wind tunnel test flutter critical wind speed (0° wind angle) is 43.8m/s, which is less than the flutter test wind speed. Through more than ten wind tunnel tests on the main girder, program 10 can effectively increase the critical flutter wind speed. This article will analyze the correlation between the flutter critical wind speed and the three-component force coefficient of the original plan (scheme 0) and scheme 10. Figure 1 shows the three-component force coefficients of the two design schemes.
Figure 1. Three-component force coefficient of different schemes of Liujiaxia Bridge

Table 1. Correlation degree between critical flutter wind speed and three-component force coefficient of steel truss section at 0° wind angle

| Scheme | Correlation Coefficient | Correlation | Flutter Critical Wind Speed (m/s) | 42.5 | 66.5 |
|--------|--------------------------|-------------|-----------------------------------|------|------|
| $C_D$  | 1.072                    | 1.152       | 0.876                             | 0.938|
| $C_L$  | 0.02                     | 0.17        | 0.333                             | 0.667|
| $C_M$  | 0.033                    | 0.042       | 0.922                             | 0.961|
| $C_D'$ | 0.031                    | 0.023       | 0.808                             | 0.404|
| $C_L'$ | -3.027                   | -1.797      | 0.781                             | 0.891|
| $C_M'$ | -0.44                    | -0.528      | 0.905                             | 0.952|
| $1/|C_D'\cdot C_M'|$ | 0.751 | 1.054 | 0.956 | 0.978 |

It can be known by calculating the correlation between the critical flutter wind speed and the three-component force coefficient of different schemes of the steel truss section $\gamma_{c_d'} > \gamma_{c_v} > \gamma_{c_u} > \gamma_{c_u'} > \gamma_{c_v'} > \gamma_{c_d'}$.

3.2. Closed steel box girder section
Humen Second Bridge Nizhou Waterway twin-tower double-span suspension bridge, the main span is 1688m, and the main beam cross-section is a closed steel box beam. The width and height of the main beam section of the main girder in Scheme 2 and Scheme 3 selected in this paper are the same, and the nozzle forms are different. Figure 2 shows the three-component force coefficients of the two design options.
Figure 2. Three-component force coefficient of different schemes of Humen Second Bridge

Table 2. Correlation degree of flutter critical wind speed and three-component force coefficient of closed steel box girder section under 3° wind angle

| scheme | scheme2 | scheme3 | Correlation coefficient | Correlation |
|--------|---------|---------|-------------------------|-------------|
| Flutter critical wind speed (m/s) | 46.8 | 70.2 | 0.570 | 0.785 |
| $C_D$ | 1.27 | 0.948 | 0.570 | 0.785 |
| $C_L$ | 0.096 | 0.05 | 0.505 | 0.753 |
| $C_M$ | 0.039 | 0.051 | 0.839 | 0.919 |
| $C_D'$ | -0.01 | 0.005 | 0.333 | 0.667 |
| $C_L'$ | -3.669 | -0.831 | 0.440 | 0.720 |
| $C_M'$ | -2.494 | -0.86 | 0.464 | 0.732 |
| $1/|C_D' \cdot C_M'|$ | 0.328 | 0.466 | 0.927 | 0.963 |

It can be known by calculating the correlation between the critical flutter wind speed and the three-component force coefficient of the different schemes of the closed steel box girder fracture $\gamma_{CL} > \gamma_{C|C|} > \gamma_{CM} > \gamma_{CM'} > \gamma_{Ct} > \gamma_{C|t|}$. 

3.3. Slotted steel box girder section
The preliminary design of the Hong Kong-Zhuhai-Macao Bridge's river-sea direct ship channel bridge is a three-tower cable-stayed bridge with a main span of 258m. Option 2 and Option 3 adopt two wind resistance measures, namely, wind camphor and no wind barrier. Figure 3 shows the three-component force coefficients of the two design schemes.
Figure 3. Three-component force coefficient of different schemes of Hong Kong-Zhuhai-Macao Bridge

Table 3. Correlation degree between critical flutter wind speed and three-component force coefficient of slotted steel box girder section at 0° wind angle

| Scheme | Correlation coefficient | Correlation |
|--------|-------------------------|-------------|
| Flutter critical wind speed (m/s) | 100.65 | 116 |
| $C_D$ | 2.018 | 1.436 | 0.814 | 0.907 |
| $C_L$ | 0.052 | 0.032 | 0.782 | 0.891 |
| $C_M$ | 0.119 | 0.105 | 0.877 | 0.938 |
| $C_D'$ | 0.01 | 0.05 | 0.333 | 0.167 |
| $C_L'$ | -1.755 | -1.84 | 0.934 | 0.967 |
| $C_M'$ | 0.311 | 0.227 | 0.820 | 0.910 |
| $1/|C_L' \cdot C_M'|$ | 1.832 | 2.469 | 0.908 | 0.954 |

It can be known by calculating the correlation degree between the critical flutter wind speed and the three-component force coefficient of the open steel box girder fracture of different schemes $\gamma_{C_L} > \gamma_{C_L C_M} > \gamma_{C_M} > \gamma_{C_L} > \gamma_{C_M} > \gamma_{C_D}$.

4. Conclusions

1. Calculate the correlation between the flutter critical wind speed and the three-component force coefficient of the three typical main girder section forms of truss section, closed steel box girder and slotted steel box girder, which can be used as a reference basis for estimating the calculation formula of flutter critical wind speed. It is convenient to quickly and accurately judge the stability of bridge flutter.

2. The three typical main beam section flutter critical wind speeds have good correlation with lift coefficient, lift moment coefficient and their derivatives.
References
[1] Bai Hua, Gao Hui. Evaluation of bridge flutter stability with the aid of three-component force coefficient [J] China Journal of Highway and Transport, 2014, 27(7): 68-73
[2] Bai Hua, Fang Cheng, etc. Parameters for rapid evaluation of bridge flutter stability and their applications [J] China Journal of Highway and Transport, 2016, 29(8): 92-98
[3] Zhu Zhiwen, Li Youxiang, Chen Zhengqing. Flutter derivative identification method for parallel long-span bridges under the influence of uncertain aerodynamic interference effects [J]. China Journal of Highway and Transport, 2011, 24(5): 40-60
[4] Zhu Zhiwen, Gu Ming. CFD-AM-CSD method for fast prediction of critical wind speed of long-span bridge flutter [J]. China Civil Engineering Journal, 2014, 47(7): 88-96
[5] Deng Julong. The theory and method of social economic gray system [J]. Chinese Social Sciences, 1984 (6): 47-60.